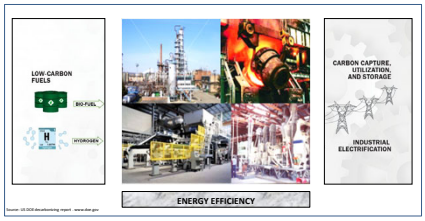
Decarbonization of Industrial Process Heating Systems



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Prepared for The Energy Solutions Center

Overview of the Sessions

- **Session 1.** Introduction to industrial process heating and pathways to decarbonization.
- **Session 2.** Efficiency improvements – low to no cost approaches to reduce CO_2 emissions. Description and effectiveness of such actions with comments on economics.
- **Session 3**. Use of non-carbon bearing / low carbon fuels. Fuel options and their use. Fuels may include H2, Bio fuels including methanol, ammonia at selected locations etc.
- **Session 4.** Use electricity – electro technologies. Available technologies for specific applications (i.e. metal melting, drying, heat treating, calcining, non-metal melting etc.).

Decarbonization of Industrial Process Heating Systems

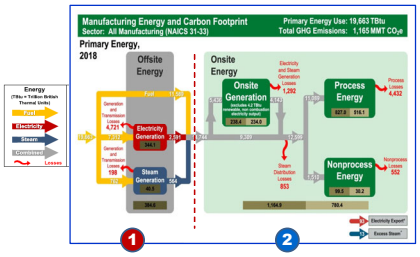
- **Session 1.1 Introduction**
  - Brief overview of industrial energy use.
  - Industrial process heating systems: thermal processes, industrial applications and heating equipment.
  - Amount of CO_2 generated from main energy sources (fuels, steam and electricity) for industrial heating systems.

Decarbonization of Industrial Process Heating Systems

- **Session 1.2 Introduction**
  - Sources of CO_2 from industrial process heating systems
    - Combustion of fuels with carbon content (fossil fuels)
    - Process generated CO_2
  - Overview of pathways or approaches to reduce and/or eliminate CO_2 emissions:
    - Efficiency improvements for process heating systems.
    - Use of alternative – carbon neutral fuels including use of hydrogen.
    - Use electricity – electro technologies to supply heat.

Energy Use in Manufacturing*

An Overview



- The latest available USA Data for the year 2018. .source: www.eia.gov

Onsite Energy Use in Manufacturing

Offsite Energy Generation	Onsite Energy Generation	Process Energy	Nonprocess Energy
Electricity	Steam - conventional boilers	Process heating	Nonprocess energy
Steam	CHP/Cogeneration	Process cooling	Facility HVAC
	Other electricity generation	Other process uses	Facility lighting
		Electro-chemical	Other facility support
		Machine drive*	Onsite transportation
			Other nonprocess

* pumps, fans, compressed air, material handling, material processing, other systems.
Source: eia.gov MECS report (2021 version)

Energy Use in Manufacturing* Summary

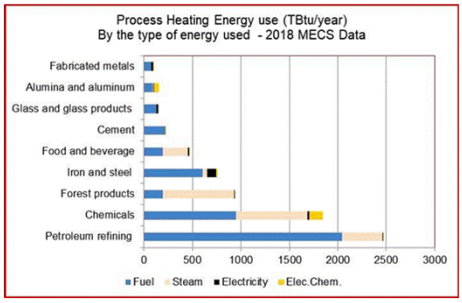
Manufacturing Energy and Carbon Footprint
Sector: All Manufacturing (NAICS 31-33)

Onsite Energy Use: 14,744 TBtu
Onsite Emissions: 780 MMT CO_2e

- Fuel energy use: 11,589 Trillion(T) Btu/yr. – almost 78% of the total onsite energy use
- Direct CO_2 emissions: 800 Million (MM) Tons/yr.
- This is 138 lbs./Million (MM) Btu
- This is higher than CO_2 generated from most fuel combustion
- However this represents combustion generated CO_2 plus process generated CO_2
- More on this later.

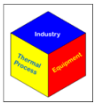
* USA Data based MECS data reported for the year 2018. The most recent survey, began in 2023 and the first data will be appearing starting in January 2025 to provide data for calendar year 2022. MECS is currently conducted on a quadrennial basis.

Process Heating Energy Use in Major Industries



- Graph prepared by using the latest available USA Data for the year 2018. source: www.eia.gov

Three Dimensions of Industrial Heating



- The industry where it is used
  - chemical, steel, petroleum refining, glass etc.
- Type of thermal process
  - Melting, reheating, fluid heating, heat treating, steam generation etc.
- Type of process heating equipment
  - Furnace, oven, fluid heater, dryer, kiln etc. Batch or continuous – using various types of energy sources.

Thermal Processes Used in Manufacturing

Thermal processes
Calcining
Bonding, curing and forming
Drying
Fluid heating
Heat treating (metal and nonmetal)
Metal and nonmetal reheating
Metal and nonmetal melting
Other heating: processing
Reactive thermal processing
Smelting, agglomeration etc..
Steam generation

Description of Thermal Processes

Thermal process category	Brief commonly used explanation*
Calcining	To heat material to high temperature, below the melting or fusing temperature, causing loss of moisture, chemical reaction or oxidation.
Bonding, curing and forming	To heat materials (commonly organics) to promote chemical change, to bond, fuse, to change shape etc. without melting.
Drying	To remove moisture or liquid from materials through thermal processing (i.e. heating)
Fluid heating	Heating of fluids (liquids and gases) using heating systems to raise temperature and promote chemical reactions or phase changes.
Heat treating (metal and nonmetal)	To produce desired characteristics, such as hardness or softness in a material by controlled heating and cooling.
Metal and nonmetal reheating	To raise temperature of metal or nonmetal without melting, fusing or changing chemical properties.
Metal and nonmetal melting	To raise temperature of metal or non-metal to (or above) its melting temperature.
Other heating: processing	To heat material or equipment (i.e. Thermal Oxidizers, Ladle Heating, Tundish Heating etc.) - catch all category
Reactive thermal processing	To heat materials with or without reaction promoters (i.e. catalysts) to promote chemical reactions
Smelting, agglomeration etc	To fuse or melt materials to separate their metallic or non-metallic constituents (as in ore reduction).
Steam generation	Water heating to produce steam at the desired temperature and pressure. A widely used fluid heating system.

* The definitions are for explaining the process using commonly understandable language. It is not detailed 'scientific" definition

Thermal Processes and Industries

Thermal process ↓	Industrial sector							
	Iron and steel	Petroleum refining	Chemical industry	Glass	Aluminum	Pulp and paper	Food processing	Cement
Calcining								
Bonding, curing and forming								
Drying								
Fluid heating								
Heat treating (metal and nonmetal)								
Metal and nonmetal reheating								
Metal and nonmetal melting								
Other heating: processing								
Reactive thermal processing								
Smelting, agglomeration etc.								
Steam generation								

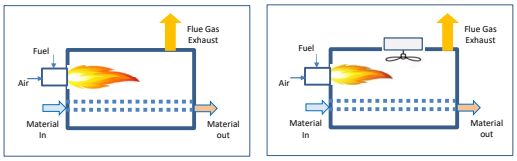
Types of thermal processes used for eight large energy consuming industries. Colors indicate temperature ranges. Blue = low temperature (<800°F); yellow = medium temperature (800°F to 1,400°F); red = high temperature (>1,400°F).

Figure by Arvind Thekdi

Examples of Thermal Processes
Iron and Steel Industry

Thermal process category	Processes used in Iron and steel Industry
Calcining	Lime production
Bonding, curing and forming	Drying and curing of paints and other coatings
Drying	Iron ore drying, ladle/tundish drying, scrap drying
Fluid heating	Blast furnace stoves - air heating, Metal cleaning tank liquid heating
Heat treating (metal and nonmetal)	Steel hardening, batch and continuous annealing
Metal and nonmetal reheating	Steel reheating for hot rolling, forging, hot working of finished parts etc...
Metal and nonmetal melting	Electric arc melting furnaces (EAF) - cupolas, induction melting
Other heating: processing	Ladle and Tundish heating, mold heating, thermal oxidizers, HVAC etc...
Reactive thermal processing	Iron ore sintering, smelting. blast furnace, coke ovens, Direct Reduced Iron (DRI) production, ladle refining, atmosphere generators etc...
Steam generation	Fired steam boilers, waste heat recovery boilers, hot water boilers.

Direct Fired Furnaces*

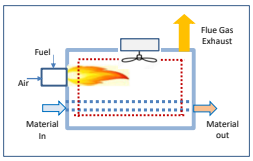


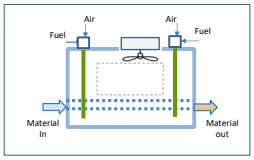
- The fuel fired burner combustion products supply the required heat to the material being heated. May use an internal recirculating fan to enhance heat transfer.
- CO_2 concertation may be high (~10%) or relatively low (<6%) in exhaust gas depending on the process and combustion conditions.

- The word "furnace" is used to describe all types of fired heating equipment i.e. ovens, heaters, melters etc.

Figures by Arvind Thekdi

High Convection and Radiant Tube Heated Furnaces



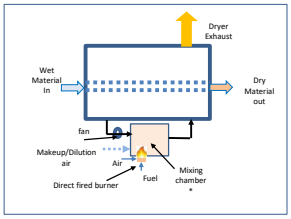


- A furnace with high capacity gas recirculating gases providing high convection. Mostly used for lower (<1000ºF) temperature processes.
- CO_2 concentration in exhaust gas may be low (<6%) or relatively high (~10%) depending on the process

- A furnace with radiant tubes with radiation and mild convection heating.
- Some furnaces may use a gas recirculating system to protect the work or enhance convection.
- CO_2 concentration exhaust gas is relatively high (~10%).

Figures by Arvind Thekdi

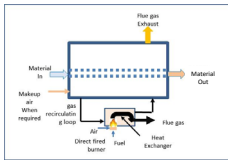
Convection Oven with Recirculating Gases: Direct Fired Burner

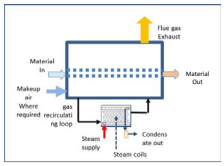


- The fuel fired burner combustion products are mixed with process gases and exhausted out of the furnace/oven.
- CO_2 concentration may be low (<6%) or relatively high (~10%) depending on the process.

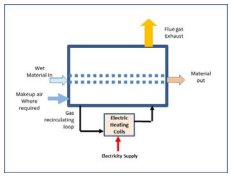
Figure by Arvind Thekdi

Oven with Recirculating Gases: Indirect Heating





- A heat exchanger (gas to gas or steam to gas) or electrical heater located within the recirculating gas path supplies heat to the gases.
- The recirculating gases provide heat and enhanced convection heat transfer to the material being heated.



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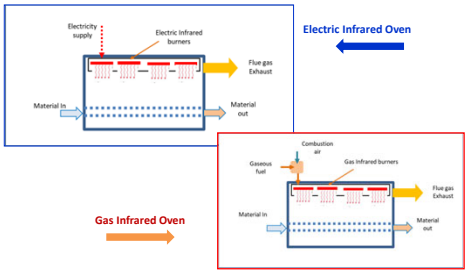
Gas and Electric Infrared Ovens



Electric Infrared Oven

Gas Infrared Oven

Figures by Arvind Thekdi

Microwave – RF Heater/Oven

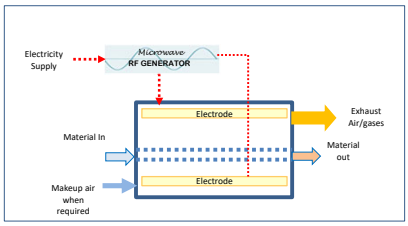


Figure by Arvind Thekdi

Other Types of Heating Systems

Induction furnace (metal heating and melting)

Electric arc furnace

Molten salt bath furnaces

Source for the photos: DOE Process Heating Source Book. www.energy.gov

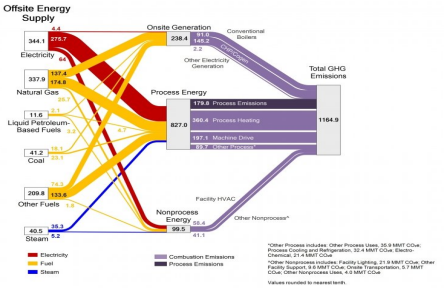
GHG Terms Explanation

Global Warming Potential (GWP) is a measure of how much energy the emission of 1 ton of a gas will absorb over a given period of time, relative to the emission of 1 ton of carbon dioxide (CO_2).

- CO_2, by definition, has a GWP of 1. CO_2 emissions cause increases in atmospheric concentrations of CO_2 that will last thousands of years.
- Methane (CH_4) is estimated to have a GWP of 27-30 over 100 years. The CH_4 GWP also accounts for some indirect effects, such as the fact that CH_4 is a precursor to ozone, and ozone is itself a GHG.
- Nitrous Oxide (N_2O) has a GWP 273 times that of CO_2 for a 100-year timescale.
- Chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are high-GWP gases. The GWPs for these gases can be in the thousands or tens of thousands.

Total GHG Emissions

Million Metric Tons (MMT) CO_2 Equivalent*

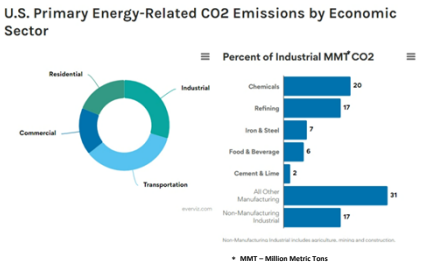


GHG – Green House Gas

- Data for all manufacturing NAICS 31-33

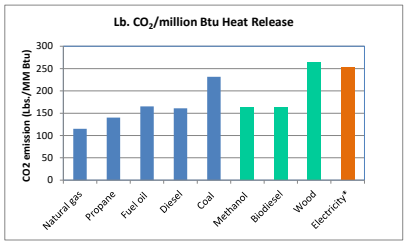
Source: www.eia.gov

Industrial Sector GHG Emissions



GHG – Green House Gas.
www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap

CO_2 Emission from Various Energy Sources



Note: CO_2 produced by complete combustion of fuels.

Carbon neutral

* For reference

Graph by Arvind Thekdi

CO_2 Production From Combustion of Natural Gas

Combustion of Methane (~ Natural gas)

$CH_4 + 2 (O_2 + 3.76 N_2) \Rightarrow CO_2 + 2 H_2O + 7.56 N_2$

Notes:

- CO_2 concentration in flue gas for stoichiometric combustion is about 12% by volume (dry flue gas).
- CO_2 concentration decrease as the excess air increases.
- However the mass of CO_2 (Lbs.) does not change with use of excess air.
- CO_2 production per MCF (thousand cu. Ft.) of natural gas – approximately 115 lbs.

CO_2 Emission - Steam Heating

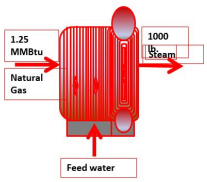
- Processes that use steam and electricity as source of heat do not have **direct** emission of CO_2 at the point of use.
- Accounting for CO_2 discharge from steam heated system requires consideration for total heat content of steam used, type of fuel used in boilers and efficiency of steam generation system.
- CO_2 emission from steam heated system that uses steam from a natural gas fired boiler can range from 125 to 160 lbs./MM Btu heat supplied to the process.
- It is also necessary to consider heat losses from the steam distribution, condensate return and process heating equipment when considering CO_2 emission associated with heating equipment.

Calculation of CO_2 Emission

Steam Production Using a Natural Gas Fired Boiler

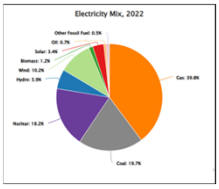
- Natural gas emission factor= **115 Lbs./MM Btu**
- Boiler steam output = 1000 lbs.
- Boiler efficiency = 80%
- Heat required to generate steam[1] = 1100 Btu/lb.
- Boiler emissions = 115*(1100/0.8)*1000/10^6 = 158 lbs. of CO_{2e}/1000 lbs. of steam

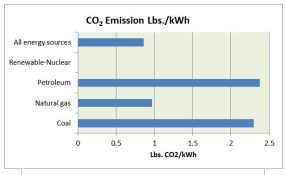
Note: 1 Steam at 300 psig, superheat temperature 400 ^{0}F., feed water temperature ~160 ^{0}F.

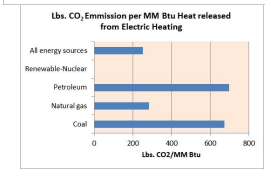


Information from Aqeel Zaidi – Enbridge Gas

CO_2 Emission with Use of Electricity





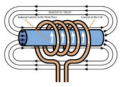


Note: All data for the USA
Graphs by Arvind Thekdi
Source: www.eia.gov

CO_2 Emission - Electric Heating

- Calculations for CO_2 emission from electrically heated system can be little more complicated because it is necessary to consider energy source (i.e. from fuel fired plants, nuclear plants, renewable sources etc.) for electricity generation.
- According to the US Energy Information Agency (EIA) in 2020, average carbon dioxide (CO_2) emission for electricity is about 0.85 lbs. per kWh for the entire country. This accounts for electricity production from all sources mentioned above.
- CO_2 emission per kWh electricity could be substantially lower than the national average with on-site electricity generation which uses combined heat and power (CHP) or cogeneration.
- Marginal CO2 emission could be higher.

CO_2 Emission - Electric Heating



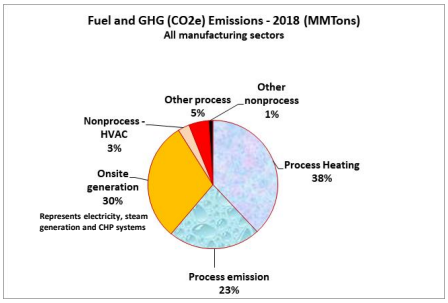
- Heat required for raising temperature of steel bars (1 ton/hour, final temperature 2400^0F) is 0.85 MM Btu or 248 kWh.
- Induction heating system efficiency: 70%.
- Heat supplied as electric heat is (248/0.7) = 354 kWh
- CO2 emission associated with the heating process is 354/0.85 = 416 lbs./MM Btu heat supplied to steel being heated,

- Actual CO_2 emission from a heating process depends on the efficiency of use of electricity.
- For example an induction system that uses electrical energy for reheating steel bars with 70% overall thermal efficiency for the induction system would have 416 lbs. CO_2 per MM Btu heat supplied to the product being heated.

Total CO_2 Emissions
From Process Heating Systems

- Source of CO_2 generation – emission in heating processes used in manufacturing.
  I. Directly from combustion of fuels fired in process heating equipment.
  II. Thermo-chemical reactions
  III. The decomposition of product itself
  IV. Other reacting materials etc.
  V. Indirectly from steam and electricity generation using fossil fuels as energy source. .
- Combustion generated CO_2 emission represent about 70% of the total.
- Combustion generated CO_2 emission depends on carbon content of the fuel and the amount of air used for combustion.
- However combustion air equal to or higher than stoichiometric air (excess air) would result in a fixed amount of CO_2 (lbs. of CO_2 per MM Btu heat release) during the combustion process.

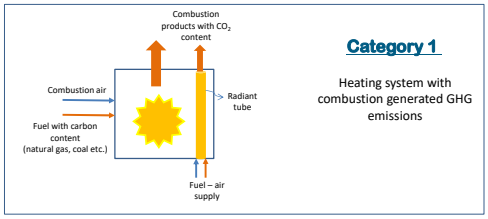
Sources of CO_2 in Manufacturing Plants



GHG emissions from US manufacturing by end uses (MMT CO_2e).

Source: Latest available MECS data. www.eia.gov

Category 1 Heating Systems
CO_2 Emission Source



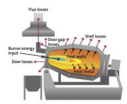
Category 1

Heating system with combustion generated GHG emissions

Examples: Fuel fired furnaces that use directly fired burners in a furnace or in radiant tubes for metal/non-metal heating, meal or glass melting, steam or hot water boilers, fired heaters, ovens, cement kilns etc.

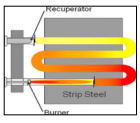
Figure by Arvind Thekdi

Category 1 Heating Systems
A Few Examples



Direct fired aluminum melting furnace

Direct fired petroleum heater

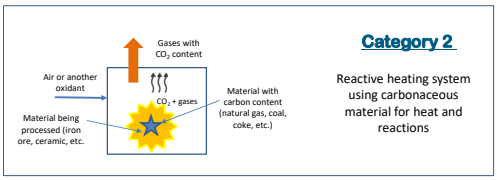


Radiant tube heating

Gas fired steam boiler

Source for the pictures/drawings:
Process Heating Source Book – US DOE (2005)

Category 2 Heating Systems
CO_2 Emission Source



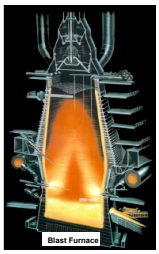
Category 2

Reactive heating system using carbonaceous material for heat and reactions

Examples: Blast furnace, cupola furnace, sintering furnace etc. using mixed carbon for reaction and heat generation.

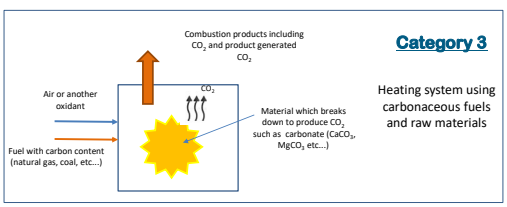
Figure by Arvind Thekdi

Category 2 Heating Systems
A Few Examples



Source for the pictures/drawings:
Process Heating Training Book – US DOE (2004)

Category 3 Heating Systems
CO_2 Emmi son Source



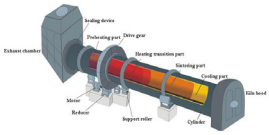
Category 3

Heating system using carbonaceous fuels and raw materials

Examples: Clinker making kilns in cement industry, Lime kilns, reaction vessels, certain reformers, etc.)

Figure by Arvind Thekdi

Category 3 Heating Systems
A Few Examples

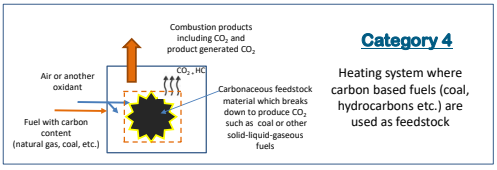


Cement or lime kiln

Iron ore reduction

Source for the pictures/drawings:
Process Heating Training Book – US DOE (2004)

Category 4 Heating Systems
CO_2 Emission Source



Category 4

Heating system where carbon based fuels (coal, hydrocarbons etc.) are used as feedstock

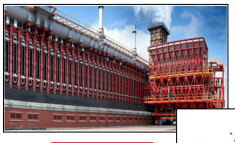
Examples: Coal/Coke pyrolysis to produce chemicals, industrial carbon products (i.e. activated carbon) etc. used by metals, chemicals and other industries.

Note: The base material may not directly discharge CO_2 but the discharged products react with the surrounding atmosphere and produce CO_2

Note: This category is very similar to category 3 with a few subtle differences.

Figure by Arvind Thekdi

Category 4 Heating Systems
A Few Examples



Coke oven Battery

Activated carbon production

Source for the pictures/drawings:
Process Heating Training Book – US DOE (2004)

Examples of Different Categories of the Heating Processes

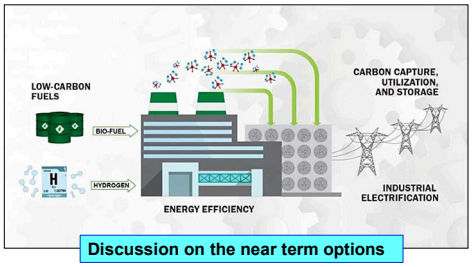
Thermal process step	Category 1	Category 2	Category 3	Category 4
General description	Heating system with combustion generated GHG emissions	Reactive heating system using carbonaceous material for heat and reactions	Heating system using carbonaceous fuels and raw materials	Heating system where carbon based fuels (coal, hydrocarbons etc.) are used as feedstock
Typical example	Carboneceous fuel is used to supply heat to the material being heated	Carboneceous material is used to supply heat and also as a reactant	Carboneceous material is used to supply heat and the processed material also discharges CO2	Carboneceous material is used as feed stock and CO2 is produced by partial combustion of the material
Calcining			Cement clinker or lime production	
Bonding, curing and forming	Rubber/plastic processing			
Drying	Textile/grain drying			
Fluid heating	Liquid/air/crude heating			
Heat treating (metal and nonmetal)	Annealing/hardening of metals	Carburizing etc.		
Metal and nonmetal reheating	Steel reheating, forging, glass- ceramics			
Metal and nonmetal melting	Aluminum melting	Iron melting	Glass melting	
Other heating: processing				
Reactive thermal processing		Catalytic reforming		Metallurgical coke production
Steam generation	Steam boilers			

Category 1
Category 2
Category 3
Category 4

Few examples of types of thermal processes used for eight large energy consuming industries and CO2 emission categories

Figure by Arvind Thekdi

Decarbonization Strategy for Process Heating Systems



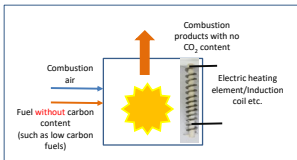
Discussion on the near term options

Decarbonization Strategy for Process Heating Systems

Energy Efficiency improvements and carbon capture

- Energy efficiency improvement is applicable to all systems discussed here.
- In many cases it is the least expensive and most cost effective method to reduce CO_2 emission from process heating systems.
- Carbon capture in a variety of forms is also an option to reduce/eliminate CO_2 emissions from process heating systems.
- However it is the most expensive and not very practical approach for majority of the industrial process heating systems.

Decarbonization Strategy for Category 1 Process Heating Systems



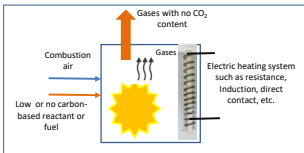
Category 1

Decarbonization Strategy
Use of non-carbonaceous fuels and/or electric heating. Heating system with no combustion generated GHG emissions.

Examples: Burner fuel used: Hydrogen, ammonia etc. with no carbon content. Use of electricity in a number of different type of heating system: resistance, induction, microwave, electric UV, arc melting, RF heating etc.

Figure by Arvind Thekdi

Decarbonization Strategy for Category 2 Process Heating Systems



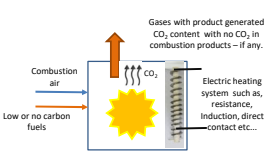
Category 2
Decarbonization Strategy

Reactive heating system using alternative reactive material or reaction paths (i.e. electrolysis) that do not produce GHGs.

Use of non carbon based fuels and/or electric heating to supply necessary heat with alternate reactants (reducing agents) such as hydrogen. Development of non thermal processes for reduction of raw materials such as iron ore (oxides).

Figure by Arvind Thekdi

Decarbonization Strategy for Category 3 Process Heating Systems



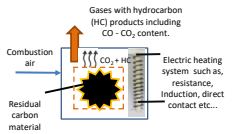
Category 3

Decarbonization Strategy
Heating system using alternative fuel or energy source to reduce GHGs. However, the product generated GHGs cannot be eliminated.

Use of hydrogen, bio fuels or electric heating (resistance, induction etc...) to supply heat to achieve the required process temperature when the material breakdowns to produce CO2. It is necessary to use a gas separation system and capture CO2 in a carbon capture system.

Figure by Arvind Thekdi

Decarbonization Strategy for Category 4 Process Heating Systems



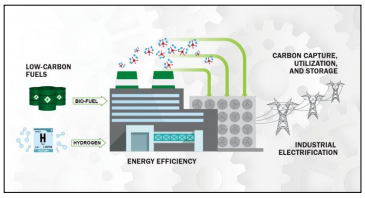
Category 4 Decarbonization Strategy

Heating system using alternate - electric heating to reduce mass flow of GHGs. However, process generated GHGs cannot be eliminated.

The required heat is supplied by partial combustion of carboneceous material. The off gases can be used as feed stock for downstream chemical processes or as fuel. CO_2 generated by oxidation of off gases need to be dealt with using carbon storage system or other methods.

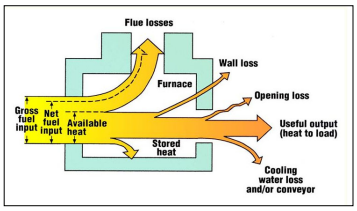
Figure by Arvind Thekdi

Decarbonization of Industrial Process Heating Systems



Introduction to the Next Three Sessions

Session 2: Efficiency Improvements



- Low to no cost approaches to reduce CO_2 emissions.
- Description and effectiveness of such actions with comments on economics.

Session 3: Use of non-carbon bearing / low carbon fuels

- Fuel options (H_2, ammonia at selected locations, bio fuels including methanol etc.)
- Availability of H_2 and required infra structure, issues such as safety, materials limitations, change of hardware (burners, piping, additional safety etc.)
- Effect on process and materials (higher flame temperature, moisture content, effect on NO_x formation etc.)
- Current information on H_2 sources, storage and distribution methods such as pipe lines at selected locations in North America etc.

Session 4: Use Electro Technologies

- Available and usable electro technologies for specific applications (i.e. metal melting, drying, heat treating, calcining, non-metal melting etc.)
- Matrix of processes and available electric heating method.
- Breakeven point (based on available heat and cost of electricity vs. fuel cost etc.)
- Comments on possibility of conversion or new installation etc.
- Effect on net reduction – change in CO_2 emission depending on the type or primary energy (fuels) of electricity.
- Availability of power supply system and size limitations etc.

Thank You