Hydrogen Steelmaking
GISH

Electrification of Process Heat
EPIXC

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Missouri University of Science & Technology

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SwRI
Southwest Research Institute

DOE Hydrogen Program
Award Number: DE-EE0009250

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PSMRC Kent D. Peaslee Steel Manufacturing Research Center

EPIXC Electrified Processes for Industry without Carbon

Missouri S&T Materials Science and Engineering

ASU

DANIELI

CLIFFS

NUCOR

SDI Steel Dynamics, Inc.®

GERDAU

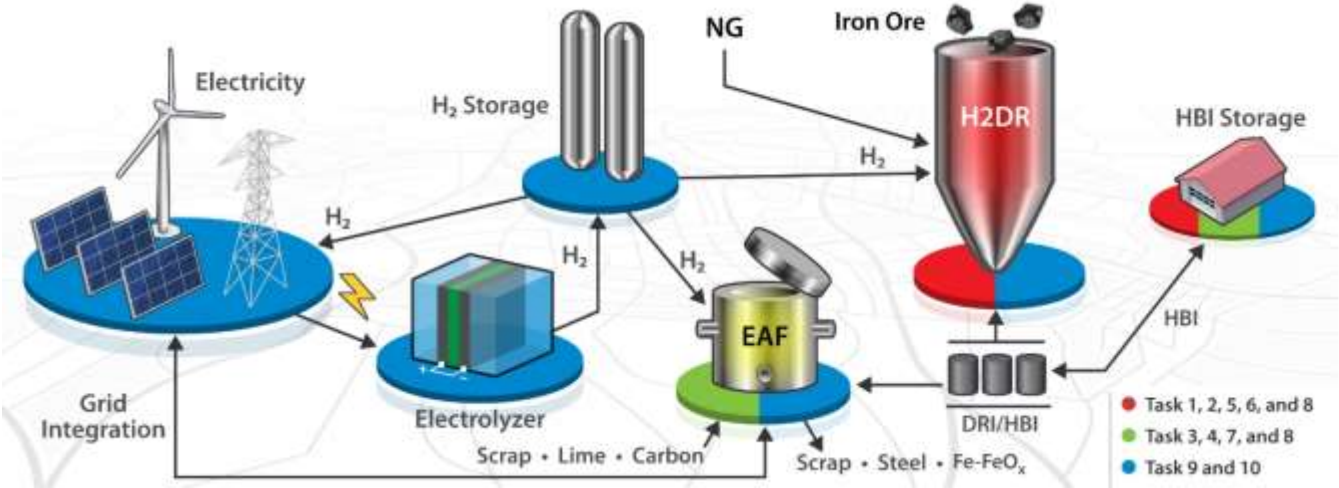
Linde

NREL Transforming ENERGY

Air Liquide

Grid-Interactive Steelmaking With Hydrogen (GISH)

The Concept



GISH proposes an integrated approach for sustainable steelmaking enabled by H2@Scale and renewable penetration. Our team will advance critical path research, development, and demonstration (RD&D) in the economic viability of a steel production system, combining a direct hydrogen-reduction furnace for ironmaking (H2DR) with electric melting for steelmaking, integrated into a flexible grid with energy storage.

Impacts

- Transition of up to 14 GJ of the 17 GJ it takes to produce a ton of steel strip (and corresponding emissions reduction of nearly 1,560 kg of emitted CO_2 per ton of steel).
- Creation of a new source of energy storage in form of ferrous products, allowing for greater flexibility and avoidance of future negative electricity prices through large scale H_2 production facilities.

Prime Recipient: Missouri University of Science and Technology
PI: Ronald O'Malley
DOE EERE Funds: $4,049,426 Cost Share: 26.8%
Total Budget $5,429,587

A Unique Academia–Steel Industry–National Laboratory Partnership

Organization	Background/ Capabilities	Project Responsibility
Missouri University of Science and Technology (MS&T)	World-class industrial research university with laboratory capabilities and home of the Steel Manufacturing Research Center	Overall project management, lead the EAF melting studies and assist in the reduction kinetics studies.
Arizona State University (ASU)	World-class industrial research university with high temp. exp. capabilities, data analytics and characterization	Experimental and analytical reduction studies and product characterization. Scale up modeling and assist with EAF melting.
Danieli USA (DAN)	Leading steel EAF and DRI* technology provider	Assistance for DRI pilot plant design, start up and testing, EAF melting tests, and knowledge for laboratory DRI production.
Cleveland Cliffs (CLF)	Operates a NG†-based HBI‡ facility in Corpus Christi, TX. Has also a full-scale electrolyzer	Support student mentoring, provide HBI and oxide pellets, contributions to process modelling and flowsheet simulation and provide input for industrial adoption of hydrogen for iron and steelmaking.
Steel Dynamics Inc. (SDI)	Leading high-value flat and long steel products mini-mill producer, metals recycler and alternate iron producer	Will provide advising, site access for plant trials and supporting data for analysis.
Gerdau North America (GNA)	Leading long steel products steel producer in the U.S., largely EAF-based	Will provide knowledge related to large scale production trials in EAF.
Nucor (Nu)	Largest steel producer in U.S. with a DRI plant in Louisiana	Will provide advising, pellets, operating data and site access for plant trials.
Linde (LIN)	Industrial gas supplier providing steelmaking technologies and H_2 supply options for steelmaking with an R&D center	Demonstration of H2 use for sidewall injectors (CoJet) in a commercial scale EAF. Participate in consortium meetings to provide advice and guidance.
Air Liquide (AL)	Industrial gas supplier providing steelmaking technologies and H_2 supply options for steelmaking with an R&D center	Will provide advising on design, TEA and usage of H2. Also advise as the safety and handling of H2.
National Renewable Energy Laboratory (NREL)	US Department of Energy (DOE) national laboratory with hydrogen R&D expertise, extensive grid modeling, and techno-economic (TEA) modeling expertise.	TEA of the GISH process. Grid modeling, and economic and safety analysis of hydrogen processes.

* direct-reduced iron; † natural gas; ‡ hot-briquetted iron

Multi-Disciplinary Research Conducted at all Scales to Close H_2 Steelmaking Knowledge Gaps at Many Levels

Laboratory Research at Missouri S&T and Arizona State University

- Mixed Gas Reduction Kinetics and DRI Structure Impact
- Impact of DR Path and Carbon Levels on Melting Efficiency in the EAF
- Influence of H_2 Plasma on Reduction Kinetics and DRI Structure
- Kinetic & Melting Model Development for Use in Commercial Scale-up

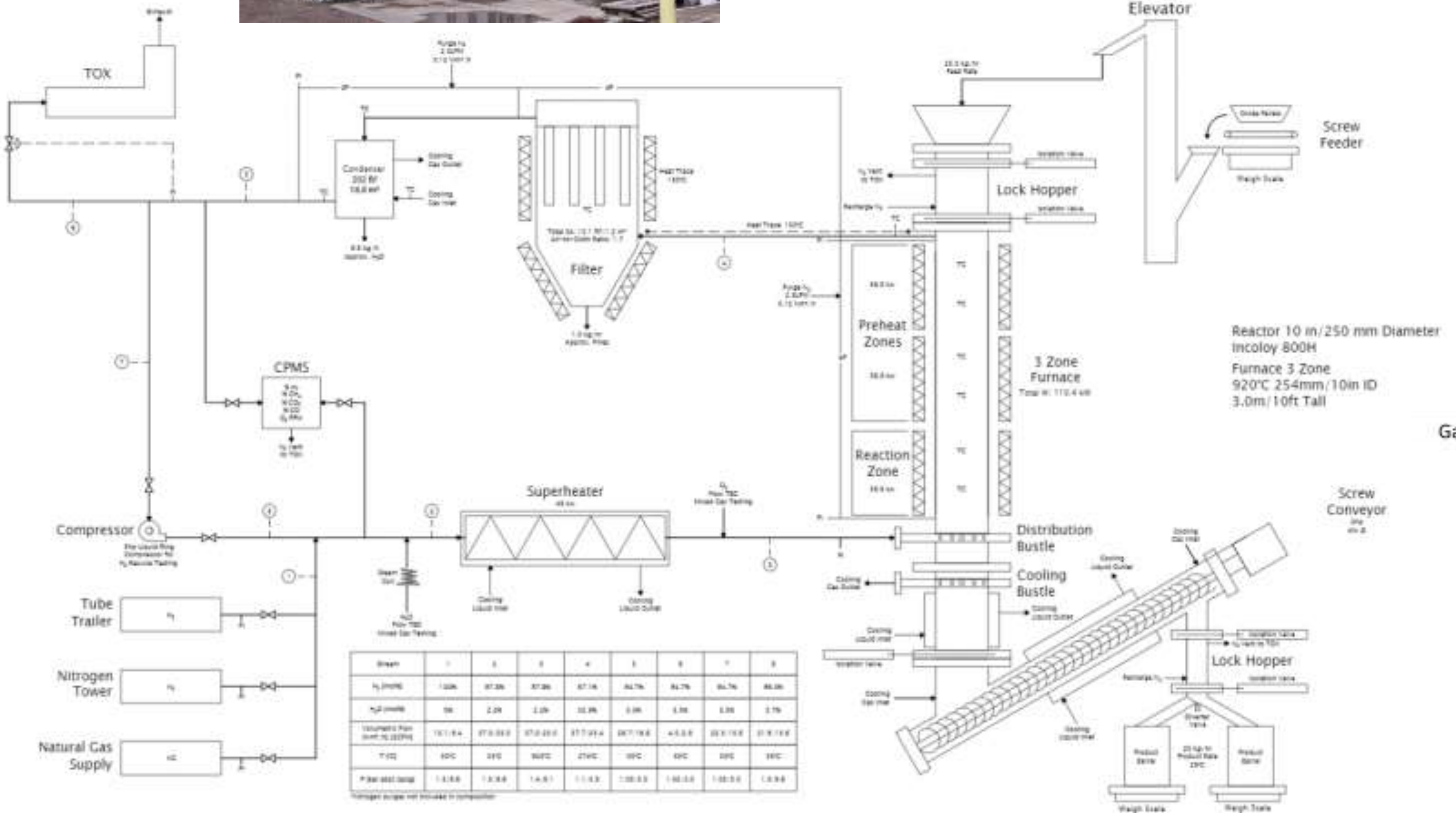
Pilot Scale Direct Reduction at Hazen Research

- Reduction Using H_2-NG Mixtures to Validate GISH Concept
- DOE Demonstration of 1 Ton/week at Specified Level of DRI Reduction with H_2 and H_2 – NG Mixtures
- Evaluation and Refinement of Scale-up of Kinetic Models for Dynamic Mixed Gas Ironmaking
- Melting Trials with Pilot DRI in Production LMF Facilities to Simulate EAF Melting
- Extrapolation of Pilot Plant Results to Scale to Industrial Production Levels

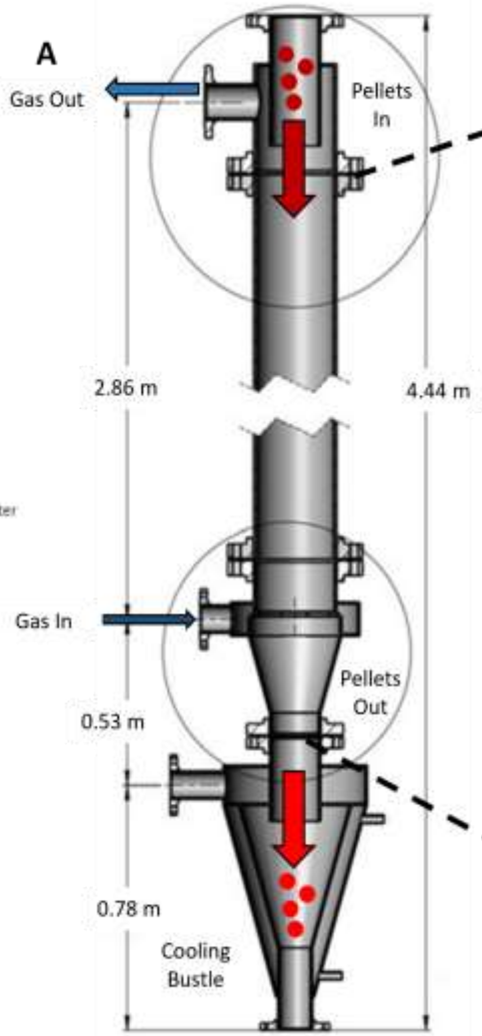
Commercial Scale Direct Reduction and EAF Steelmaking Trials

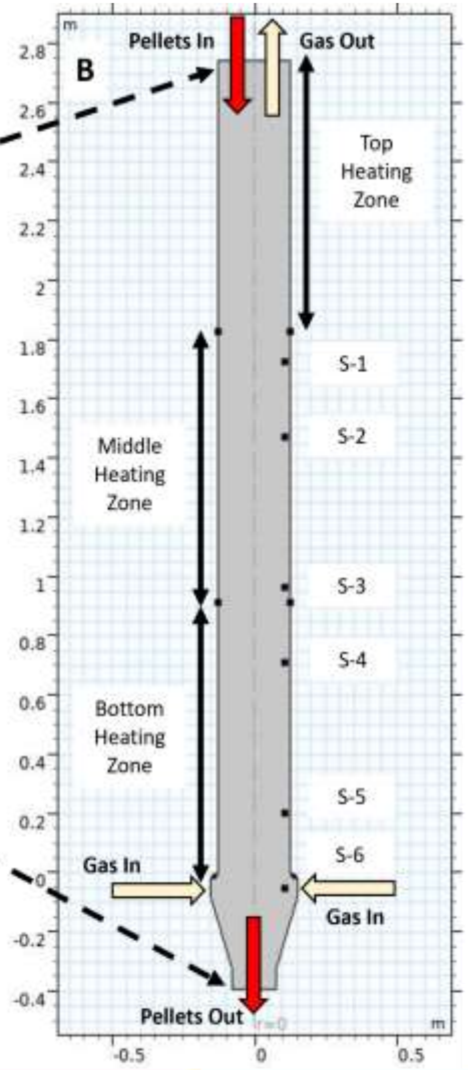
- Production of Trial Lots of DRI & HBI at Low and High C levels at Commercial Facilities
- Evaluation of Trial Lots Commercial DRI/HBI in Partner EAF Melting Facilities
- Assessment of Impact of DRI/HBI Trial Lots on EAF Efficiency, Production and Yield
- Identification of Alternative Strategies for Low C DRI/HBI use in the EAF
- Conduct a TEA of the GISH Process

GISH Pilot Plant for Mixed H_2 and Natural Gas DRI Production

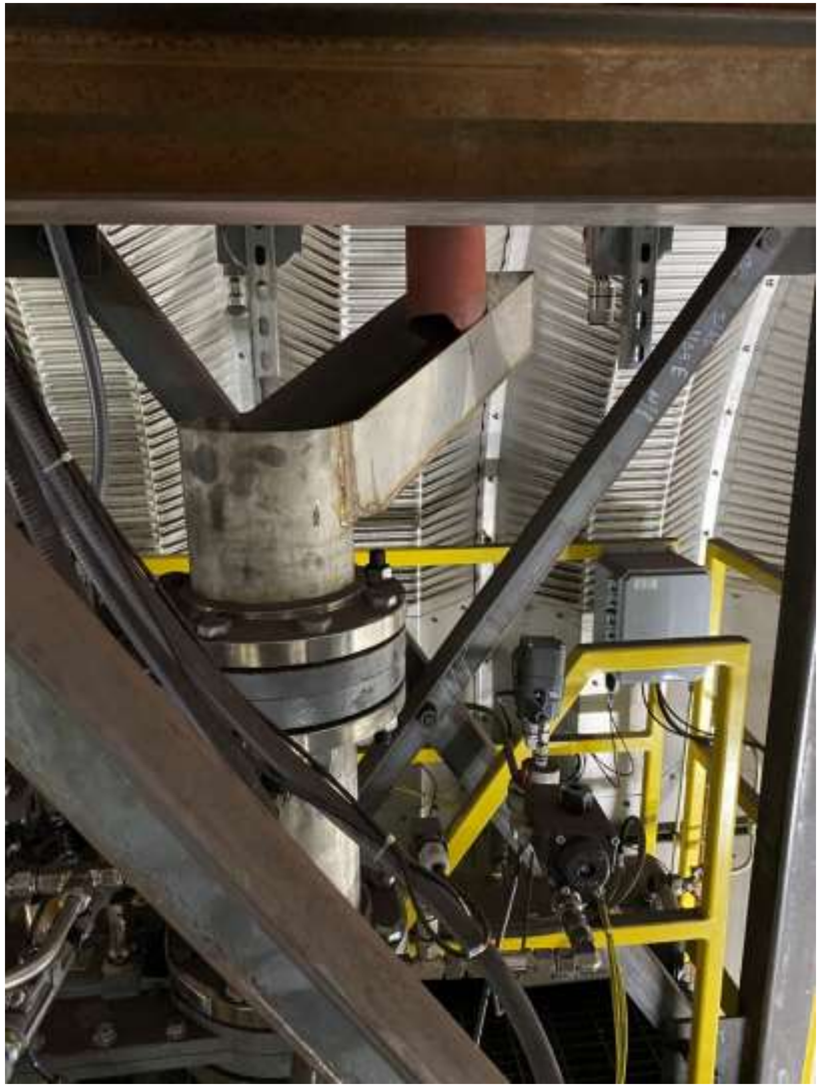


Stream	1	2	3	4	5	6	7	8
H_2 (mol%)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
H_2O (mol%)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Volumetric Flow	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
T (°C)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
P	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]





GISH Reactor – Pellet Feed System



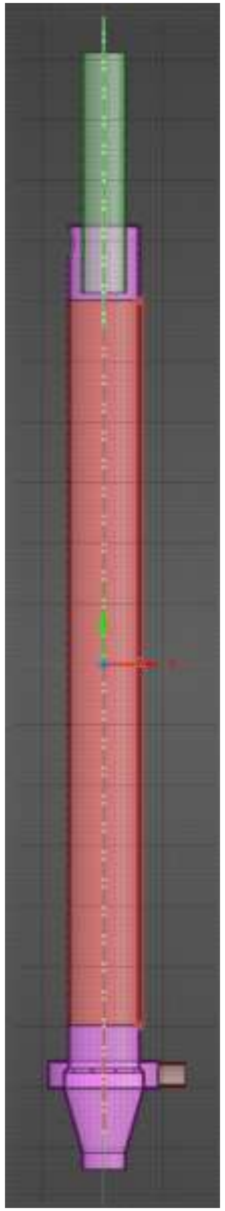
GISH Reactor

GISH Reactor – Cooler & Discharge

Pilot Plant Campaigns

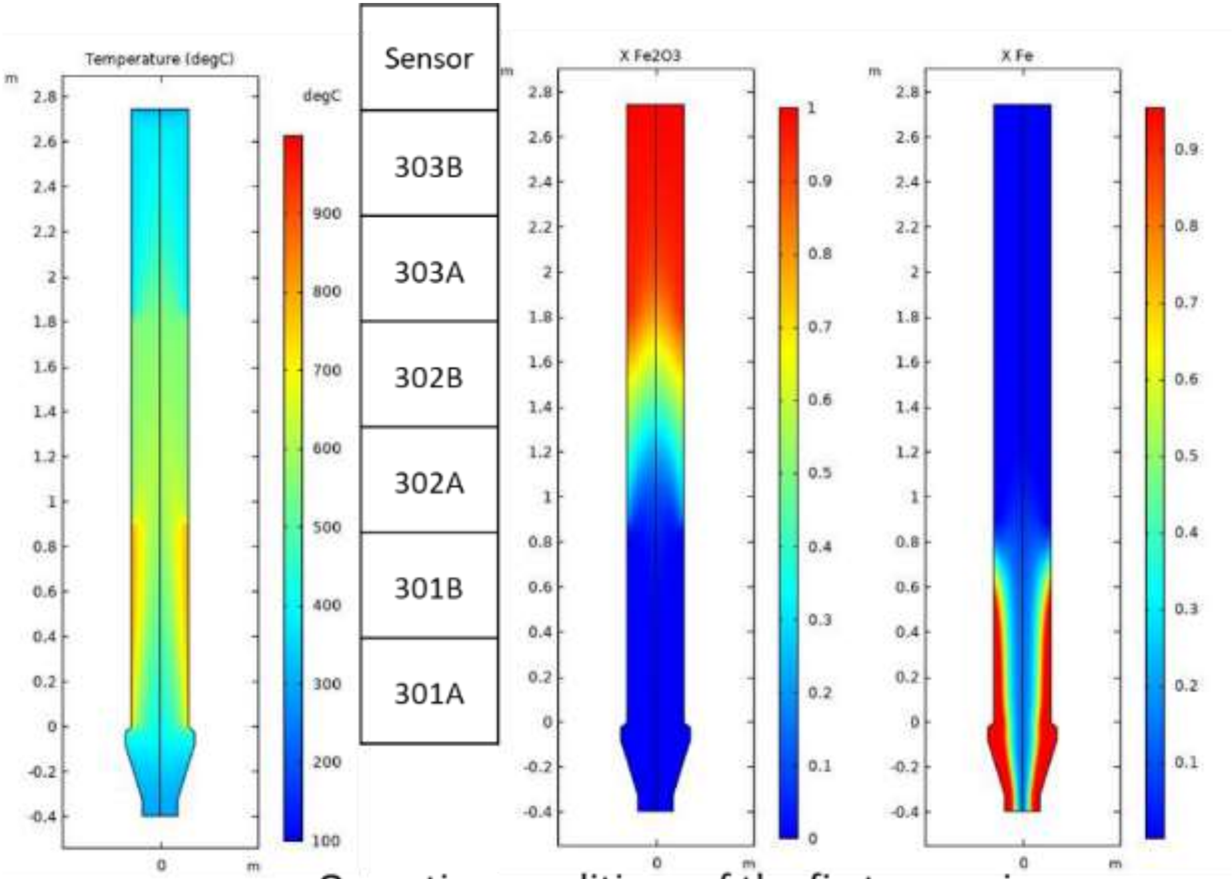
- GISH H2-DRI pilot plant constructed and commissioned in Golden, CO at Hazen Labs
  - ➢ DOE Target: DRI production of 1 ton per week
- Campaigns 1 and 2
  - Process shakedown and troubleshooting in Campaign 1 – ASU Process model used to assist in setting operating parameters
  - Continuous operation achieved at high levels of metallization (+90%) in Campaign 2 with ~ 1 ton of DRI produced at >90% metallization.
- Campaign 3 Produced 2 tons at +93% metallized H2-DRI pellets
  - Push up reactor temperature
  - Improved oxide pellet quality
  - Coat pellets with lime to reduce sticking
- Campaigns 4 Produced 2 tons at +95% metallized H2-DRI pellets
  - Implemented hot oxygen injection at gas inlet for mixed gas for carbon control
  - Demonstrated mixed gas reduction

Reaction Scale-Up Model - Temperature Profiles and Metallization



Reactor Model Geometry

Milestone 5.3: Go/No-Go 5.6: Go/No-Go 5.6: "Reactor Model Agreement with Pilot within +/- 5%" - completed



TC#	Trials	Model
303B	401.03 °C	399.27 °C
303A	450.95 °C	554.52 °C
302B	585.41 °C	573.60 °C
302A	657.62 °C	613.57 °C
301B	735.50 °C	742.67 °C
301A	574.33 °C	694.17 °C

Bottom Coil Temperature	Average Model Metallization	GOI Test Metallization
800 °C	75.36%	76.94%

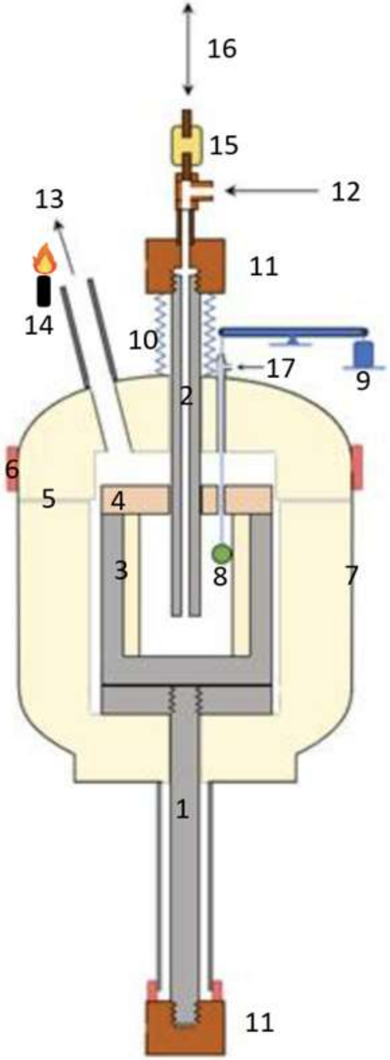
- **COMSOL model for H_2 and mix gas reduction of pellets in pilot plant is created**
- The samples from reactor operation were chosen randomly for Gain On Ignition (GOI) tests to evaluate the metallization rate
- Model validated by temperature sensors inside the reactor and GOI Metallization tests
- **Accuracy of the model prediction is over 90% achieved – Milestone 5.6 satisfied.**

Operation conditions of the first campaign

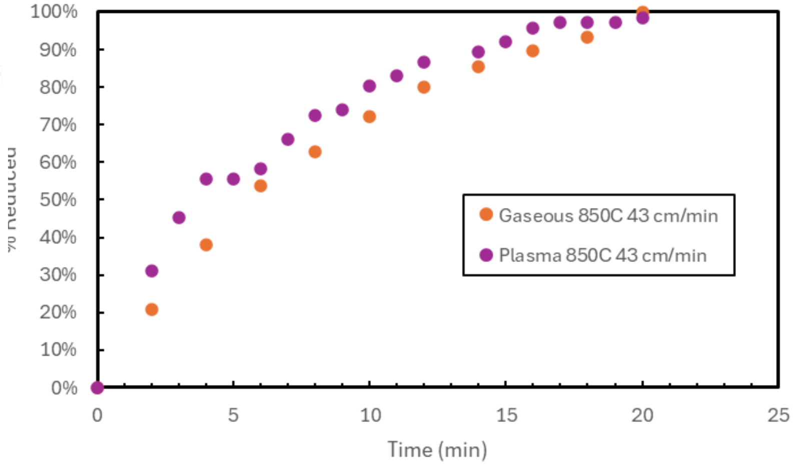
H_2 flow rate: 500 L/min (99.99%)
Pellet feed rate: 21 kg/h
H_2 started at 20kg/hr. product feed

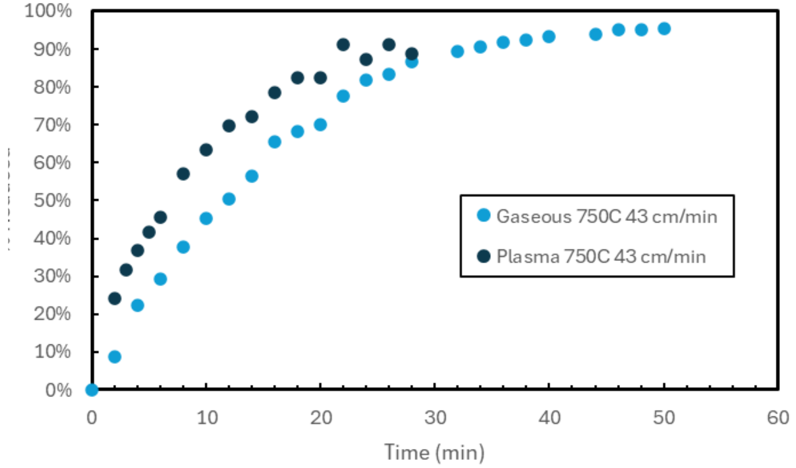
Top (°C)	Middle (°C)	Bottom (°C)	Gas inlet (°C)
300	300	800	340

Hematite Pellet Reduction with Hydrogen Plasma



1. Bottom graphite electrode and graphite pedestal
2. Top hollow graphite electrode
3. MgO/Al203 lined graphite crucible
4. Mullite tile lid
5. MgO Castable safety lining
6. Rubber seal
7. Steel Shell
8. Iron ore pellet suspended by wire, and internal thermocouple location (not pictured)
9. Load cell on lever arm
10. Stainless steel bellows
11. Copper electrode holders
12. Gas inlet
13. Off Gas
14. Pilot light and pilot light sensor
15. Electrical isolator
16. Electrode Z axis movement
17. Purge gas for sample port

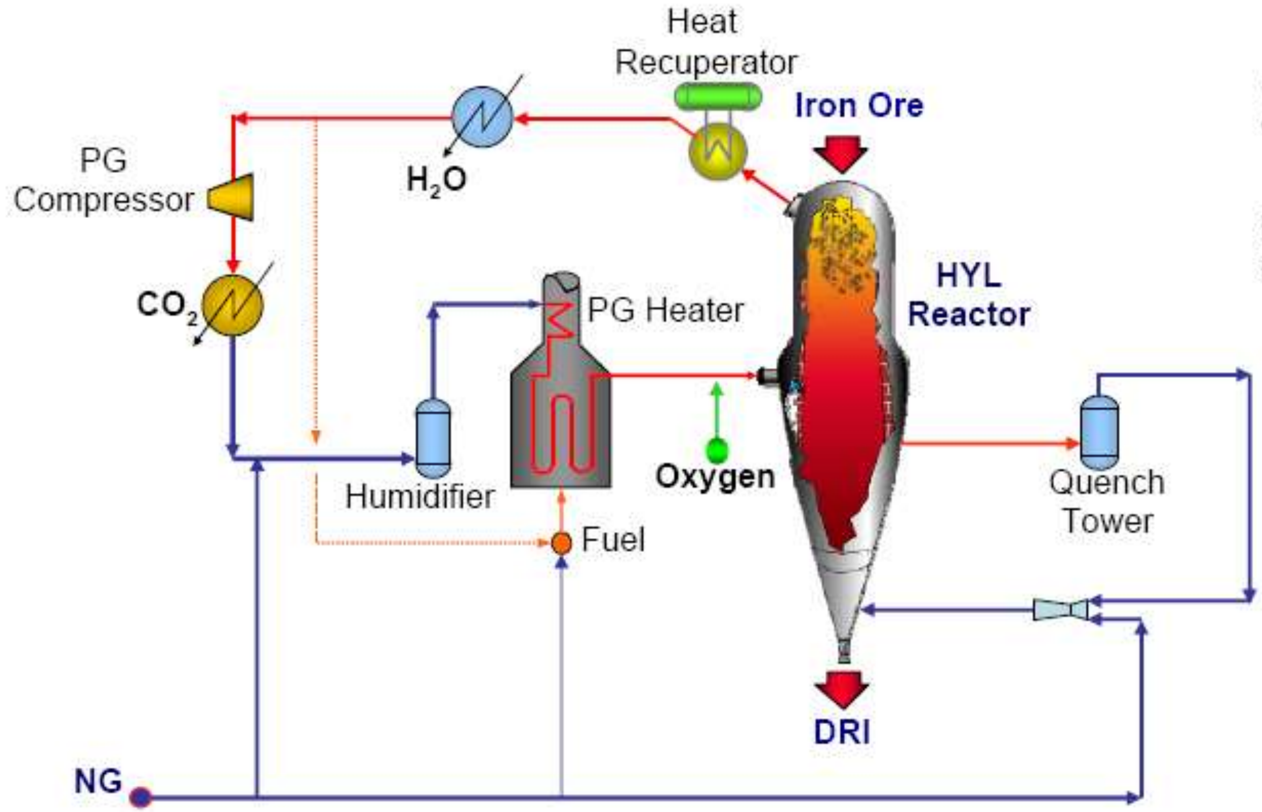




- Milestone 2.6: Oxide Reduction >80%
  - At both 750C and 850C, oxides reduction of >90% was achieved
- Milestone 2.8: Reduction Kinetics Enhanced >20%
  - Kinetic enhancement evident at 750C and 850C
  - At 750C, plasma reduction was ~33% faster

Commercial Direct Reduced Iron (DRI) Production

Danieli ENERGION ZR® Process (Operated by Nucor)



In-situ Reforming

$CH_4 + H_2O \rightarrow CO + 3H_2$

$CH_4 + CO_2 \rightarrow 2CO + 2H_2$

Reduction

$Fe_2O_3 + 3CO \rightarrow 2Fe^{\circ} + 3CO_2$

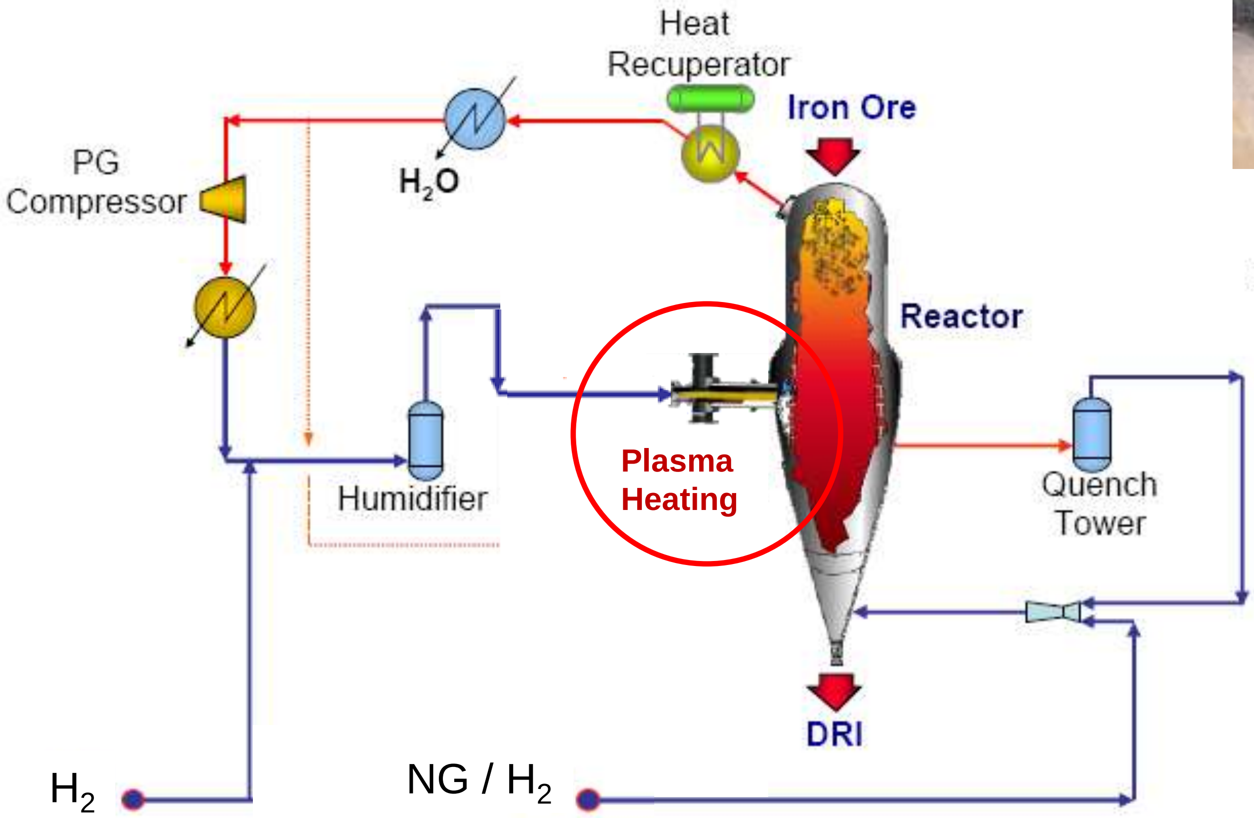
$Fe_2O_3 + 3H_2 \rightarrow 2Fe^{\circ} + 3H_2O$

Carburization

$3Fe^{\circ} + CH_4 \rightarrow Fe_3C + 2H_2$

ENERGIRON THE INNOVATIVE DIRECT REDUCTION TECHNOLOGY

Concept: Plasma Heated H_2 - DRI Production



Reduction

$Fe_2O_3 + 3H_2 \longrightarrow 2Fe^{\circ} + 3H_2O$

Carburization

$3Fe^{\circ} + CH_4 \longrightarrow Fe_3C + 2H_2$

Combustion Heating Superalloy Tube Bundles - 800-1000 C

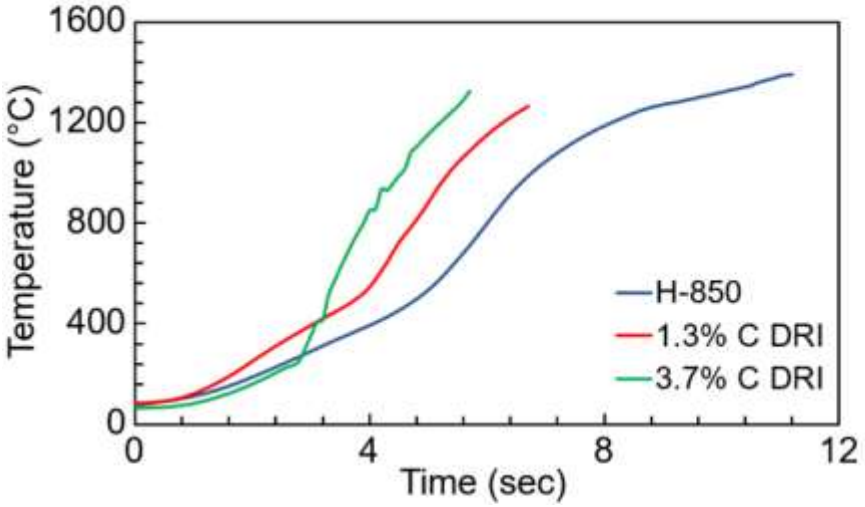
H_2 Dissociation / Ionization Provides:

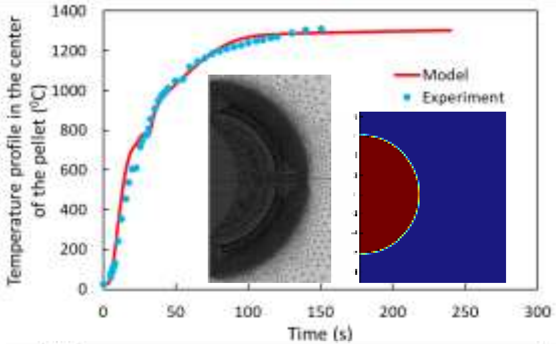
- Enhanced reduction kinetics
- Enhanced enthalpy transport
- Electrified heating
- Elimination of costly combustion heat exchanger system

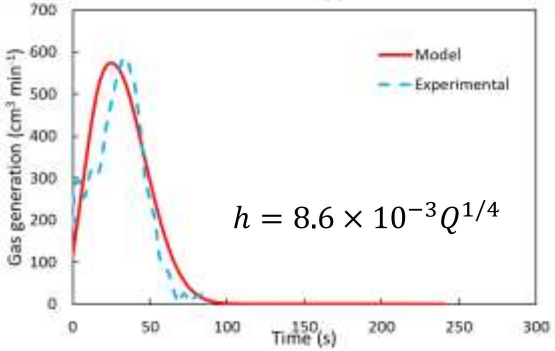
DRI Melting – Effects of Carbon Content on Melting Rate

	Nucor DRI	Voest DRI	Voest HBI
Fe Total	90.9	90.2	91.1
Fe Metallic	85.6	87.1	83.8
% Metallization	94.1	96.6	92.0
% Total Carbon	3.7	1.3	1.3
Leco % C*	2.7	1.8	0.7
% Graphitic C	0.15	-	-
% P	0.02	0.04	0.04
% S		0.003	0.003
Leco % S*	0.005	0.001	0.000
% Gangue	4.6	5.28	5.26
SiO2	2.21	3.37	3.23
CaO	1.36	0.9	1.01
Al2O3	0.54	0.38	0.39
MgO	0.35	0.63	0.63
Na2O	0.03	-	-
TiO	0.11	-	-

$$FeO_{(s)} + C_{(s)} \rightarrow Fe_{(s)} + CO_{(g)}$$

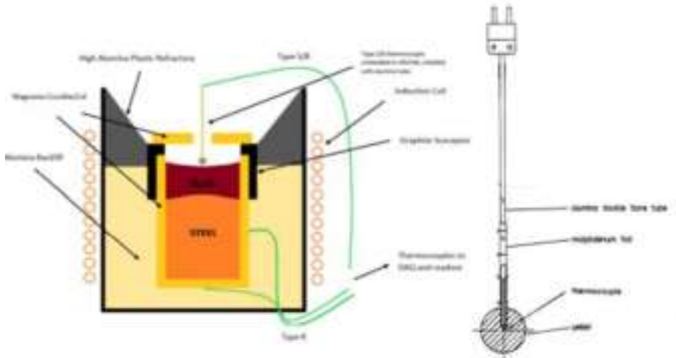




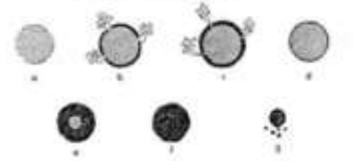


DRI Melting

Laboratory DRI Melting Studies



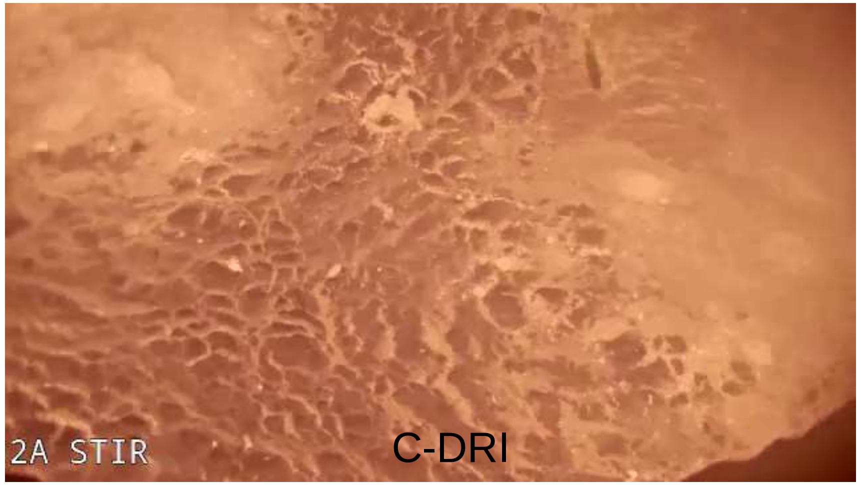
Complex Melting Behavior in Slag-Metal Environment of the EAF

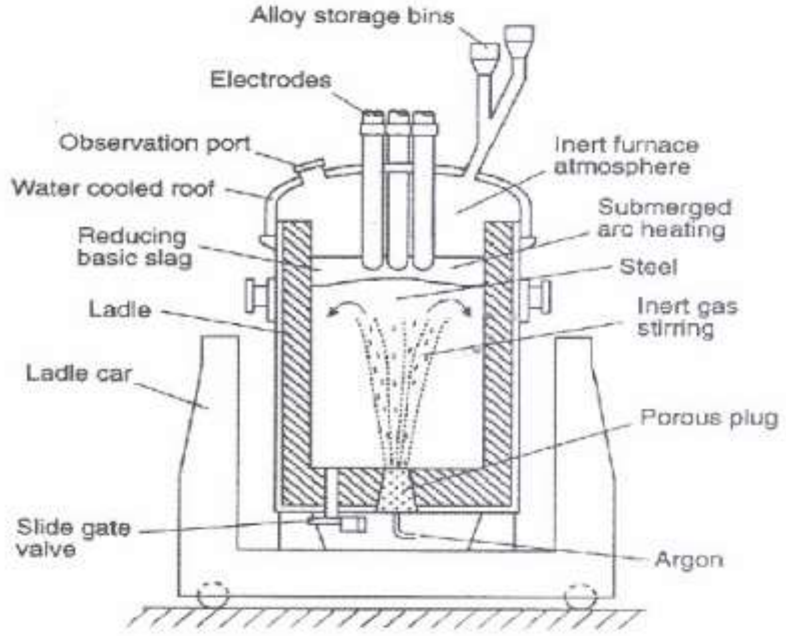


Plant DRI Melting Trials

Plant Trials with HBI

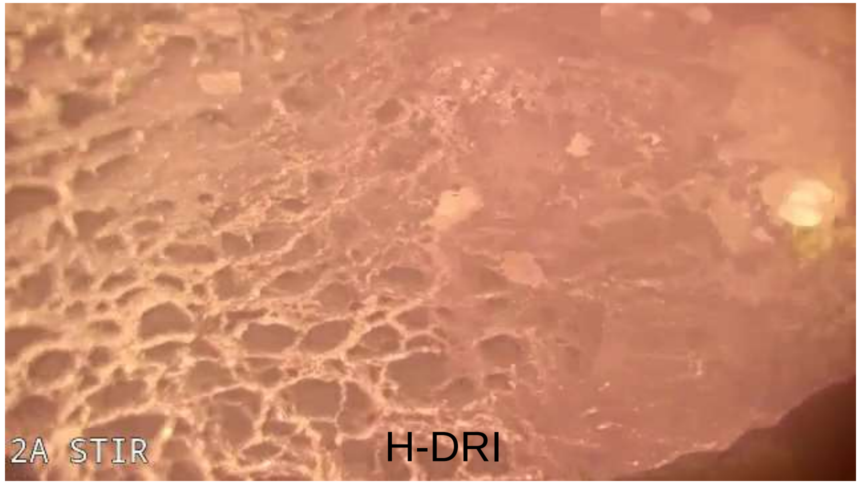
EAF melting studies with *production high & Low C HBI* to evaluate melting behavior and yield.





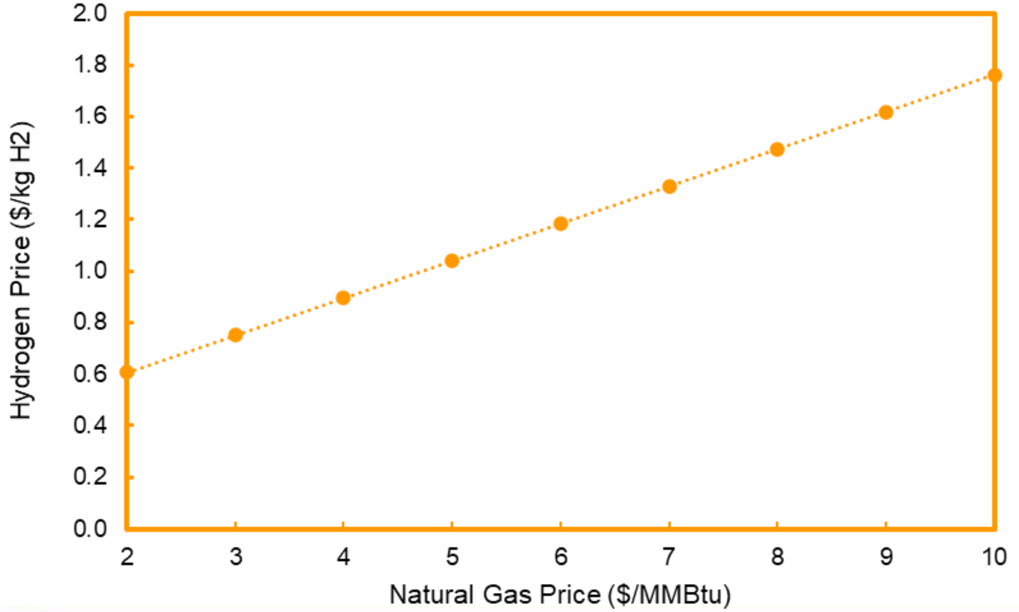
Ladle Furnace Trials with H2DRI

Use as a proxy for EAF melting studies with *pilot produced quantities of H2DRI and Commercial DRI* to evaluate melting behavior and yield.



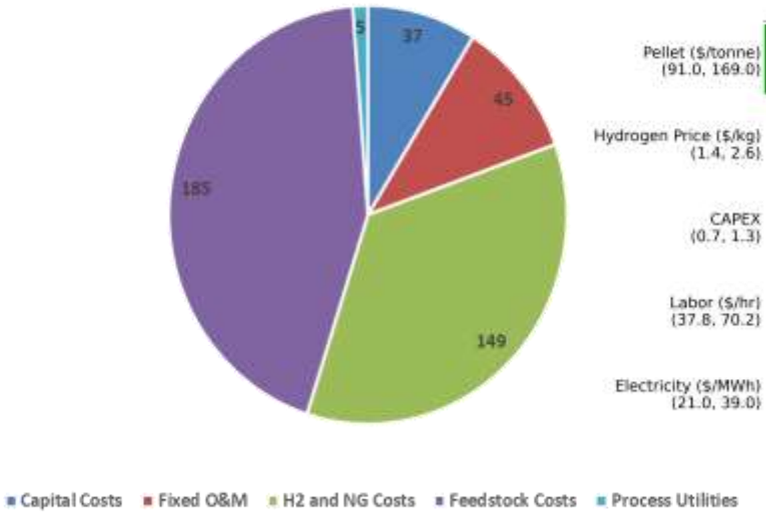
TEA - Cost-Competitive with100% H_2 DRI

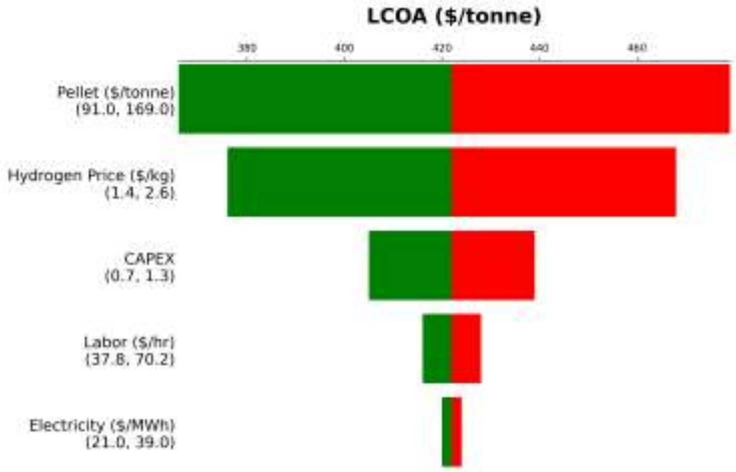
Hydrogen Gas Break Even Prices as a Function of Natural gas Prices



- Hydrogen prices are varied as a function of natural gas prices to identify when DRI production costs are identical
- Historical Henry Hub gas prices indicate that break-even hydrogen prices range from 0.6$/kg H_2 to 1.47 $/kg H_2 @ 2-8 $/MMBtu natural gas

422 $/tonne DRI for H2-DRI





EPIXC

EPIXC, or Electrified Processes for Industry without Carbon, is DOE’s seventh Clean Energy Manufacturing Innovation Institute.

epixc.org

- EPIXC is a public private partnership with over 100 member companies
- Our federal budget is $70M/5year from IEDO
- EPIXC aims to electrify manufacturing processes
- EPIXC will advance education and workforce development (EWD) to train at least 3000 individual jobs over five years

CEO: Sridhar Seetharaman

Lead University: Arizona State University

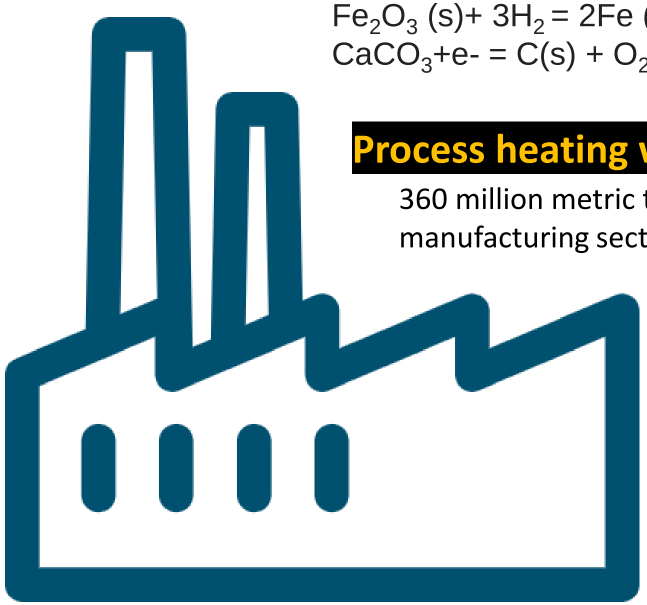
The Scale of the Problem

- The industrial sector accounted for 30% of energy-related carbon dioxide emissions in the U.S. in 2020. [1]
- Worldwide this is about 10% if ALL GHG Emissions

Non-carbothermic reactions

Fe_2O_3 (s)+ $3H_2$ = 2Fe (s,l)+ $3H_2O$ (g)
$CaCO_3$+e- = C(s) + O_2 (g) +CaO

Green power and its accessibility



Process heating with electric heating or low-carbon fuels

360 million metric tons of CO_2e GHG emissions, representing 31% of the manufacturing sector's total energy-related emissions

Carbon capture and utilization

Energy efficiency

1. https://www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap

Vision and Mission

- EPIXC's vision - Electric heating is economical and supports manufacturing decarbonization everywhere for everyone.
- The EPIXC mission is to develop and scale innovative electric heating concepts for advanced manufacturing.

Our Core Partners

Stanford University

Tuskegee University

Missouri S&T

Texas A&M University

The University of Texas at Austin

Arizona State University

U.S. Department of Energy – Energy Efficiency & Renewable Energy

Navajo Technical University

NC State University

Penn State

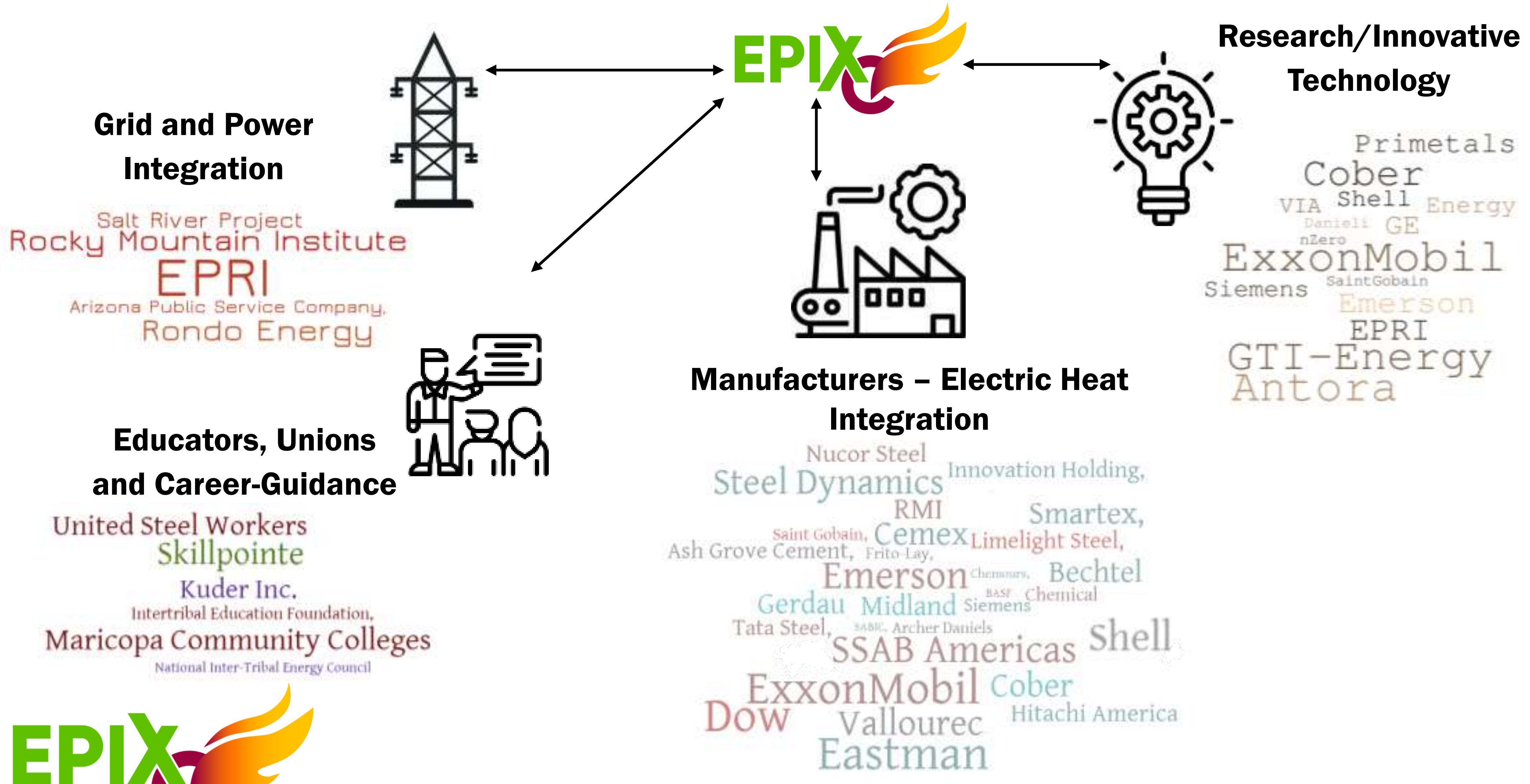
National Energy Technology Laboratory

NREL – Transforming Energy

Idaho National Laboratory

EPIXC

EPIXC Engages the Industrial Supply Chain

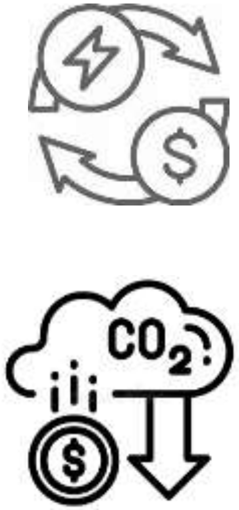


Complexity of the Transition towards Electrification

New Grid Mixes

Electricity producers

New Markets

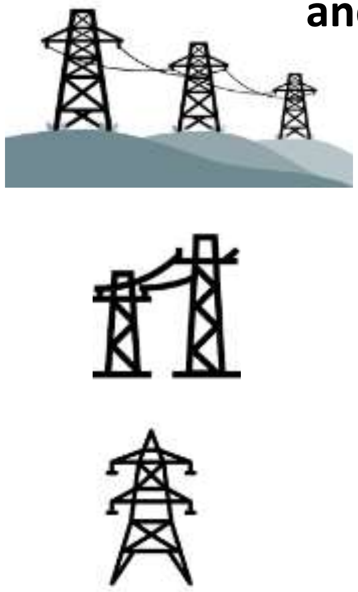


Electricity trading

Carbon markets

When and where does it become economical?

New Capacities, Connections and Flows



National grid(s)

Regional grids

Microgrids

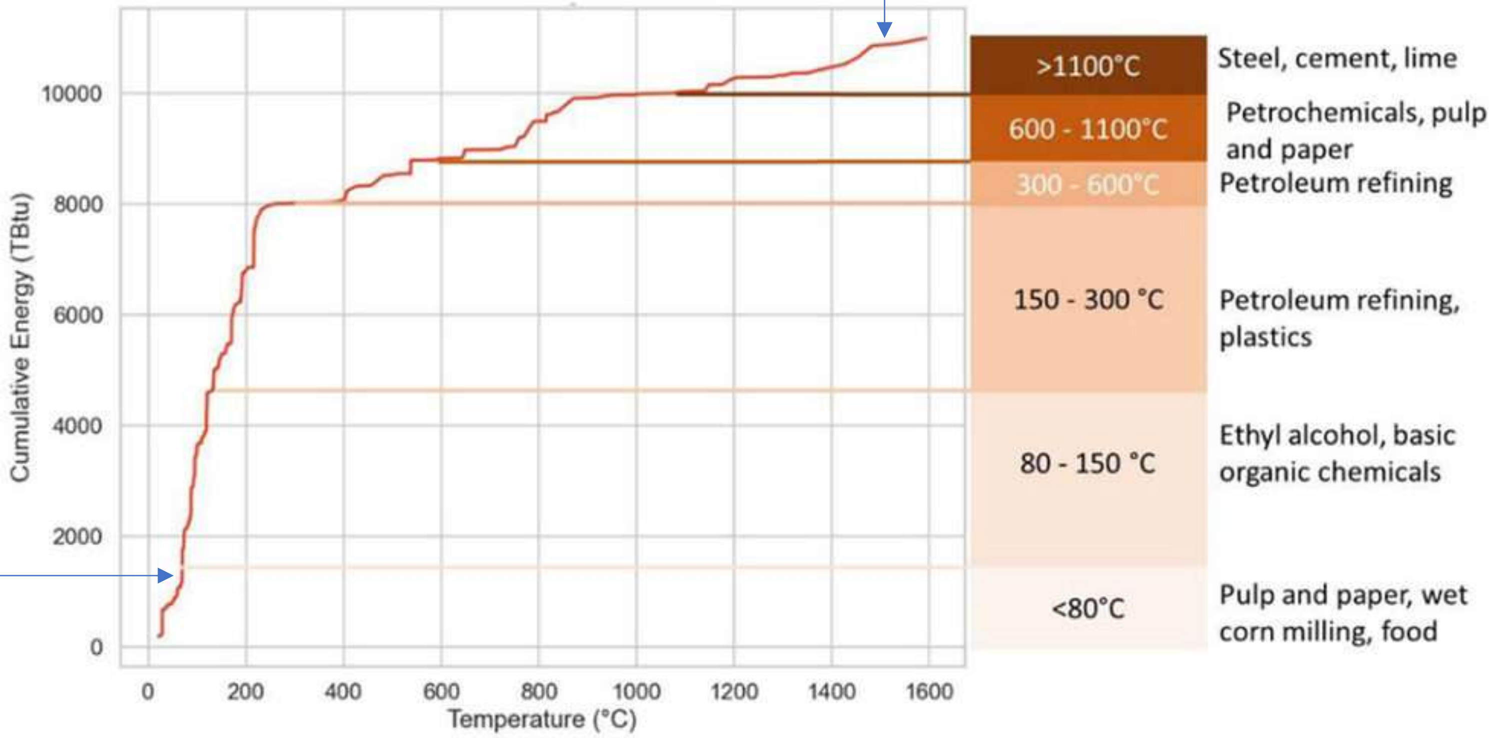
Electricity users

Increased demand and flexibility

Targeted sectors

Challenging, but single plant may yield high impact ?

High Impact if you demonstrate at narrow temperature range. Less capital cost and modular?

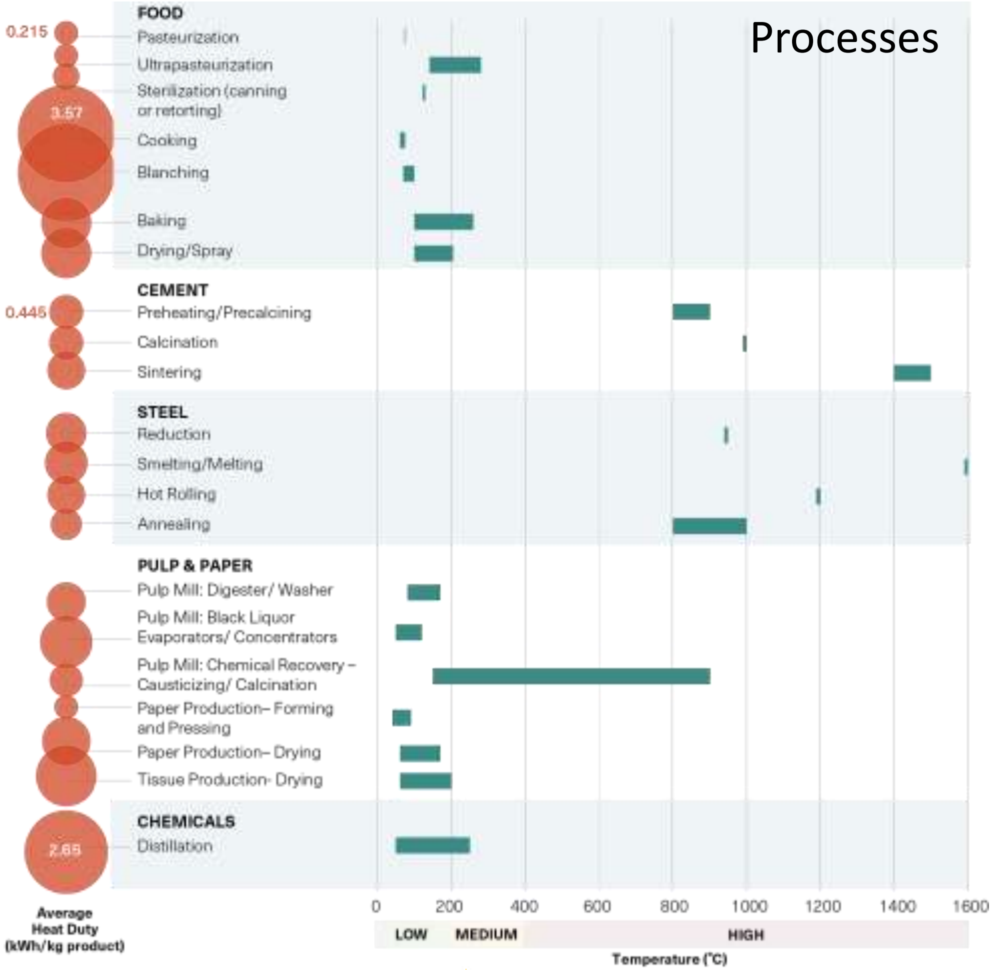


Akar, Sertaç, Parthiv Kurup, Matthew Boyd, Elizabeth Wachs, and Colin McMillan. 2023. *Renewable Thermal Energy Systems: Modeling Developments and Future Directions (Report 3).* Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-83021. https://www.nrel.gov/docs/fy23osti/83021.pdf.

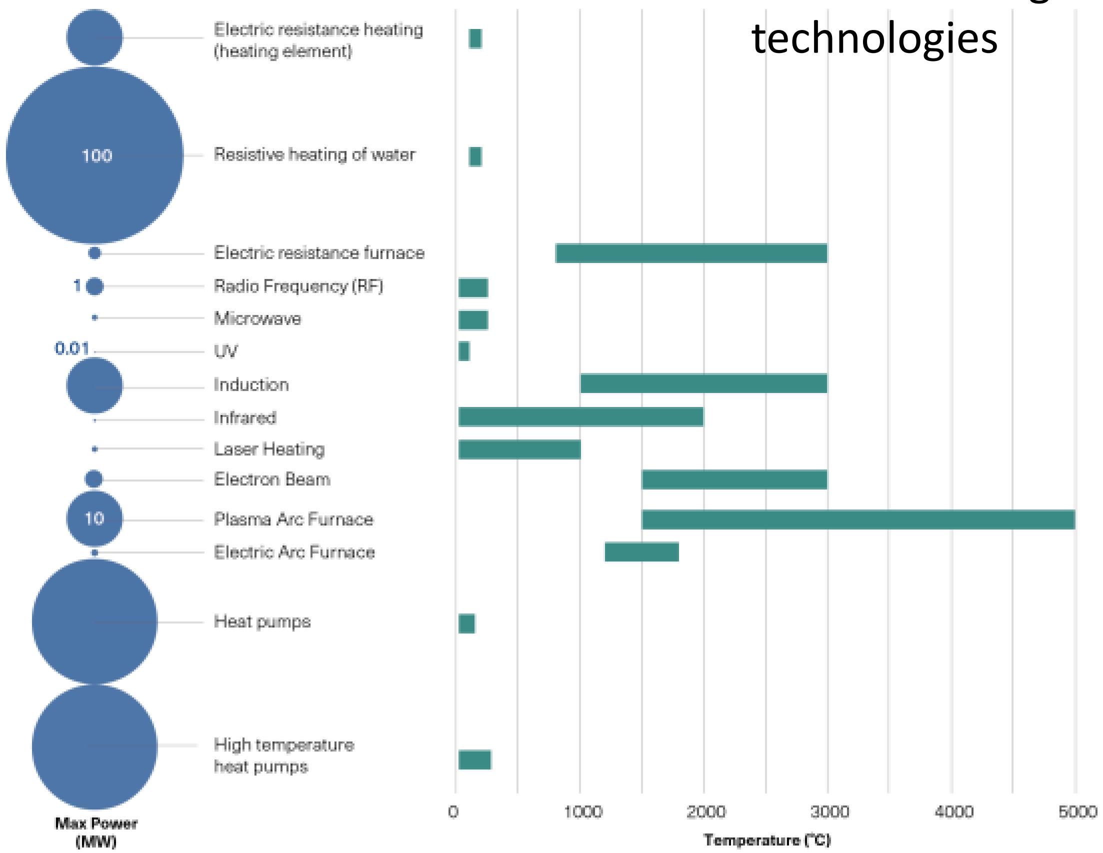
EPIXC

From our roadmap

Processes



Electric heating technologies



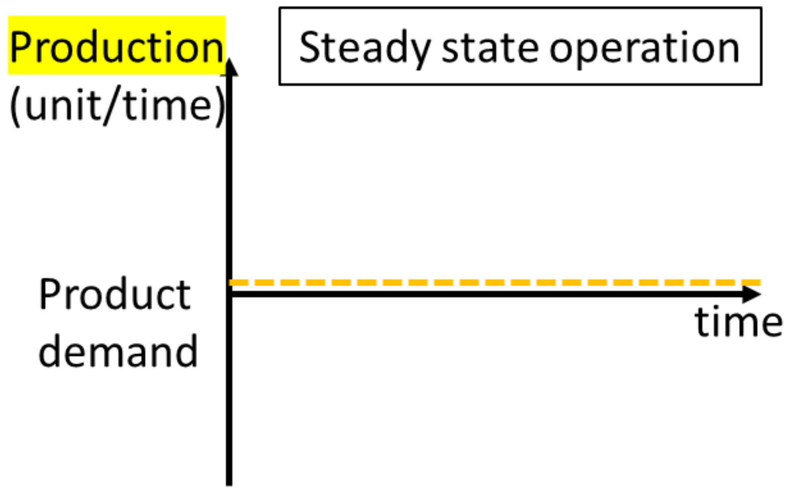
Steam generation: Latent heat to vaporize 2260 kJ/kg

Steel smelting: Latent heat to melt steel 300 kJ/kg

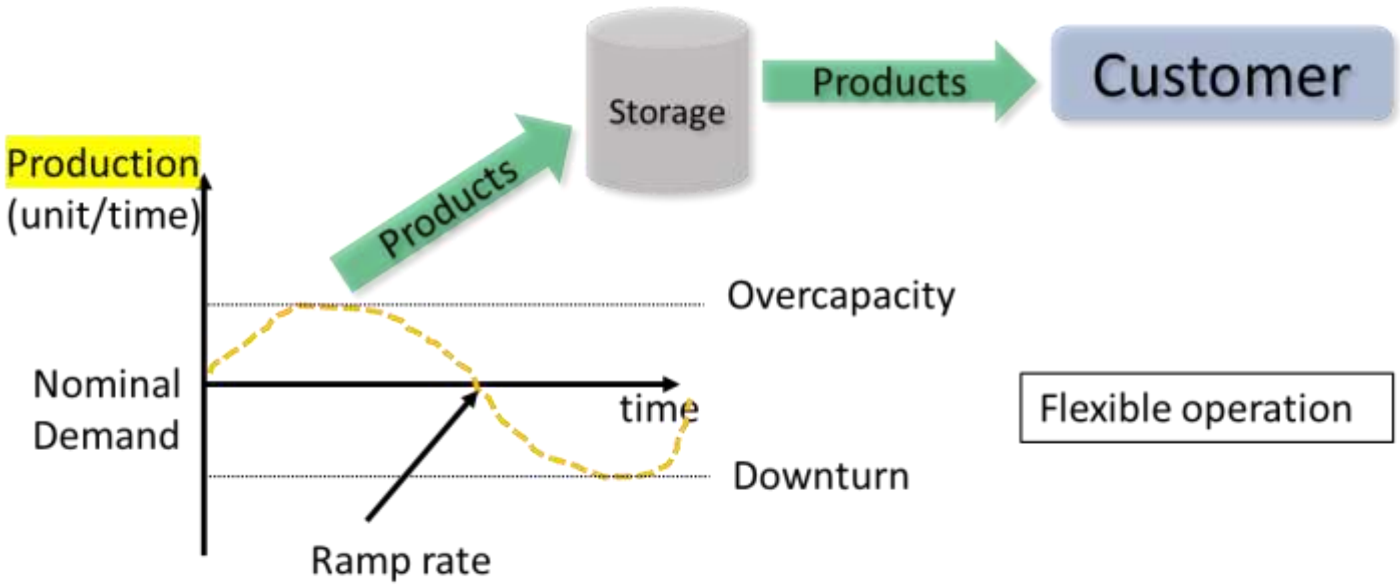
EPIX

Example of Research Questions – Grid Integration

Industrial Flexibility?



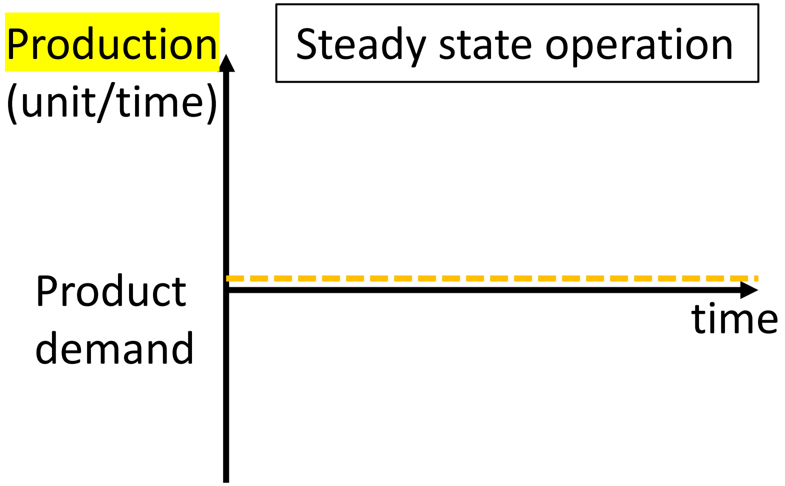
Requires energy storage or hybrid technology



Requires product storage and excess production capacity

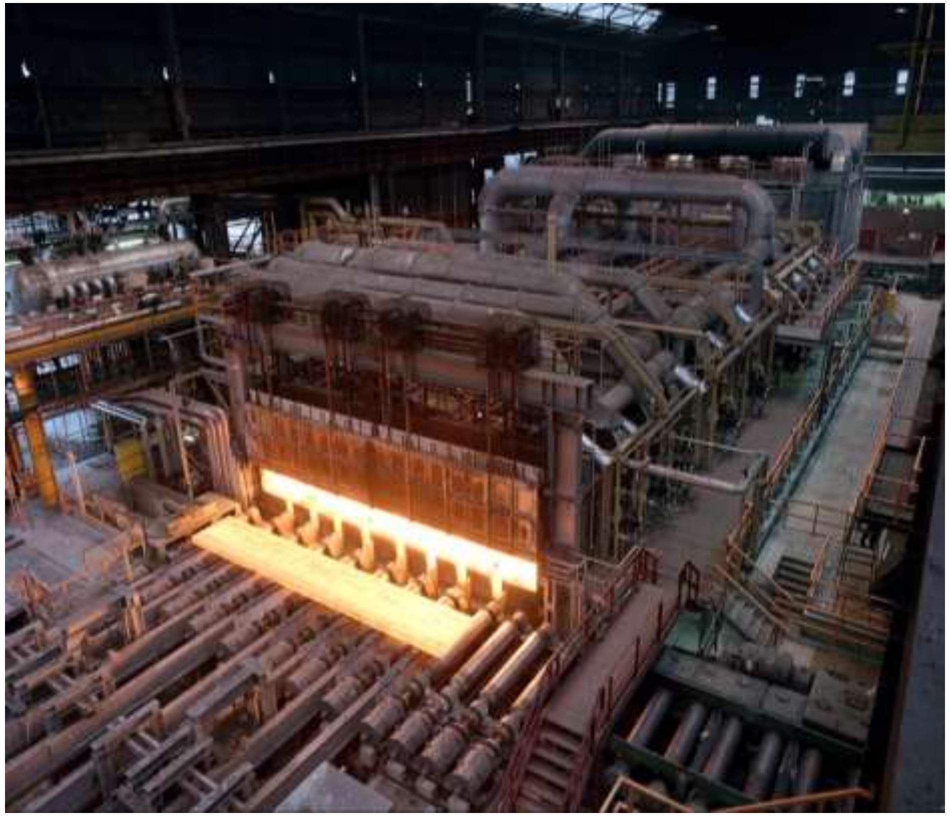
Example: Variable Operation Costs

Technical solution ?



Electrified
Thermal
Solutions

Example: Slab Reheating in Steelmaking



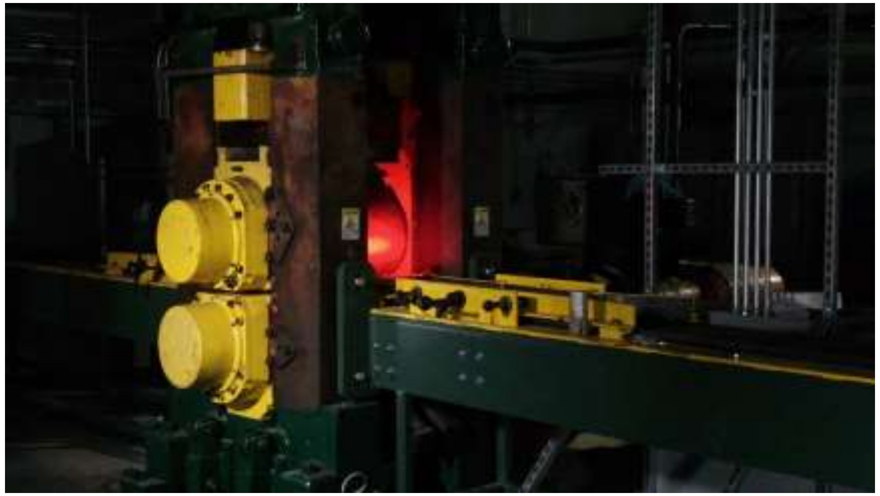
Walking Beam Furnace

Tunnel Furnace

Reheating with natural gas or process off-gasses
1100 - 1300 C

Example: EPIXC Steel Electrification Testbed

Supply-chain, techno-economic- and Life Cycle Analysis

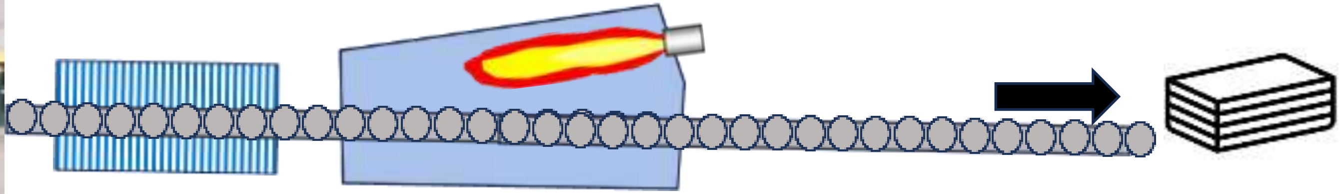


Existing Pilot Rolling Mill at Missouri S&T

Raw Material Constraints ?

14” wide Pilot Hot Rolling Mill

Electrified Heating & Cooling Testbeds



Controlled Cooling

Plasma, Induction Heating

Product Quality?

Pilot Testbed Space

Atmospheric Pressure Microwave Plasma Heating

Loss of recovered heat?

Clean power availability?

Our vision !

Demonstrate that Electric heating is economical and supports manufacturing everywhere for everyone.

Questions?