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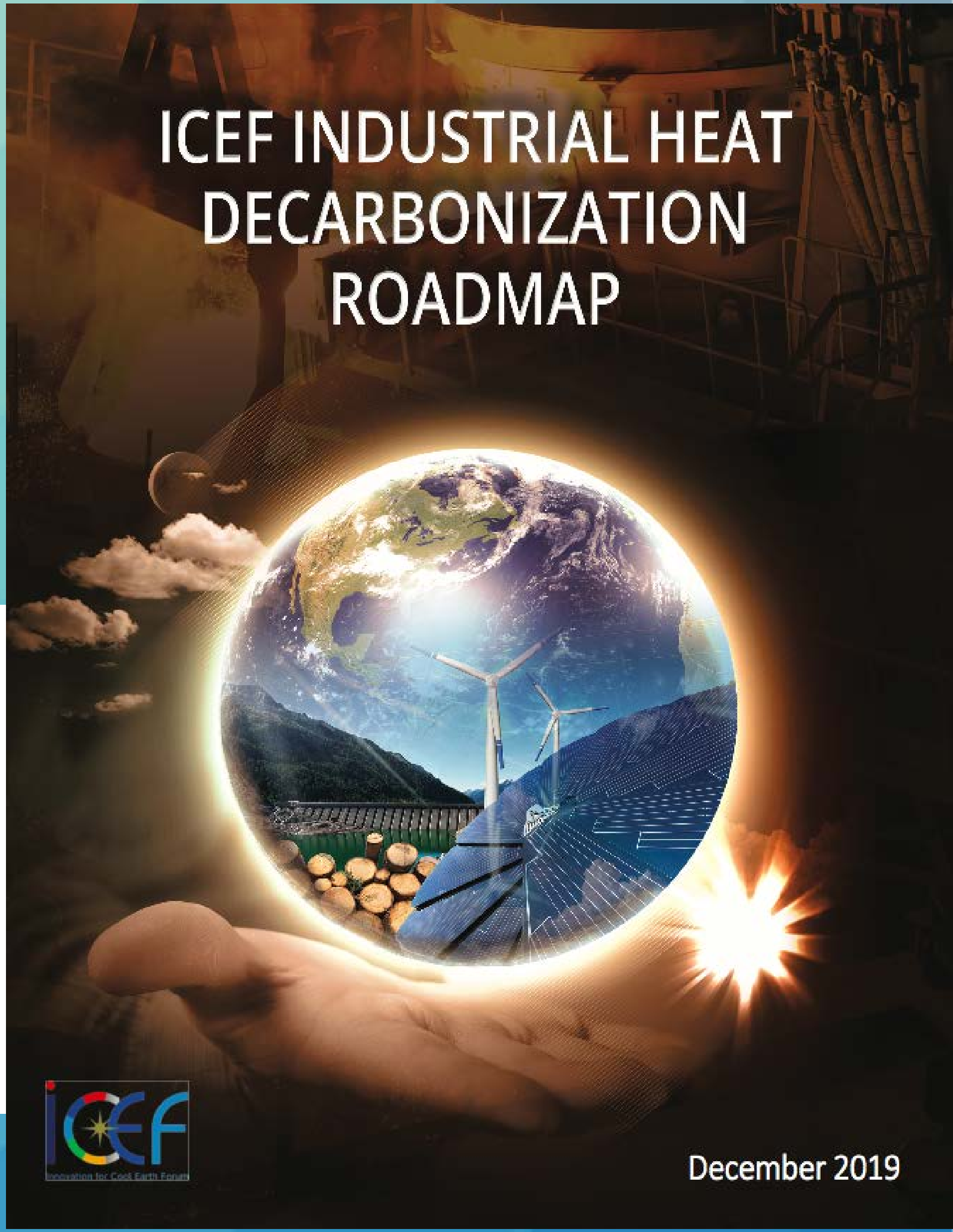
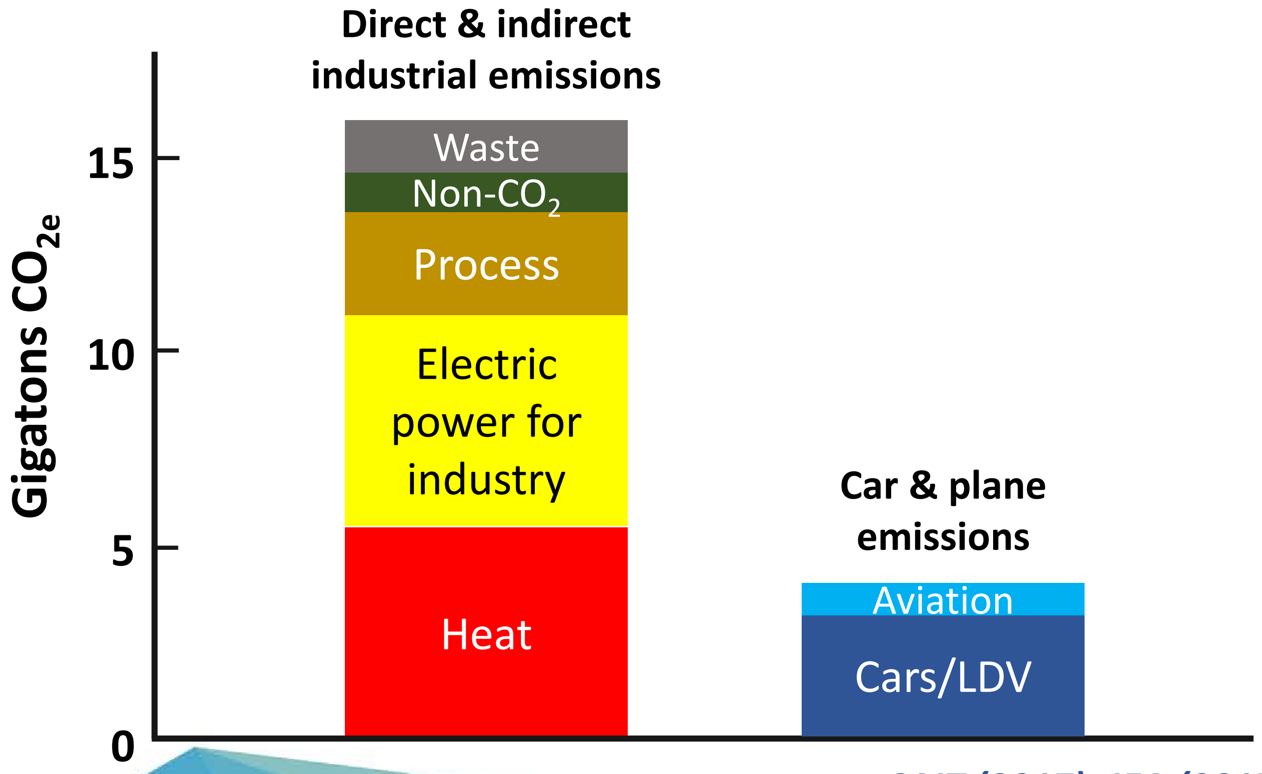
**December 13, 2019**

**Madrid, Spain**



# $CO_2$ emissions from industrial heat production are 5 Gt/year -- ~10% of global $CO_2$ emissions

## *More than cars + planes combined*




*CAIT (2017); IEA (2017, 2019)*

# Key industries

Cement

Iron and Steel

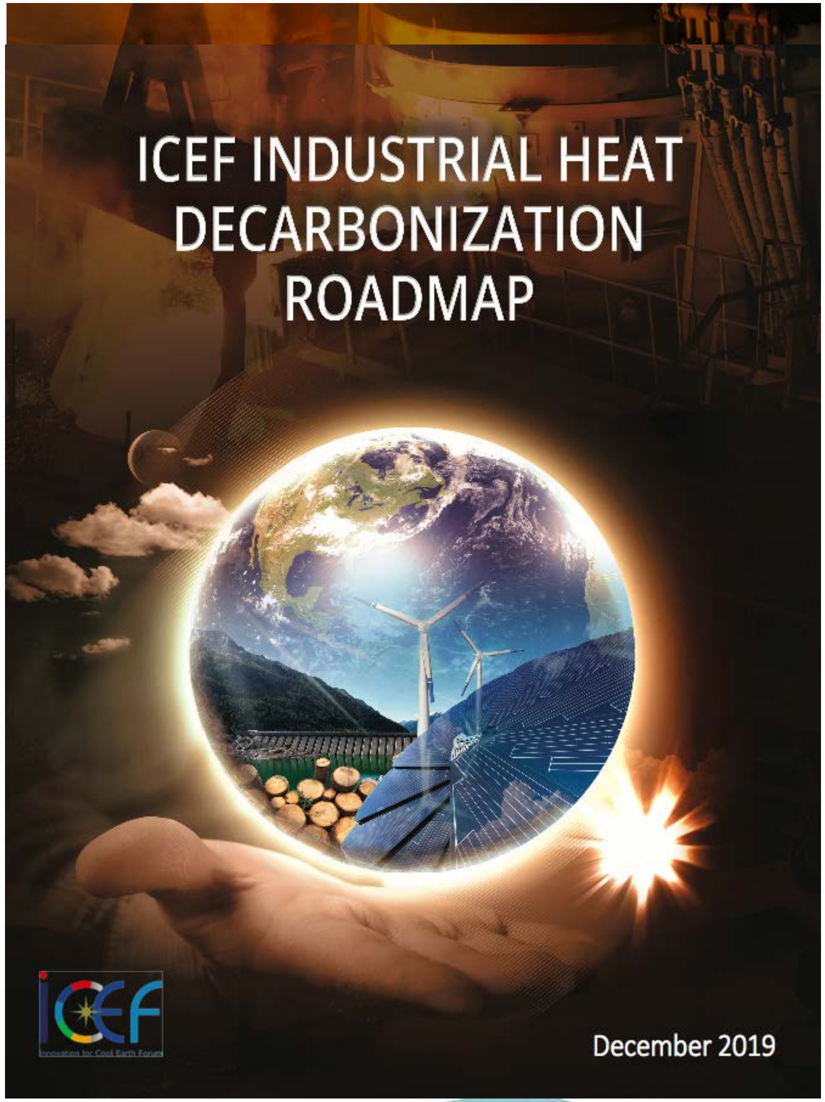
Chemicals

# Decarbonizing industrial heat is challenging

- Technology options are limited
- Existing capital stock lasts decades
- Industries operate on small margins
- Governments value some industries as strategic assets
- Many facilities must operate continuously
- Many facilities are far from renewable resources

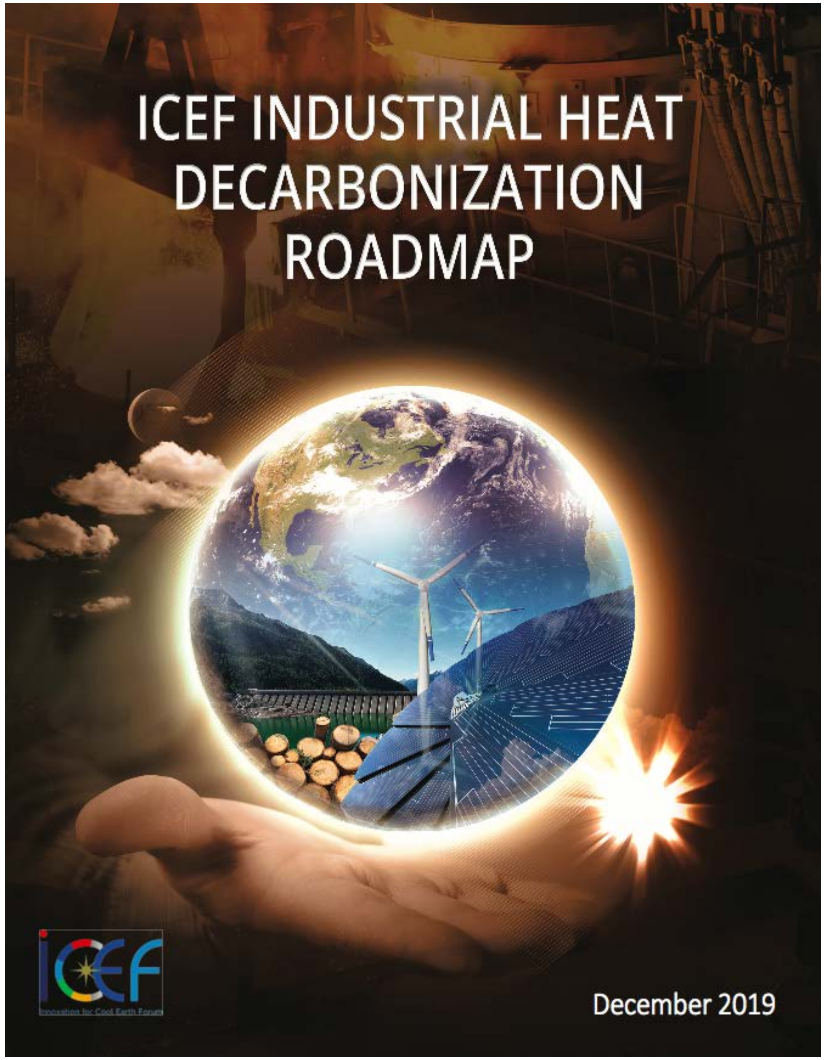
# ICEF Industrial Heat Decarbonization Roadmap
# Table of Contents





# ICEF INDUSTRIAL HEAT DECARBONIZATION ROADMAP – KEY MESSAGES

- Important, challenging problem, with much more work needed
- Hydrogen, biomass, electrification and CCUS offer potential solutions.
- We need better options – RD&D essential
- Many policy options available
- Government procurement is particularly powerful tool.



# Technology Options

# Observations about low-C industrial heat

*Lack of scholarship and data*

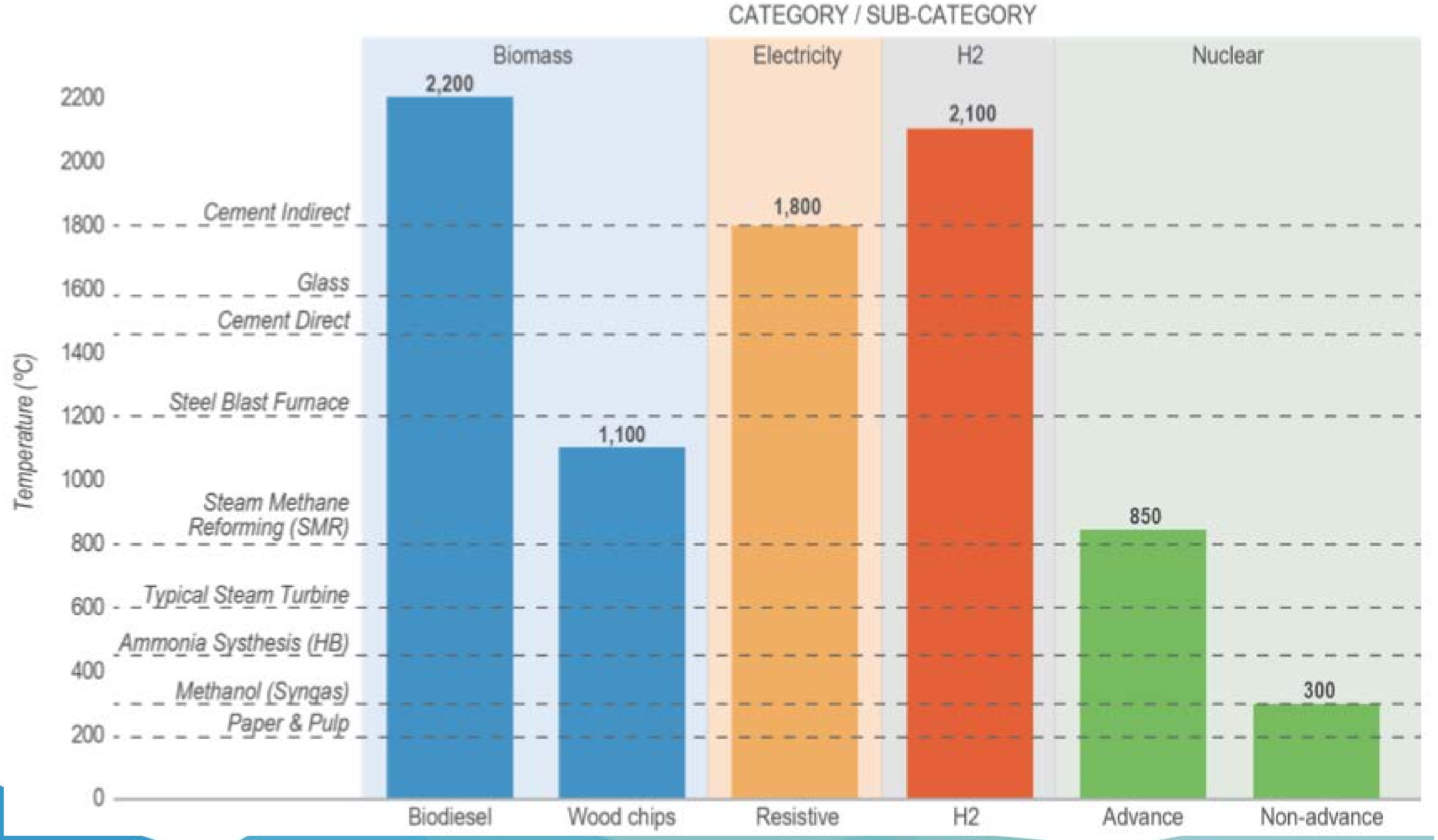
- **Very few papers on industrial heat production**
- **Data are scarce and disaggregated**
- **Lots of hypothetical new processes, very little on existing facility modification**

*Few options:*

- **Nuclear heat unsuitable (temperature)**
- **Solar thermal – limited availability**

***Complexity of industrial heat production is daunting***

# High temperature requirements (300-1800°C) limit decarbonization options




*Friedmann et al., 2019*

# Hydrogen: versatile & could be cost effective

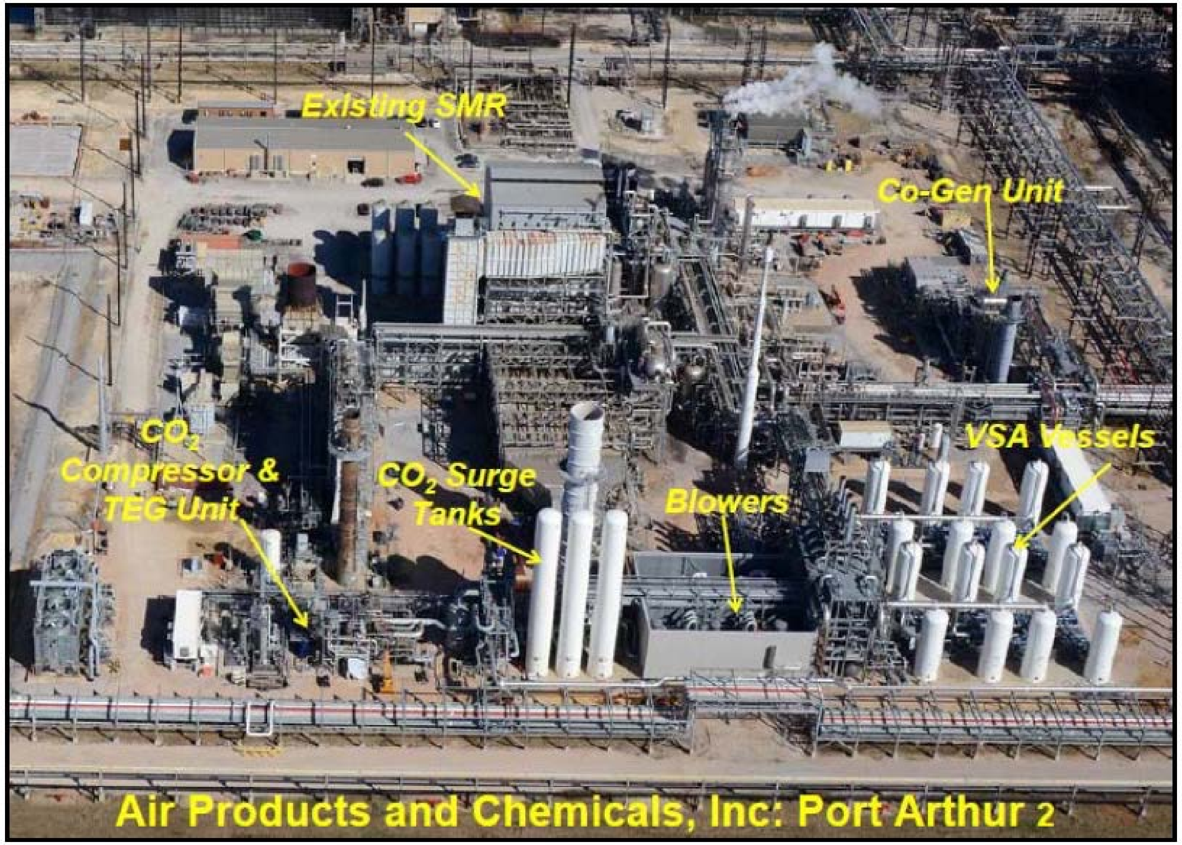
## *Burns at 2100° C in air and made today at industrial scale*

*Carbon footprint depends on fuel source*

- **Coal or gas reformation with no CCS (gray hydrogen) -- *higher $CO_2$ emissions***
- **Gas reformation with CCS (blue hydrogen) -- *50-90% $CO_2$ cuts***
- **Water + zero-C electricity (green hydrogen) – *near 100% $CO_2$ cuts***

*Costs today:*

- **Blue - + appr. 50%**
- **Green - + appr. 500%**



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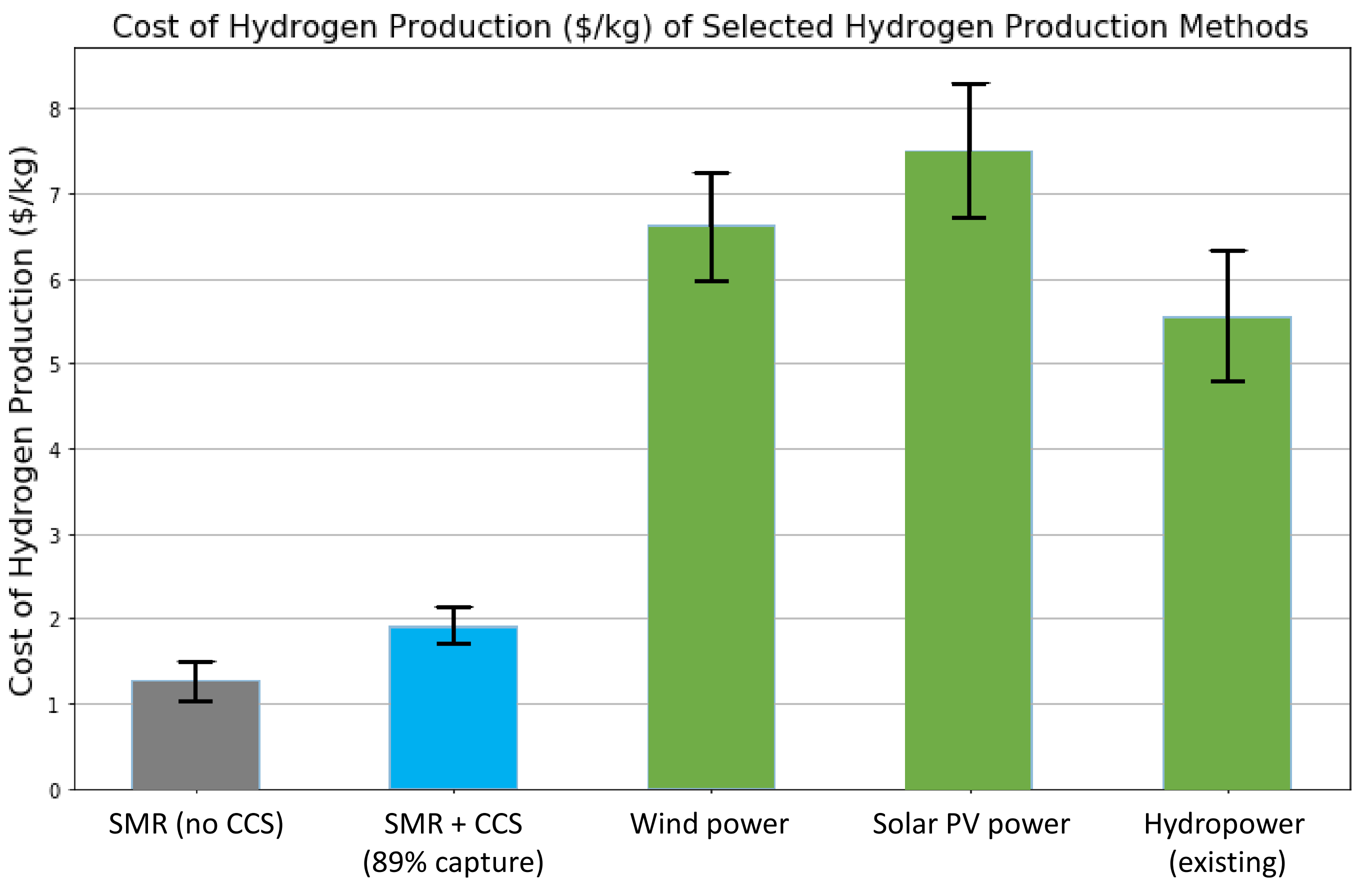



*Friedmann et al., 2019*

# Hydrogen: versatile & could be cost effective

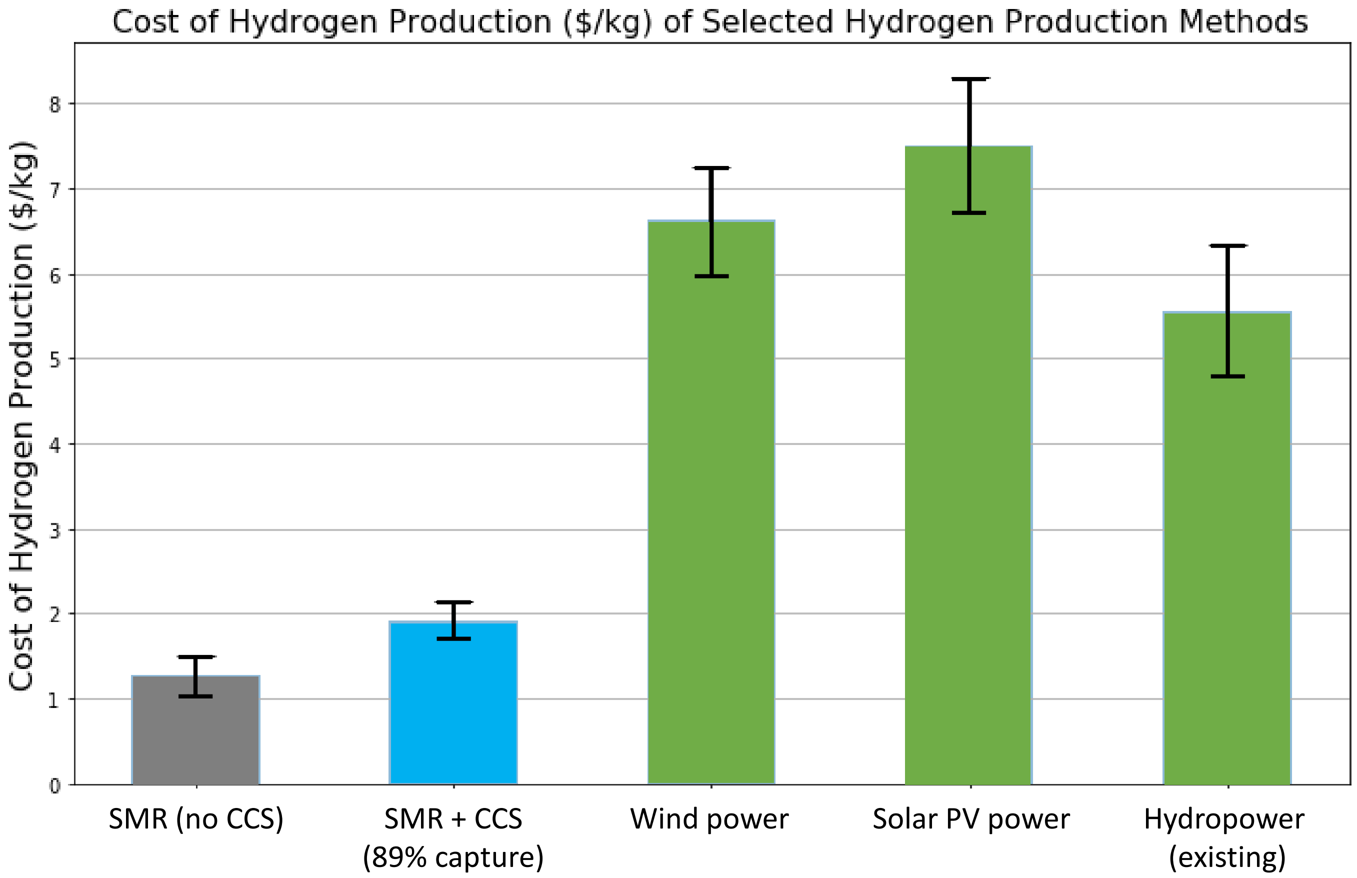
*Burns at 2100° C in air and made today at industrial scale*

*C footprint: Grey, blue & green*

- **Gas reformation with no CCS (higher than gas heat)**
- **Gas reformation with CCS (50-90% C reductions)**
- **Water + zero-C electricity (near-zero C reduction)**

*Costs:*

**Blue seems reasonable,**
**Green seems expensive**




*Friedmann et al., 2019*

# Hydrogen: additional challenges

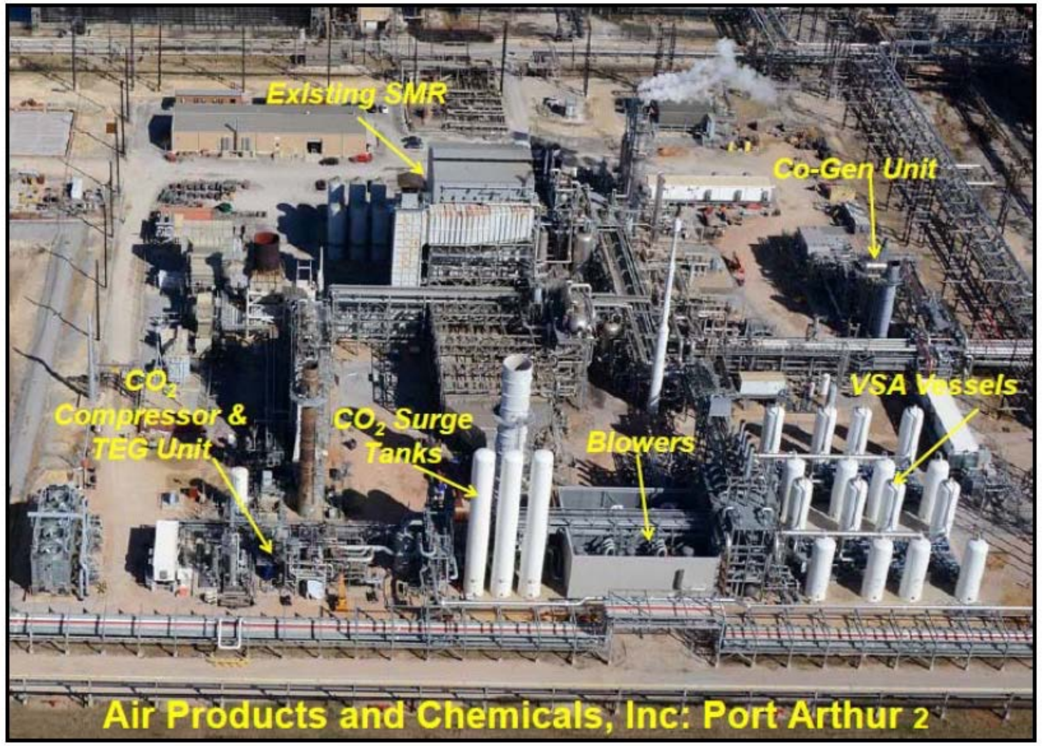
## *Although used today in steel (DRI) and chemicals, challenges remain*

*Technical*

- **Burns invisible (sensors, controls, safety)**
- **Embrittlement & corrosion**

*Other:*

- **Infrastructure (pipelines, transmission)**
- **Can't work in solid fuel applications without major engineering**




*Likely applications in chemicals, some steel & cement*

# Biomass/biofuels: versatile & could be cost effective

## *Hot enough and comes in solid, liquid or gas*

*C footprint: Extremely complicated*

- **Enormous variations (e.g., waste, feedstock, dedicated crops, conversion method)**
- **Controversial accounting**
- **Concerns about carbon leakage**

*Costs:*

- **Enormous variations**
- **Generally expensive**
- **All need development & policy support**

# Biomass/biofuels: additional challenges

## *Scale-up and sustainability are important potential barriers*

*Technical*

- **Scale-up: esp. for biogas and liquids, availability and flux limits are real**
- **Energy density & mass handling for solids**

*Other:*

- **Concerns about impact/competition with food**
- **Sustainability (biodiversity, water, fertilizer)**
- **Geographic limits**

*Vaxtkraft biogas production plant (waste-to-gas)*

*Likely applications in steel & cement, some chemicals*

# Electrification: potential and challenges

## *Enormous amounts of new zero-C generation needed (2x-5x or more)*

*C footprint = the footprint of power supply*

- **Grid power provides little advantage**
- **Zero-C power is commonly low capacity factor**
- **Almost all new generation must be built and must be fir**

*Costs:*

- **Generally very expensive**
- **Costs are dropping**
- **Unclear when zero-C power is cheap enough to be a strong option**

# Electrification: additional challenges

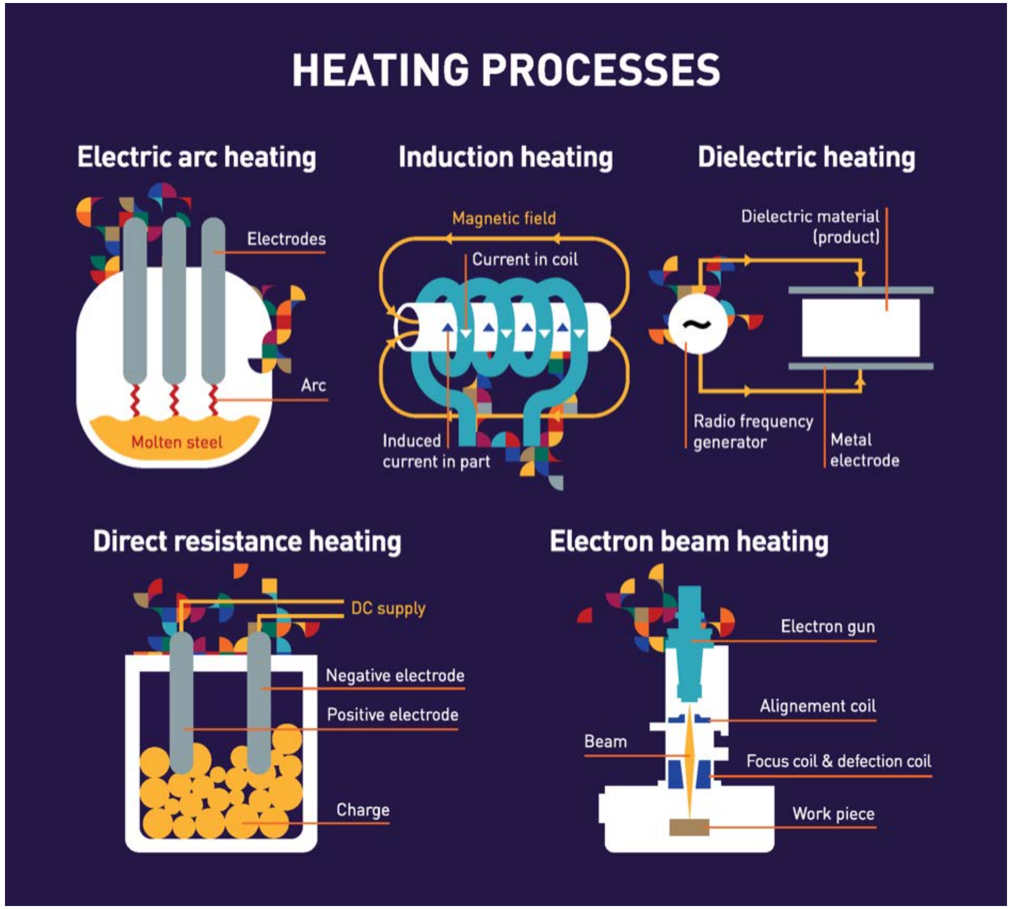
*Here, the innovation agenda is most compelling*

*Technical*

- **Heat deposition (resistance, dielectric)**
- **Novel reactors (beyond steam)**
- **Overpotential reduction**

*Other:*

- **Infrastructure limits (local and regional)**
- **System generation (scale of zero-C generation for industry would be enormous)**



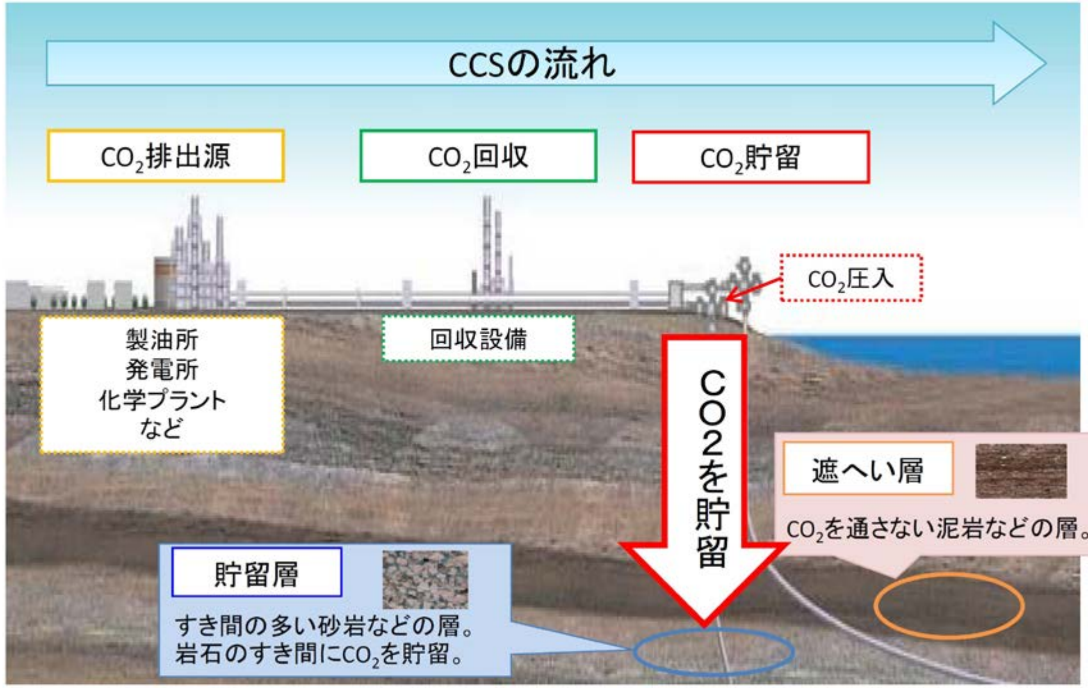
# CCUS: *applicable to almost all industrial processes*

C footprint

- Can capture heat *and* process emissions
- Geological storage permanently locks away $CO_2$; utilization options more complex
- Reductions offset by upstream fuel emissions

Costs

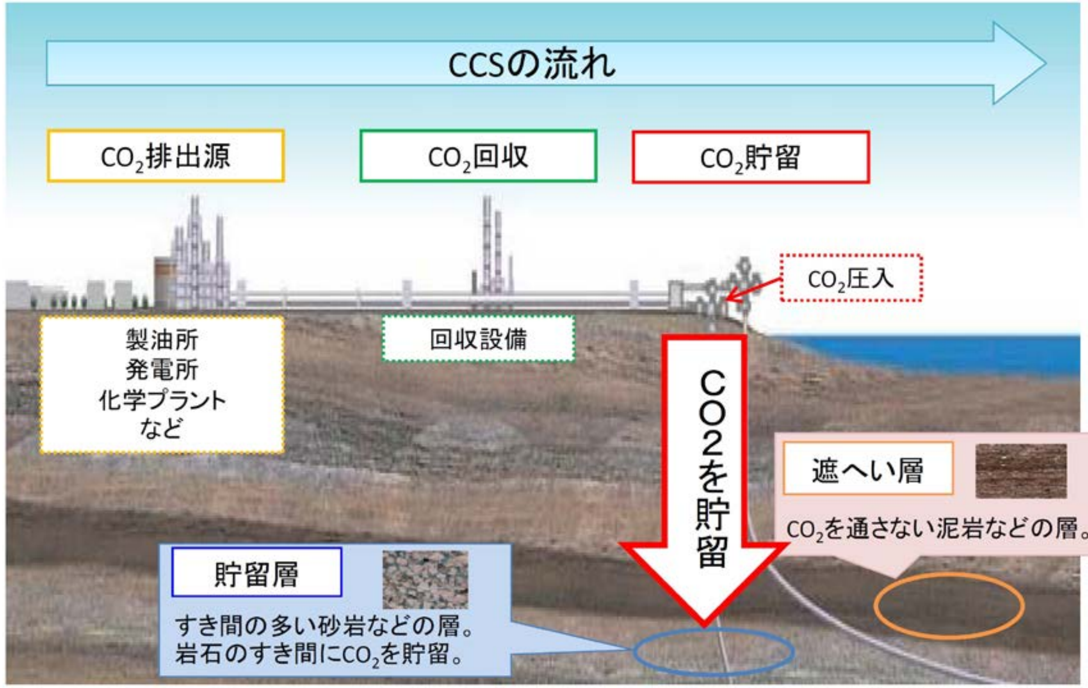
- Expensive, but less than $H_2$ or electricity in current processes
- Opportunities to reduce cost through integration with industrial processes
- Integration can lead to increased complexity



# CCUS: *applicable to almost all industrial processes*

Technical

- Post-combustion capture can be applied in to most industries
- Other capture options may be a better fit for specific industrial processes (e.g., calcium looping in Cement)
- Challenges due to distributed nature of emissions in chemicals and refining




Other

- Geological constraints may limit local storage
- Need to develop transport and storage infrastructure

# Industries

# Cement industry: 6% of global $CO_2$ emissions

# Heat for cement : ~2% of global $CO_2$ emissions

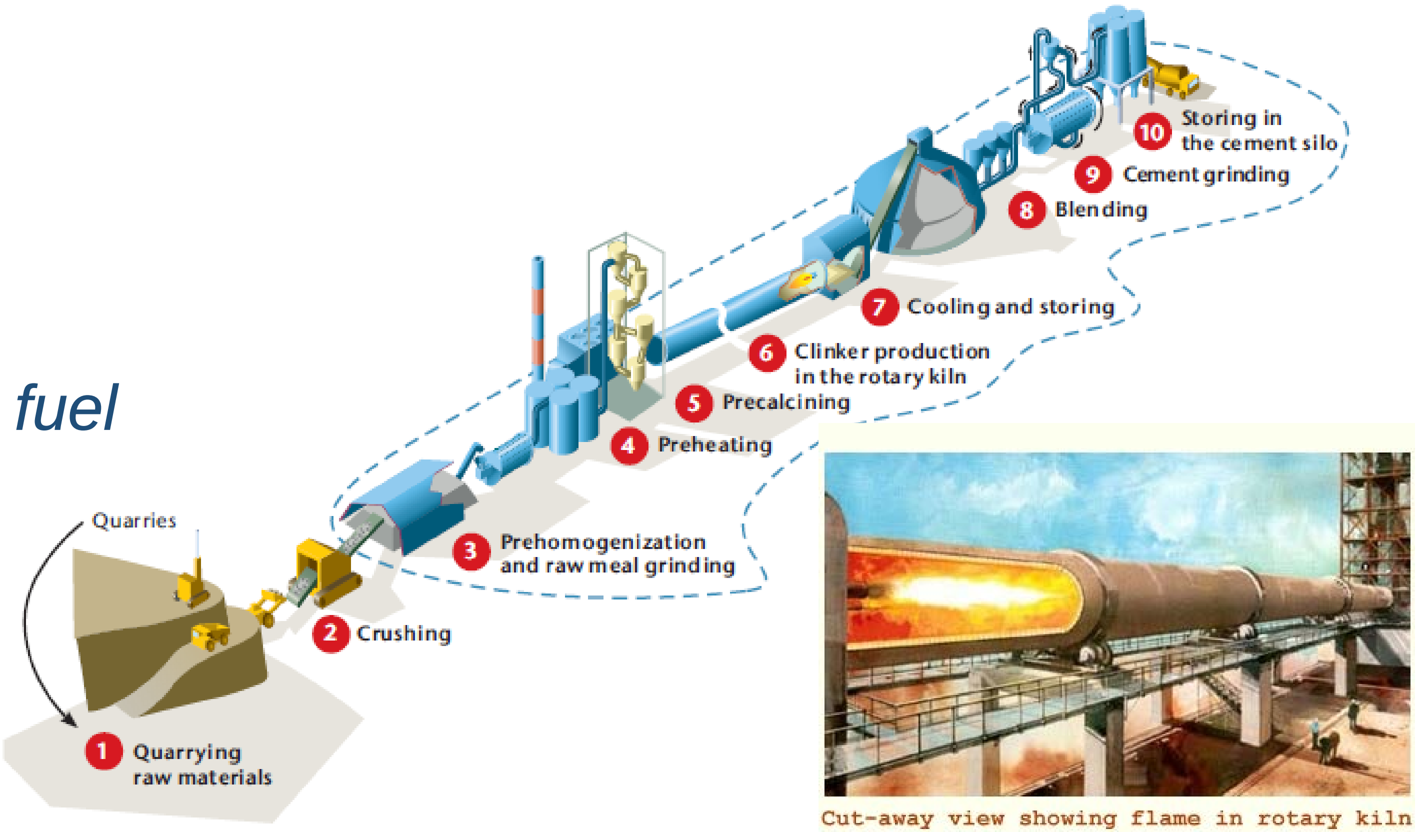
*Requires 1450° C and continuous operations*

*Current heat applications*

- **Preheating and calcining**
- **Rotary kiln**

*Current heat sources: mostly solid fuel*

- **Coal & petcoke**
- **Waste (tires to biowastes)**
- **Some natural gas**




Cut-away view showing flame in rotary kiln

# Cement industry: 6% of global CO2 emissions

# Heat for cement : ~2% of global CO2 emissions

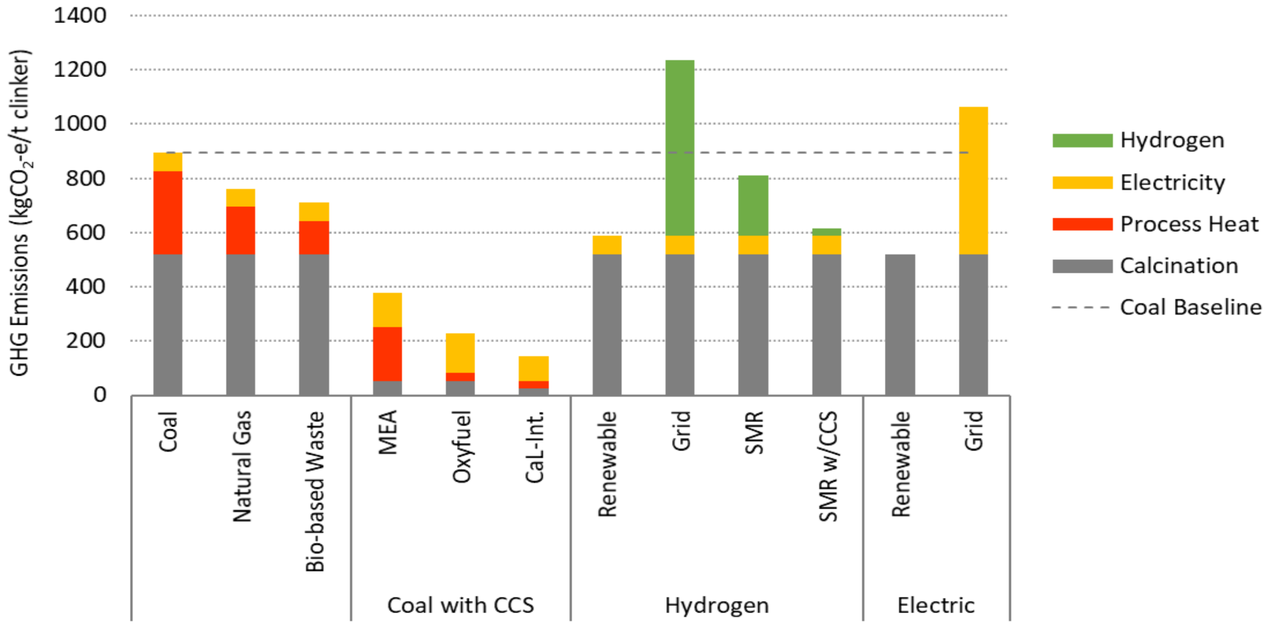
## *Requires 1450° C and continuous operations*

### *Best options (cost & footprint)*

- **CCS on whole system**
- **Biomass mix**

### *Other decarbonization options:*

- **Clinker substitution**
- **Efficiency**
- **Alternative binders**
- **Novel processes (e.g., Ca-L, electrical decomposition)**



# Iron & Steel: 5% of global CO2 emissions

# Heat for Iron and Steel: ~2.5% of global CO2 emissions

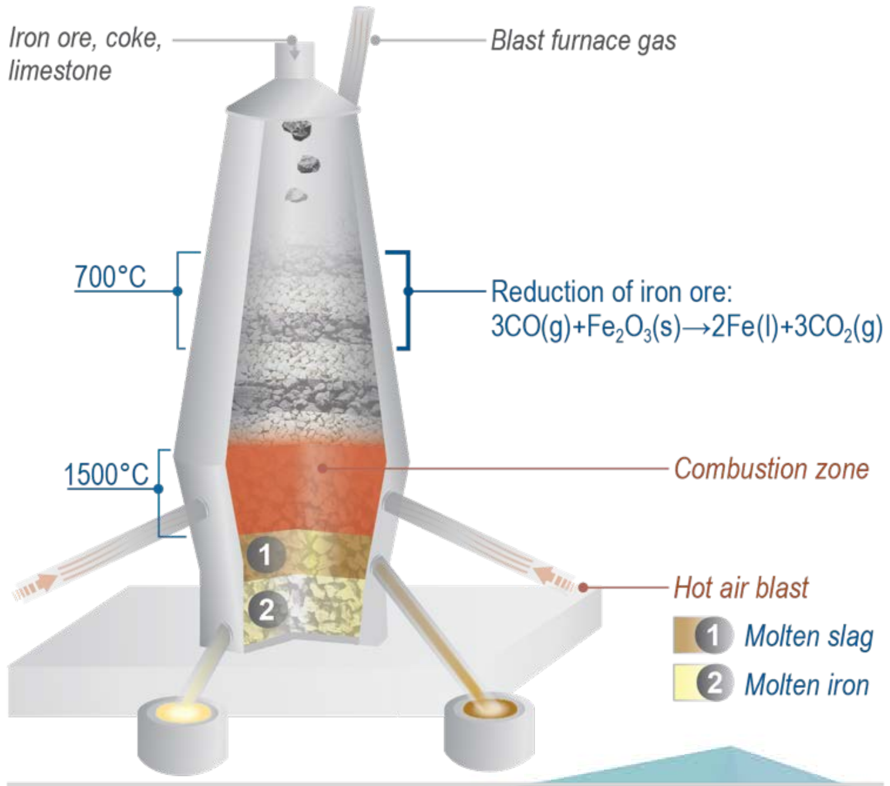
## *Requires 1200° C and continuous operation*

*Current heat applications*

- **Blast furnace; Basic oxygen furnace**
- **Lime kiln, coking, sinter plant**
- **Hydrogen production (DRI only)**

*Current heat sources: mostly solid fuel*

- **Coke (mostly from coal)**
- **Recycled process gas, some natural gas**



# Iron & Steel: 5% of global CO2 emissions

# Heat for Iron and Steel: ~2.5% of global CO2 emissions

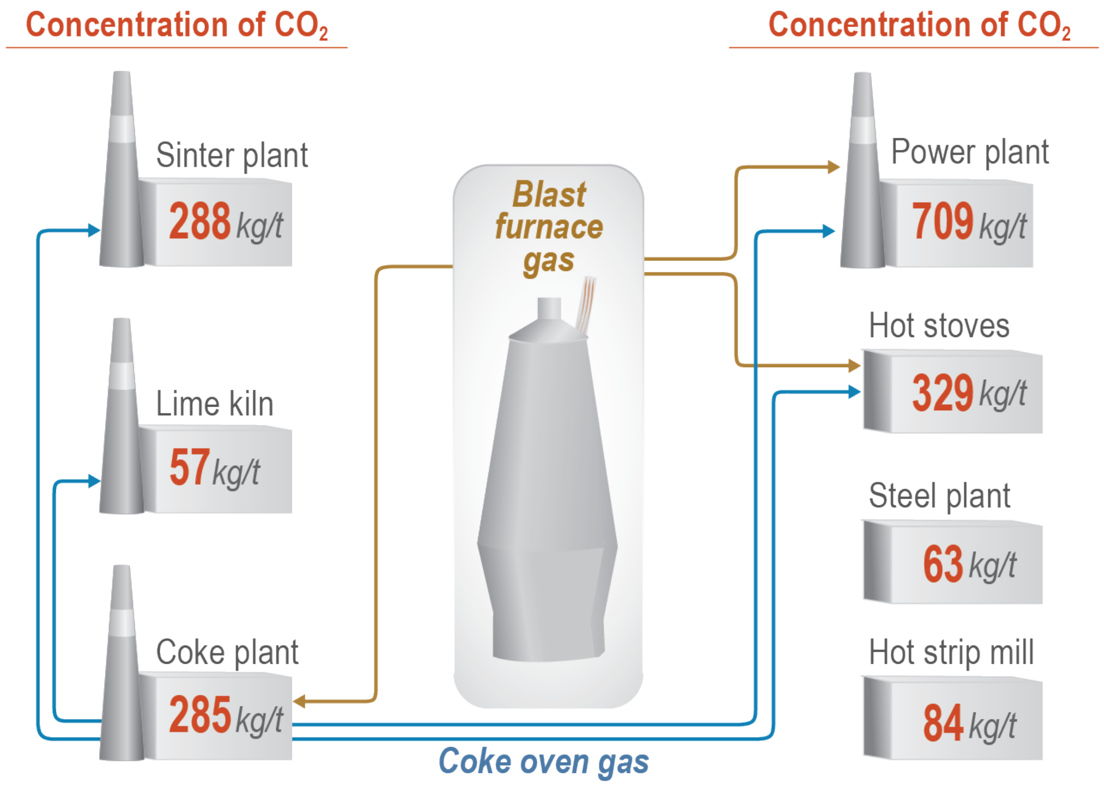
## *Requires 1200° C and continuous operation*

### *Best options (cost & footprint)*

- **CCS on whole system**
- **”Biocoke”**
- **Some hydrogen (Nippon Steel)**

### *Other decarbonization options:*

- **Efficiency**
- **Modified coking**
- **Adopting EAF (w/ DRI & zero-C $H_2$)**
- **Novel processes (e.g., upgraded smelting, electrical reduction of ore)**



# Chemicals: 3% of global CO2 emissions
# Heat for chemicals: ~1.5% of global CO2 emissions
## *Wide range of processes, uses, footprints, options*

### *Current heat applications*

- **Burners, boilers, furnaces**
- **Bespoke reactors**
- **Highly distributed across facilities**

### *Current heat sources: mostly gaseous fuel*

- **Natural gas (some H2)**
- **LPGs, some other petroleum fuels**
- **Coal or coal-syngas (developing countries)**

# Ammonia: non-C bearing chemical

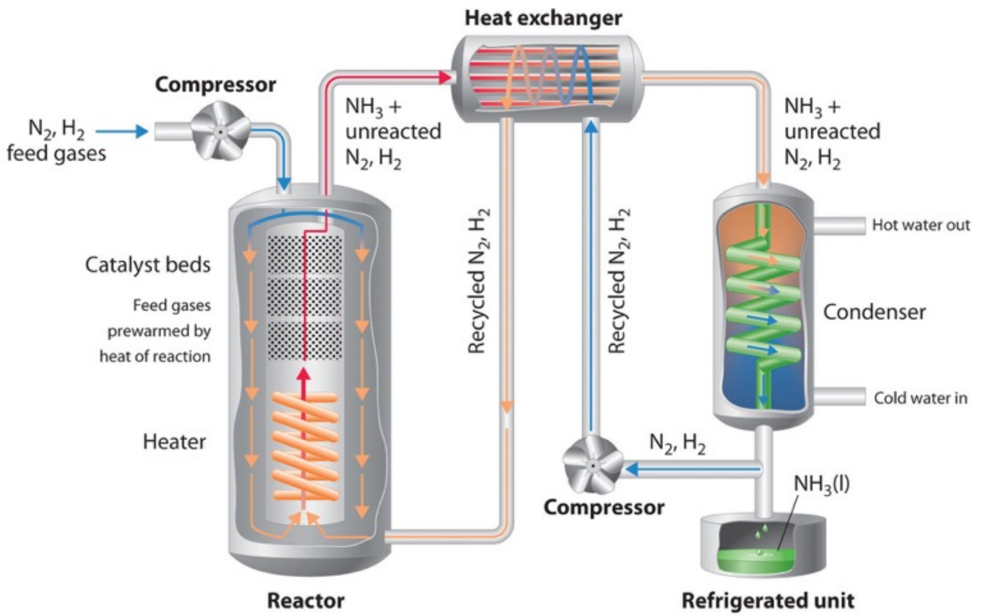
## *850° C for hydrogen production, 500° C for synthesis*

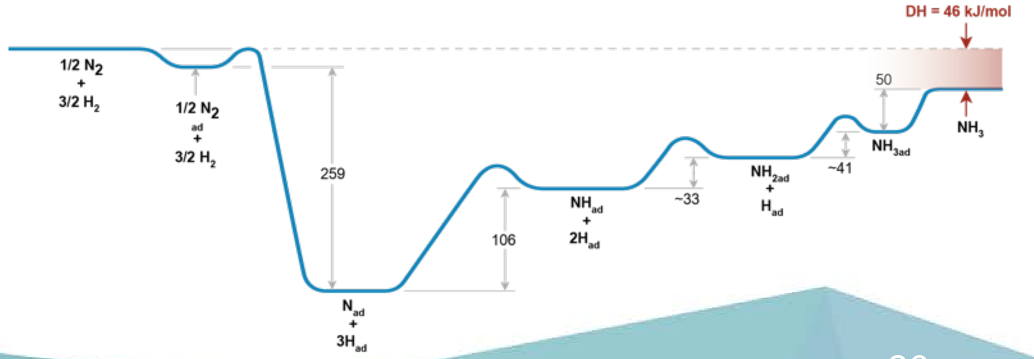
### *Current heat applications*

- **SMR**
- **Synthesis reactor**
- **Distillation columns**
- **Other small furnaces/boilers/burners**

### *Current heat sources: mostly solid fuel*

- **Almost 100% natural gas or syngas**



# Methanol: C-bearing chemical

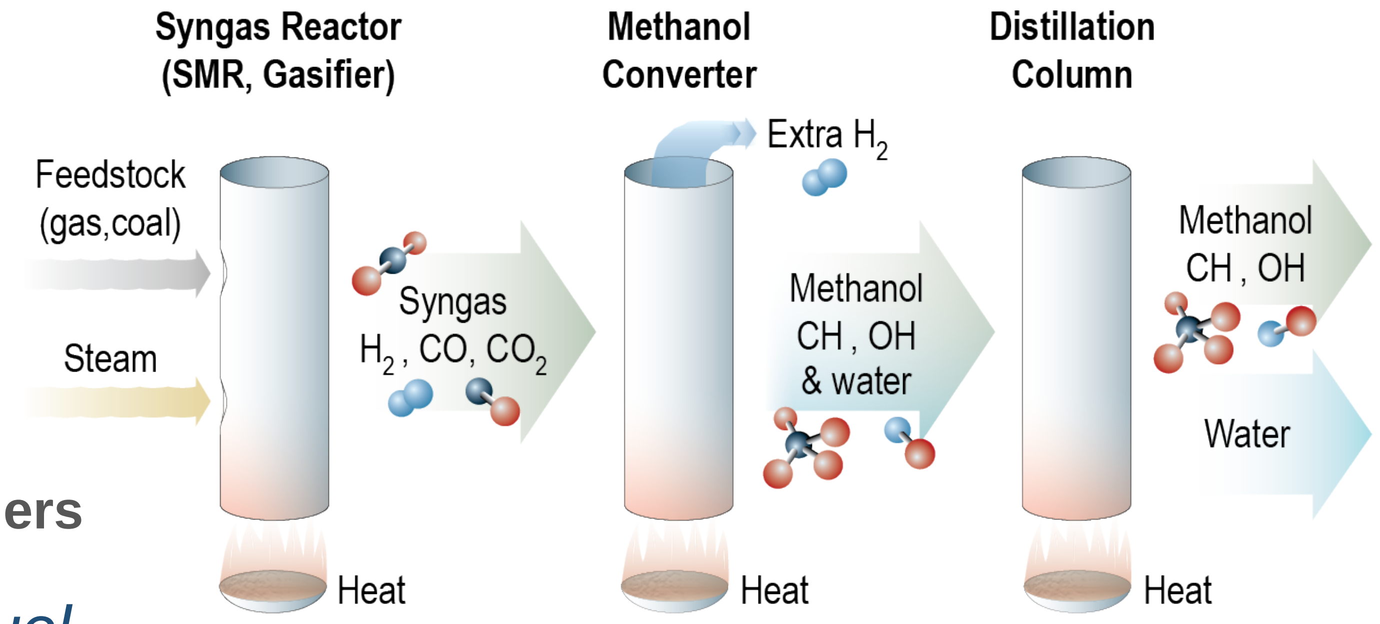
*300° C for synthesis*

*Current heat applications*

- **SMR or gasifier**
- **Methanol synthesis**
- **Distillation columns**
- **Other small furnaces/boilers/burners**

*Current heat sources: mostly solid fuel*

- **Almost 100% natural gas or syngas**



# Chemicals: 3% of global CO2 emissions

# Heat for chemicals: ~1.5% of global CO2 emissions

## *Wide range of processes, uses, footprints, options*

### *Best options (cost & footprint)*

- **Hydrogen (first blue $H_2$ then green $H_2$)**
- **Biogas, biomethane**
- **Partial electrification (esp. for steam)**

### *Other decarbonization options:*

- **Efficiency (large opportunity)**
- **Novel processes (e.g., electrolytic chemical production; $CO_2$ upcycling)**

*Grangemouth ethylene plant, Scotland*

# Next Steps

# Innovation issues: moving forward

*Analysis of  options and trade-offs*

- **Power to gas and renewable $CH_4$**
- **Electrification methods and benefits**

*New approaches:*

- **Zero-carbon industrial gas**
- **Industrial heat storage**
- **Better electrification technology**

# Innovation issues: cross-cutting approaches

*Hybrid and time-phased options*

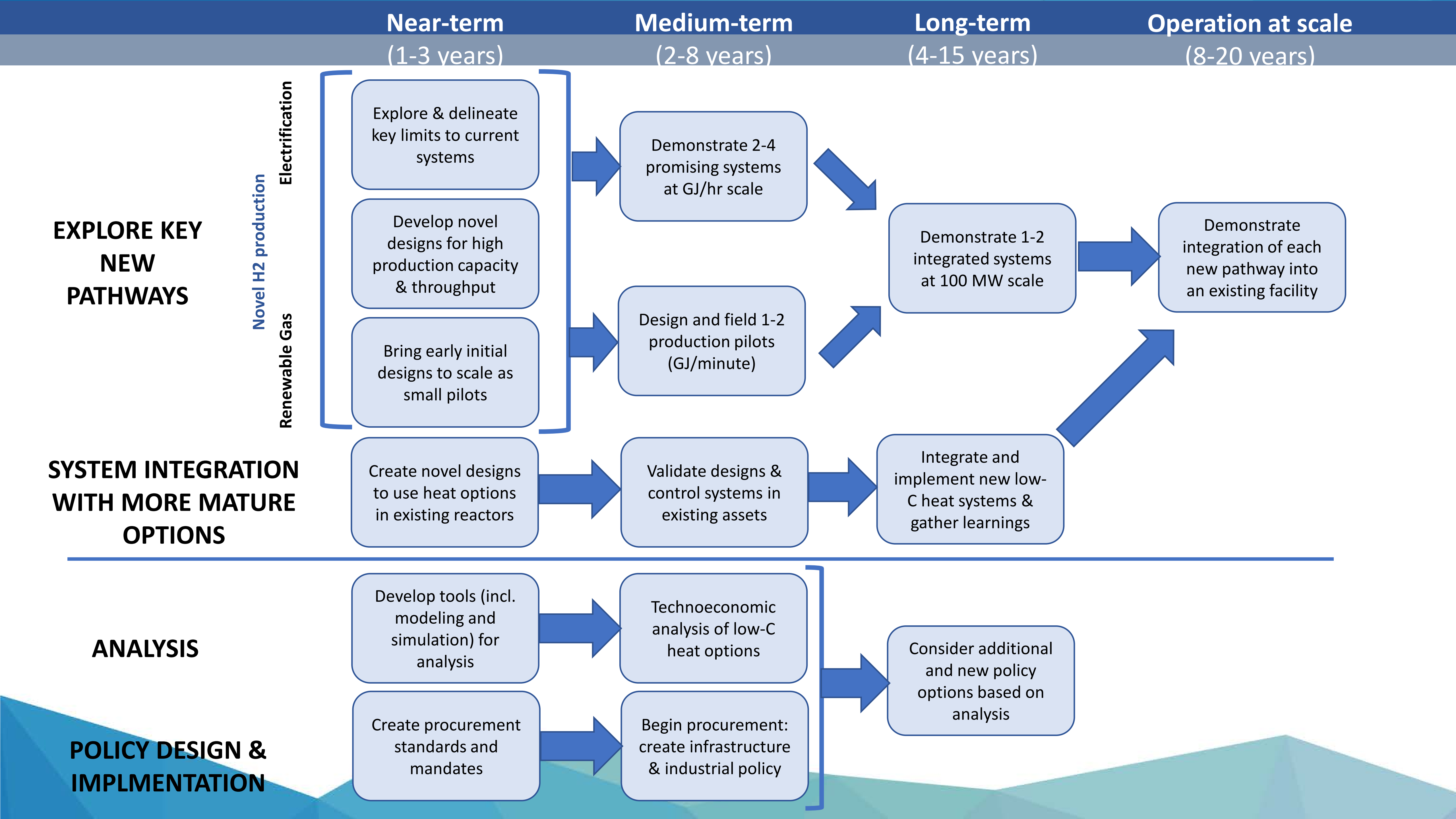
- **Combined CCS, efficiency, and new fuels**
- **Partial hydrogen and biomass substitution**
- **Partial electrification (esp. steam)**

*System approaches:*

- **Global delivery of decarbonized fuel (hydrogen and biomass)**
- **Air capture to compensate remaining industrial emissions**

# Policy support is essential

1. Government support for R&D
2. Government procurement
3. Fiscal subsidies
4. Mandates
5. Infrastructure development
6. Carbon prices/carbon tariffs
7. Industry associations
8. Clean Energy Ministerial



Near-term
(1-3 years)
Medium-term
(2-8 years)
Long-term
(4-15 years)
Operation at scale
(8-20 years)
EXPLORE KEY NEW PATHWAYS
Novel H2 production
Electrification
Renewable Gas
Explore & delineate key limits to current systems
Develop novel designs for high production capacity & throughput
Bring early initial designs to scale as small pilots
Demonstrate 2-4 promising systems at GJ/hr scale
Design and field 1-2 production pilots (GJ/minute)
Demonstrate 1-2 integrated systems at 100 MW scale
Demonstrate integration of each new pathway into an existing facility
SYSTEM INTEGRATION WITH MORE MATURE OPTIONS
Create novel designs to use heat options in existing reactors
Validate designs & control systems in existing assets
Integrate and implement new low-C heat systems & gather learnings
ANALYSIS
Develop tools (incl. modeling and simulation) for analysis
Technoeconomic analysis of low-C heat options
POLICY DESIGN & IMPLMENTATION
Create procurement standards and mandates
Begin procurement: create infrastructure & industrial policy
Consider additional and new policy options based on analysis

# Future work: complex field requires more scholarship

**Systems analysis**: Many ways to improve insight

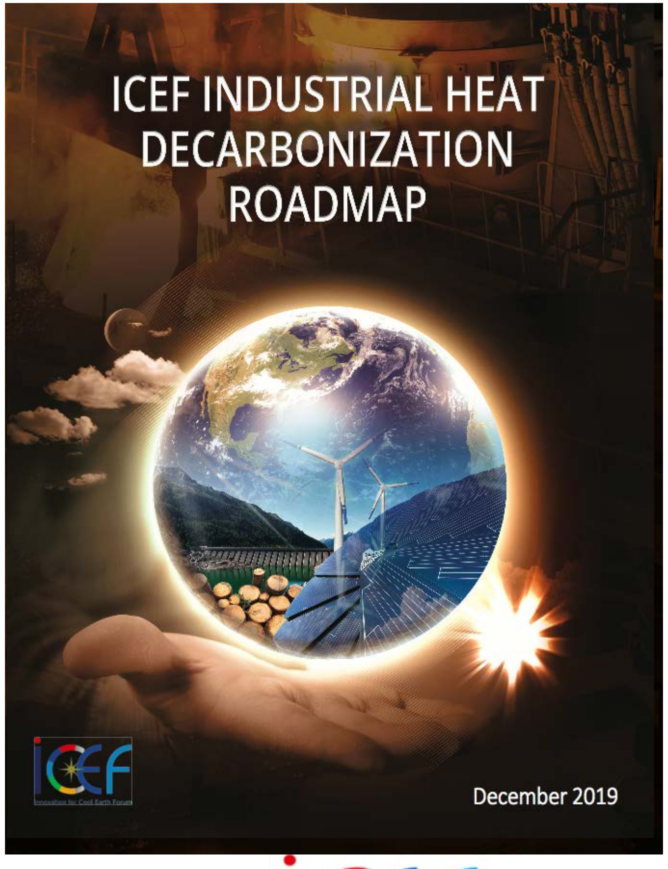
- Improved data assessment & synthesis
- System design parameters
- Optimization
- Trade-offs

**Deeper technoeconomic analysis:** We've only started

- Biofuels and electrification as key targets
- Improved CCUS integration
- Focus on cement and steel as hardest sectors
- Focus on existing facility modification or enhancement

**Policy design:** Complexity demands careful design & implementation

- Potential impacts & benefits to jobs, trade
- Novel mechanisms (e.g., co2 utilities, sectoral international partnerships
- Pilots policy programs and assessment




ICEF
Innovation for Cool Earth Forum

# ICEF INDUSTRIAL HEAT DECARBONIZATION ROADMAP – KEY MESSAGES

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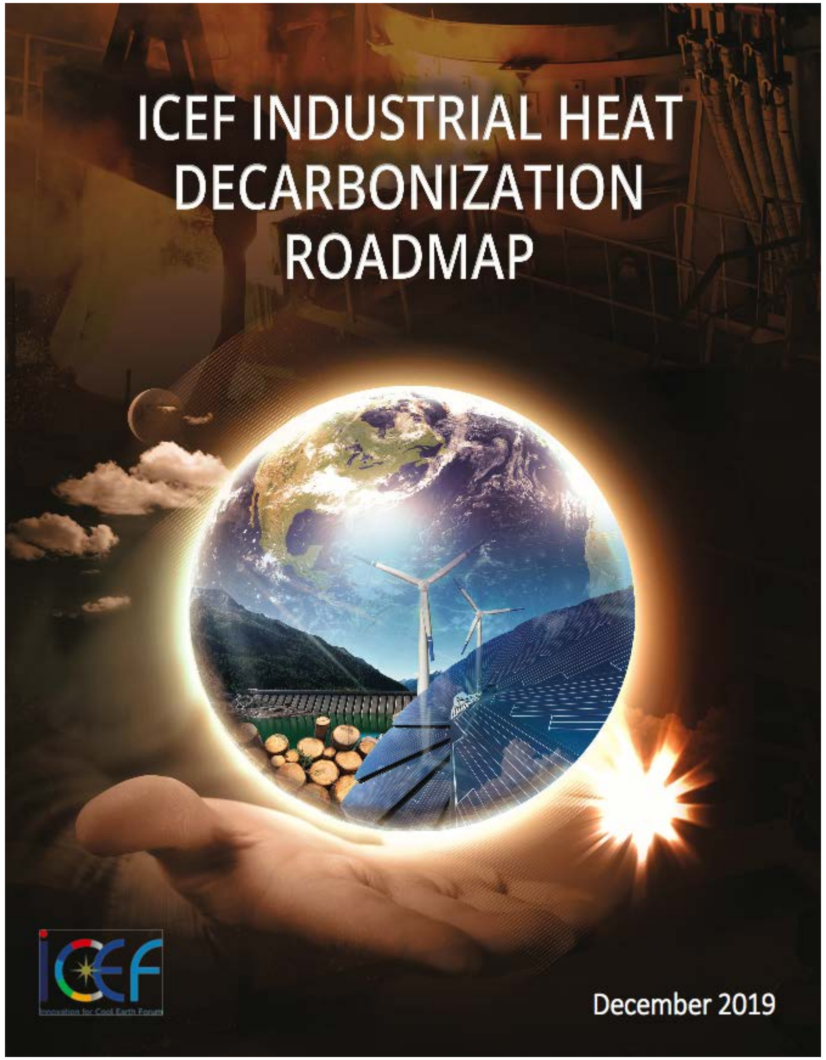
- We need better options – RD&D essential
- Many policy options available
- Government procurement is particularly powerful tool.



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Roger Aines and Joshuah Stolaroff contributed to the technical evaluations in this document. The policy recommendations were prepared by other contributors.