Iron & Steel

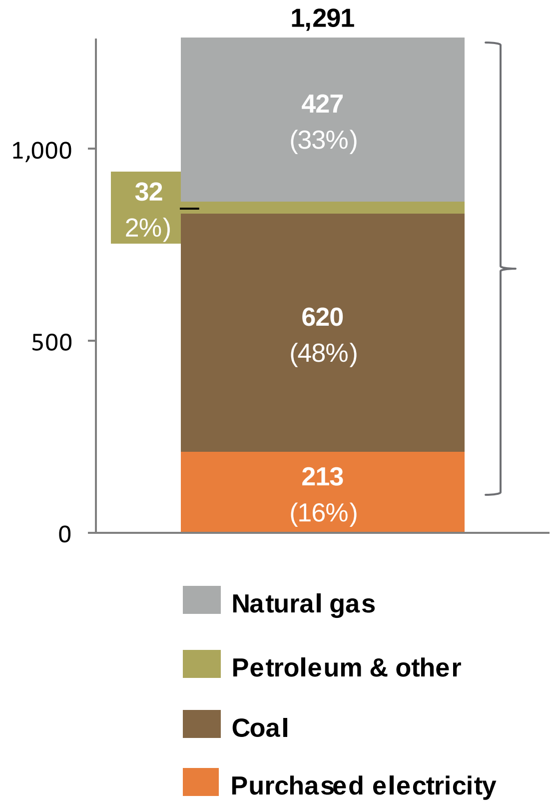
Sector Perspectives

RENEWABLE THERMAL COLLABORATIVE

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

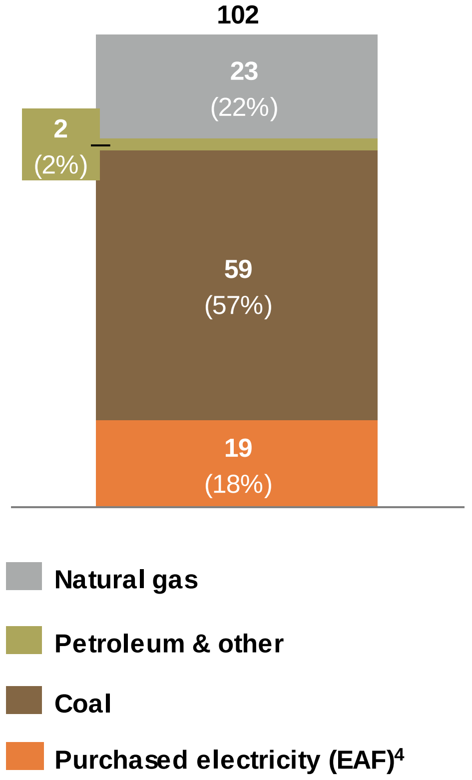
Total energy consumption (2018)[1]

Trillion Btu



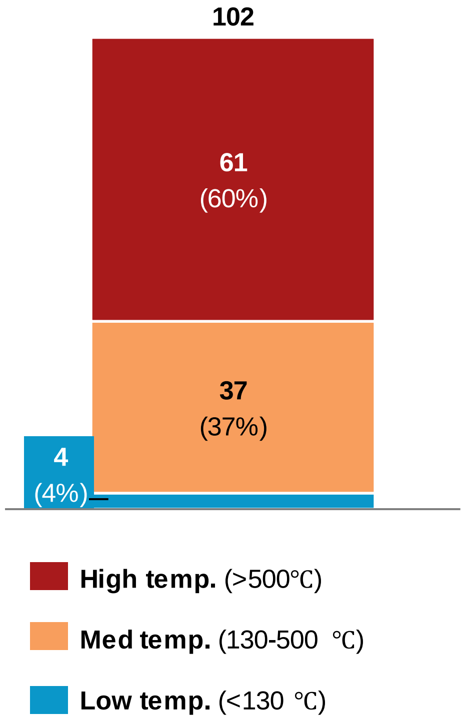
Thermal emissions (2018)[2]

Million Tonnes of CO2e



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

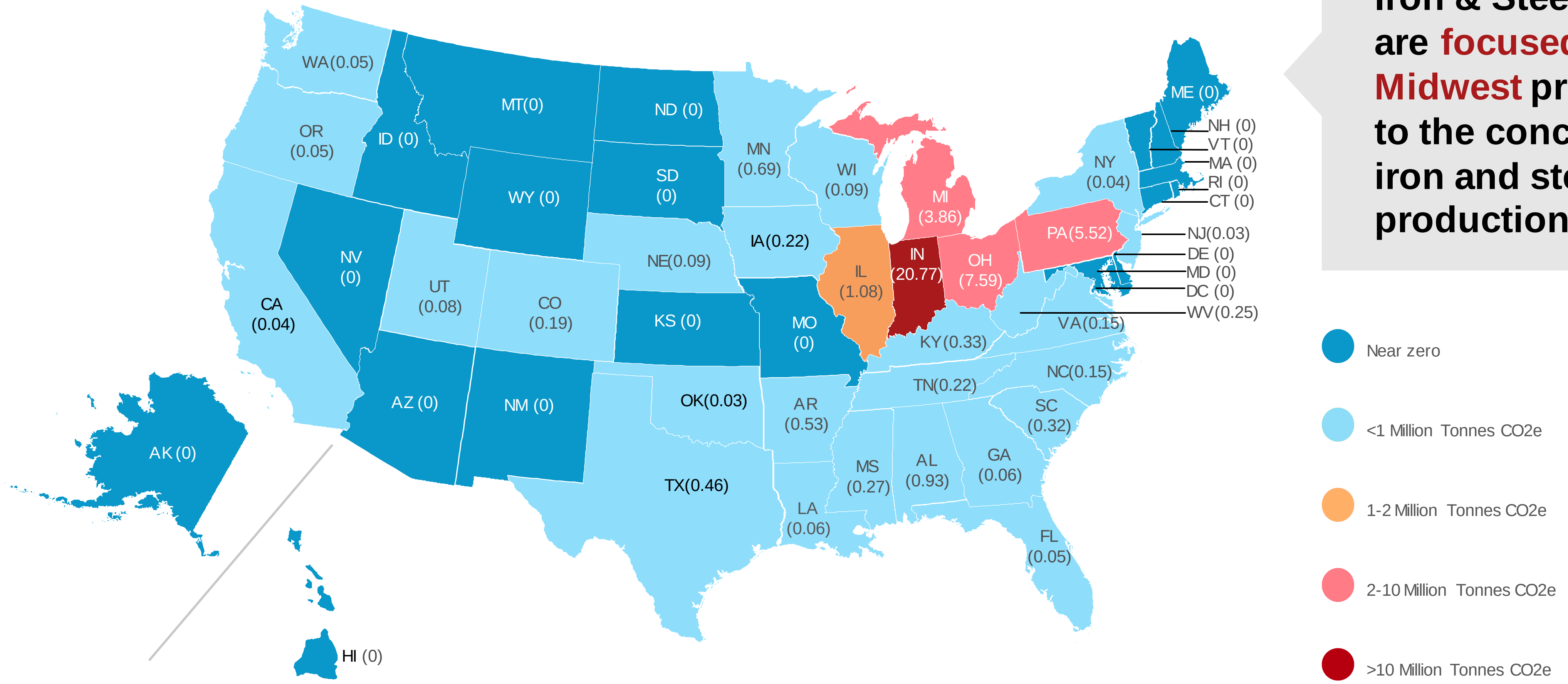
Million Tonnes of CO2e



1. EIA Annual Energy Outlook 2019 2. Based on AEO 2019 Outlook for 2018 energy consumption by combustible fuel (excludes purchased electricity) and EPA emissions intensity of individual fuels; RNG and green hydrogen are considered net zero, biomass is estimated at 15 kg CO2e/mmBtu 3. Calculated using the NREL MECS survey data for thermal energy use (2014) 4. More than 2/3rds of Iron & Steel facilities use electric arc furnaces (instead of blast furnaces); for purposes of this analysis ~50% of purchased electricity is estimated to be used for thermal applications (electric arc furnaces) Source: EIA; EPA; NREL; BCG analysis

Thermal emissions are concentrated in the Midwest

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



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

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

Core applications occur at high temperatures

Pelletizing
1000-1200 ºC

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

Blast Furnace
2200-2300 ºC

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

Basic Oxygen Furnace
1600 ºC

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

Electric Arc Furnace
1800 ºC

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

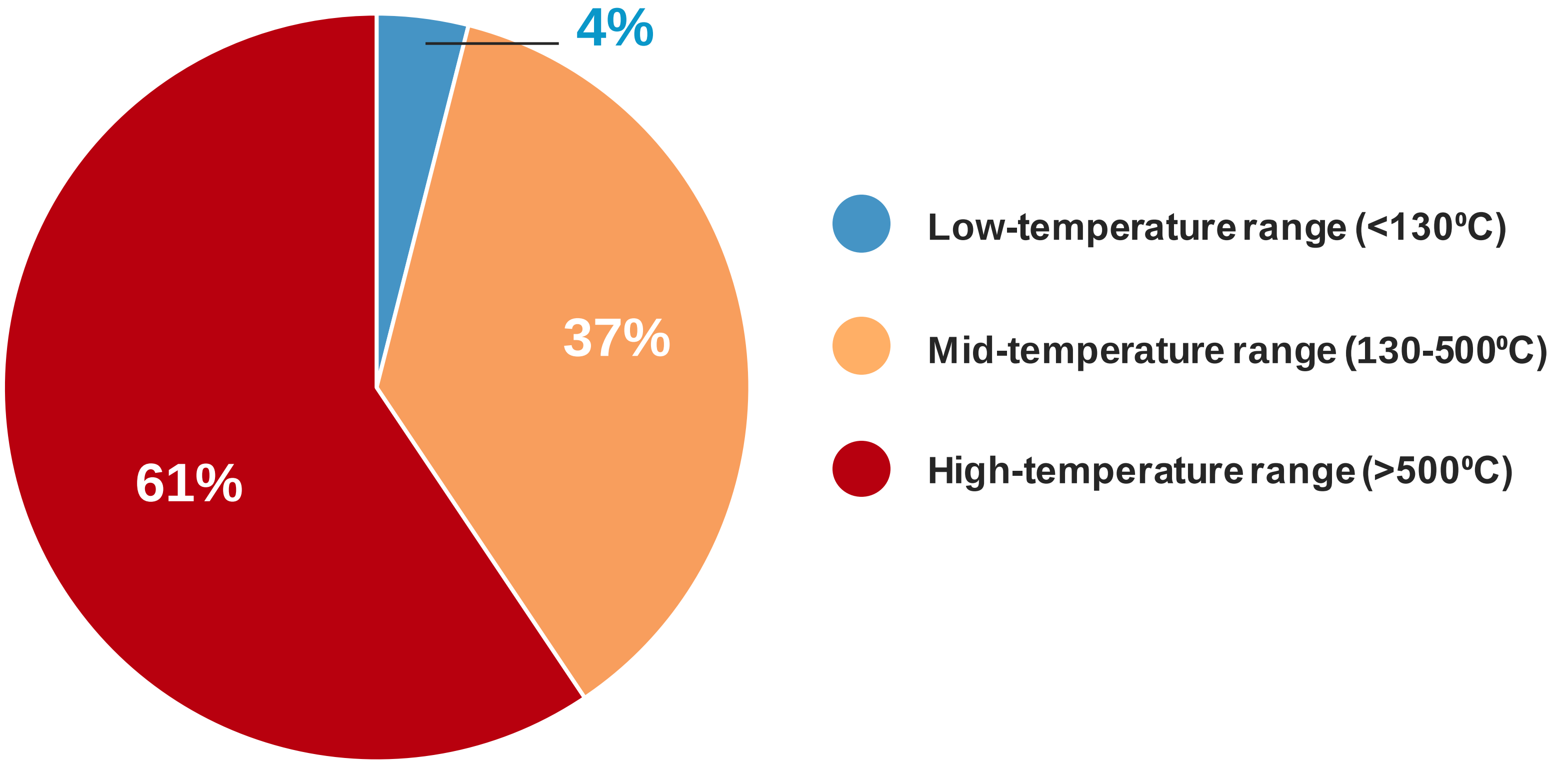
Rolling
1000-1300 ºC

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

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

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

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



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

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

BF-BOF
(Blast furnace – Basic oxygen furnace)

~10 facilities[1]

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

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

~77% of thermal emissions[1]

Scrap-EAF
(scrap metal with electric arc furnace)

~100 facilities

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

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

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

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

3 facilities

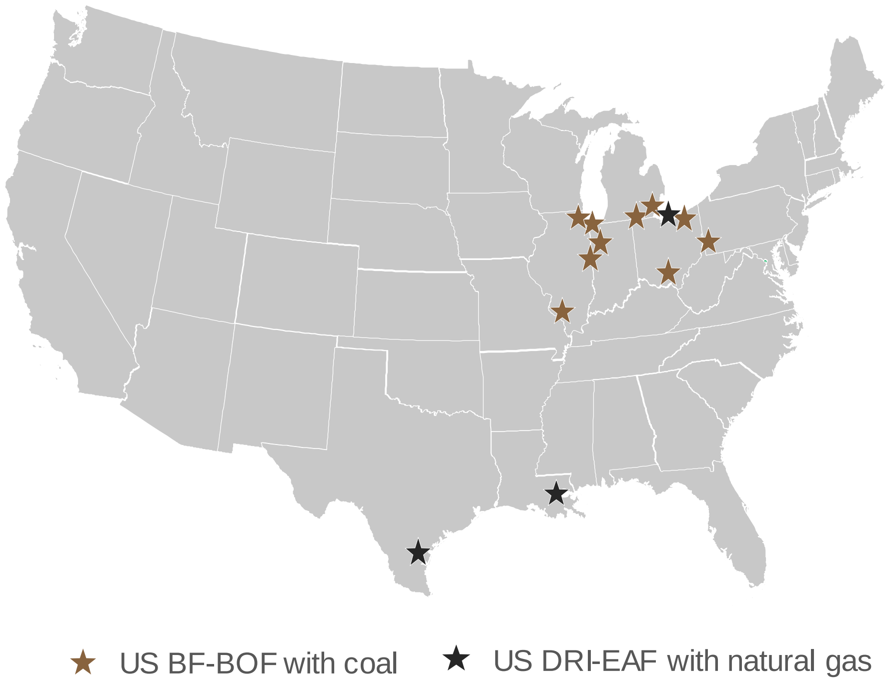
To produce higher quality steel, DRI (direct reduced iron) can be fed into EAFs along with scrap metal

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

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

~23% of thermal emissions

US BF-BOF & DRI-EAF locations



1. There were 10 active plants running BF-BOFs the US in 2018, representing 34 million tonnes of CO_2e and 77% of sector thermal emissions; this represents 8% of the total US industrial thermal emissions across all sectors included in this analysis; in 2020, one BF-BOF plant shut down its BF-BOFs and there are now approximately 9 plants operating BF-BOFs in the US Source: EPA GHGRP 2018; BCG analysis

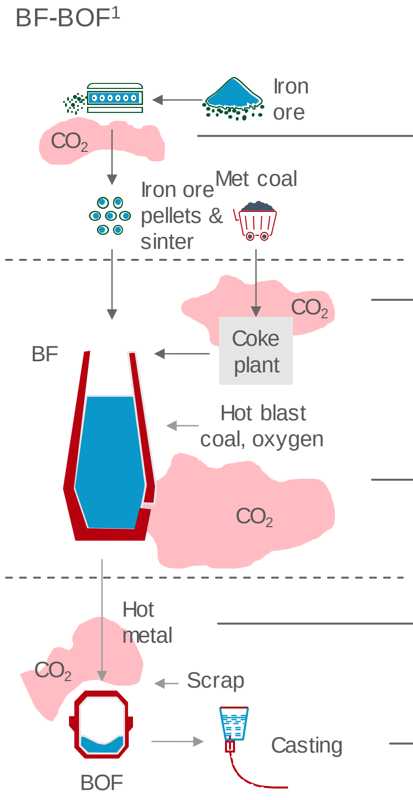
~9 US steel plants running BF-BOFs represent ~7-8% of total US industrial thermal emissions[1]

Starting point: BF-BOF[2]

Raw material inputs

Ironmaking

Steelmaking & casting



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

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

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

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

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

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Source: EPA GHGRP 2018; BCG analysis

Area represents amount of CO_2 emissions

Primary decarbonizing approaches divide in two main pathways

BF-BOF plants (~77% of emissions)

EAF plants (~23% of emissions)

OR

Switch to DRI-EAF with H_2

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

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

Deploy CCS

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

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

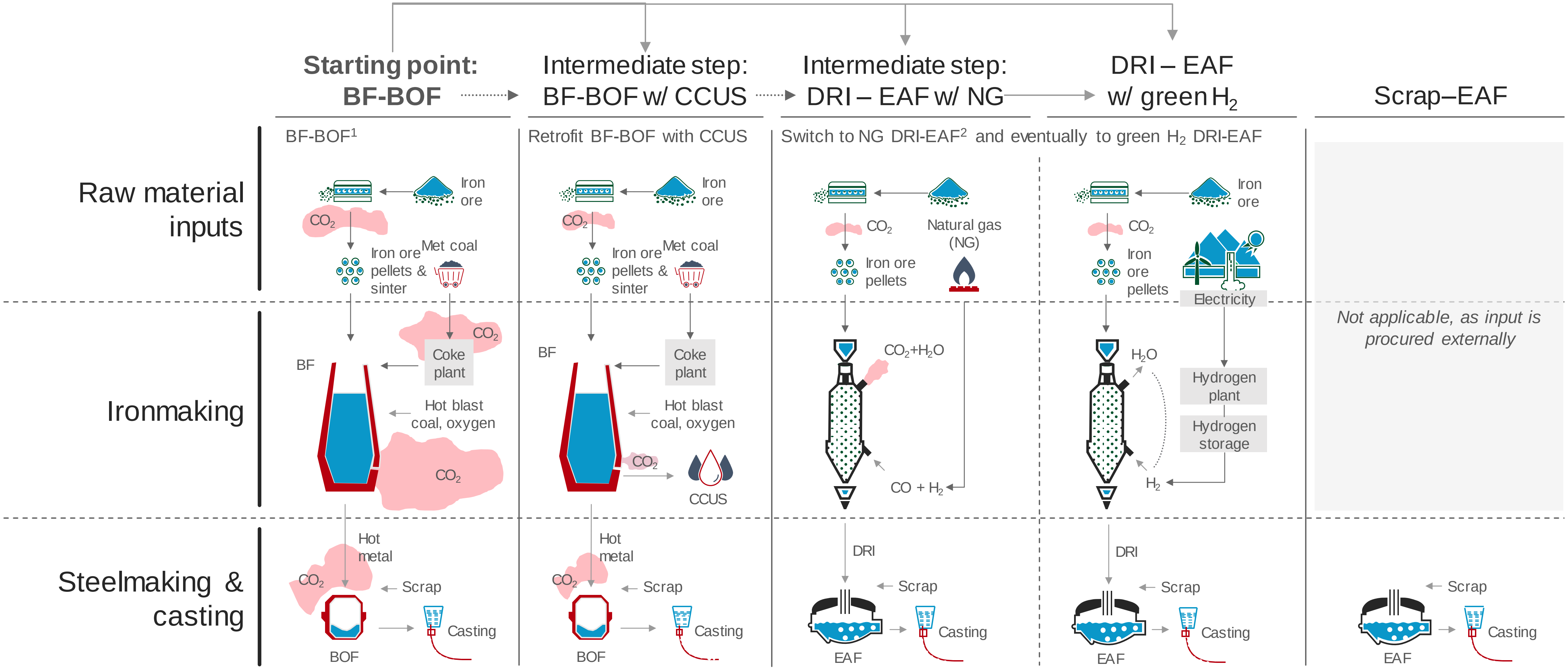
Eliminate fossil fuel combustion

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

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

Represents a process change

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



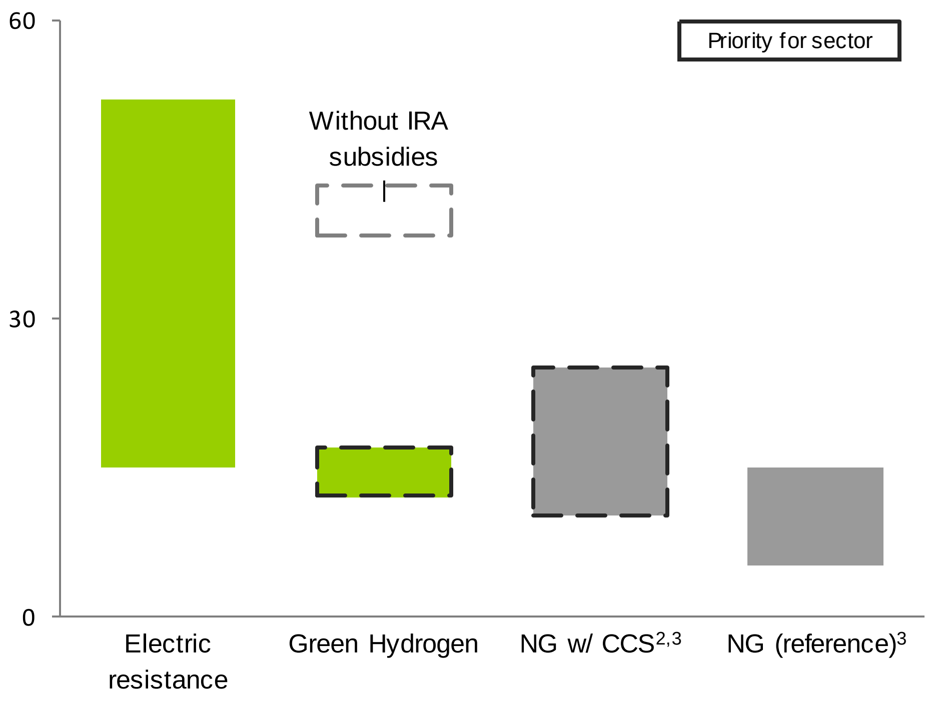
1. Blast Furnace-Basic Oxygen Furnace 2. Direct Reduced Iron-Electric Arc Furnace
Source: BCG analysis

Area represents amount of CO_2 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

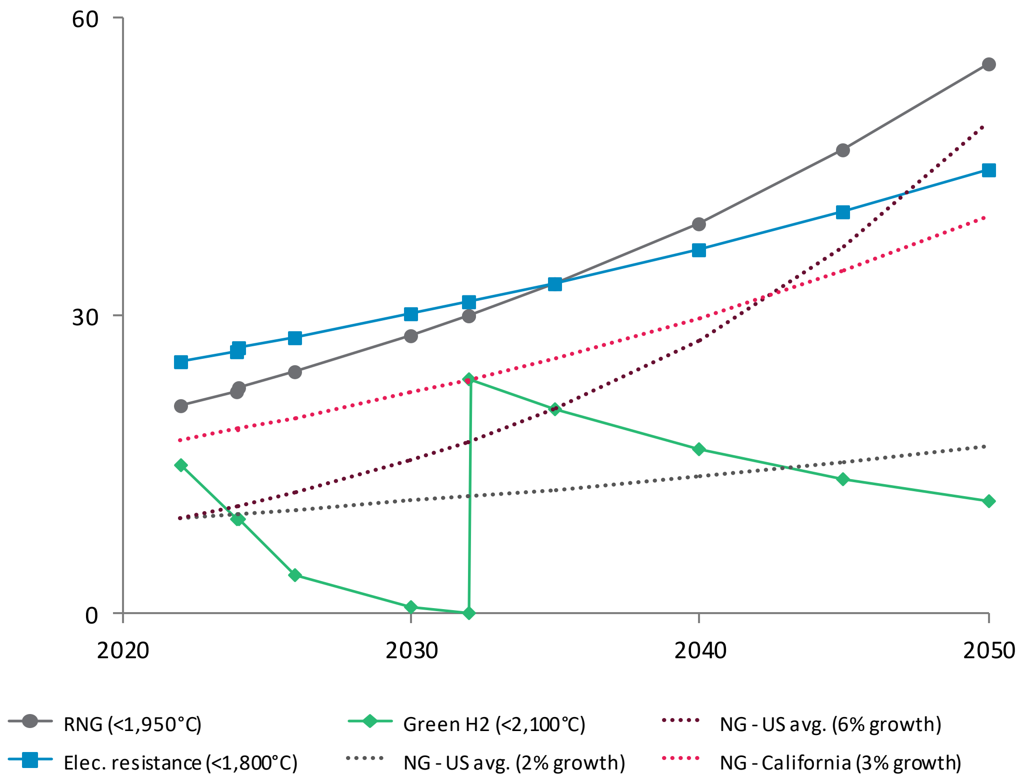
2022 LCOH for relevant technologies[1]

($/MMBtu)



Projected LCOH for relevant technologies[1]

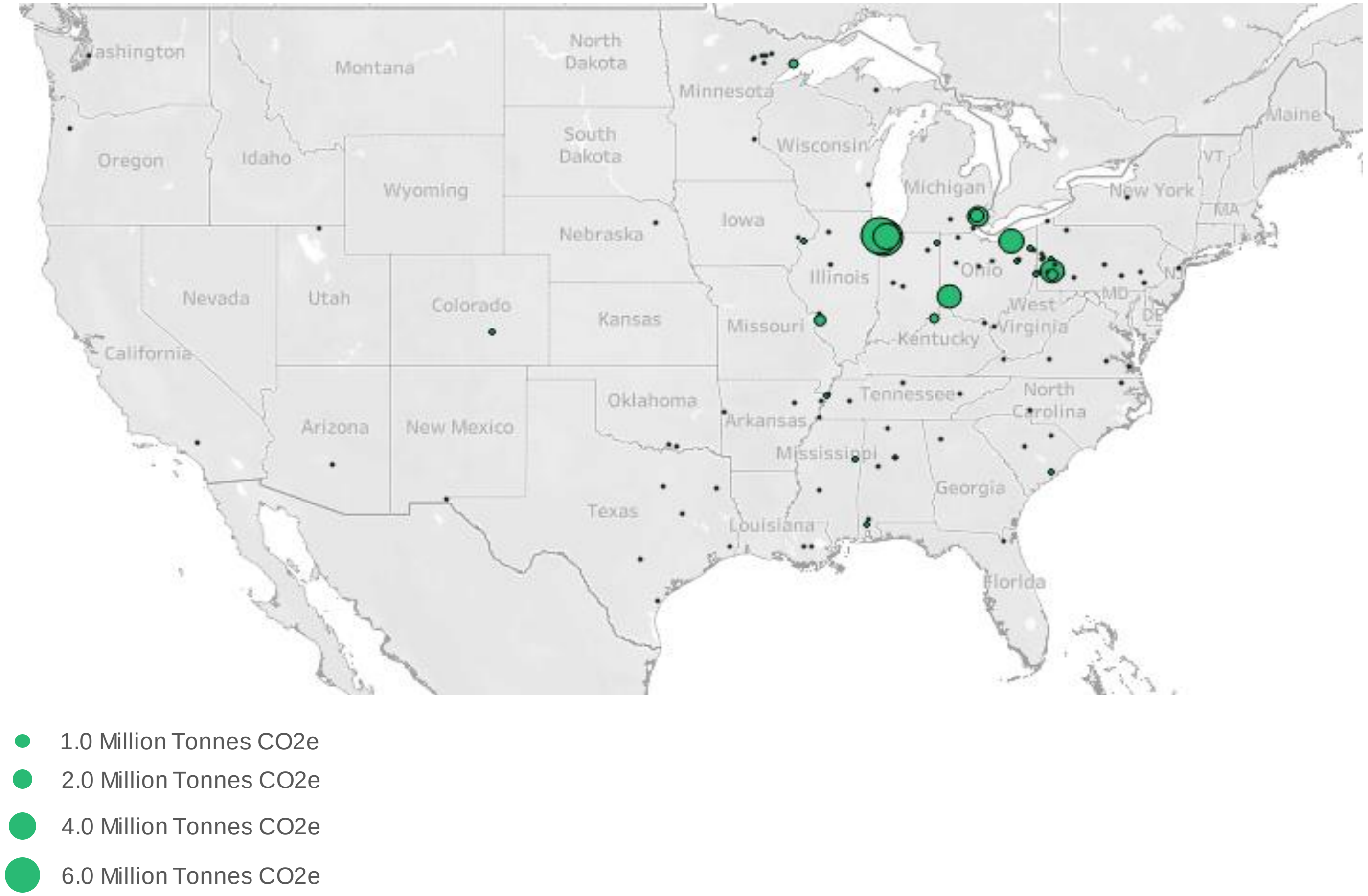
Average US LCOH ($/MMBtu)



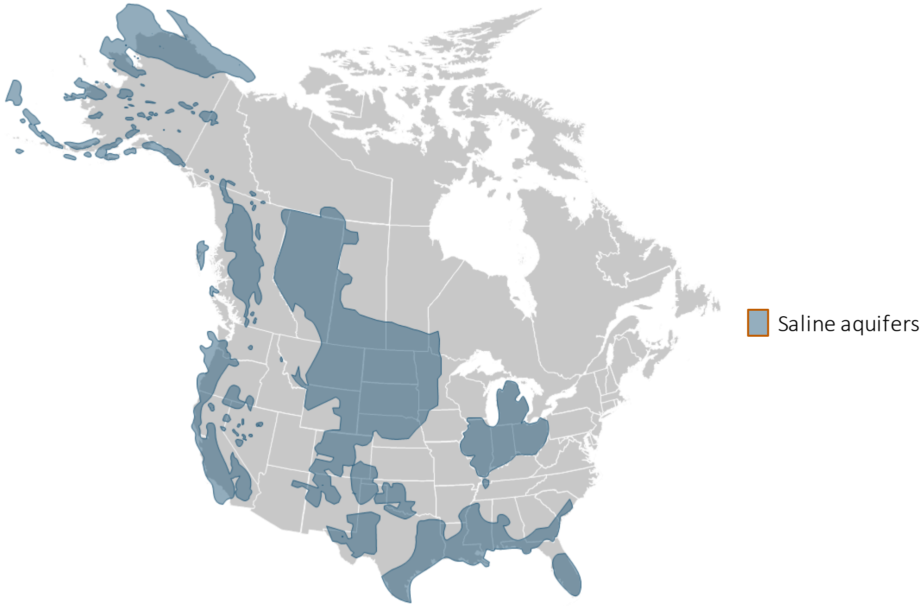
1. LCOH compares project lifetime costs against lifetime energy produced; costs include capital expense of equipment, fuel costs, and maintenance expense assumptions over the usable life of the energy asset. Electricity and natural gas pricing is based on national weighted average wholesale industrial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

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

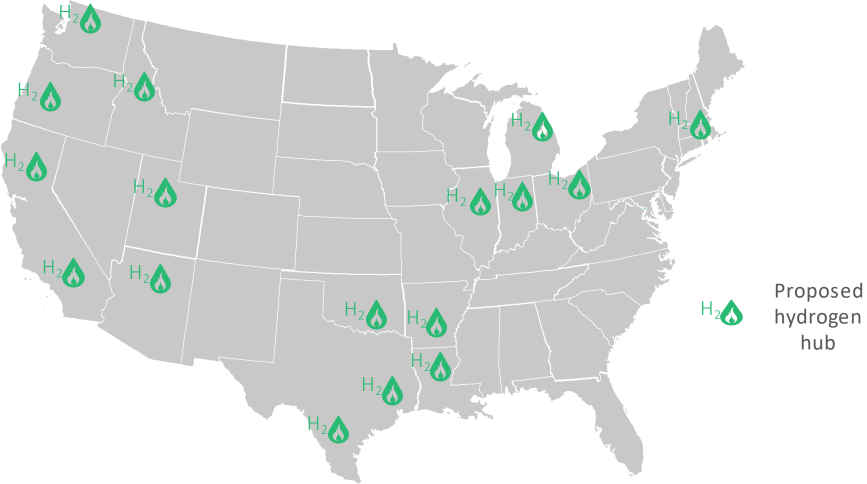
US Iron & Steel sector thermal emissions by zip code[1]



CCS sequestration geographies[2]



Proposed hydrogen hubs[3]



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

Decarbonization pathways

Coal
Displaced by renewable fuels

Natural Gas
Displaced by renewable fuels

Pathway	Considerations	Target First Movers
Electric Arc Furnaces – Convert blast furnace / basic oxygen furnaces to direct reduction iron / electric arc furnace where possible	Iron and steel making value chain (i.e., simultaneous deployment of DRI with EAF), grid or PPA supports emissions savings	End-of-life or greenfield steel mills, ability to procure inexpensive electricity
RNG – Increase use as blend in NG supply until supply constraints are met and costs are prohibitive	Adequate supply of fuel	Regions with grid RNG blending (Midwest, Southeast)
CCS & Other Carbon Capture – Implement to capture combustion emissions from fossil fuel combustion	Concentration of CO2 in flue gas, government subsidies	Regions with iron & steel clusters and adequate geology for storage

2022 → 2050

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

Thermal decarbonization pathways

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

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

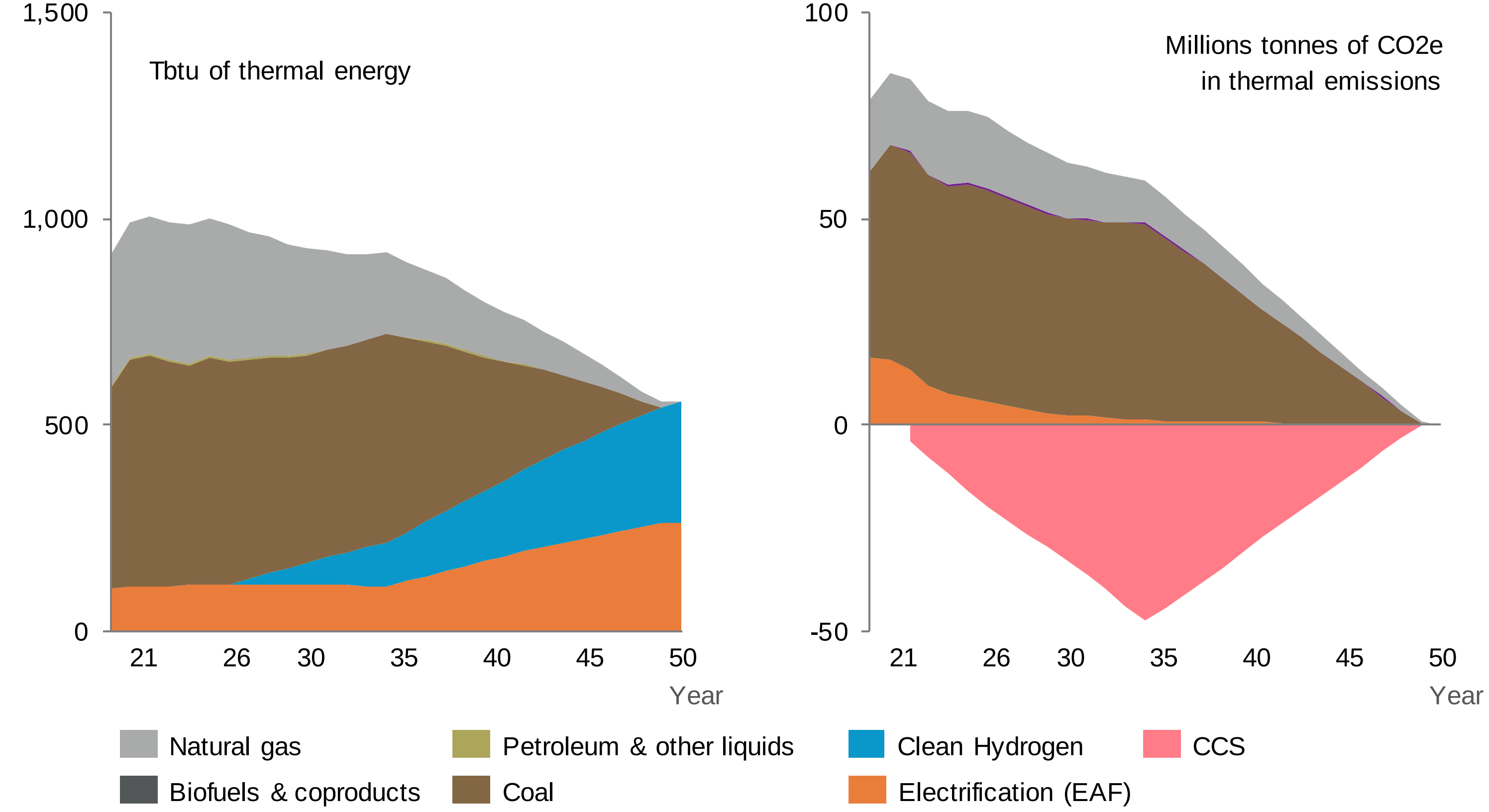
Data suggests current stock of BF-BOFs will require upgrades from 2023-2036 period, however, due to various sector specific factors including insufficient DRI supply to produce high quality steel, the remaining BF-BOFs are not expected to convert to DRI-EAF w/ green hydrogen in the short and medium term.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

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

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

Thermal energy consumption[1]

Thermal emissions[2]



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

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