Innovation for Cool Earth Forum

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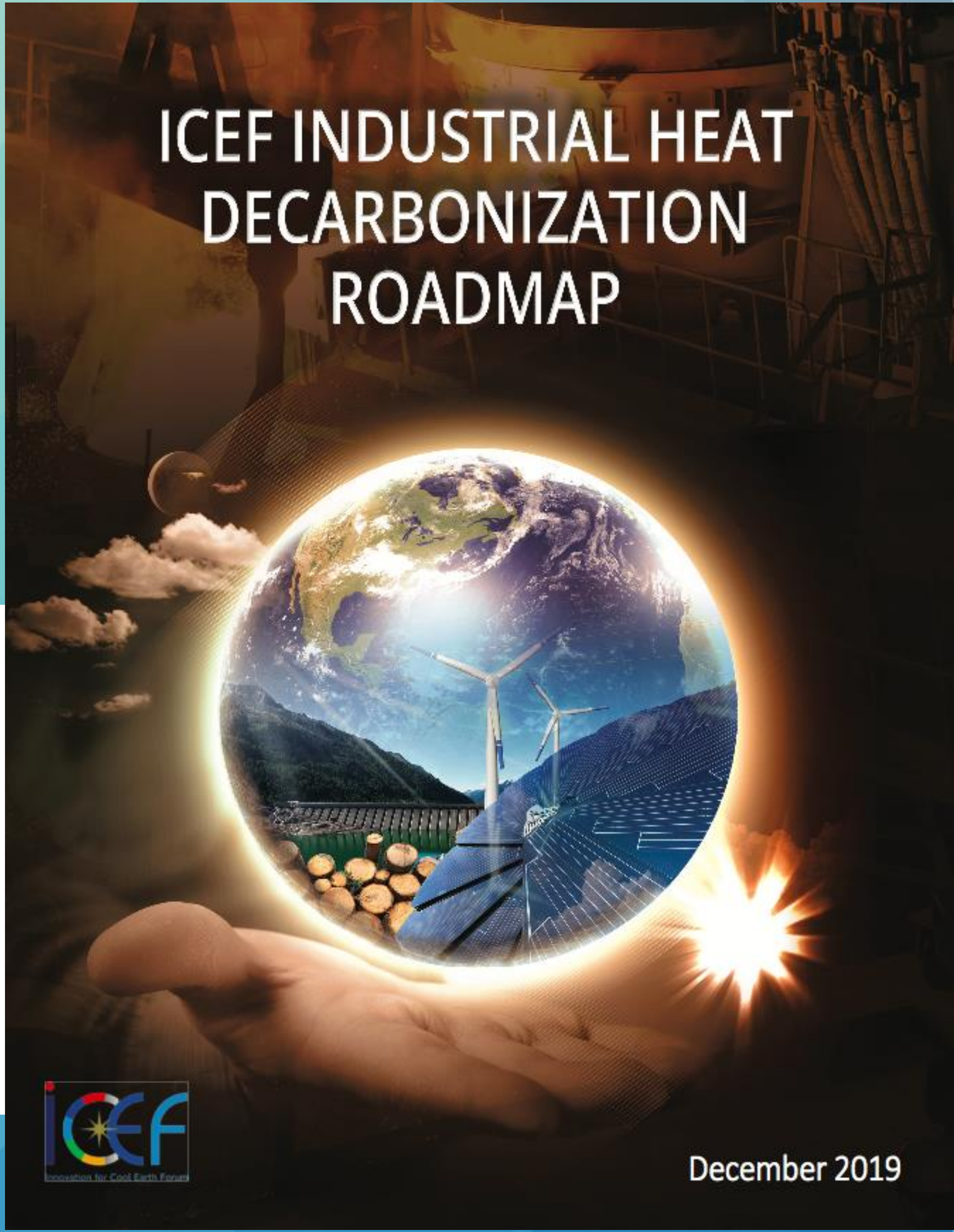
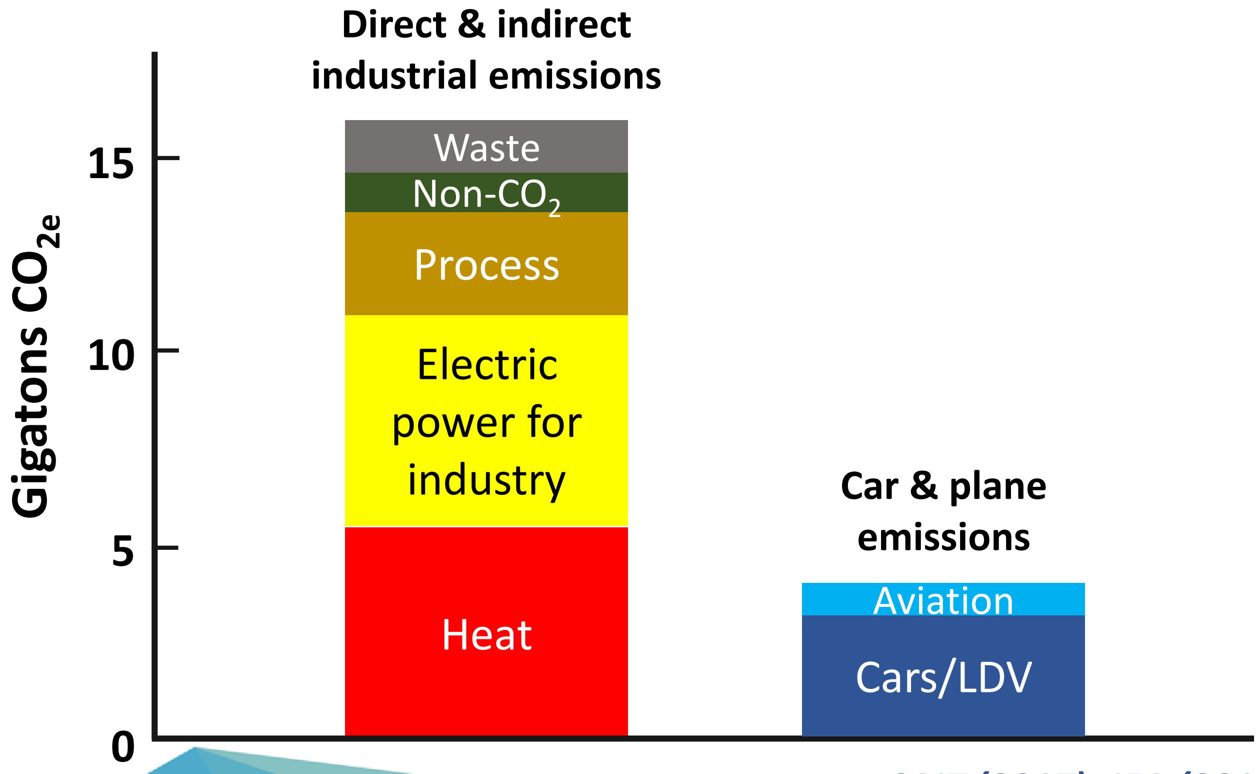


CO_2 emissions from industrial heat production are 5 Gt/year -- ~10% of global CO_2 emissions

More than cars + planes combined



CAIT (2017); IEA (2017, 2019)

Key industries

Cement

Iron and Steel

Chemicals

Several characteristics of heavy industries limit options

- Long-lived capital assets: Hard to replace and modify
- Small margins: small cost changes can dramatically affect competitiveness
- Global markets: international competitiveness is important
- High capacity factors: often 80-90% operational schedules required
- Geographic constraints: often far from some renewable resources

ICEF Industrial Heat Decarbonization Roadmap
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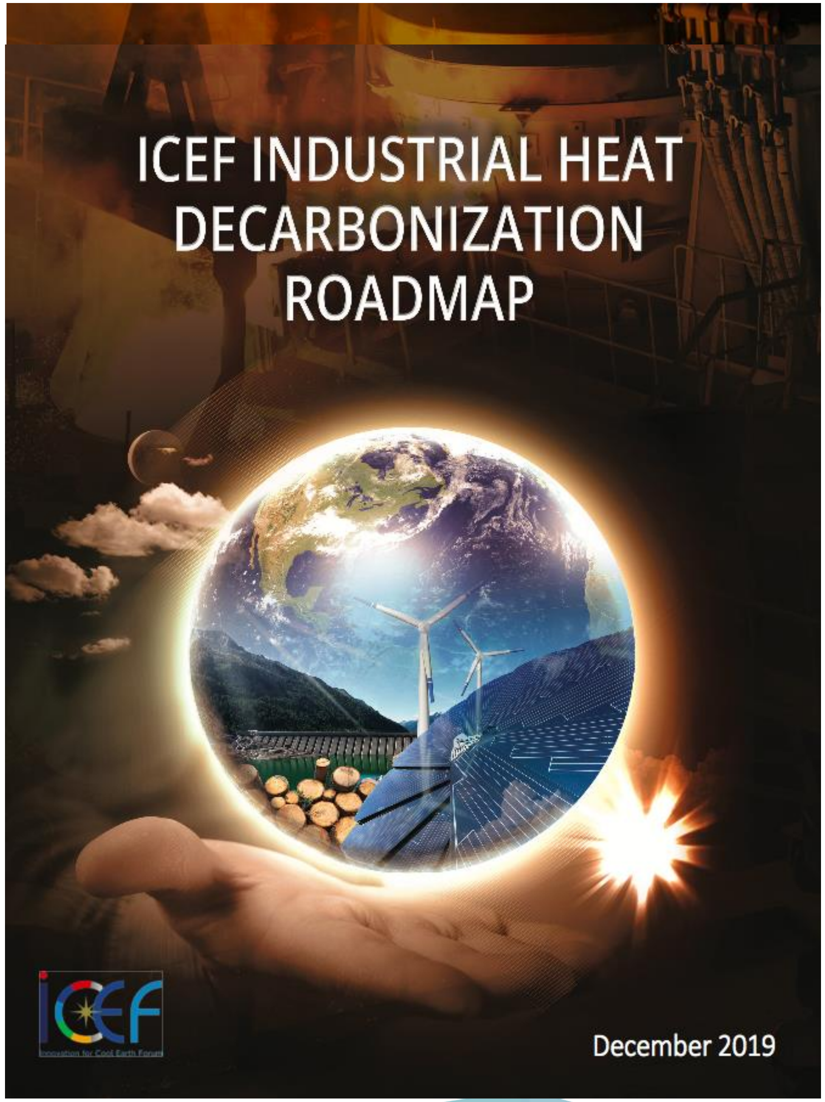
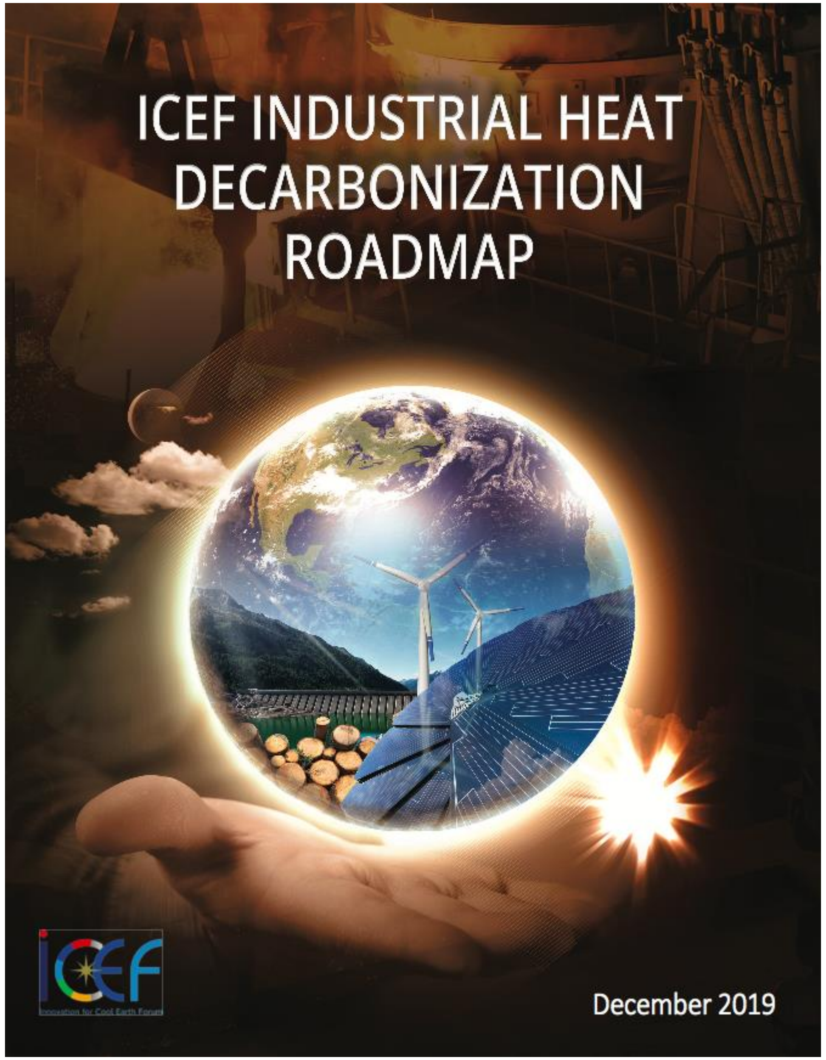


ICEF INDUSTRIAL HEAT DECARBONIZATION ROADMAP – KEY MESSAGES

- Important, challenging problem, with much more work needed
- H2, 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

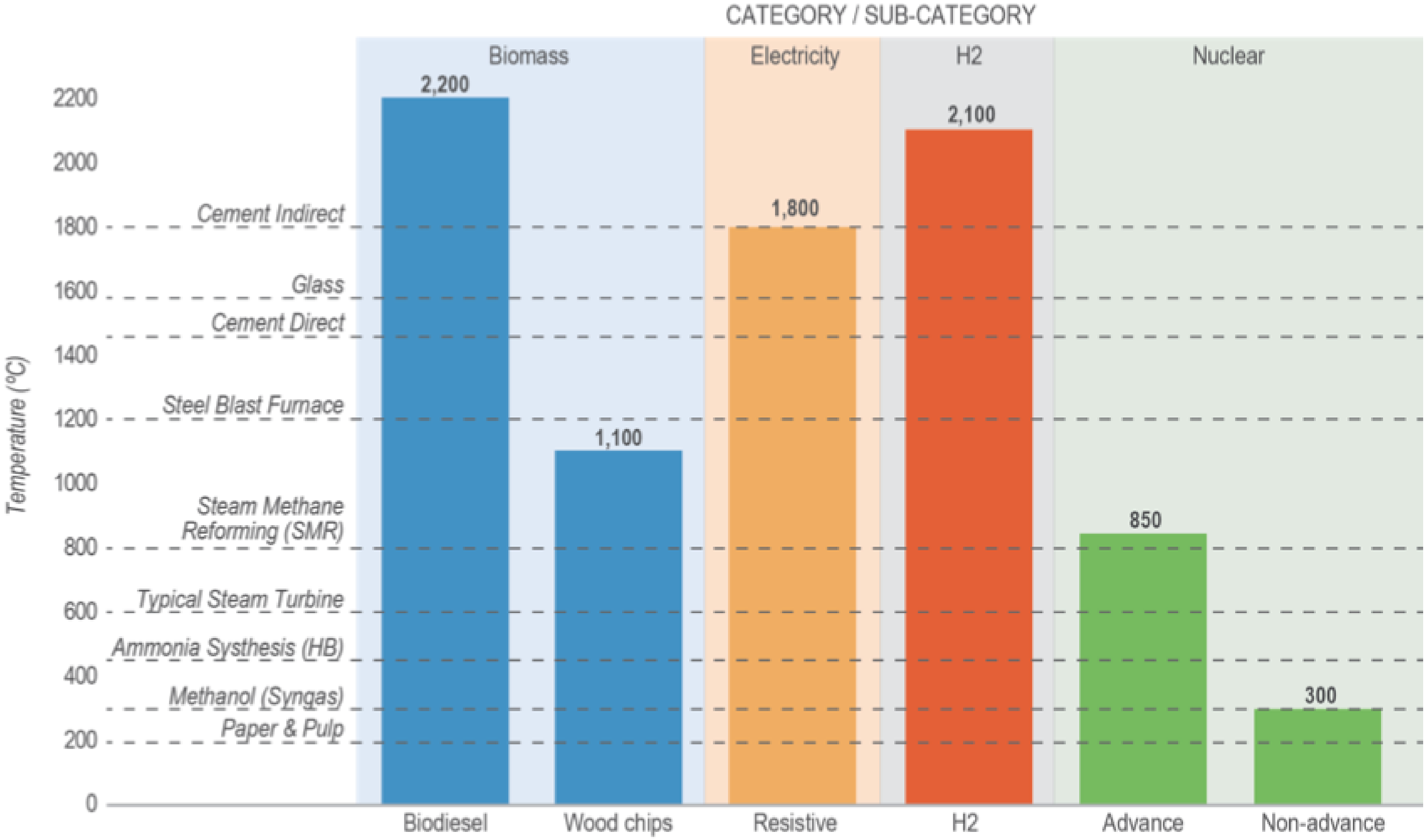
- **Very few papers on industrial heat production**
- **Data are scarce and disaggregated**
- **Lots of hypothetical new processes, very little on existing facility modification**

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

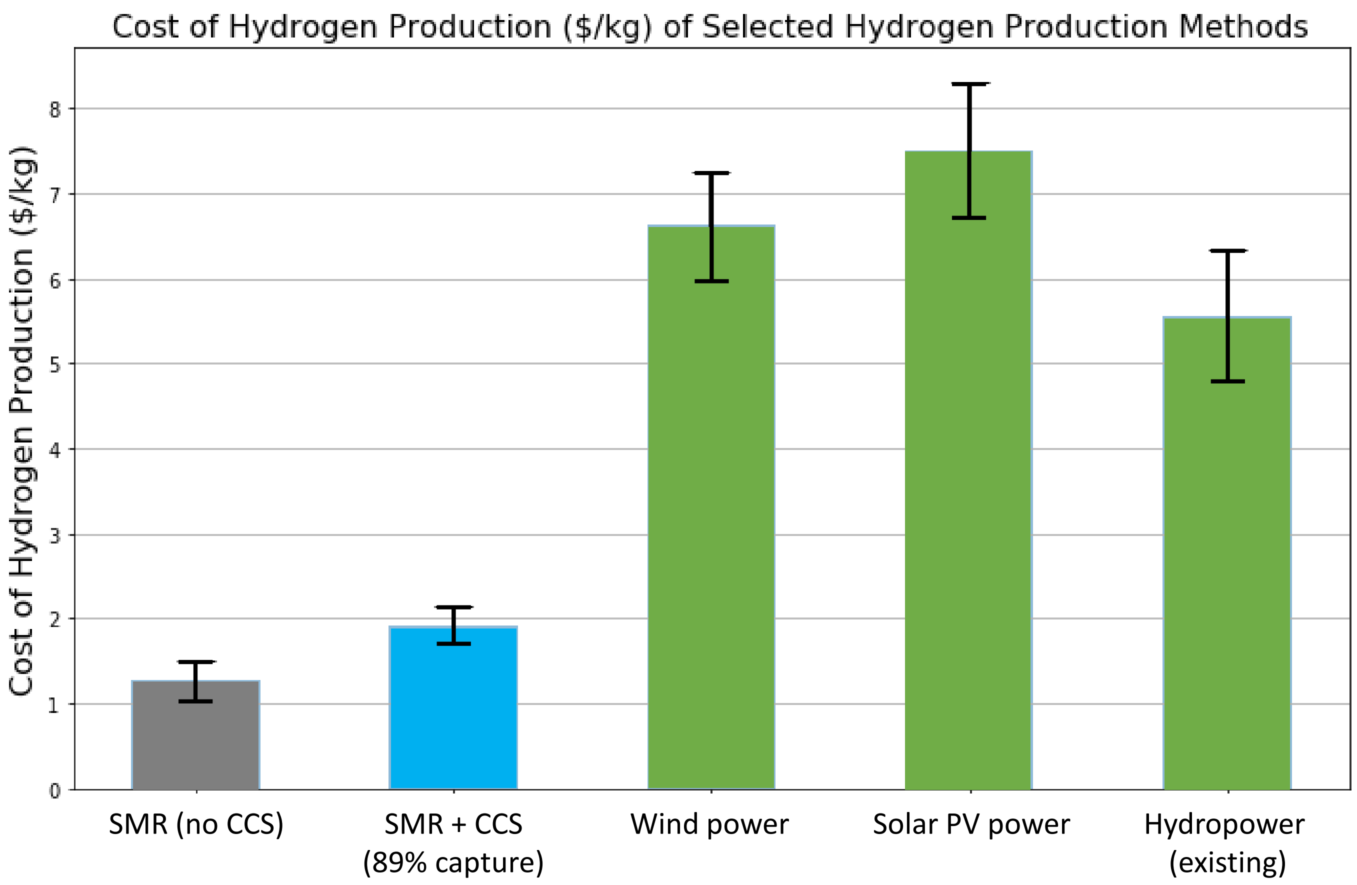
Burns at 2100° C in air and made today at industrial scale

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

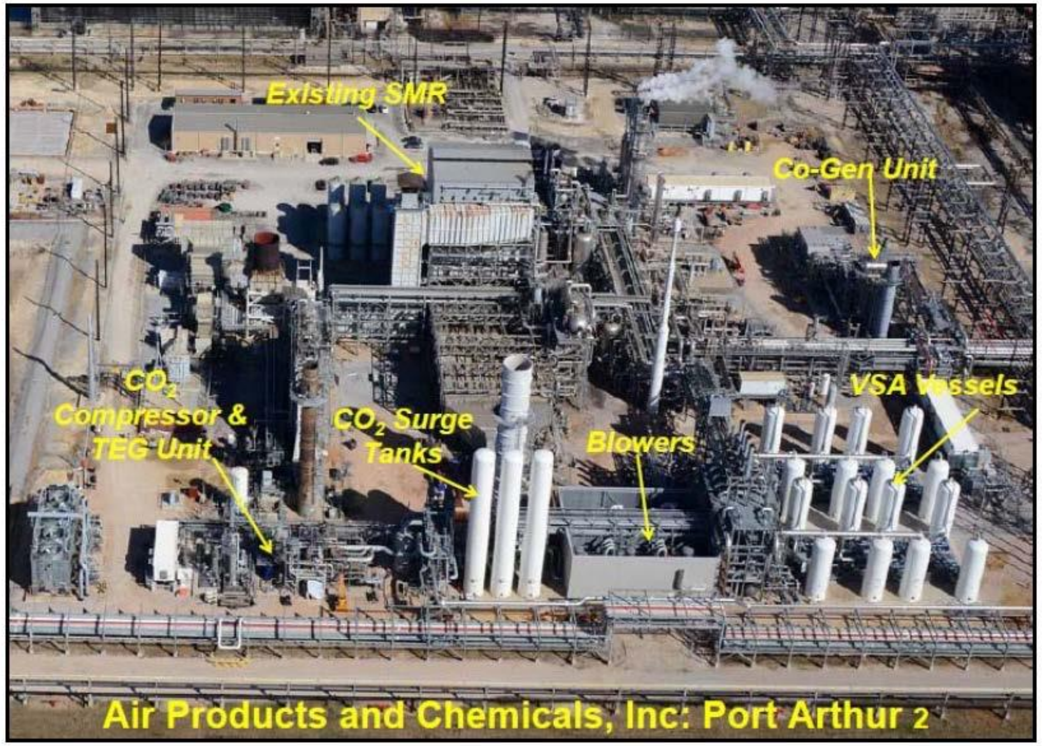
Although used today in steel (DRI) and chemicals, challenges remain

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 (biomethane & biodiesel) and in solid, liquid, gas forms

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

Electrifcation: Benefits 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

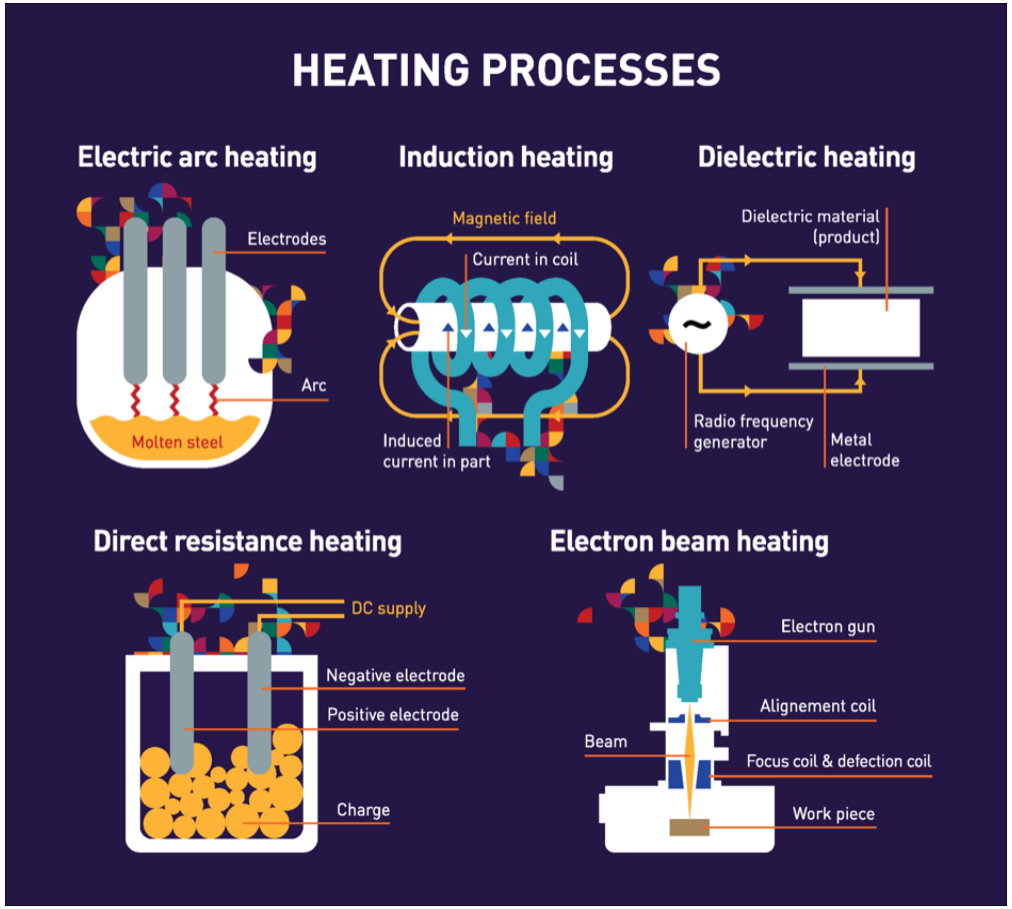
Here, the innovation agenda is most compelling

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)**



Electrification: Benefits and challenges

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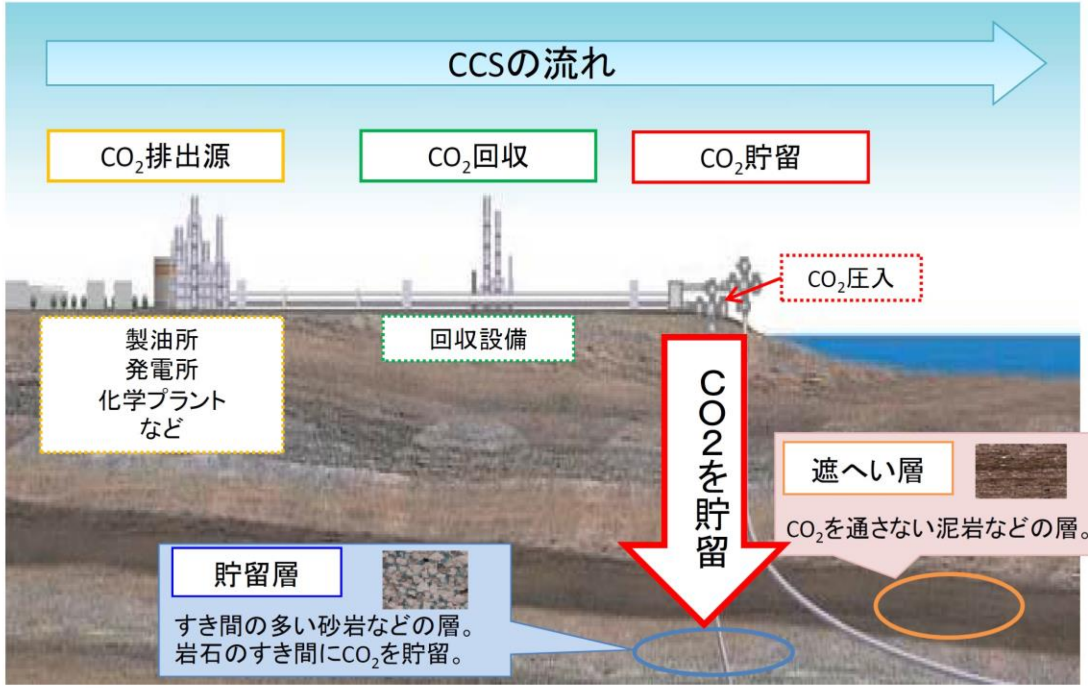
CCUS –
applicable to almost all industrial processes

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

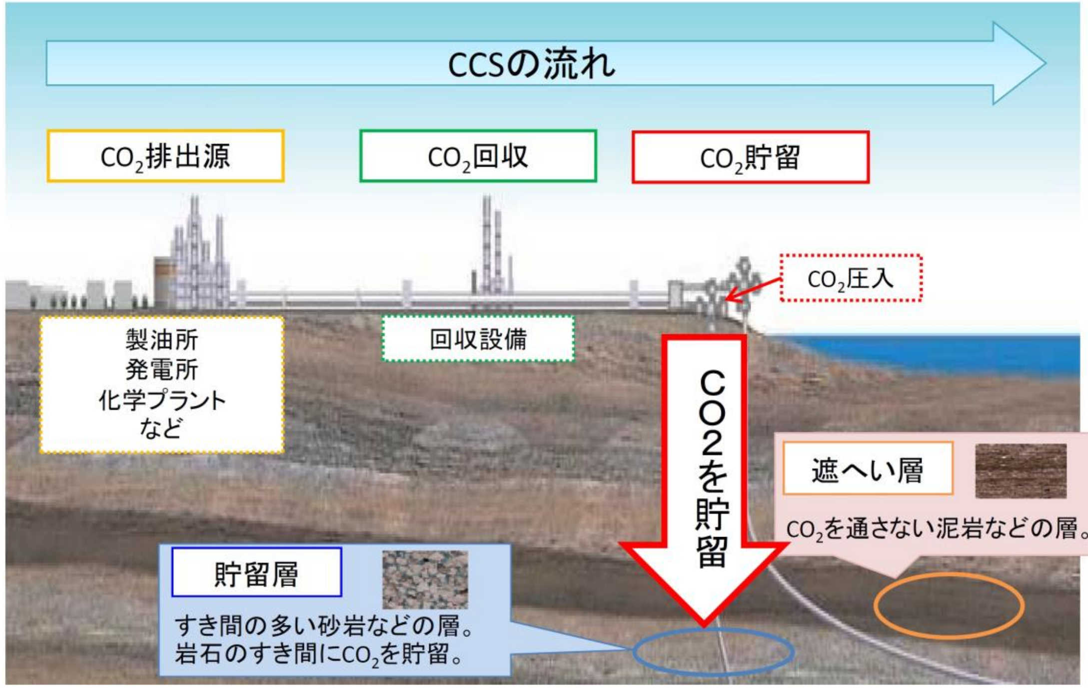
· Other capture options may be a better fit for specific industrial processes (e.g., calcium looping in Cement)

· 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 CO2 emissions

Heat for cement : ~2% of global CO2 emissions

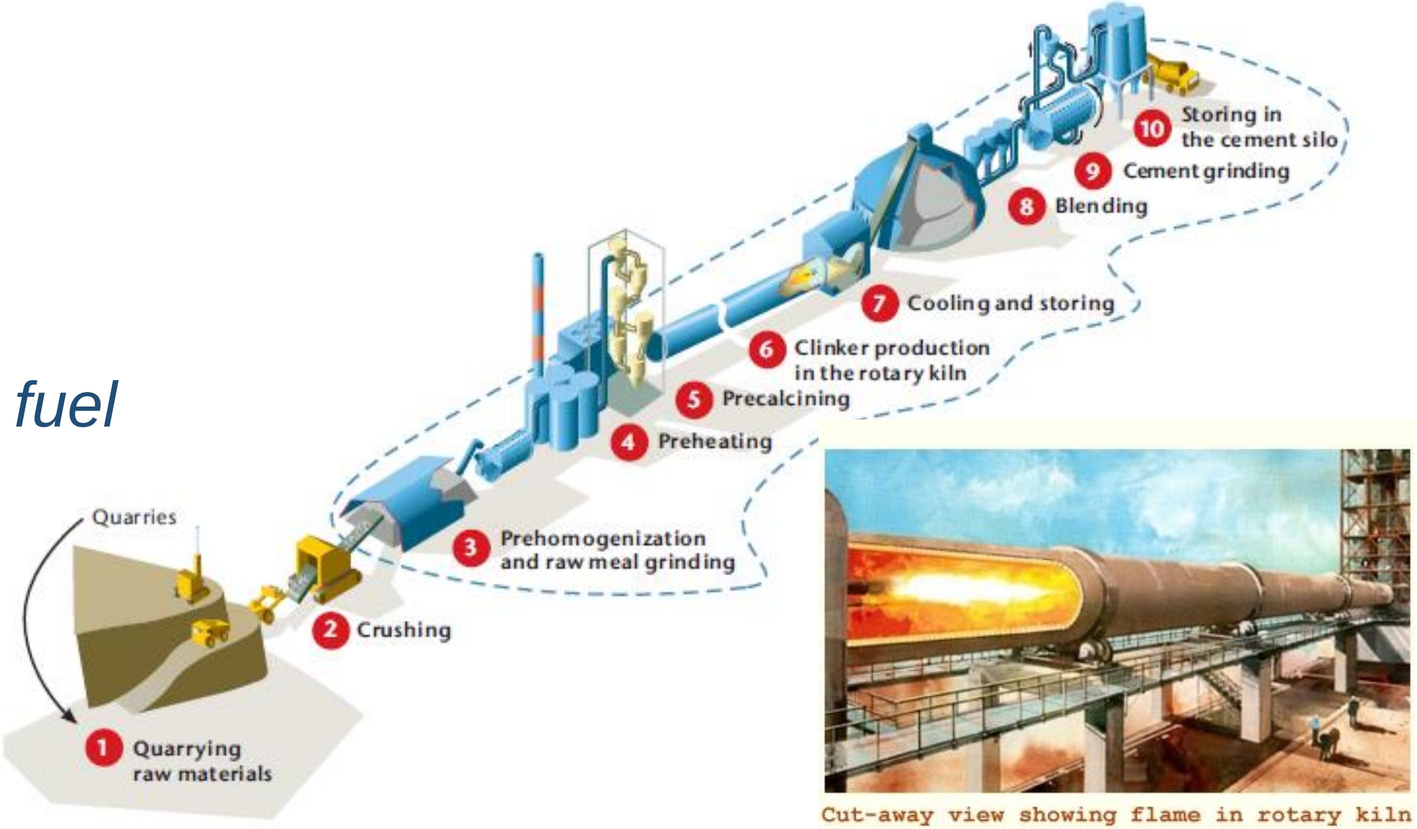
Requires 1450° C and continuous operations

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

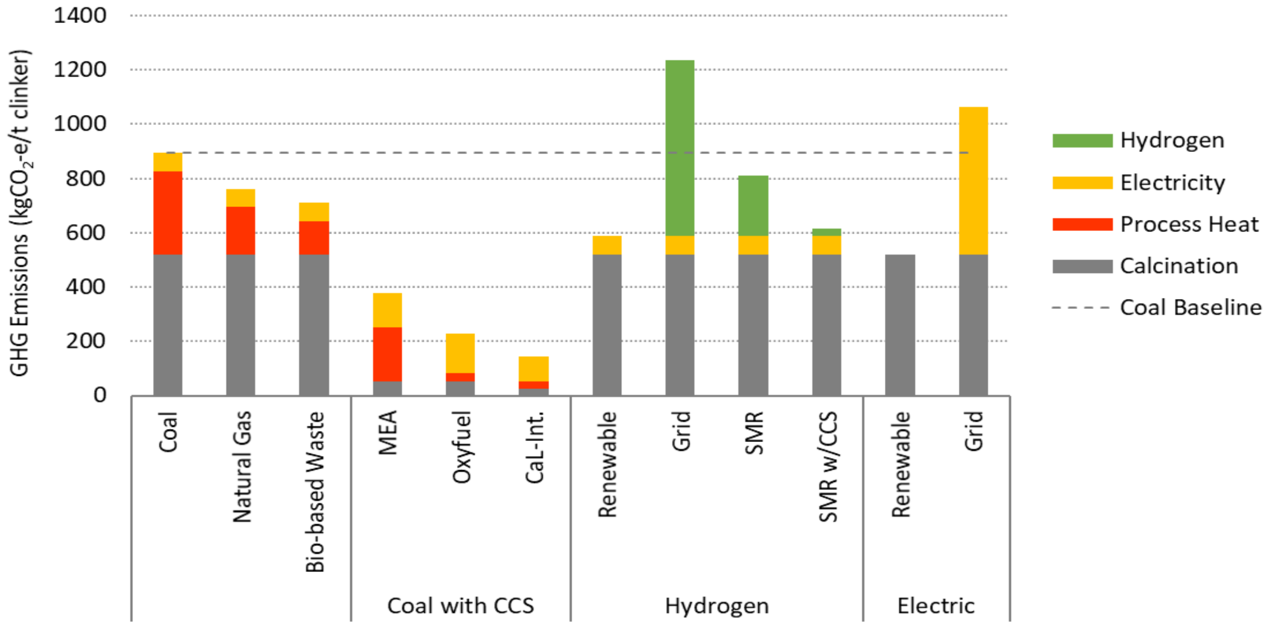
Requires 1450° C and continuous operations

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

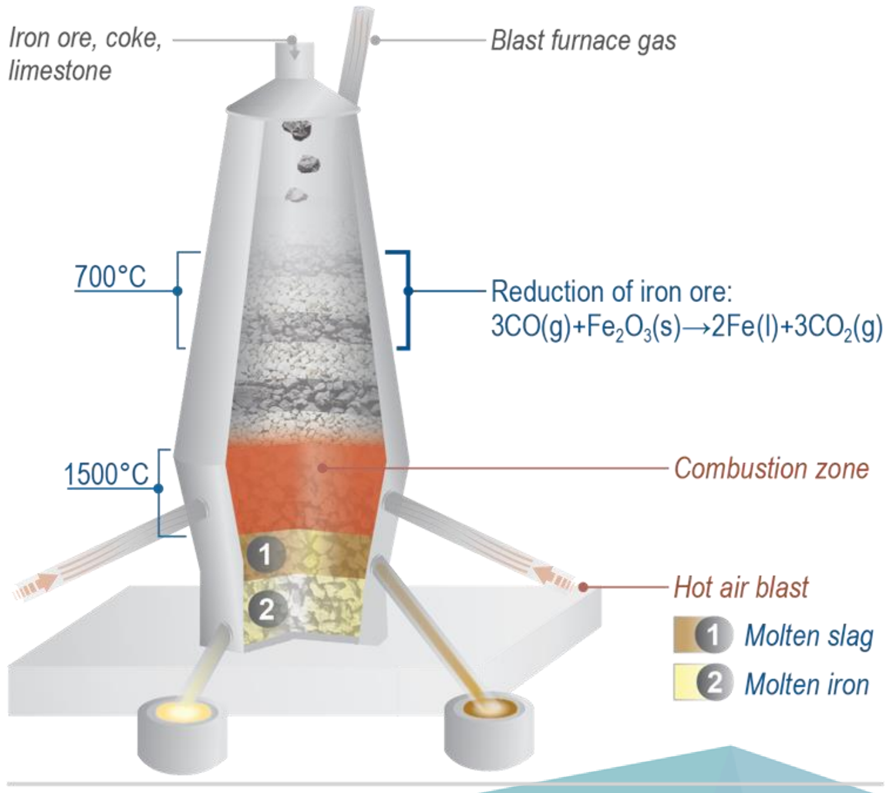
Requires 1200° C and continuous operation

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

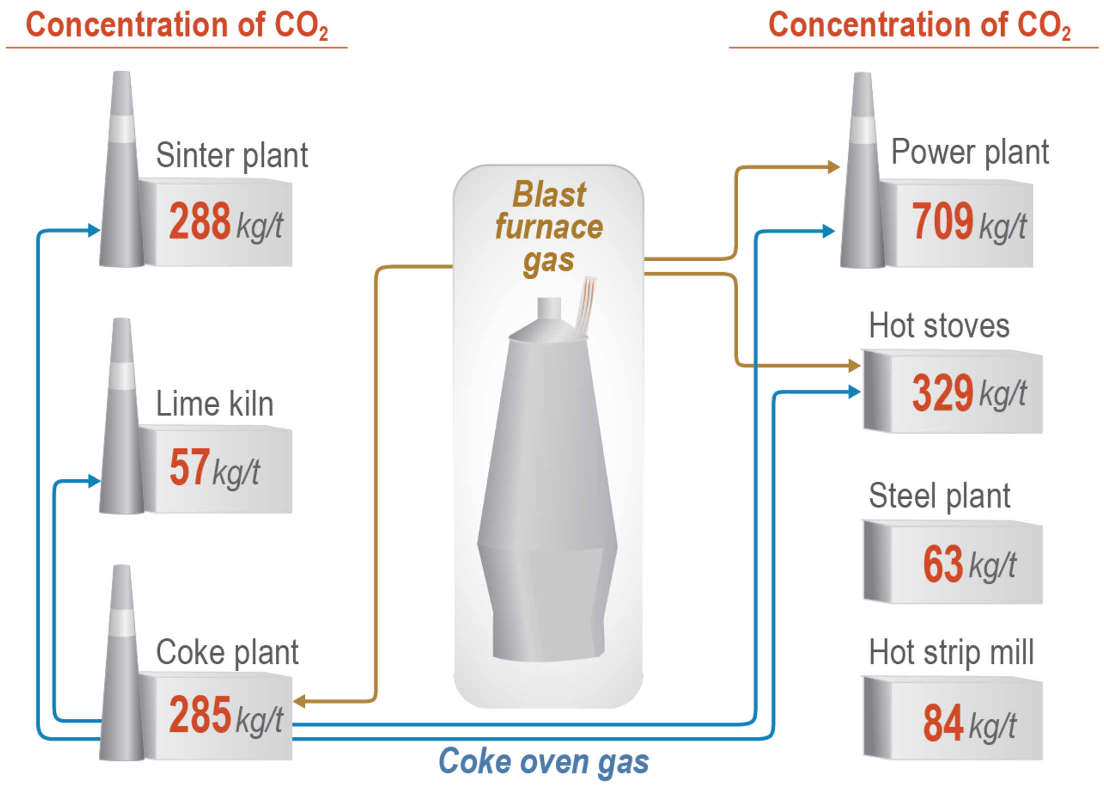
Requires 1200° C and continuous operation

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 CO_2 emissions

Heat for chemicals: ~1.5% of global CO_2 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 H_2)**
- **LPGs, some other petroleum fuels**
- **Coal or coal-syngas (developing countries)**

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Ammonia: non-C bearing chemical

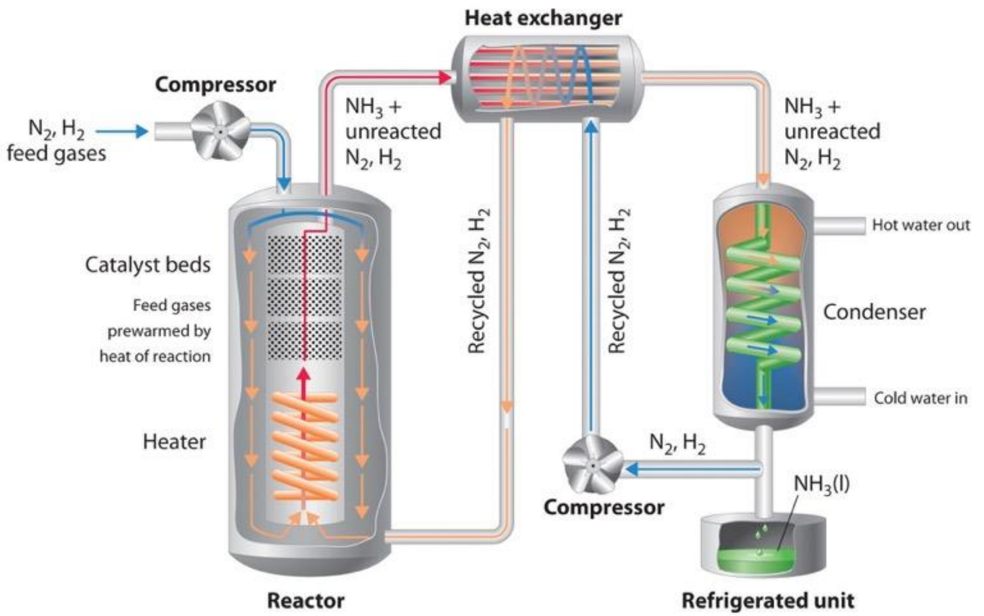
850° C for hydrogen production, 500° C for synthesis

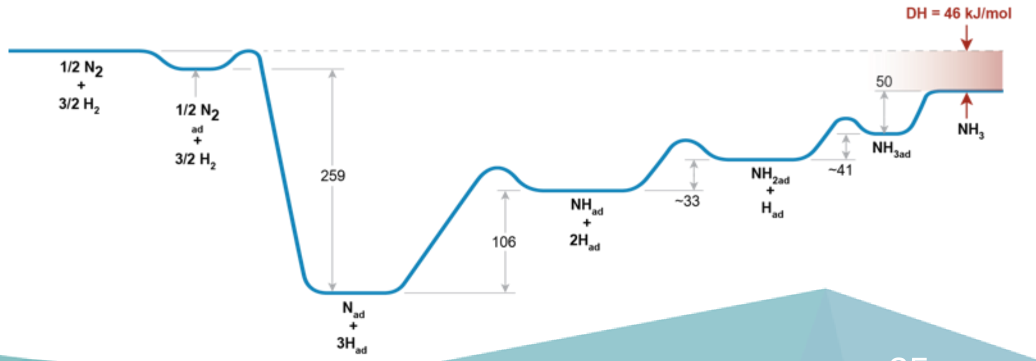
Current heat applications

- **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

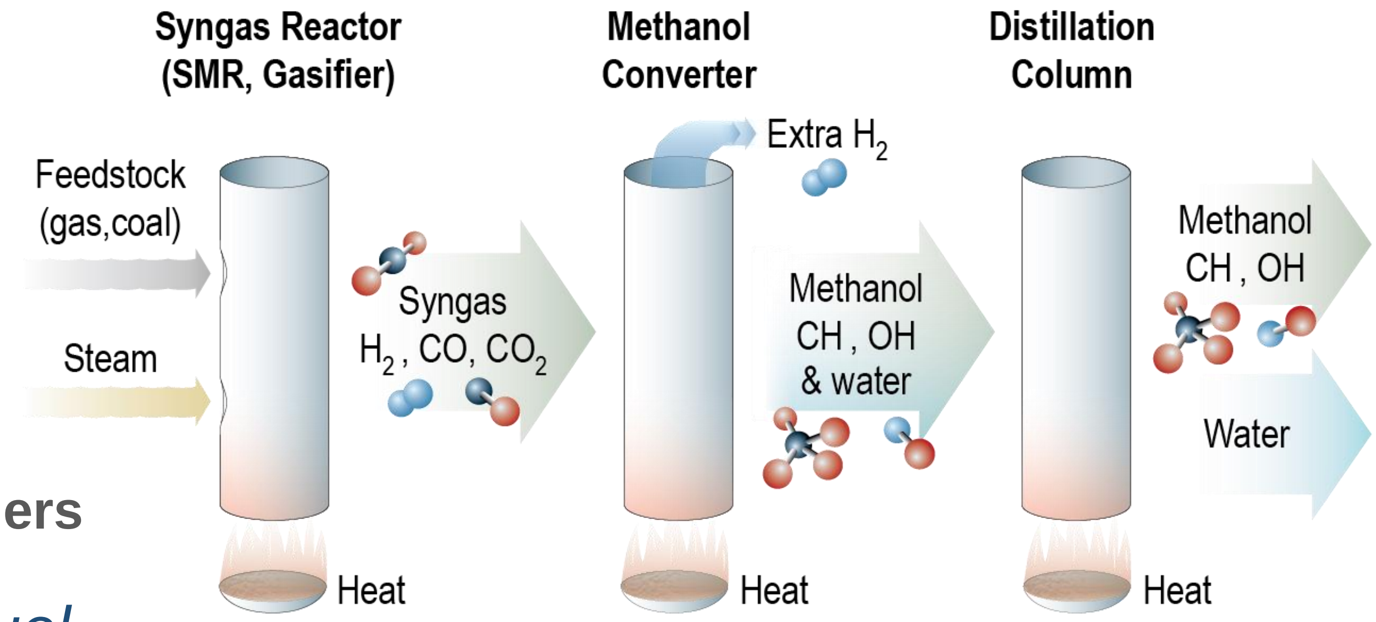
300° C for synthesis

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)**

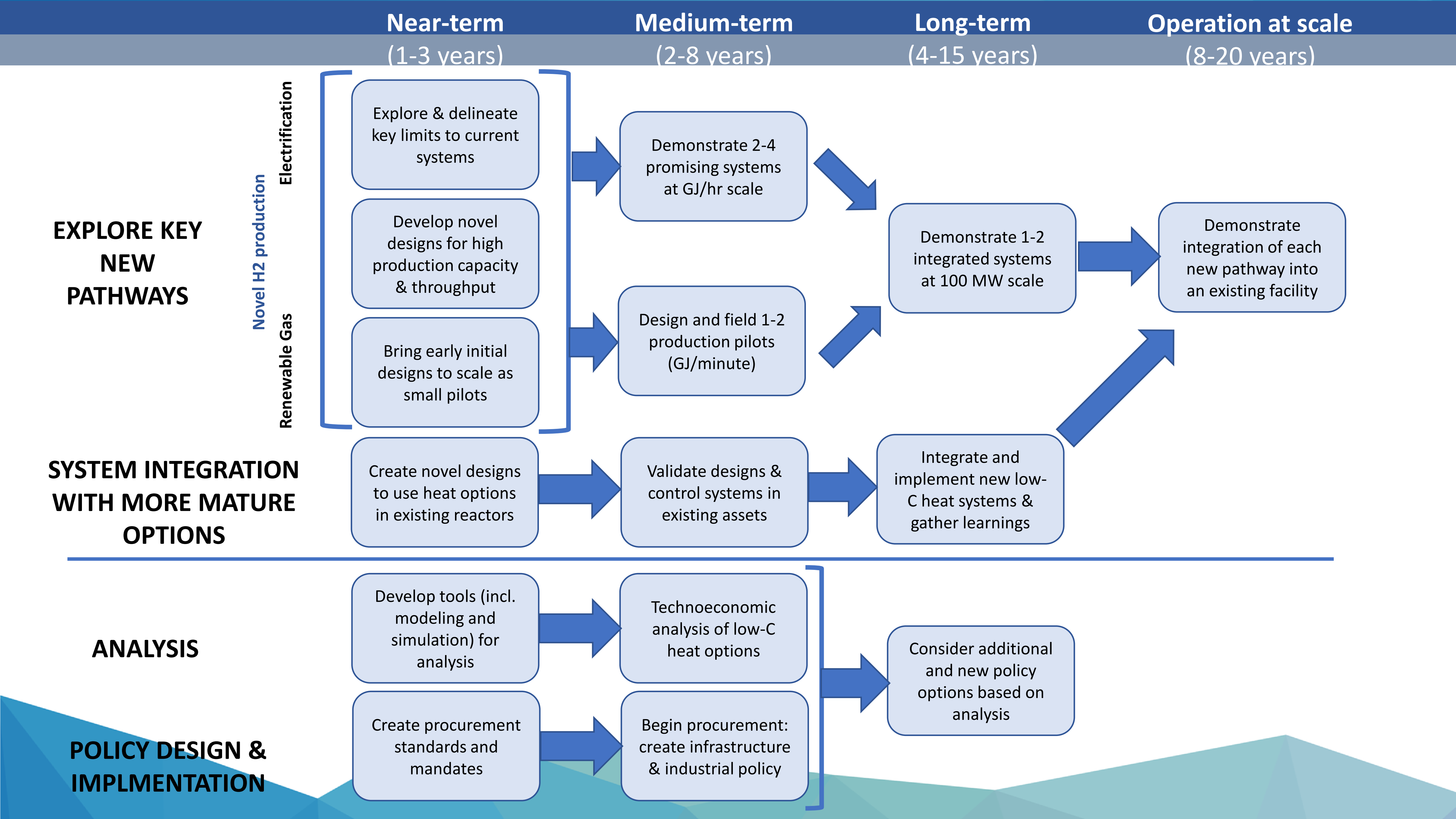
System approaches:

- **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



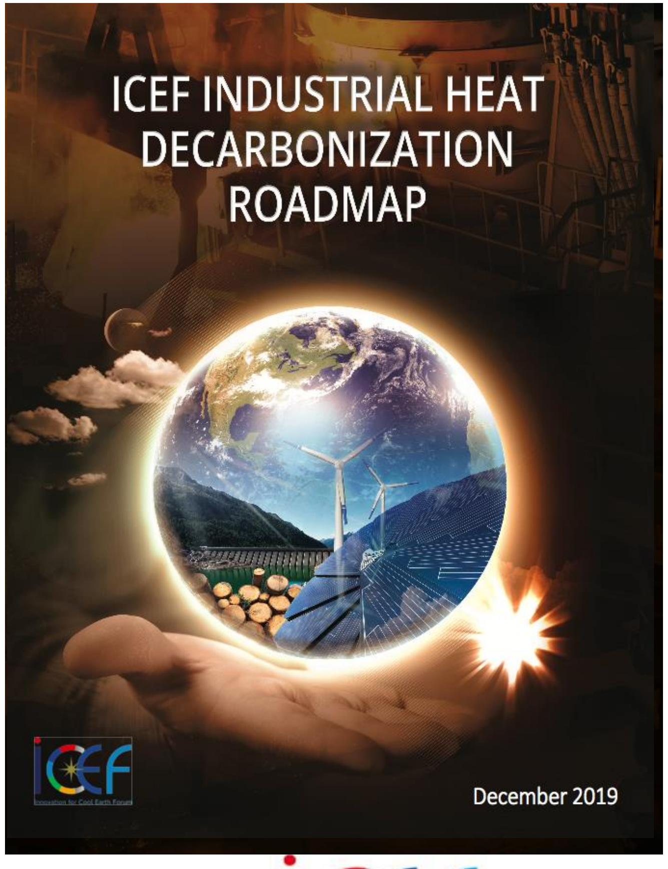

Near-term
(1-3 years)
Medium-term
(2-8 years)
Long-term
(4-15 years)
Operation at scale
(8-20 years)
EXPLORE KEY NEW PATHWAYS
Novel H2 production
Electrification
Renewable Gas
Explore & delineate key limits to current systems
Develop novel designs for high production capacity & throughput
Bring early 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



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- Many policy options available
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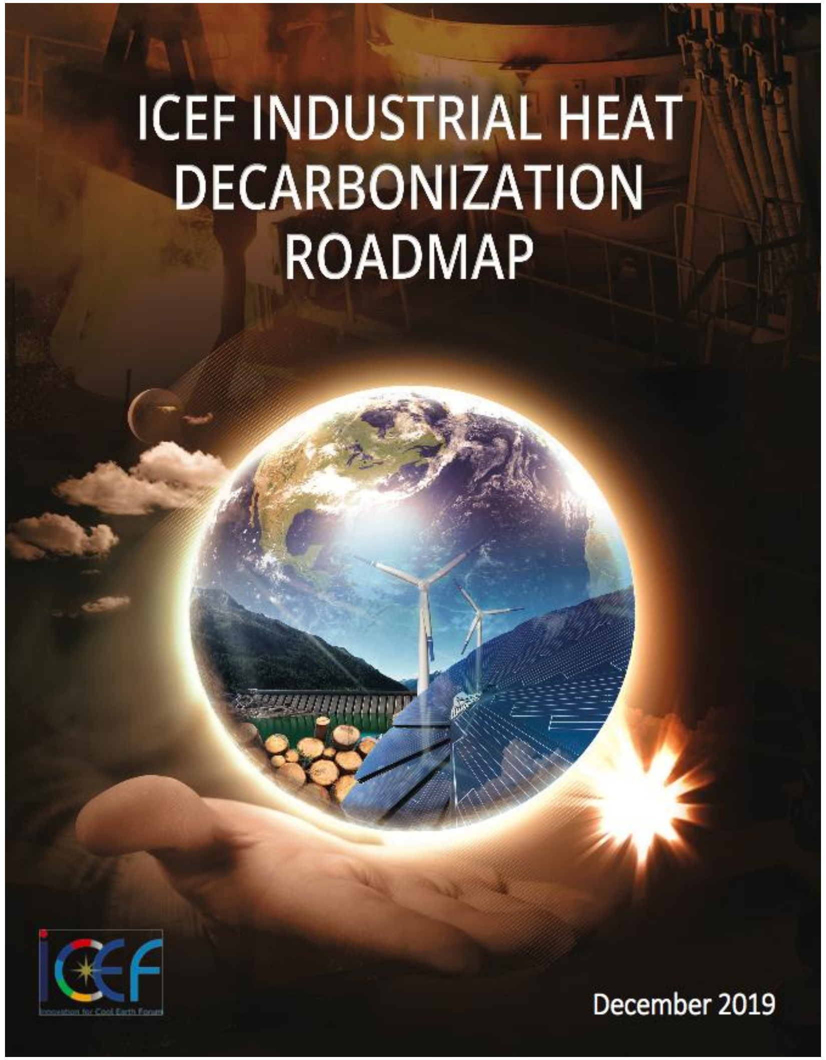

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