Industrial Thermal Decarbonization

RENEWABLE
THERMAL
COLLABORATIVE

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)

Contents

Industrial thermal emissions and abatement options

Decarbonization pathways to net zero 2050

Decarbonization roadmaps for industry and key sectors

Supporting materials:

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

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

Emission Types

Fuel combustion related

Electricity generation

Process related

Product lifecycle

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

Decarbonization Technological Pillars[1]

Low-carbon fuels & energy sources

CCS[2]

Low-carbon feedstocks

Electrification

Energy storage

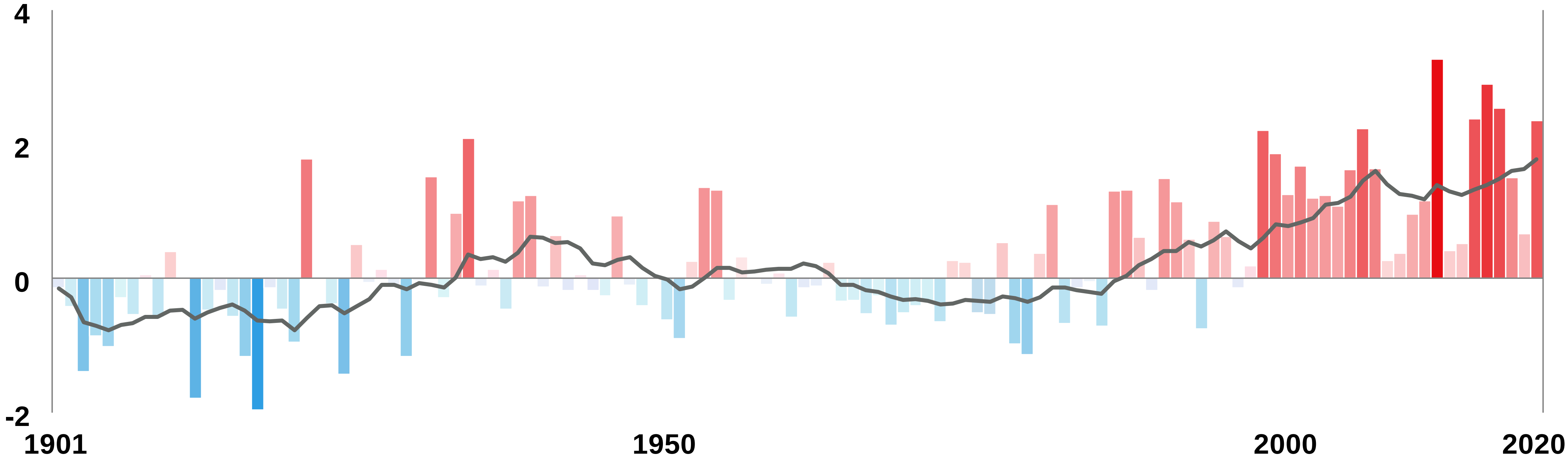
Energy efficiency

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

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

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

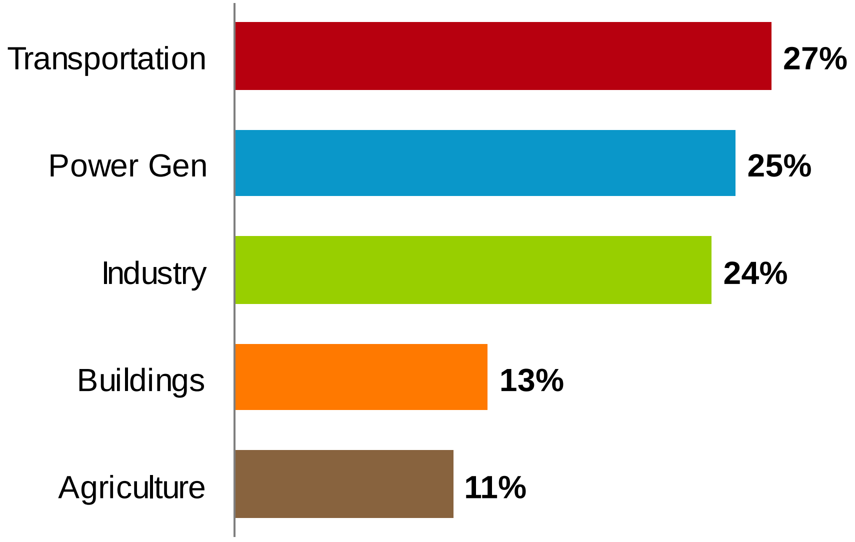
Average air temperature anomaly in the 48 contiguous states (°C)



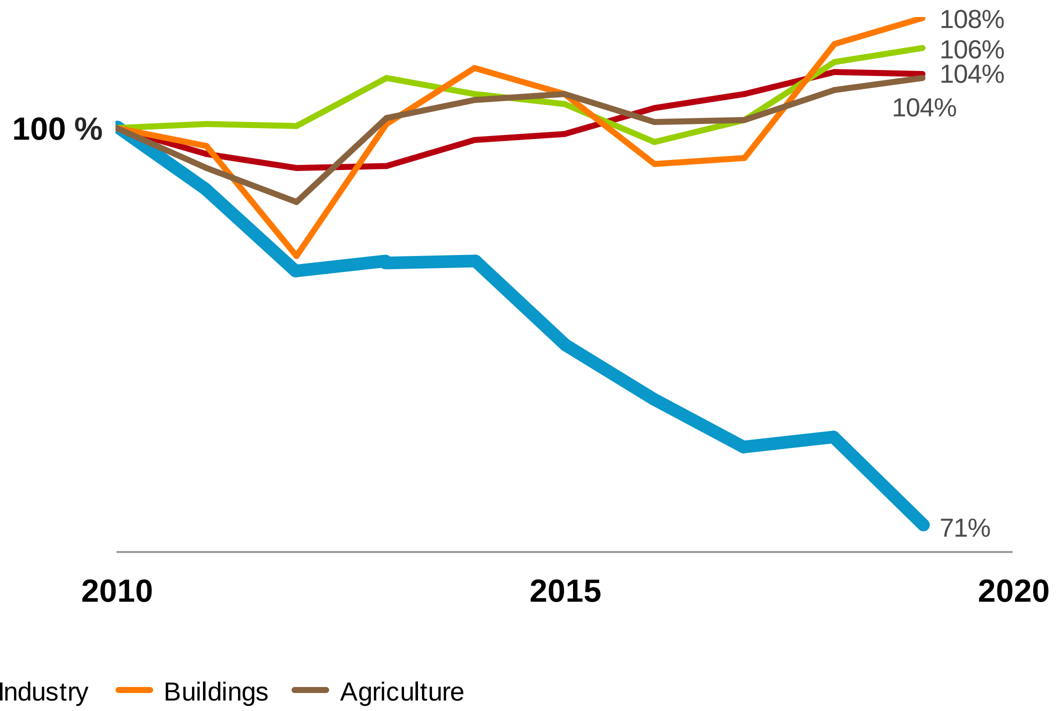
Source: USGCRP (U.S. Global Change Research Program) 2017 Climate science special report: Fourth National Climate Assessment, volume I

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

Industrial emissions represent
24% of total US emissions …



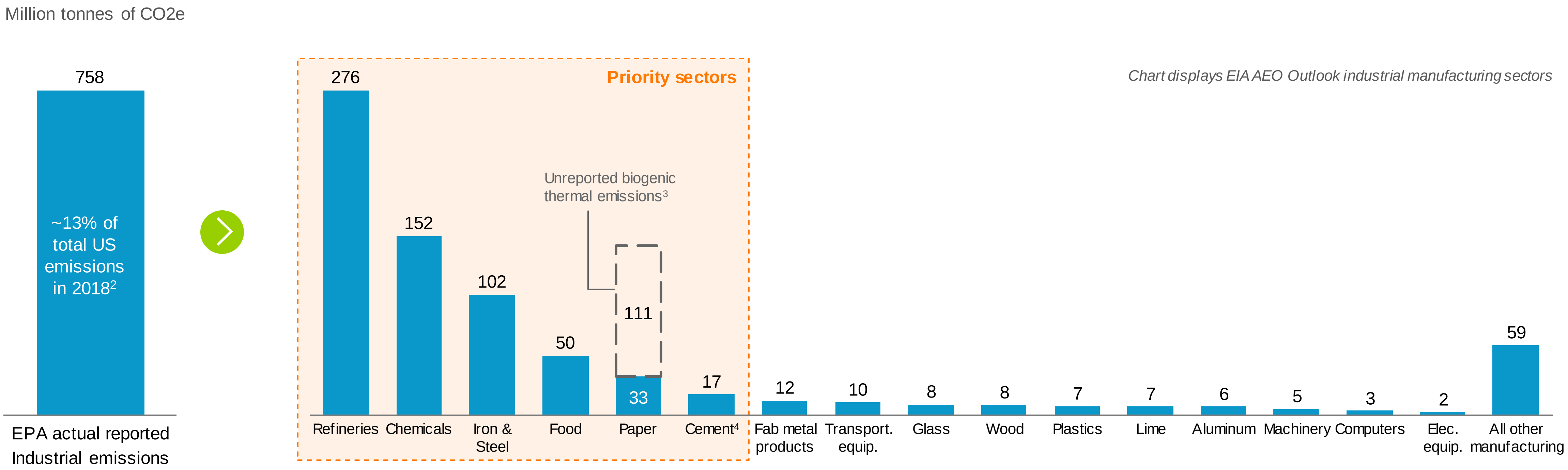
… and have been increasing since 2010;
only Power Gen has shown improvement



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

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

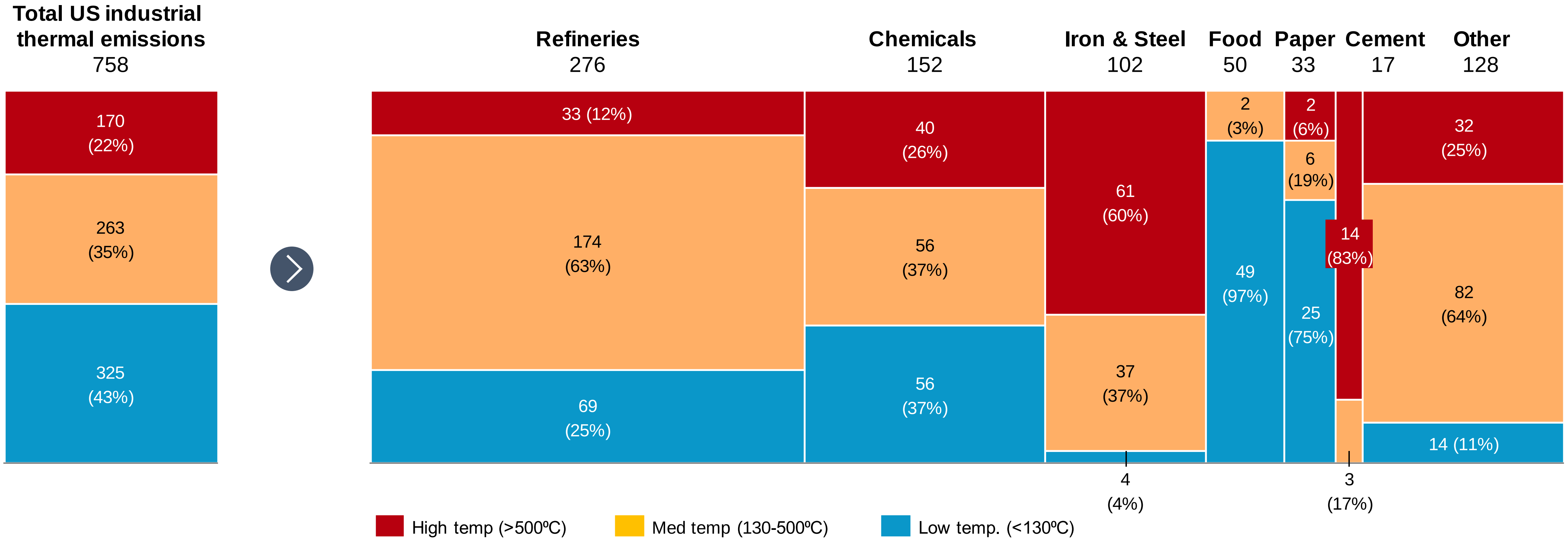
US industrial thermal emissions for all industrial manufacturing sectors (2018)[1]



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 CO2e/mmBtu; excludes non-manufacturing sectors of Agriculture, Construction, Mining 3. Biogenic emissions are considered 'net zero' by the EPA and are not included/reported in US industrial thermal emissions 2. Based on net emissions (including sinks) of 5,903 million tonnes of CO2e in 2018; gross emissions were 6,677 million tonnes of CO2e 4. Cement sector is estimated to represent 71.8% of the EIA Cement & Lime sector energy consumption
Source: US EIA Energy Outlook 2019 (2018 data); EPA emissions intensity by fuel type (June 2022); NREL (cement energy consumption)

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

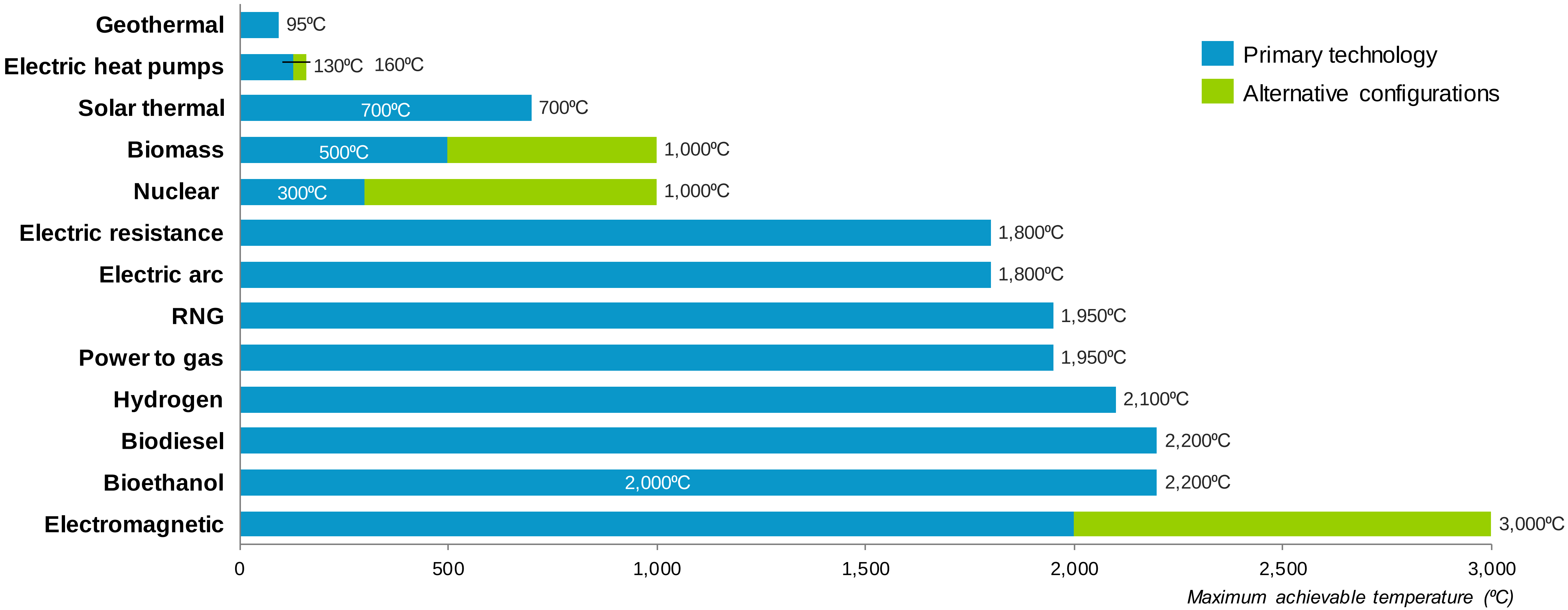
Estimated share of 2018 thermal emissions by temperature range (million tonnes of CO_2e)



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 for high temperature processes (e.g. coal in steel making) Source: NREL Manufacturing Thermal Energy Use in 2014 (provides thermal energy use by temperature); EIA Outlook 2019 (provides 2018 energy consumption by fuel); EPA emissions intensity by fuel

Renewable thermal technologies are available across a range of temperatures

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



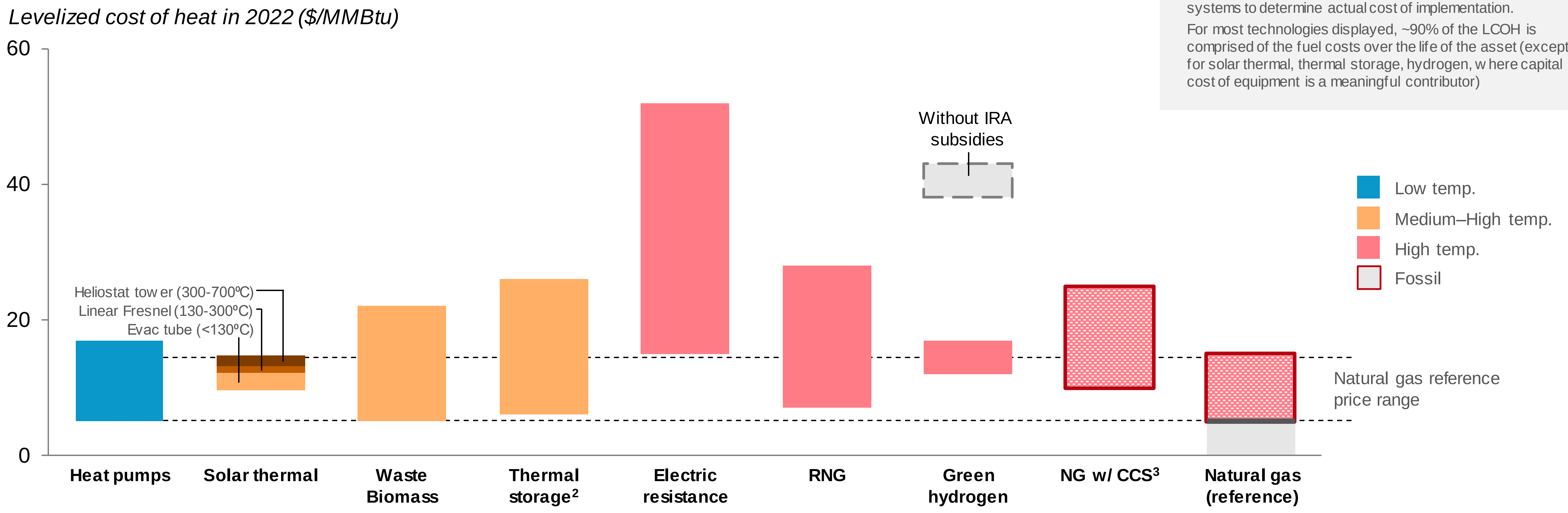
Source: DOE; research reports, papers, and studies; BCG analysis

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

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

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

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

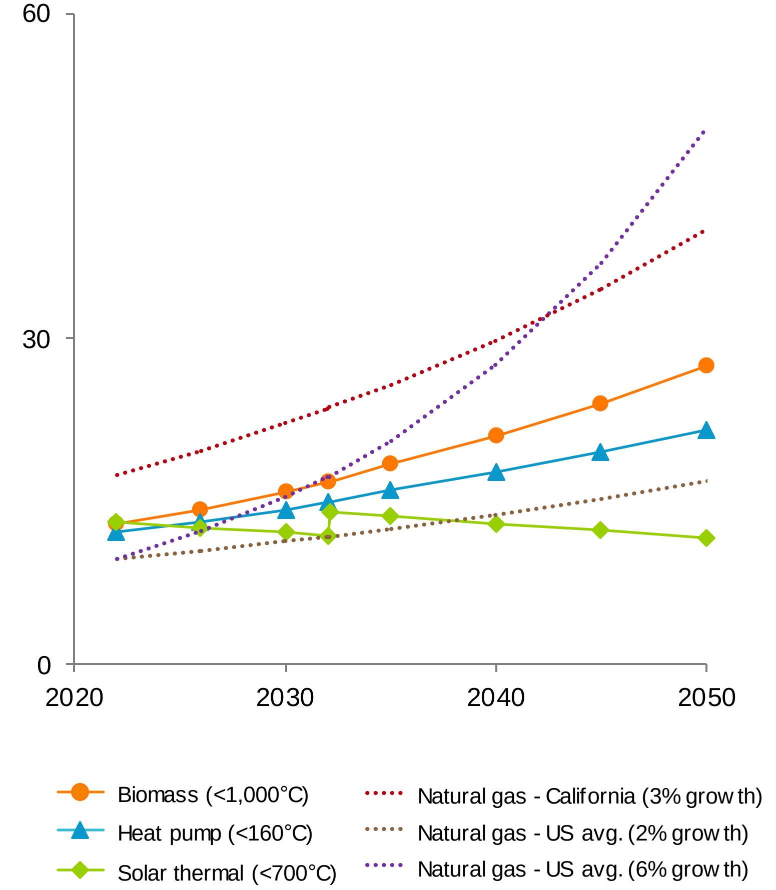


1. LCOH compares project lifetime costs against lifetime energy produced; costs include capital costs of equipment, fuel costs, and maintenance cost assumptions over the usable life of the energy asset. Electricity and natural gas pricing is based on state wholesale industrial end user electricity and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

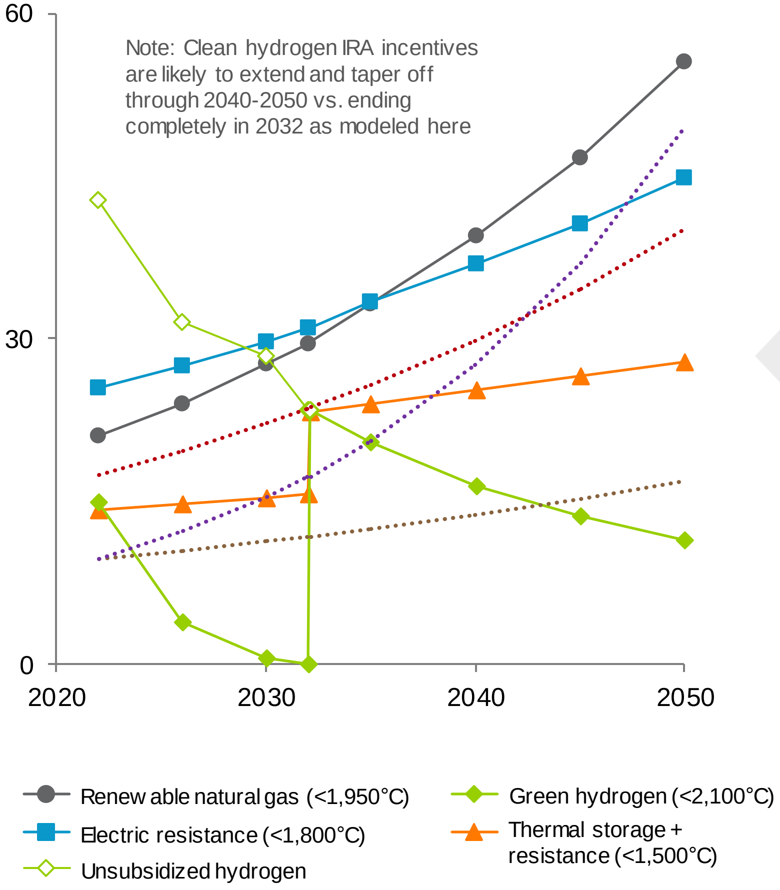
Projected LCOH

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

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



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



Key assumptions

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

1. LCOH compares project lifetime costs against lifetime energy produced; costs include capital expense of equipment, fuel costs, and maintenance expense assumptions over the usable life of the energy asset. Electricity and natural gas pricing is based on national weighted average wholesale industrial end user electricity and natural gas prices for the past 1 year as of June 2022 industrial electricity modeled to grow at 2% per year. Electric heat pumps, electric resistive, and natural gas heating efficiencies modeled at 300%, 99%, 75%, respectively. Includes Inflation Reduction Act incentives 2. EIA electricity nominal pricing projected to grow at 1.8% per year through 2050 3. Inflation Reduction Act section 48C offers a broad 30% ITC for industrial heat decarbonization projects that reduce emissions by 20%; funding is limited to ~$10B, after which costs for some technologies (excluding hydrogen) would revert to their pre-incentive cost (e.g. solar thermal) Source: US EIA, IRA, BCG analysis

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

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

✓ (applicable) Technology is applicable in the sector   ✓ (priority) Technology identified as priority for the sector to evaluate

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 at inexpensive intermittent electricity rates; should be evaluated for economics and deployed across sectors where economic 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

Contents

Supporting materials:

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

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

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

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

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

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

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

Parallel pathways to decarbonize industrial heat[1]

Electrify industry processes

- Electrify low temperature processes with cost competitive heat pumps
- Electrify remaining US steel blast furnaces with DRI-EAF[2]
- Electrify steam boilers & deploy other electric resistance technologies in medium-high temp. processes

Green the grid

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

Deploy renewable fuels

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

Deploy renewable technologies

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

Capture & store carbon

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

Energy efficiency spans across pillars[1]

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

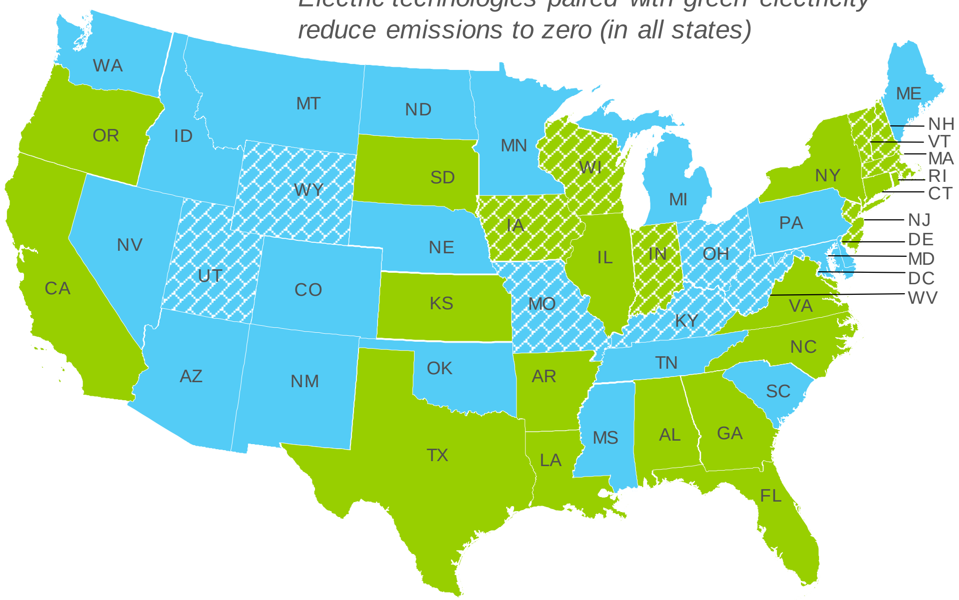
Electrification is a primary decarbonization pathway in the short, medium, and long-term

Electricity offers immediate decarbonization opportunities and a sustainable net zero fuel

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

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

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



LCOH for heat pump vs. natural gas

- Heat Pumps Cheaper
- Natural Gas Cheaper

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

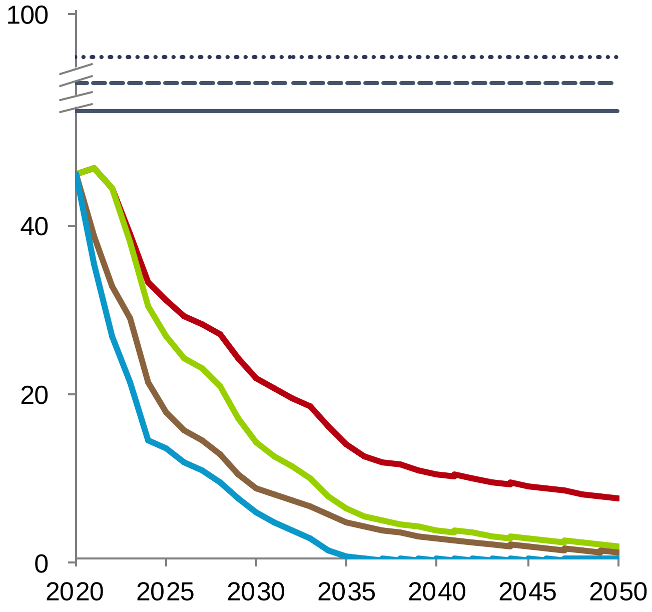
- Today (2022)
- By 2035 or sooner[4]

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

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

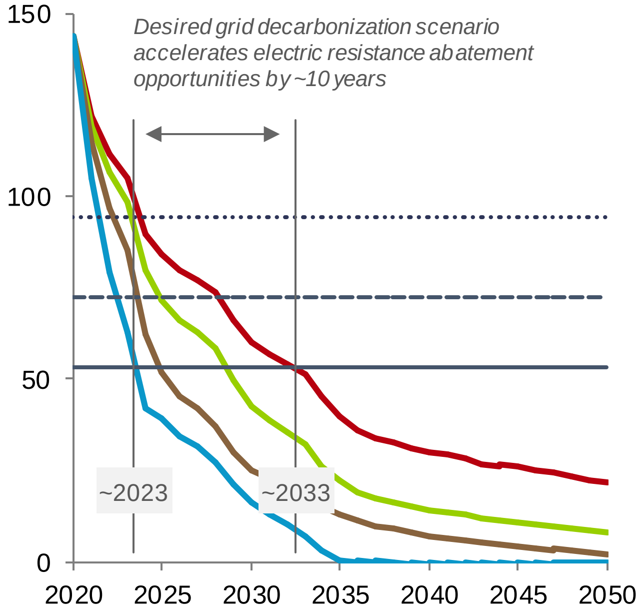
Heat pumps with grid electricity reduce emissions immediately

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



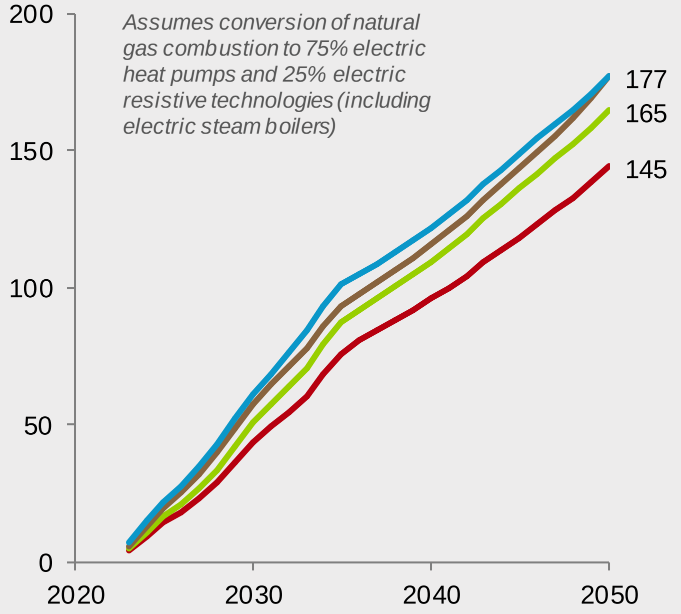
Elec. resistance with grid electricity offers abatement in a few years

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



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

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



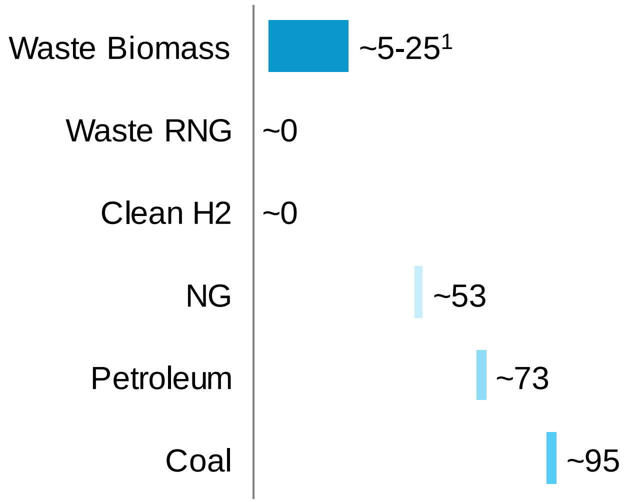
Low grid decarbonization | Expected grid decarbonization | Desired grid decarbonization | Most ambitious grid decarbonization | Natural Gas | Petroleum | Coal

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

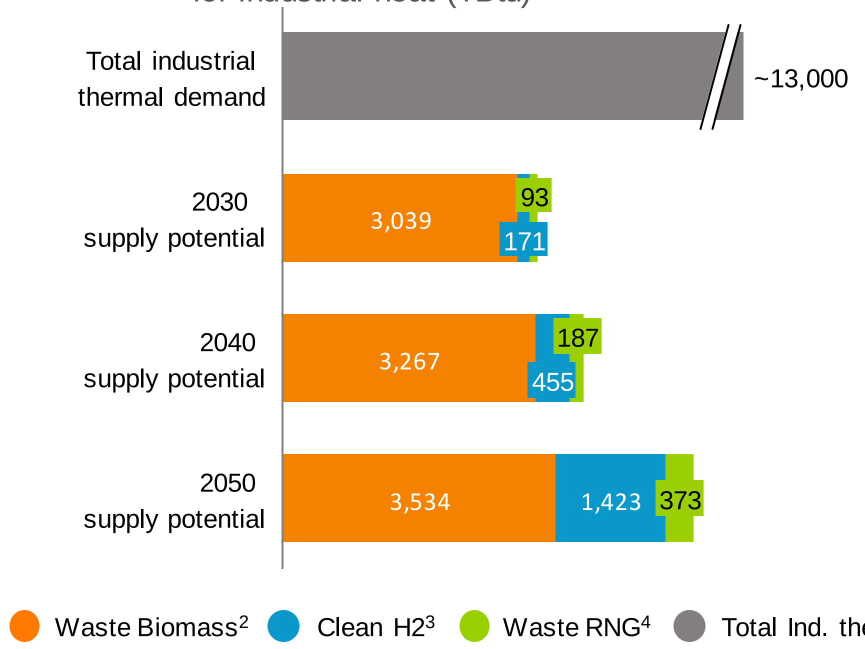
RNG & clean H2 are preferred over biomass but …

Emissions intensity (kg CO_2e / mmBtu)



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

Low carbon fuel supply potential for industrial heat (TBtu)



… all 3 fuels likely needed to decarbonize industrial heat

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

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

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

Strategically deploy carbon capture & prioritize low carbon fuels for impact

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

Deploy hybrid technology configurations to maximize impact of renewables

Thermal storage & Intermittent renewables

- Thermal storage can resolve renewable intermittency and expand process heating potential
- When sufficient intermittent electricity can be sourced at ~$10/MWH, thermal storage can have an LCOH of potentially of ~$6/mmBtu and be economic v. natural gas
- Storage can expand solar thermal potential beyond limited hours of high solar irradiation by ~28%[1] and reduce LCOH by ~$5/mmBtu[2]

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_2e in 2018 from biogenic emissions[3] (~3x the reported paper sector thermal emissions) - offering significant opportunity for negative emissions

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

Contents

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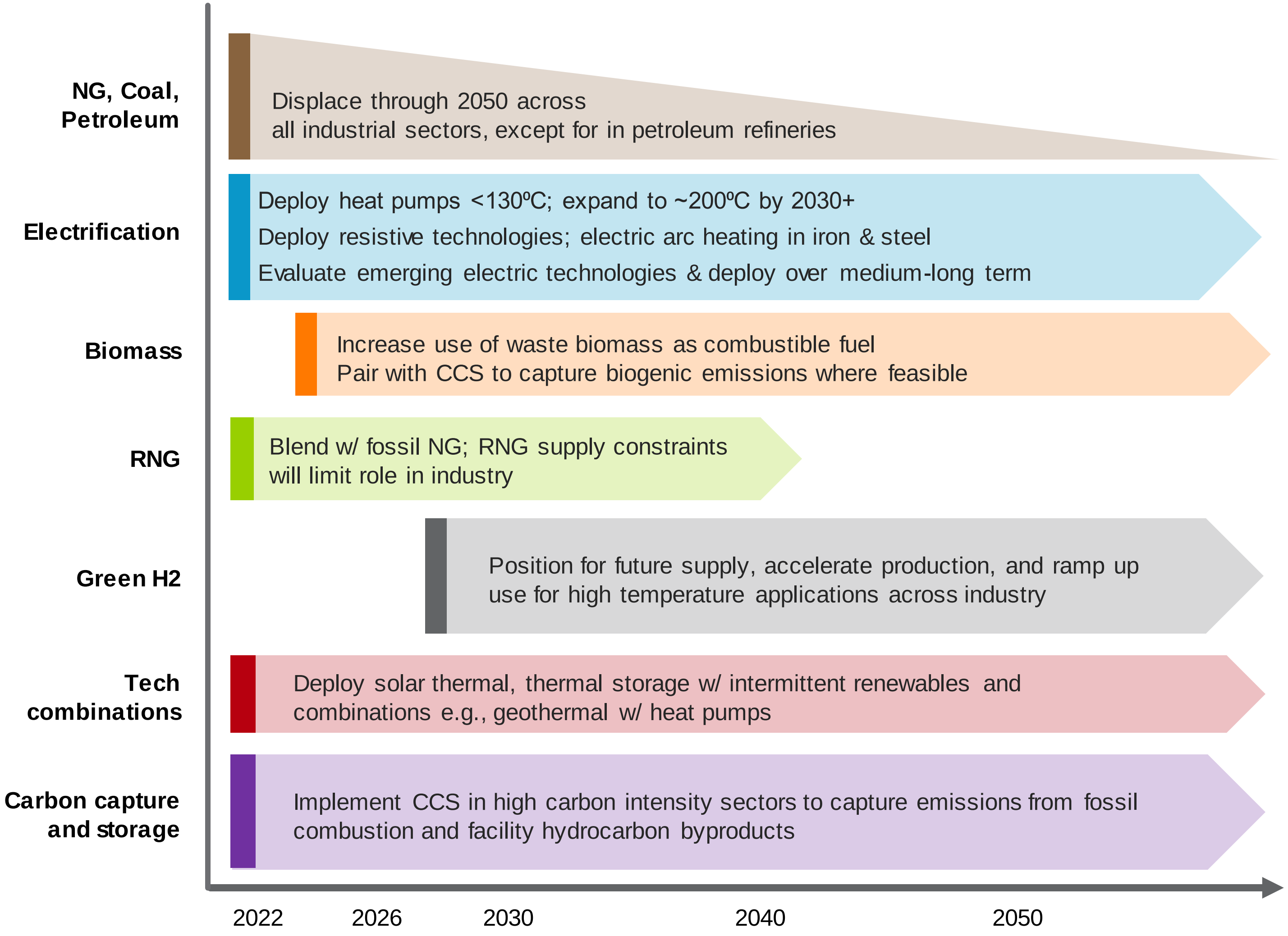
The full suite of abatement levers will be needed to achieve short- and long-term goals

Thermal energy & technology actions across industry



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

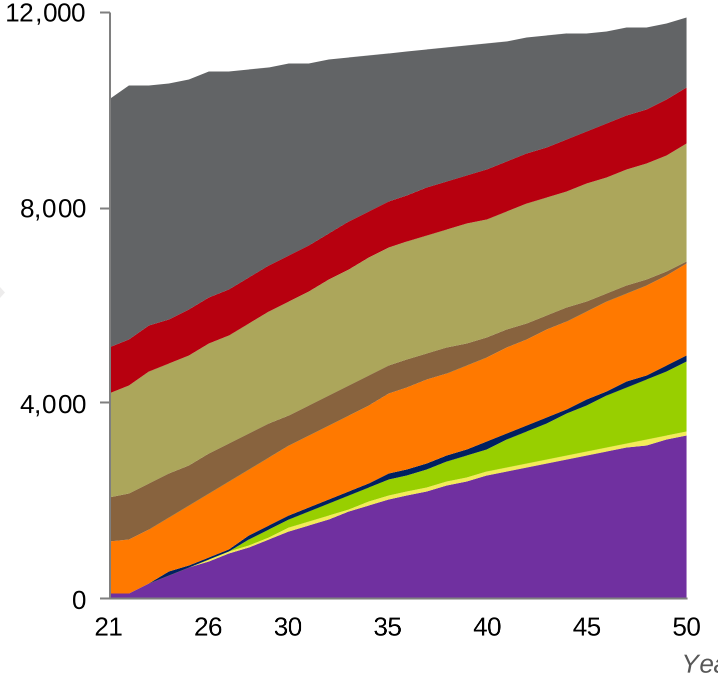
**For consistency across sectors, EIA energy consumption forecast for refineries is used below; however, refinery energy consumption is likely to decline in the 2030-2050 period as fossil fuel usage is reduced globally. Accordingly, overall thermal energy consumption, thermal emissions, and related carbon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

Decarbonization pathways

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

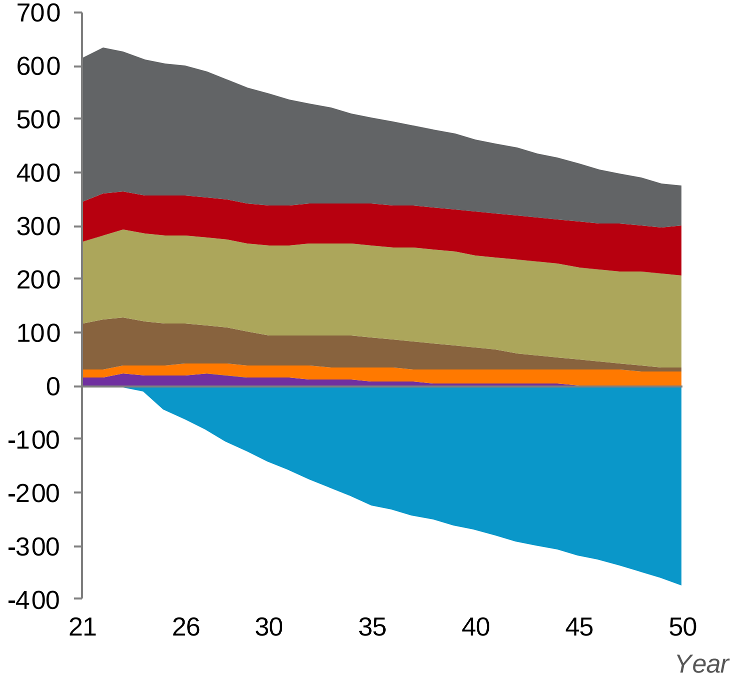
Thermal energy consumption[1]

Tbtu of thermal energy



Thermal emissions[2]

Millions tonnes of CO2e in thermal emissions



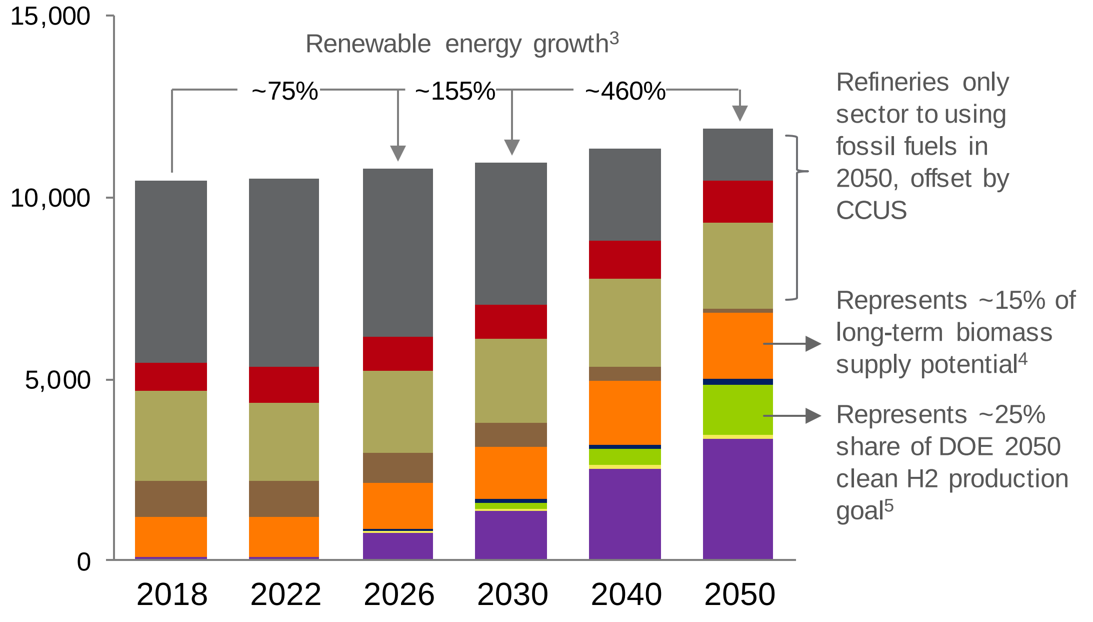
Natural gas | Petroleum & other | Coal | Clean Hydrogen | Electrification
Biofuels & coproducts | Waste Biomass | RNG | Solar thermal | CCS

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

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

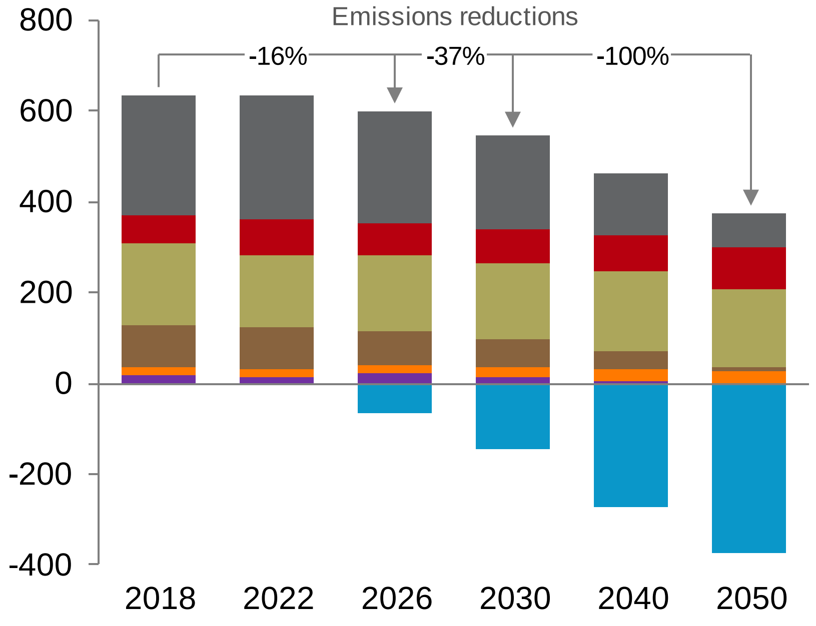
Thermal energy consumption[1]

TBtu of thermal energy



Thermal emissions[2]

Million tonnes of CO2e thermal emissions



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

1. Total thermal energy consumption based on EIA Outlook; forecasted energy mix per BCG analysis 2. Thermal emissions calculated based on emissions intensity of individual fuels; RNG and clean hydrogen assumed to be net zero fuels, biomass assumed to have an emissions intensity of ~15 kg CO2e per mmBtu, electricity based on forecasted US electric grid emissions intensity assuming 80% and 100% renewables by 2030 and 2050 3. Renewable energy includes biomass, RNG, hydrogen and electrification 4. Biomass supply potential per DOE and EIA 5. DOE target of 50 mmT of clean hydrogen by 2050 translates to 5,690 TBtu Source: EIA outlook; EIA emissions intensity; BCG analysis

Food

Thermal Energy Decarbonization

Decarbonization pathways

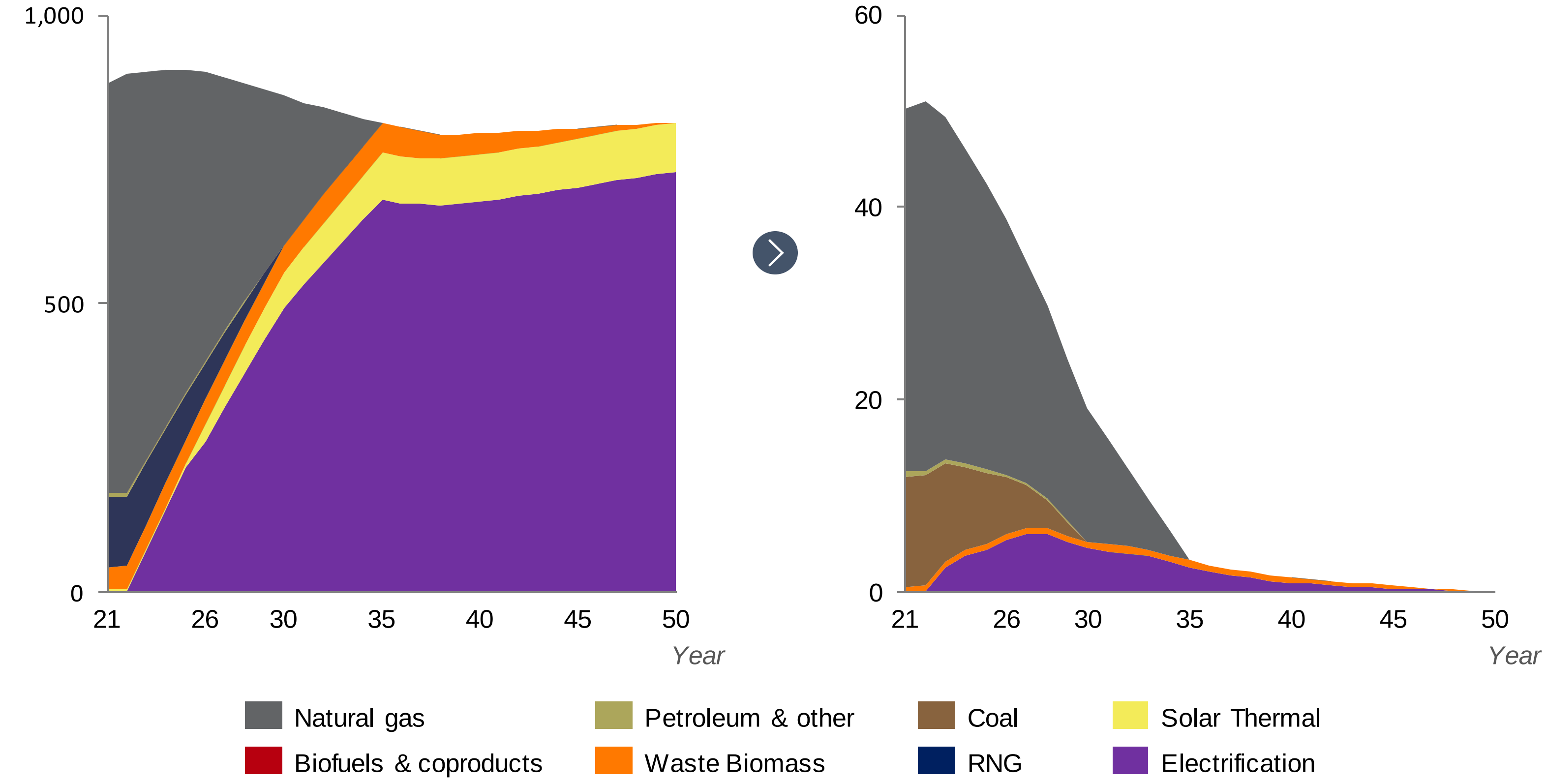
- 97% of industrial heat needs are for applications is in the low temperature range (<130ºC), which can be decarbonized on an accelerated timeline with electrification and heat pumps. Natural gas, which combusts at ~1,850ºC is not required for most heat needs in the sector
- Use of fossil coal and petroleum is phased out by 2030, and natural gas phased out by 2035 - replaced with electrification
- Solar thermal energy with battery storage should also be considered, particularly in the US Southwest, and/or when electric heat pumps have a higher cost to generate heat than fossil natural gas (e.g. California)
- Thermal storage with electric resistance heating when paired with inexpensive electricity (<$20/MWH) should be evaluated and deployed

Thermal energy consumption[1]

Tbtu of thermal energy

Thermal emissions[2]

Millions tonnes of CO2e in thermal emissions



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

Paper

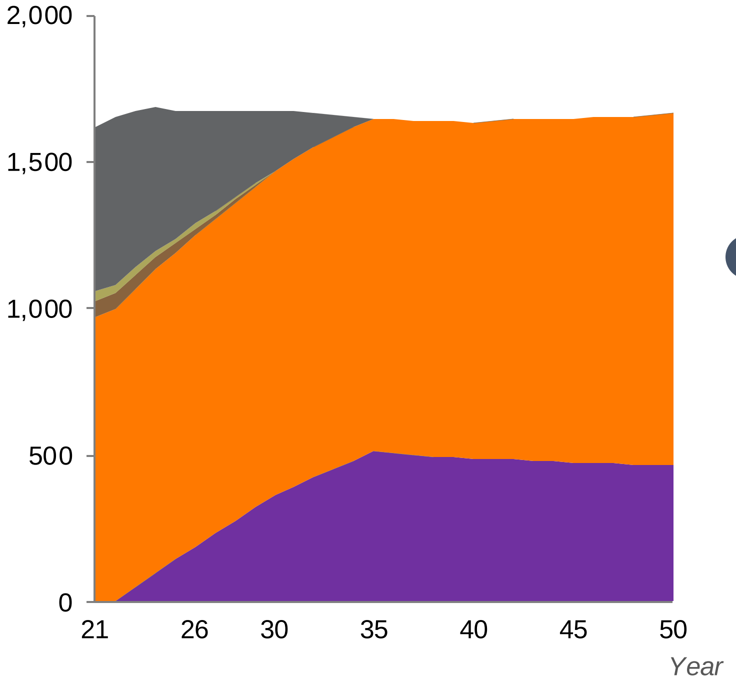
Thermal Energy Decarbonization

Decarbonization pathways

- 94% of industrial heat is in low (75%) and medium (19%) temperature ranges, which can be decarbonized on an accelerated timeline with electrification and heat pumps
- Use of fossil coal and petroleum is phased out by 2030, and natural gas phased out by 2035 – replaced primarily by electrification
- Woody biomass represents majority of current energy consumption; increased efficiency in use of biomass is recommended to reduce released carbon from waste
- The sector generated 111 million tonnes of biogenic CO2e3,4 in 2018 primarily due to combustion; while these emissions are unreported, there is an opportunity for the sector to capture this carbon, equating to a ~15% reduction in total US industrial thermal emissions
- Cost of carbon capture on biomass ranges from $60-$120/tonne of carbon with cost reductions expected due to technology maturity; EIA estimates cost of transport and storage at $12-24/tonne of carbon. The Inflation Reduction Act offers a credit of $85/tonne of carbon, which may allow a significant portion of the biogenic emissions to be captured economically over the short and medium term (with increasing economic viability over time)
- Thermal storage with electric resistance heating when paired with inexpensive electricity (<$20/MWH) should be evaluated and deployed

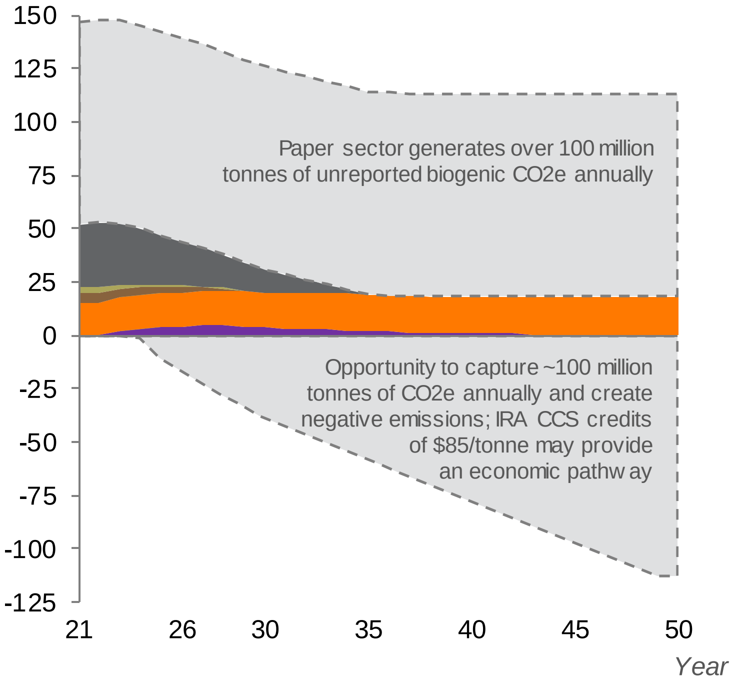
Thermal energy consumption[1]

Tbtu of thermal energy



Thermal emissions[2]

Millions tonnes of CO2e in thermal emissions



Natural gas | Petroleum & other | Coal | Electrification | Biofuels & coproducts | Waste Biomass | Clean Hydrogen | Biogenic CO2e & CCS

1. Total thermal energy consumption based on EIA 2022 Outlook; forecasted energy mix per BCG analysis 2. Thermal emissions calculated based on emissions intensity of individual fuels; RNG and clean hydrogen assumed to be net zero fuels, biomass assumed to have an emissions intensity of 15 kg CO2e per mmBtu, electricity modeled based on US electric grid emissions intensity assuming 80% and 100% renewables by 2030 and 2050 3. Biogenic emissions are not included in EPA GHGRP stationary combustion emissions since EPA accounts for these fuels as net zero 4. Biogenic combustion is unlikely net zero; the US has lost tree cover annually since 2000; 16% total loss from 2000-2021 equating to 17.4Gt of CO2e Source: EIA outlook; EIA emissions intensity; Global Forest Watch; USDA; industry reports; BCG analysis

Chemicals

Thermal Energy Decarbonization

Decarbonization pathways

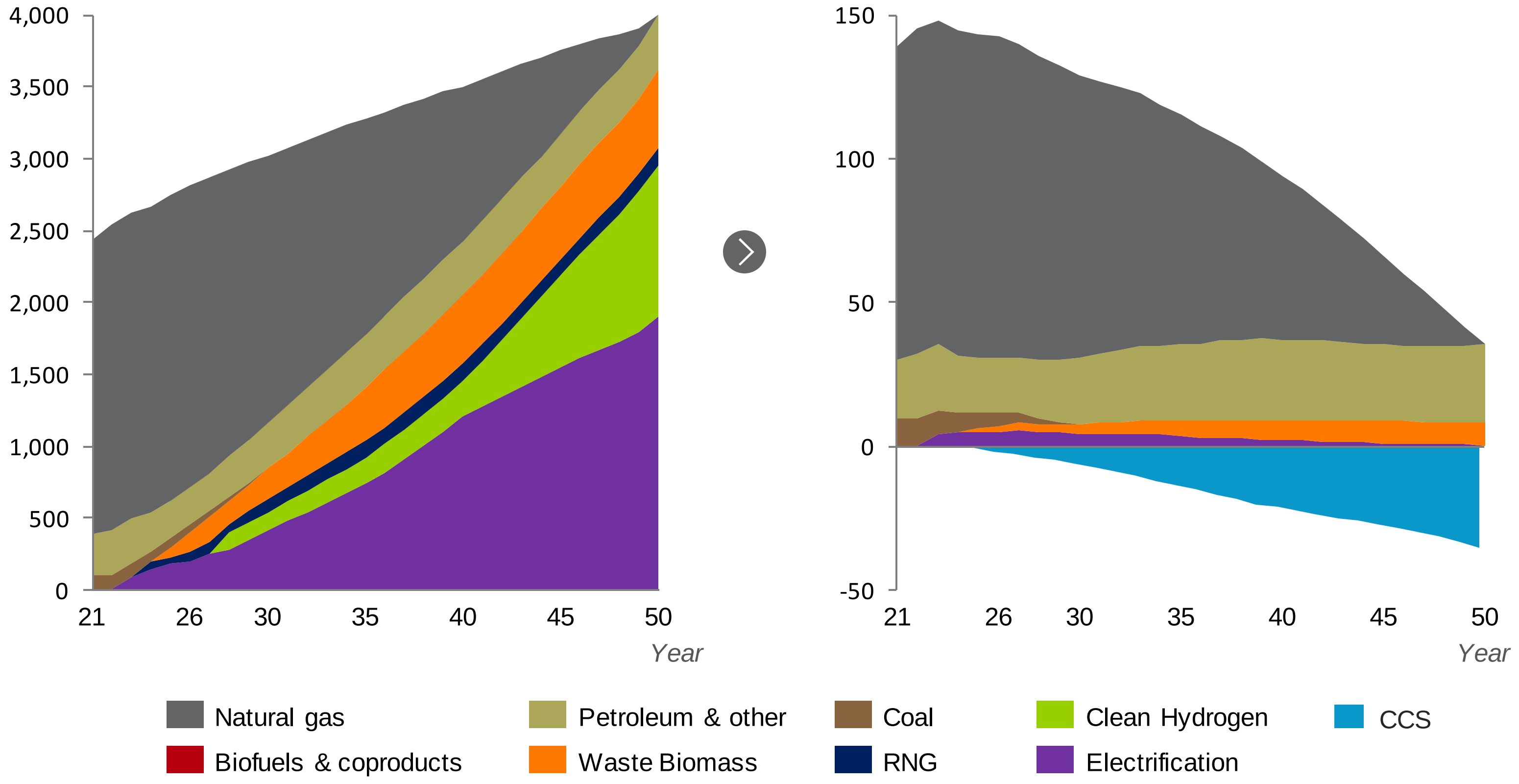
- Use of fossil natural gas is eliminated through 2050
- RNG and biomass are deployed as immediate solutions for medium and high heat applications; Biomass use continues to grow over the forecast period (RNG use is not expected to scale due to RNG supply constraints)
- Electrification of low and medium temperature applications is deployed beginning immediately; electric grid emissions intensity is lower than fossil NG for heat pumps in nearly all states today; can be deployed against <130ºC processes representing ~37% of total thermal emissions in the sector. As heat pumps improve to ~200ºC, higher heat applications can be electrified
- 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 storage with electric resistance heating when paired with inexpensive electricity (<$20/MWH) should be evaluated and deployed

Thermal energy consumption[1]

Tbtu of thermal energy

Thermal emissions[2]

Millions tonnes of CO2e in thermal emissions



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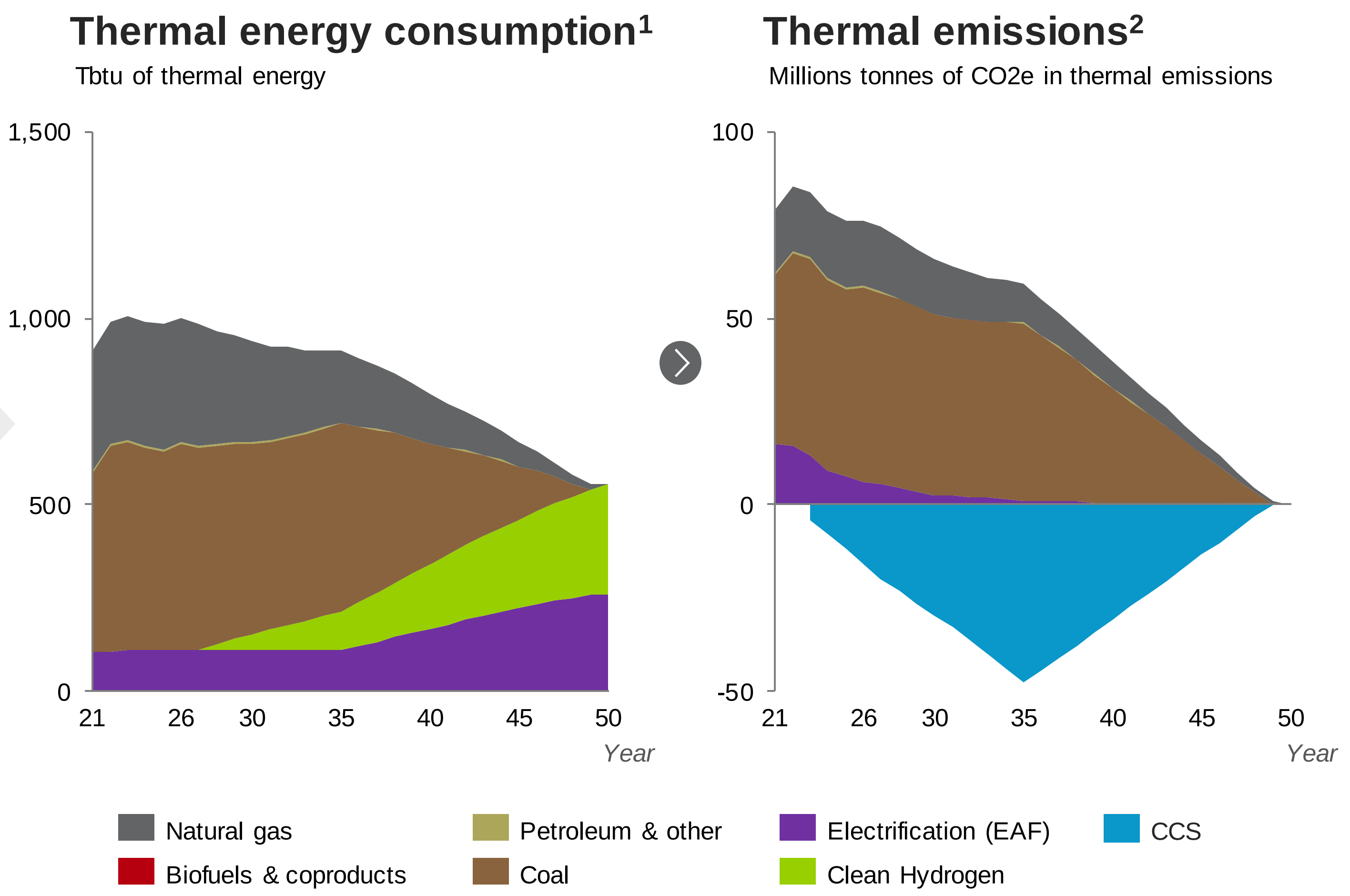
Thermal Energy Decarbonization

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



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_2e per mmBtu, electricity modeled based on US electric grid emissions intensity 80% and 100% renewables by 2030 and 2050 Source: EIA outlook; EIA emissions intensity; BCG analysis

Cement

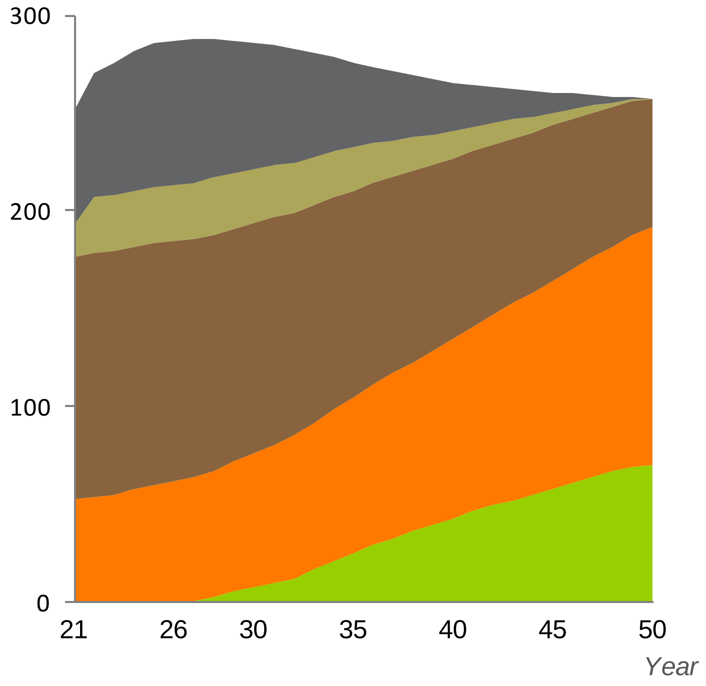
Thermal Energy Decarbonization

Decarbonization pathways

- The Cement sector creates more process emissions than thermal emissions, and both emissions are typically emitted in the same air stream. As a result, it is difficult to distinguish between process and thermal emissions and the EPA GHGRP flight database does not identify meaningful thermal emissions. However, thermal emissions make up ~42% of total emissions (process emissions make up ~58%)[3]
- The cement industry heat process applications require heat driven by fossil fuel combustion as well as fossil coal as a feedstock
- Heavy emitting coal, which is used for heat and as feedstock in the rotary kiln, can be partially displaced with biomass, which can compose up to 50% of the total rotary kiln mix by 2050; some European cement manufacturers are using ~60% alternative fuels in their rotary kiln mix (displacing ~40% of coal)[4]
- Given the inability to distinguish process and thermal emissions, it is likely that carbon capture deployed to capture process emissions (~58% of total emissions) will also be used to capture thermal emissions (~42% of total emissions), until a longer-term alternative for coal-based cement production is developed
- Thermal storage with electric resistance heating when paired with inexpensive electricity (<$20/MWH) offers low-cost heat and should be evaluated

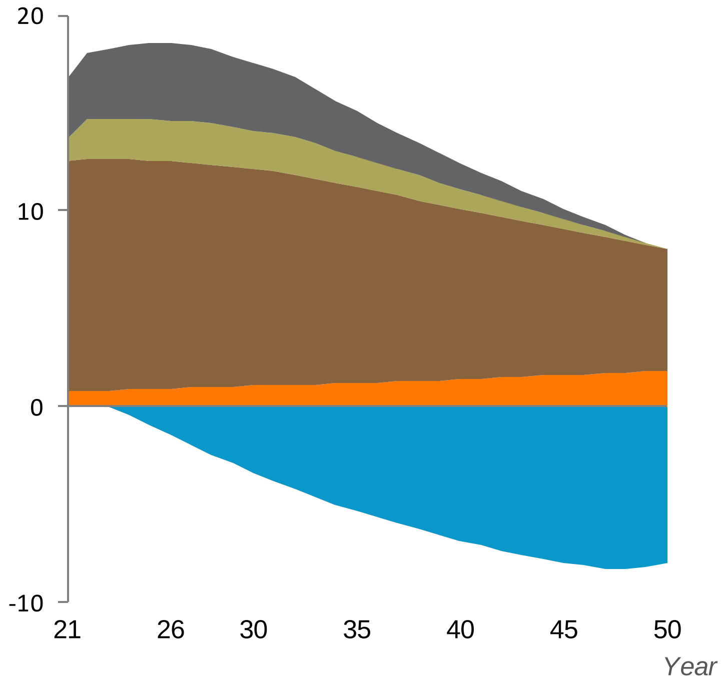
Thermal energy consumption[1]

Tbtu of thermal energy



Thermal emissions[2]

Millions tonnes of CO2e 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 CO2e per mmBtu, electricity modeled based on US electric grid emissions intensity 80% and 100% renewables by 2030 and 2050 3. DOE Industrial Decarbonization Roadmap (2022) 4. PCA Roadmap to Carbon Neutrality (2021) Source: EIA outlook; EIA emissions intensity; BCG analysis

Refineries*

Thermal Energy Decarbonization

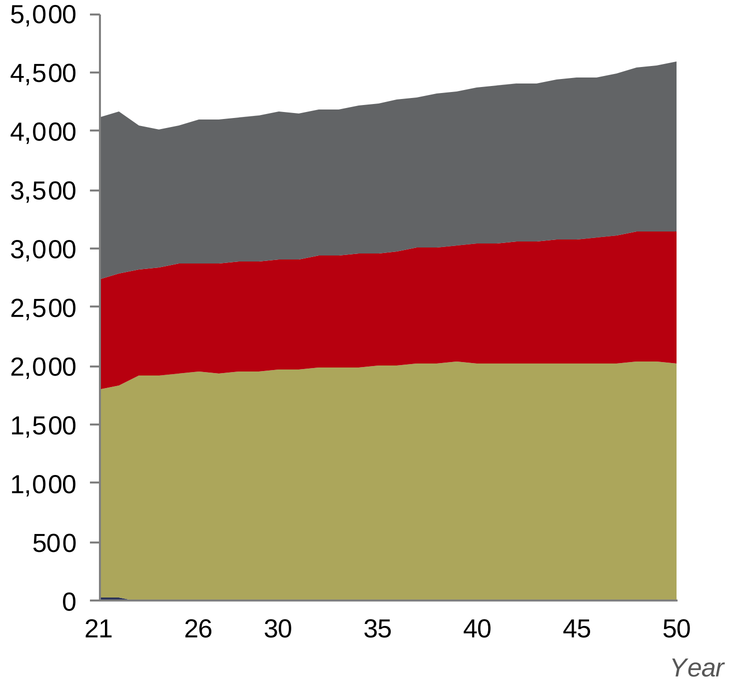
**For consistency across sectors, EIA energy consumption forecast for refineries is used below; however, refinery energy consumption is likely to decline in the 2030-2050 period as fossil fuel usage is reduced globally. Accordingly, overall thermal energy consumption, thermal emissions, and related carbon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

Decarbonization pathways

- Refineries generate process heat by burning natural gas as well as refinery byproducts such as still gas. Byproducts form the majority of combusted fuels, representing ~2/3rds of total fuel combustion; natural gas combustion represents ~1/3rd
- Refinery byproducts can typically be consumed as fuel (current case), flared (releases carbon), or potentially sequestered (CCS). Refineries are likely to continue using byproducts as combustible fuels and deploy CCS to abate related emissions
- Natural gas combustion in refineries can be switched to low carbon fuels, but such fuels are supply constrained and may be better prioritized for other sectors (e.g., the refinery demand for green hydrogen to displace natural gas combustion would rival the demand for green hydrogen to replace NG combustion in all other industrial sectors combined)
- As a result carbon capture is likely one of the primary decarbonization pathways for the sector
- Thermal storage with electric resistance heating when paired with inexpensive electricity (<$20/MWH) offers low-cost heat and should be evaluated

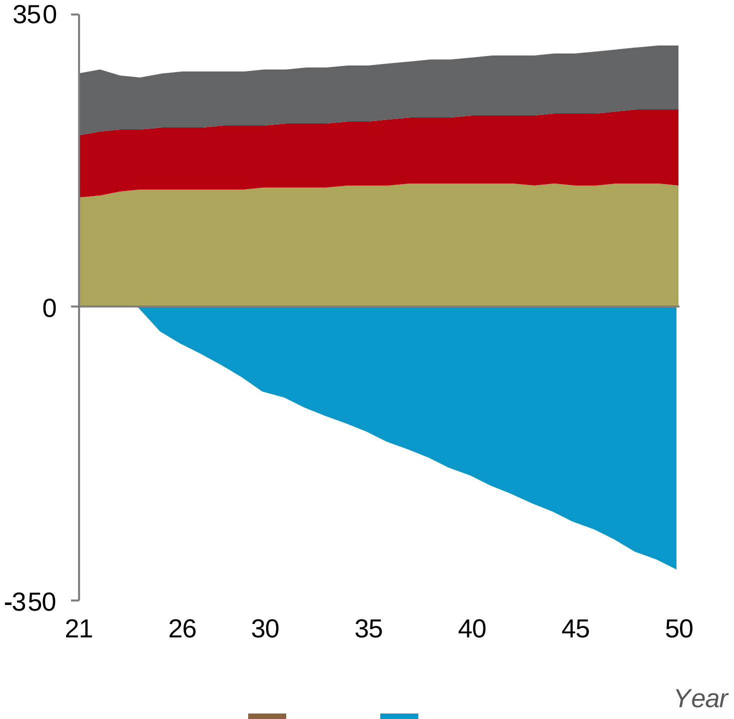
Thermal energy consumption[1]

Tbtu of thermal energy



Thermal emissions[2]

Millions tonnes of CO2e in thermal emissions



Natural gas | Biofuels & coproducts | Petroleum & other | Coal | CCS

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Appendix: Supporting Materials

US Industrial Thermal Energy Needs & Emissions

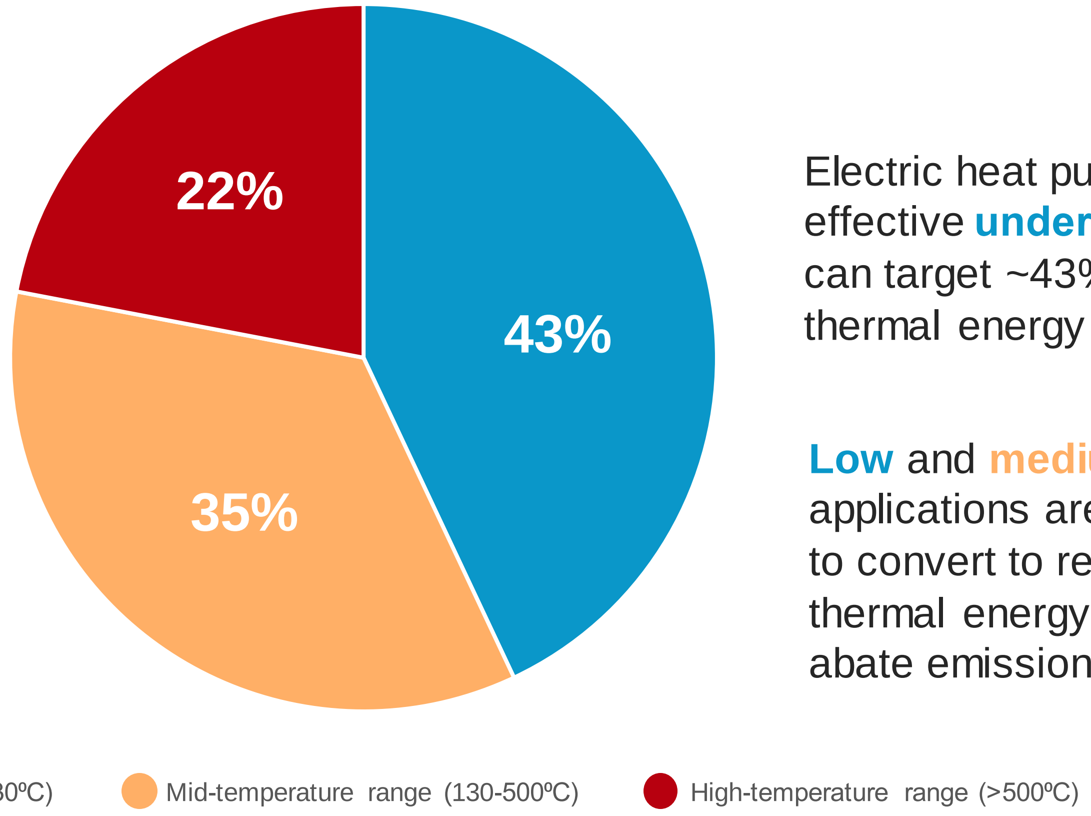
US industrial thermal energy use

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

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**

Industrial thermal energy consumption by heat temperature range



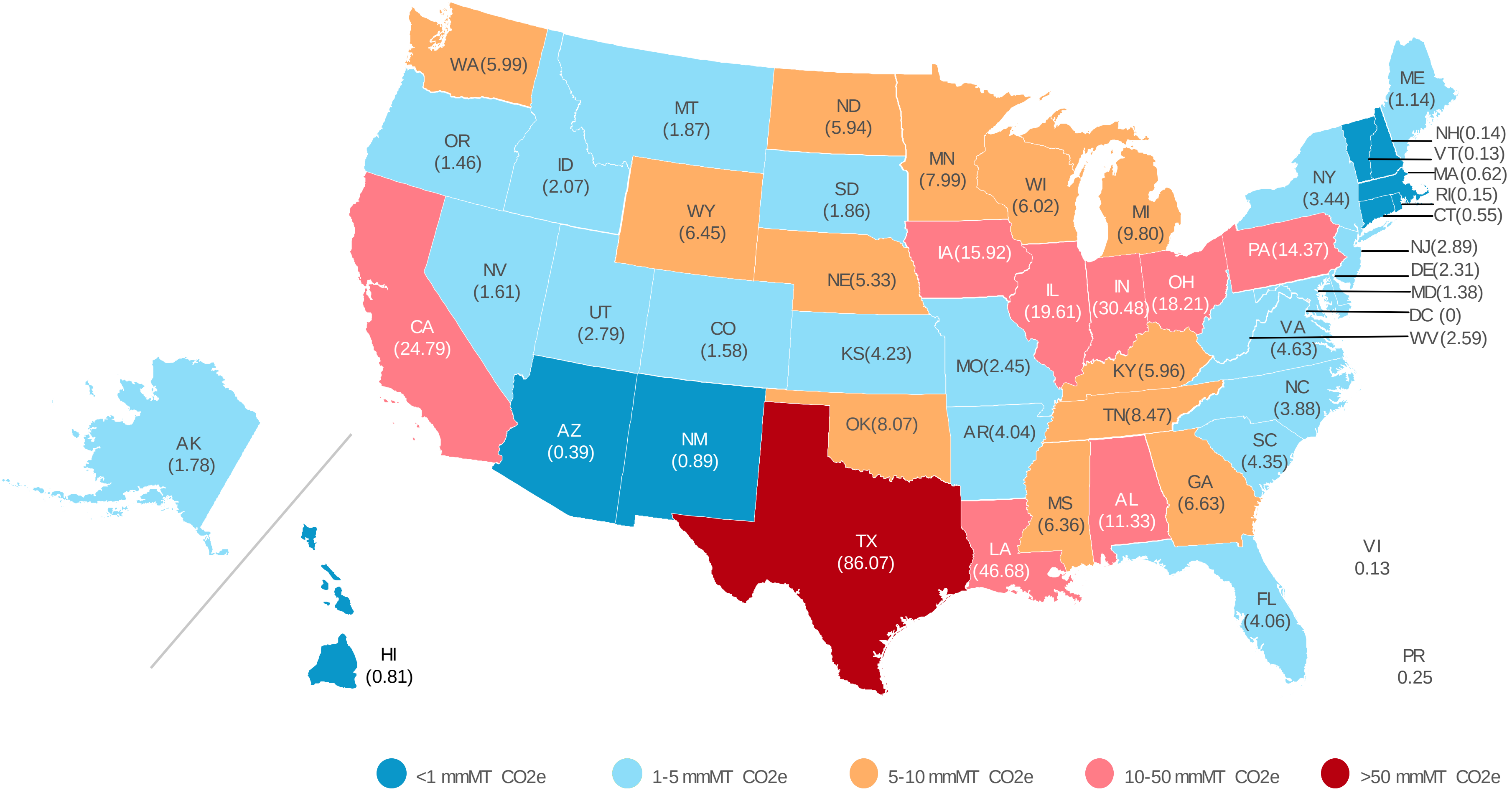
Electric heat pumps are effective **under ~130ºC** and can target ~43% of industrial thermal energy use

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

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

US industrial thermal emissions

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



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

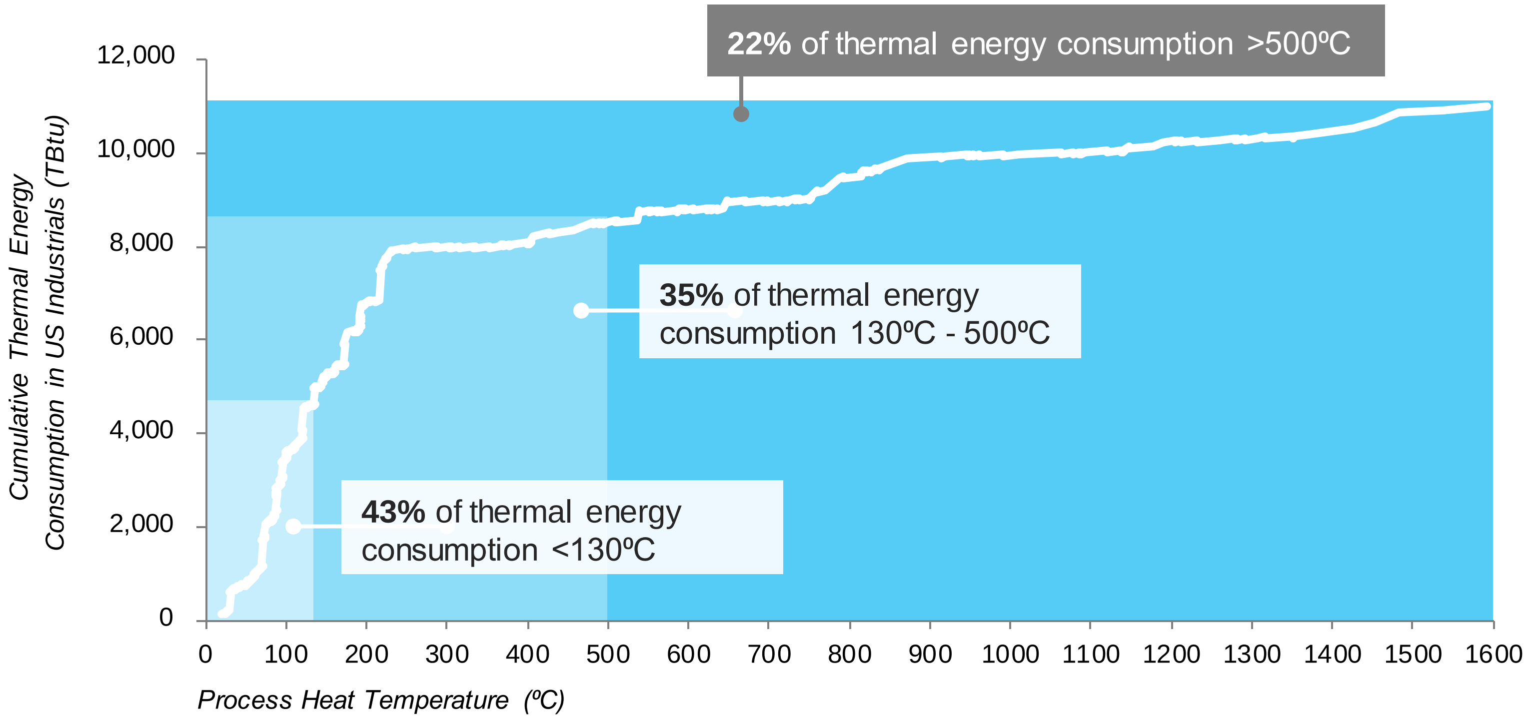
- Refineries
- Chemicals
- Iron & Steel
- Paper
- Food
- Cement

Source: US EPA GHG Inventory Flight Database 2018; captures large emitter emitting >25K tonnes of CO_2e per year

US industrial thermal energy use

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

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 ~130ºC 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

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

Most industrial sector applications occur at low & medium heat temperatures

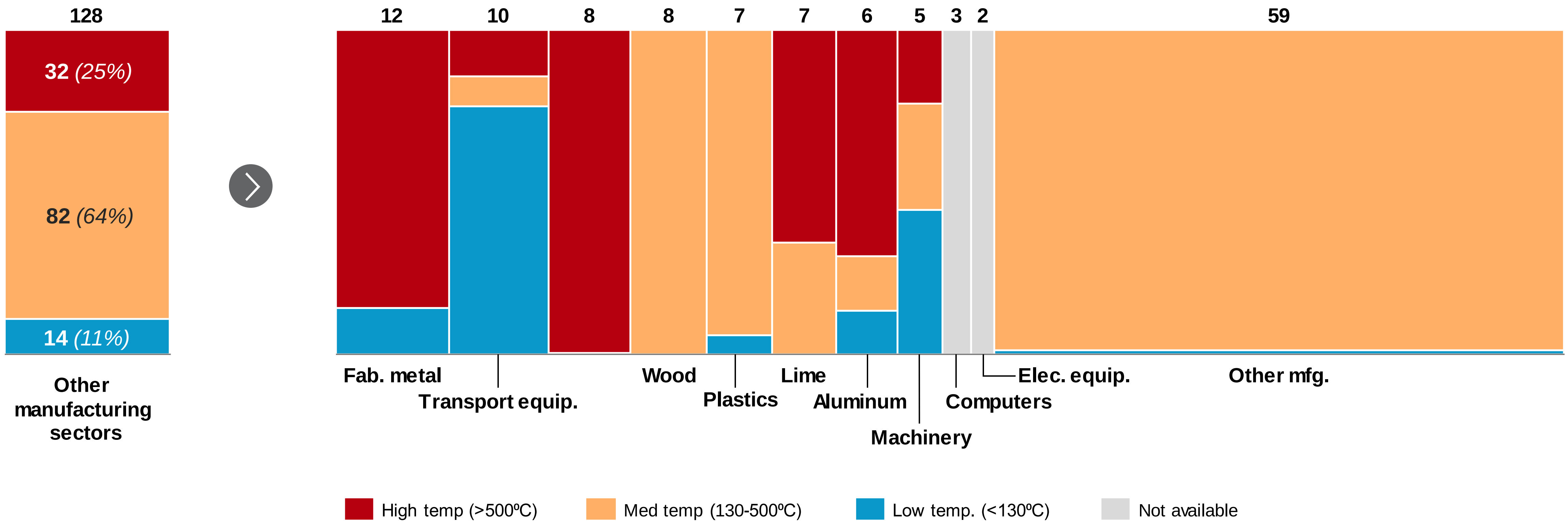
Sector	2018 Emissions (Million Tonnes of CO2e)	Heat Processes Applications
		Low heat <130℃; Medium heat 130℃ - 2000℃; High heat >2000℃
Petroleum	276	Reactors (260-480ºC) Distillation (150-370ºC)
Chemicals	152	Reactors (500-900ºC) Distillation (100-300ºC) Drying (150-200ºC)
Iron & Steel	102	Pelletizing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

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

Other Manufacturing Sectors

Estimated Thermal Emissions by Temperature

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



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

Appendix: Supporting Materials

Renewable Thermal Technology Prioritization

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

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

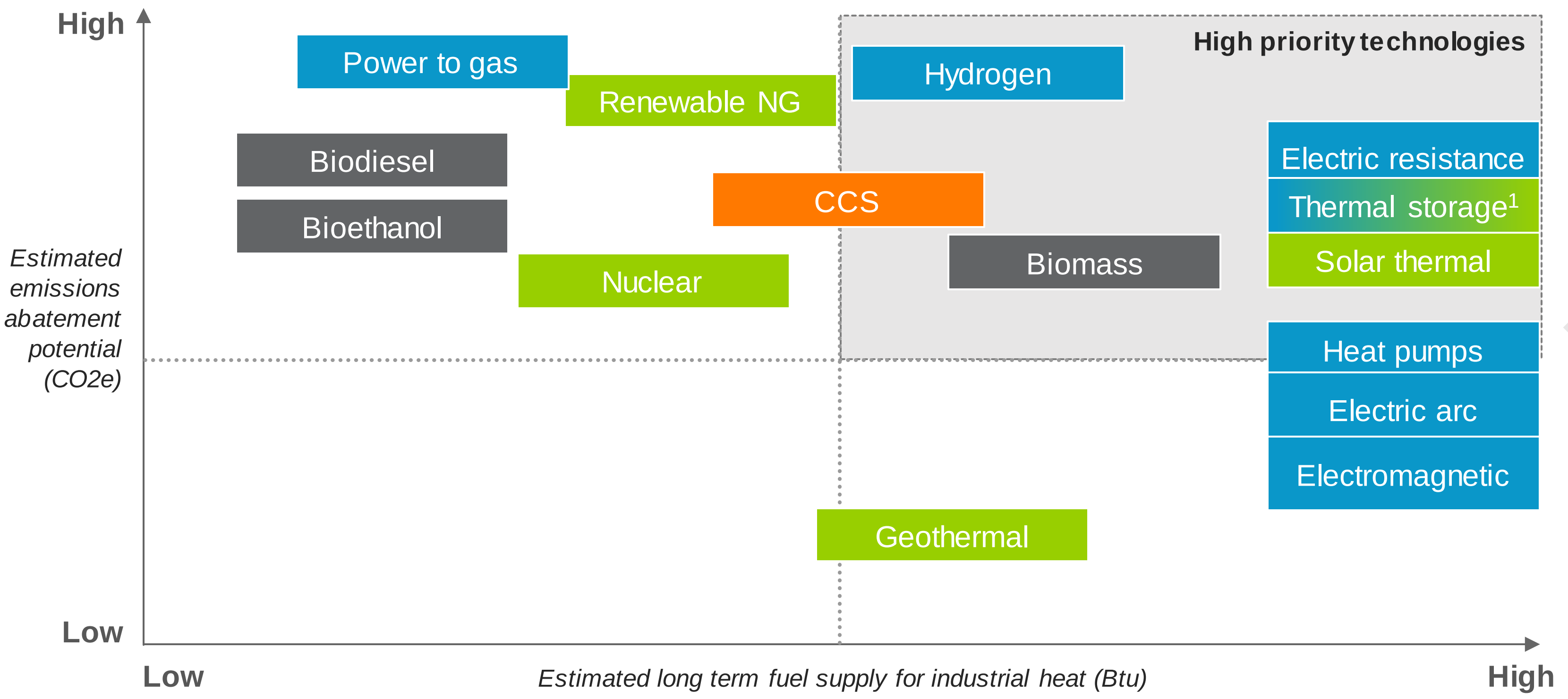
✓ (high) High applicability ✓ (moderate) Moderate applicability

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

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 pow er to gas technology, is listed separately; 4. Combined w ith electric resistance heating Source: DOE; research reports, papers, and studies; BCG analysis

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

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



Long term emissions intensity

- Net zero / near net zero
- Net zero with decarbonized grid
- Unlikely to be net zero
- Carbon capture

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

1. Combined with electric resistance heating; net zero when paired with intermittent or other renewables Source: DOE; research reports, papers, and studies; BCG analysis

Disclaimer