Decarbonization of Industrial Process Heating Systems

Session 3. Use of Alternate Energy Sources for Process Heating

Source: US DOE decarbonizing report . www.doe.gov

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March 2025
Prepared for The Energy Solutions Center

ENERGY SOLUTIONS CENTER

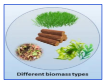
Overview of the Sessions

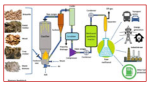
- **Session 1.** Introduction to industrial process heating and pathways to decarbonization.
- **Session 2.** Efficiency improvements – low to no cost approaches to reduce CO2 emissions. Description and effectiveness of such actions with comments on economics.
- **Session 3**. Use of no/low carbon fuels. Fuel options and their use in process heating. Fuels include renewable natural gas (RNG), H_2, 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.).

Overview of the Presentation Content

1. Low carbon/no carbon fuels, their sources and properties.
2. Use of these fuels in industrial process heating systems. Where and how they can be used.
3. Results of use of these fuels: effects on emissions, processes and products, heating equipment etc.
4. Status of equipment availability.
5. Retrofit considerations.

Low/No Carbon Fuels

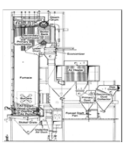




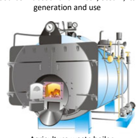
- Solid biofuels -by products of forest products, agriculture residue etc. Used on only in some specially designed steam generators and steam used for process heating systems. Rarely used for industrial process heating.
- Liquid biofuels – methanol, ethanol, glycerin, bio-diesel etc. derived from organic material sources.
- Gaseous fuels – hydrogen, renewable natural gas (RNG), ammonia, synthetic methane, bio gases produced by gasification of organic solids.

AZ2

Solid Bio-fuels Used for Steam Generation



Wood-fired Power Boiler With Travelling Grate
Source- Babcock and Wilcox, Steam, its generation and use

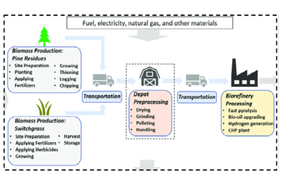


Agriculture waste boiler
Source: Thermodyne Engineering Systems

- Solid biofuels: Indirectly used for process heating in steam heated applications such as drying (pulp and paper, food, textile, etc.), biorefineries, reactant in chemical industry and liquid (mostly water) heating to produce steam in certain industries.
- Examples of use of biomass in industrial applications:
  - Pulp and Paper Industry: Biomass fuels include wood waste boilers that use hog (wood waste) are commonly used in pulp and paper mills.
  - Agriculture and food processing: Rice husks, straw, stalks, agave fiber, sugar cane bagasse etc., Energy Crops**:** Purpose-grown crops like switchgrass and miscanthus used as fuel.
  - Biorefineries: Biorefineries can use their own biomass-derived waste streams as boiler fuels.

AZ1

Liquid Bio Fuels



- Liquid Biofuels suitable for furnaces include Methanol, Ethanol, Bio Diesel, other 'Bio-Oils' derived from cellulosic pyrolysis, glycerin, and various process waste oils.
- Liquid bio-derived fuels (LBF's) are extracted from natural, organic sources such as corn, sugarcane, various plant oils and numerous products and byproducts of industrial processes.
- Combustion equipment such as burners previously developed for fuel oil firing are often suitable for handling LBF's, with minor modifications

Slide 5

AZ0 Black liquor is used only in kraft pulp mills, hog (wood waste) fuel boilers are most commonly used in the pulp an paper industry. Since very few pulp mills use black liquor boiler, you may replace it with the wood waste boiler. See the diagram on the next slide.
Aqeel Zaidi, 2025-03-20T17:49:26.127

AZ1 Add source for the diagrams
Aqeel Zaidi, 2025-03-20T17:50:25.532

AZ2 Delete word "paper' since black liquor boilers are used in the kraft pulp mills.
Aqeel Zaidi, 2025-03-21T20:24:05.031

Liquid Fuel Options for Process Heating

Fuel	Chemical formula	Heating value (Btu/lb.)	Cost/MM Btu	Comments
Methanol	CH2OH	9,875	$ 21	Lower NOx, luminous flame, highly volatile so hazardous.
Ethelyn	C2H5OH	12,827	$ 30	
Glycerin	C3H8O3	7,756	$ 110	Very similar to fuel oil, requires mild preheating before use in traditional oil burners
Bio-fuel	-	12,00 to 18,000	$27 to $50	Derived from wood, burns like fuel oil, highly luminous flame, Nox depends on burner design
Fuel Oil	-	~18,850	$35	#2 fuel oil, used for furnaces and boilers for a long time.
Natural gas For reference	Mostly CH4	~22,000	$5 to $7.50	Commonly used, flame shape size and Nox emission depends on burner design

Note: Cost is for 1 MM Btu heat content

No or Low Carbon Gaseous Fuels

Key points about low carbon gaseous fuels:

- **Zero carbon emissions**
  - Hydrogen and ammonia, when produced using renewable energy, are considered "zero-carbon" fuels as they contain no carbon atoms and therefore emit no CO_2 during combustion.
- **Renewable sources:**
  - Biogas derived from organic waste through anaerobic digestion, makes it a renewable and low-carbon fuel option.
  - RNG is methane from decomposing organic matter and upgraded to meet pipeline quality.
- **Production process matters:**
  - The carbon footprint of these fuels depends heavily on how they are produced. For example, hydrogen produced from fossil fuels still has carbon emissions associated unless C is permanently sequestered.

AZ0

Renewable Natural Gas

AZ0

Source:

Derived from organic waste materials like food waste, animal manure, and landfill gas..

Production:

Involves capturing methane from decomposing organic matter and upgrading it to pipeline quality. The principal constituents are methane and carbon dioxide that has been upgraded for use in place of fossil natural gas

Environmental Impact:

RNG can reduce methane emissions from landfills and wastewater treatment plants, and it can also be used as no-low carbon fuel to substitute fossil natural gas .

Examples:

RNG used for heating, electricity generation transportation etc. .

Cost:

In the range of $15 to $25 per MM Btu.

Slide 8

AZ0 Unless CO_2 or C is permanently sequestered.
Aqeel Zaidi, 2025-03-20T17:56:14.265

Slide 9

AZ0 $7 is very low, typically greater than $15, is there a source for the range included in the slide?
Aqeel Zaidi, 2025-03-20T18:00:20.282

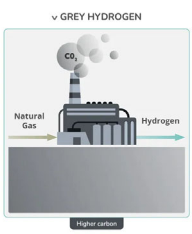
Colors of Hydrogen

AZ0

- Hydrogen is a colorless, odorless gas but it has been given names of many colors!
- **Why is a colorless gas given so many colorful terms?**
  - Depending on the type of production used, different color names are assigned to the hydrogen. But there is no universal naming convention and these color definitions may change over time, and even between countries.
  - Green hydrogen, blue hydrogen, brown hydrogen, turquoise hydrogen, pink hydrogen, and even yellow hydrogen, etc.
  - They're essentially color codes, or nicknames, used within the energy industry to differentiate between the types of hydrogen.

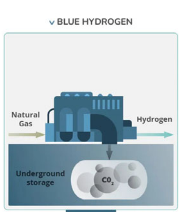
    Note: latest trend is to move away from the colors and call it low carbon H_2 except for grey H_2.

Grey Hydrogen



- Hydrogen produced by steam (H_2O) – Methane (CH_4) reaction.
- $CH_4 + 2H_2O \rightarrow CO_2 + 3H_2$
- Approximately 7.33 to 12 lbs. CO_2 produced per lb. of H_2
- Lowest cost production of H_2 with high emission of CO_2
- Currently, this is the most common form of hydrogen production

Blue Hydrogen



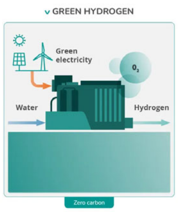
- Hydrogen produced by steam (H_2O) – Methane (CH_4) reaction.
- CO_2 is stored in an underground storage using carbon capture and storage (CCS) technology.
- Actual CO_2 emission depends on the % CO_2 removed or stored before use of H_2.
- Cost of H_2 depends on the amount (fraction) of stored CO_2. For 90% storage of CO_2 , cost of H_2 increases by 60% to 70%.

Slide 10

AZ0 Add a comment that latest trend is to move away from the colours and call it low carbon H_2 except for grey H_2

Aqeel Zaidi, 2025-03-20T18:02:27.479

Green Hydrogen

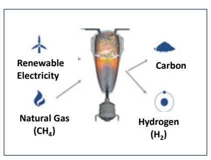


AZ0

- Hydrogen produced by electrolysis process where water molecule "broken" in H_2 and O2 by using electricity from non-fuel or "renewable" sources.
- No production of CO_2 during the electrolytic process. However, the carbon intensity depends on the source of electricity
- Cost of H_2 depends on the source and cost of electricity.
- Recent data indicates that cost of H_2 by this method can be 1.5 to 2.5 times higher than the blue or gray H_2 while using wind or solar generated electricity.

Turquoise Hydrogen

Production Process: Turquoise hydrogen is produced through methane pyrolysis, a process that splits methane into hydrogen and solid carbon, avoiding CO_2 emissions.



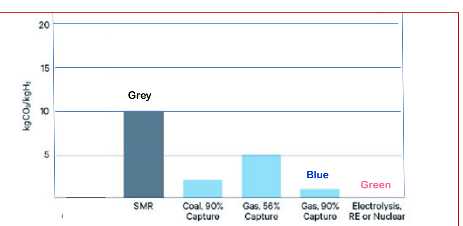
CO_2 Emissions: Turquoise hydrogen production doesn't generate CO_2 as a byproduct.

Solid Carbon Byproduct: The solid carbon produced can be used in various applications, such as making synthetic graphite for batteries or other industrial materials.

Estimated Cost: Estimated to cost around $1 to $2 per kilogram or $7 to $14 per MM Btu depending on the cost of natural gas, electricity and carbon. It can be potentially lower if the by-product carbon is sold for high value.

Source: Thunder Said Energy: https://thundersaidenergy.com/

CO_2 Emissions for Different Hydrogens



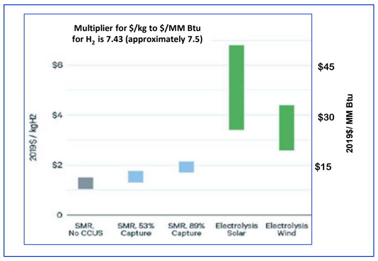
Source: IEA 2019. Note: Includes only CO2 emissions from combustion and chemical conversion. RE = renewable energy. SMR = steam methane reforming.

Slide 13

AZ0 Although the carbon intensity depends upon the source of electricity

Aqeel Zaidi, 2025-03-20T18:06:27.926

Approximate Cost of Hydrogen



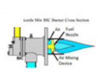
For reference: Average industrial electricity price in USA (December 2024) was $0.08 per kWh or $23.43 per MM Btu

Source: Decarburized hydrogen in the US power and industrial sector by Jay Bartlett and Alan Krupnick. Published by Resources for the future, December 2020

Properties of Hydrogen and Natural Gas

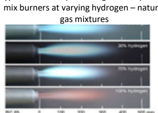
Property	Units	Hydrogen	Natural Gas	Ratio or comment
Heating Value, LHV	Btu/scf	275	958	0.29
Flame Speed	ft/s	~9.8	~1.4	~7
Flamability Range	Lean Limit % volume	4	5	More flammable
Flamability Range	Rich Limit % volume	75	15	Much more flammable
Combustion Air-to-Fuel, 1.1 λ	scf/MM Btu, LHV	9520	11482	0.83
POC-to-fuel, 1.1 λ, wet	scf/MM Btu, LHV	11345	12568	0.90
POC-to-fuel, 1.1 λ, dry	scf/MM Btu, LHV	7709	10418	0.74
POC, %H20, 1.1 λ	% by volume	32	17	
Flame temperature	°F, 1.0 λ, 100°F gas, 100°F air	3872	3533	+339 °F
Flame temperature, Regen	°F, 1.1 λ, 100°F gas, 1800°F air	4454	4105	+349 °F
Flame Color/Radiation		Clear, Lt Blue	Orange, Yellow	Less radiant flame

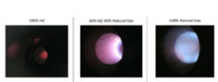
Flames with Use of Various H_2-NG Mixtures



Premix Burner

Typical flame shapes for high velocity nozzle mix burners at varying hydrogen – natural gas mixtures

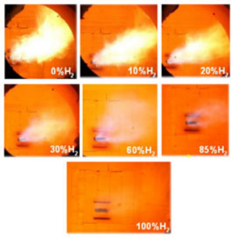




- Hydrogen flame is almost invisible with naked eye. However, they can be detected by using an UV sensor.
- The conventional UV flame detectors can be used safely for high hydrogen flames.

Source: Hydrogen Mixtures on Industrial Burners Designed for Natural Gas
Josh Weaver, Hans DeWolf, Abderahman Rabhiou, Lars Schroder, Heinz-Peter Gitzinger Honeywell Thermal Solutions

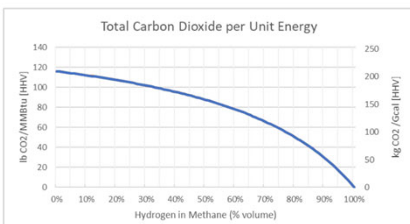
Flames with Use of Various H_2-NG Mixtures



Images of burner flame with different volumetric hydrogen-natural gas mixtures

Source: Combustion of hydrogen-natural gas mixtures applied to the cooking of ceramic products: emissions and flame properties. 2022.
S. Ferrer, E. Monfort, R. Pereira, J. Viduna, J. Montolio, A. Mezquita, J. Vedri

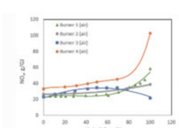
CO_2 Emission Reduction
NG-H_2 Mixture Combustion



H2 Enrichment	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
% Reduction CO2	0%	3.40%	7.40%	12.00%	17.50%	24.10%	32.30%	42.60%	55.90%	74.10%	100%

Note: CO_2 reduction is not linear. Up to about 50% hydrogen – NG mixture, CO_2 reduction is less than 30% of the reduction with 100% hydrogen

NOx Emissions
H_2 – Natural Gas Mixture Firing
Effect of Burner Type



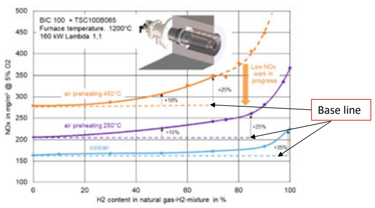
Burner no.	Type of burner	Industry
1	Forced Draught Burner	Hot water and steam production/metal
2	Swirl burner	Metal industry
3	High velocity burner	Ceramic/metal industry
4	Hot air burner	Glass industry

- Effect hydrogen blending on NO_x emission depends on burner type
- For burner types no. 1, 2 and 4 an (exponential) increase in NO_x is observed
- In contrast, burner no. 3 initially shows a substantial increase in the NO_x emission upon hydrogen addition followed by a decrease.

Conclusion: Nox formation/emission depends on the type of the burner.
There is not one simple answer.

Source: Hydrogen heating Network – June 2023 presentation
Suppled by Aqeel Zaidi – Enbridge Gas Canada

NOx Emissions
H_2 – Natural Gas Mixture Firing
Effect of Preheated Combustion Air



No_x emissions for a high velocity nozzle mix burner at various hydrogen-natural gas mixtures and preheated air at the Lotte, Germany test facility – Honeywell Thermal Solutions

Hydrogen Mixtures on Industrial Burners Designed for Natural Gas
Josh Weaver, Hans DeWolf, Abderahman Rabhiou, Lars Schroder, Heinz-Peter Gitzinger
Honeywell Thermal Solutions

Combustion Products Gas Analysis
Combustion of H2 and Natural Gas

100% H_2 with 10% excess air

Flue Gas Analysis **By Volume**

Flue gas composition - content →		CO2	H2O	O2	N2	Total
Total volume of gases - Ft^3./cu.ft of fuel		-	0.99900	0.10517	2.28810	3.39
% By volume - wet analysis		0.0%	29.4%	3.1%	67.5%	100.0%
% By volume - dry analysis		0.00%	0.00%	4.39%	95.61%	100.00%
% By weight - wet analysis		0.0%	20.9%	3.9%	75.1%	100.0%
% By weight - dry analysis		0.0%	0.0%	5.0%	95.0%	100.0%

100% Natural Gas with 10% excess air

Flue Gas Analysis **By Volume**

Flue gas composition - content →		CO2	H2O	O2	N2	Total
Total volume of gases - Ft^3./cu.ft of fuel		1.0233	1.97497	0.18830	8.27710	11.46
% By volume - wet analysis		8.9%	17.2%	1.6%	72.2%	100.0%
% By volume - dry analysis		10.8%	0.0%	2.0%	87.2%	100.0%
% By weight - wet analysis		14.1%	11.1%	1.9%	72.9%	100.0%
% By weight - dry analysis		15.8%	0.0%	2.1%	82.0%	100.0%

Note higher (almost double) H_2O content for H_2 combustion

Calculations by Arvind Thekdi, E3M Inc.

Effect of Higher Moisture in Flue Gases

Fuel	Wet analysis by Volume %			
	CO2	H2O	O2	N2
Hydrogen	0	29.4	3.1	67.5
Natural gas	8.9	17.2	1.6	72.2

AZ0

- Hydrogen combustion gives approximately 70% higher water vapor, almost 100% increase in oxygen and marginal decrease in nitrogen content in combustion products.
- This may have effect on product quality such as reheating of steel and drying of wet materials, quality of food (i.e. bread) in direct fired ovens etc. .
- It may affect furnace insulation performance, particularly the fiber insulation used in many ovens and furnaces
- Possibility of condensation in flue gas heat recovery systems such as a recuperator or regenerator.

Slide 24

AZ0 Should this be decrease
Aqeel Zaidi, 2025-03-20T18:15:21.851

Considerations for Use of H_2 as Fuel

AZ1

- The fuel (H_2)'s cost – high compared to natural gas. Cost of pyrolytic could be competitive with RNG.
- The availability of the fuel (H_2) and other considerations such as storage.
- The fuel (H_2) and combustion product compatibility with the process or product(s) being heated.
- Effect of (H_2) on the piping and other materials coming in contact with (H_2).
- Size and pressure rating of the gas system components (valves, controllers, sensors, regulators etc.)
- The environmental impact NOx emissions, GHG (CO_2) emission associated with the fuel (H_2) production.
- Personnel and property safety systems for fuel (H_2) handling outside and inside the plant.
- Considerations for the required regulatory approval, certification, insurance etc.

Status of Nozzle Mix Burners For H_2-NG Mixture

AZ0

Nozzle mix burners:

– Conventional direct fired nozzle-mix burner designs have been tested successfully in the test furnaces with H2-NG mixtures of varying proportion, reaching close to 100% H2.
– Most burner suppliers have experience with design and long term operation burners using fuels with high hydrogen content.
– The tests have been conducted in their facilities or on experimental basis in production furnaces for a limited period.
– Issues or concern are not related to the burner performance but mainly related to a reliable supply of large volumes of hydrogen and the use of existing fuel piping and components of the fuel supply system.
– H2/NG gas mixtures can be used in existing burners without changes in the hardware.

Status of Premix Burners For H_2-NG Mixture

Premix burners:

– Premix burner designs using premixing of air and hydrogen are susceptible to flashback, especially at turndown, since the flame speed of hydrogen in air is up to 9 times faster than the flame speed of natural gas in air.
– For most pre mix burners testing of hydrogen as a fuel has been limited to mixtures of hydrogen and natural gas with no more than 8% of the total fuel volume.
– Burner design or burner component materials modifications and testing would be needed if greater amounts of hydrogen enrichment were to be used for premix burners and special flame shape burners.
– None tested in production furnaces for a long (~ hundreds of hours) duration

Slide 25

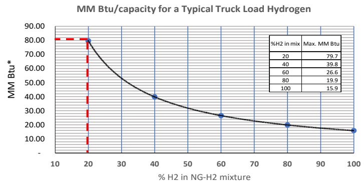
AZ0 The cost of Pyrolytic h2 is predicted to be not very high. Consider deleting word "very". Also add a comment that the cost of pyrolytic H2 could be competitive with RNG
Aqeel Zaidi, 2025-03-20T18:18:29.625

AZ1 Codes and standards
Aqeel Zaidi, 2025-03-20T18:20:26.682

Slide 26

AZ0 Should we mention a %blend where minor modification is required. I think it is up to 30% h2 blend by volume
Aqeel Zaidi, 2025-03-20T18:23:48.889

Limits of Trucked-in Hydrogen Supply



- This graph shows the total firing or heat input limit for one truck load (80 kg. capacity) of hydrogen at different hydrogen-natural gas mixture.
- For example, at 20% enrichment, one truck load of hydrogen can last for 80 MM Btu heat input in a furnace or oven.
- This limits the use of hydrogen unless it is available through a pipeline or on site production

Final Thoughts – Conclusion

AZ0

Wide scale use hydrogen as fuel in process heating systems requires developments on several fronts.

- Availability of hydrogen in large volume without installing on-site storage or onsite production.
- Competitive price of hydrogen
- Current prices*:
  - Hydrogen. From \$7 to \$25 (turquois or grey H2) to \$75 (green H2) per MM Btu
  - Natural gas ~\$4 per MM Btu
  - Electricity \$0.08 per kWh or \$23 per MM Btu
- Use of hydrogen in process heating equipment: Suppliers of the burners, combustion system components etc. are technically ready to meet the industry requirements.
- Unknown response from the regulatory and insurance agencies for the use of hydrogen in process heating equipment.
- Even with "every thing" in place or available, the cost of conversion is very high, perhaps prohibitive.

* Prices from the US DOE – EIA.

The Future of Industrial H_2
U.S. DOE Hydrogen Shot™

- The Hydrogen Shot™ aims to reduce the cost of clean hydrogen to \$1 per kilogram within a decade (by 2031).
- This cost reduction could result in at least a five-fold increase in the use of hydrogen and expand existing hydrogen markets, create new markets for hydrogen, and create jobs through DOE's investment and the resulting mobilization of private capital.
- By 2050, this growth in clean hydrogen use would **enable a 10% reduction in greenhouse gas (GHG) emissions** economy-wide—a reduction greater than the emissions from trucks, buses, aircraft, and ships in the United States today.
- https://www.energy.gov/topics/hydrogen-shot

AZ0 Is it worth adding a comment that prices are expected to drop with H_2 production at scale.
See this comment for the US DOE Hydrogen Shot "The Hydrogen Shot™ aims to reduce the cost of clean hydrogen to $1 per kilogram within a decade (by 2031)."
https://www.energy.gov/topics/hydrogen-shot
Aqeel Zaidi, 2025-03-20T18:29:00.560

Acknowledgement

- Information about the burner performance used here is obtained from representatives of several burner companies and other component suppliers in the USA and other countries.
- This presentation has been reviewed by Mr. Aqeel Zaidi of Enbridge Gas Inc. and many suggestions made by him are included in this presentation.
- Several end users have supplied information during private conversations regarding their experience and issues related to the use of hydrogen and other alternate fuels.

Thank You