CHANGING WHAT'S POSSIBLE

Zero-Emissions Ironmaking & Sustainable Steel

Technology-to-Market Introduction

Workshop Day 2 Overview

Patrick Finch, T2M Advisor (BAH)

Sept. 1, 2021

Built on DARPA foundation, but with key differences…

What people sometimes think T2M is…

Idea

Research

Break-through

New products

Secure future

Fame, Fortune

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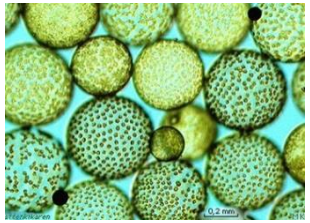
…But realizing the full potential of a technology is a more complex process

Technology	First market	Intermediate Markets	Market disrupted
Li-Ion Batteries 	 Long lived, energy dense cells	 Long lived, energy dense, rechargeable	 Long lived, energy dense, rechargeable, cost-effective
Photovoltaics 			
		Decreasing cost →	
Algae Fuels 	 Nutrition supplements, pharmaceuticals	 	Commodity fuels? 

Tech-To-Market Approach

Scope

Provide strategic market insights necessary to create innovative, commercially-relevant programs

Manage

Manage project teams' T2M efforts through T2M plans and jointly developed milestones

Advise

Support project teams with skills & knowledge to align technology with market needs

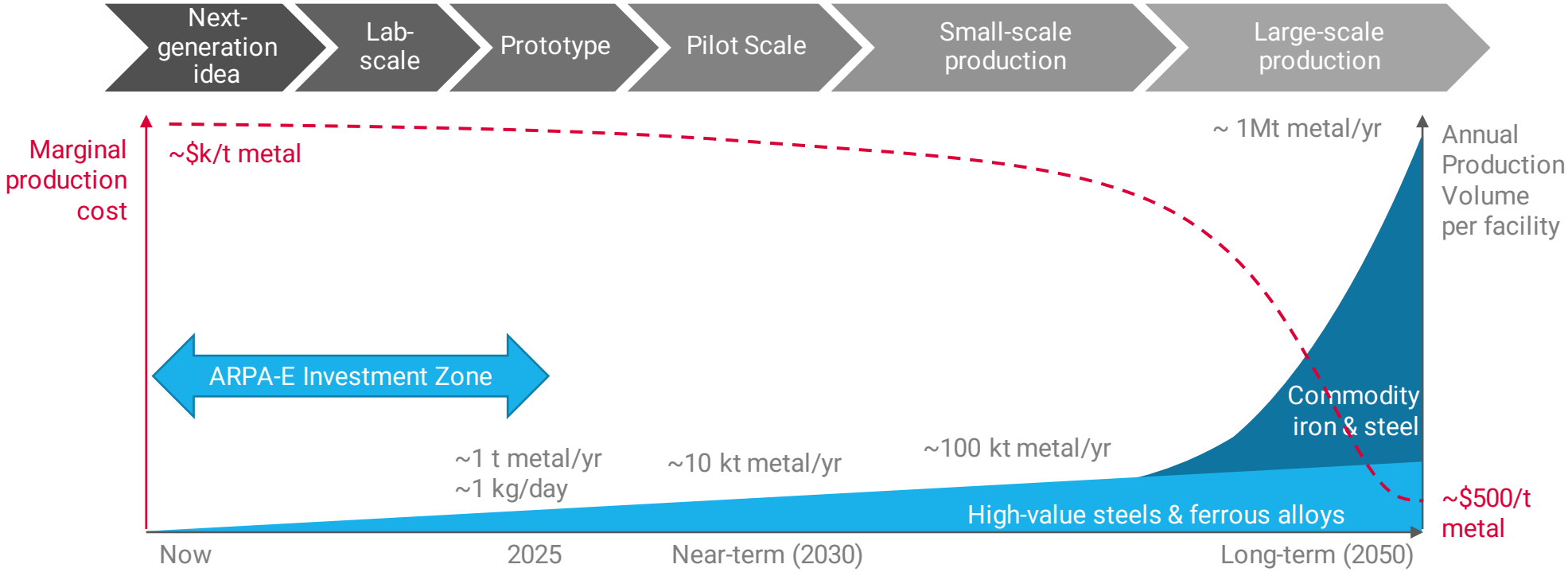
Partner

Engage third-party investors and partners to support technology development towards the market

Catalyzing zero-emissions ironmaking in the U.S.

Ironmaking Processes to De-risk (examples)

- Zero-emissions reductants (H_2, CO, CH_3OH, biomass +)
- Low-T and High-T direct ore electrolysis to iron
- H_2 plasma reduction
- Electric heating via induction, resistive, arc



Potential Near-Term Products

- Higher purity iron without additional processing
- Electrical steels, amorphous iron
- Stainless steels, high-performance steels
- Direct ore-to-powder process for Additive Mfg
- Ores, alloys that are impossible today

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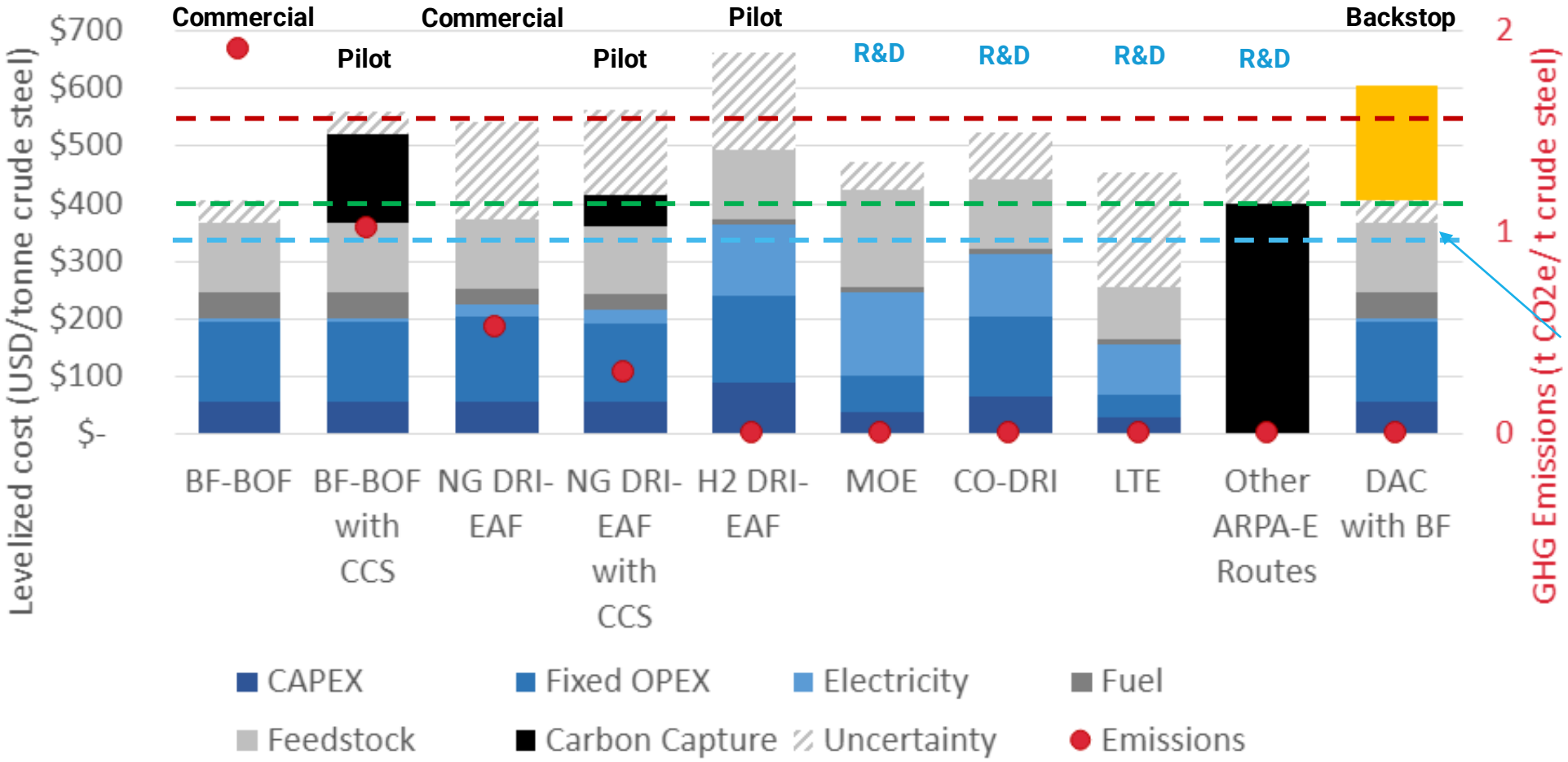
As steel is a commodity market, cost is a critical factor for long-term program success

Many new approaches are within the cost error margin for Blast Furnace + CCS costs... fewer are for Blast Furnace with no CCS



- **Upfront capex** may actually be a larger barrier to entry for new technology in this space…
- **Should we aim higher?** Is parity with BF-BOF O&M costs necessary to move the needle?

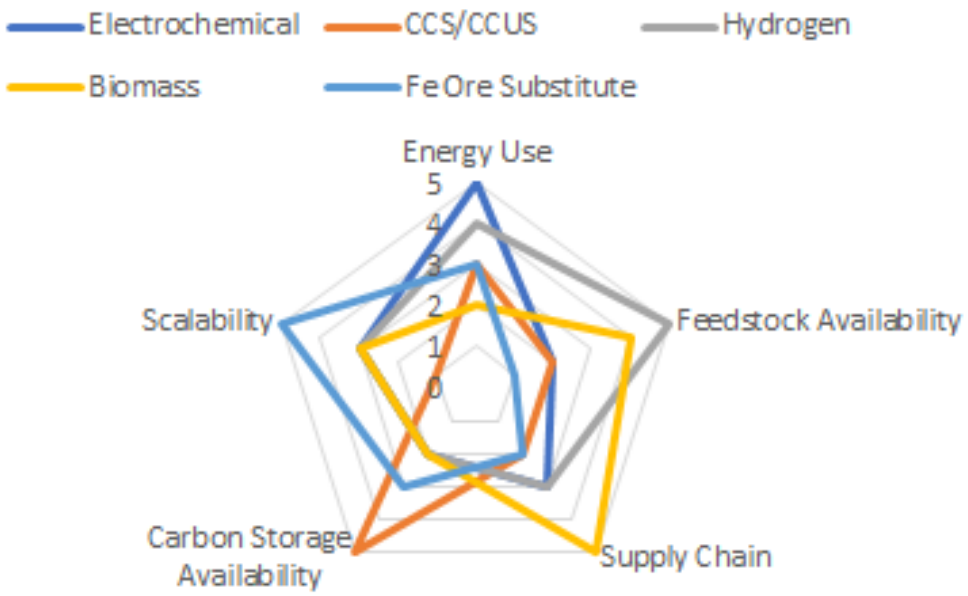
As cost is impacted by a range of risk drivers, research should be targeted at mitigating specific risks for each technology

- Risk varies by ironmaking approach
- Competitiveness of these technologies is dependent on:
  - Location
  - Supply chain
  - Geography
  - Regional demand (product stream)
- Working hypothesis: "All of the above" portfolio
  - May be required to meet global demand
  - Different T2M strategies for each approach

Can we move each of these approaches closer to the middle?

Illustrative

Cost & Risk Drivers for Zero-Emissions Ironmaking Technologies



Industrial and Customer Commitments are driving demand for "Green" Steel

- **Does this give us headspace to sell initial products at a "Green Premium?"**

Share of automotive producers with targets addressing value chain emissions
Based on units sold

Examples of targets set by companies

Toyota	Zero life cycle CO_2 emissions by 2050 materials included
SKANSKA	Net-zero carbon emissions by 2045, within the whole value chain
Vestas	Reduce supply chain emissions by 45% per MWh generated by 2030
Electrolux	Net-zero emissions by 2050, throughout the value chain

Source: Mission Possible Partnership, Steeling Demand: Mobilising buyers to bring net-zero steel to market before 2030, Steel Data Network 04 August 2021

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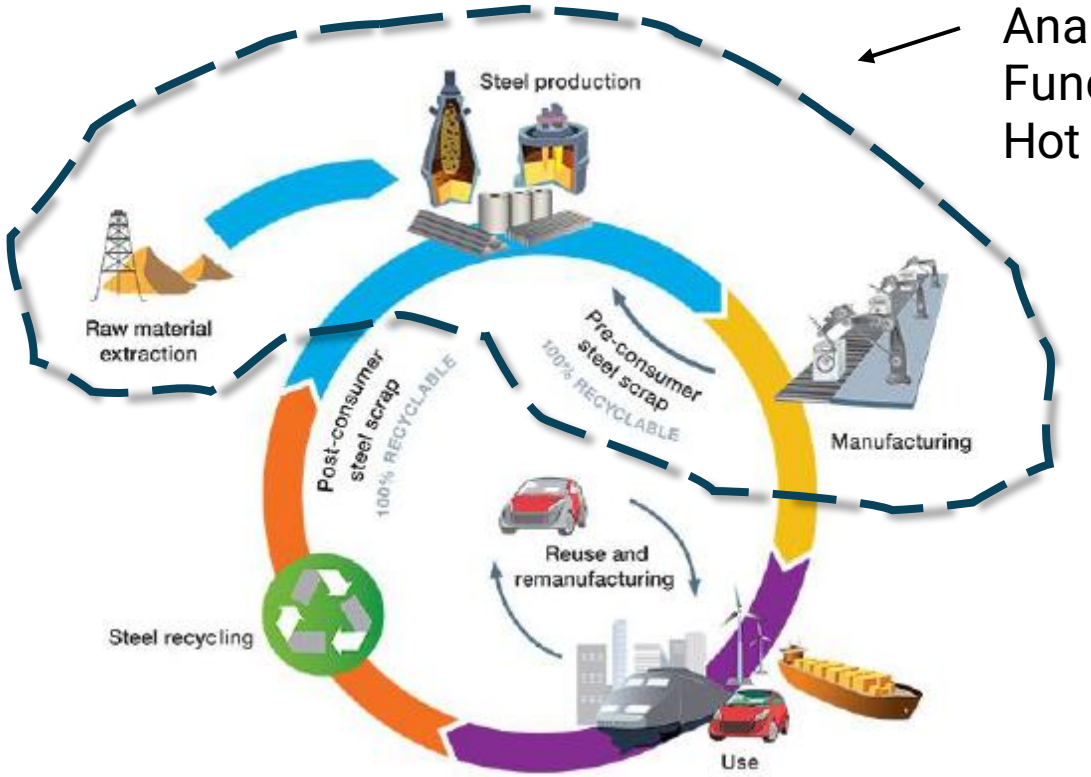
Steel Example: Define Analysis

Baseline Technology: Blast Furnace - Basic Oxygen Furnace (BF-BOF) both with and without CCS
New Technology: Low Temperature Electrolysis (LTE) with ARPA-E efficiency goals

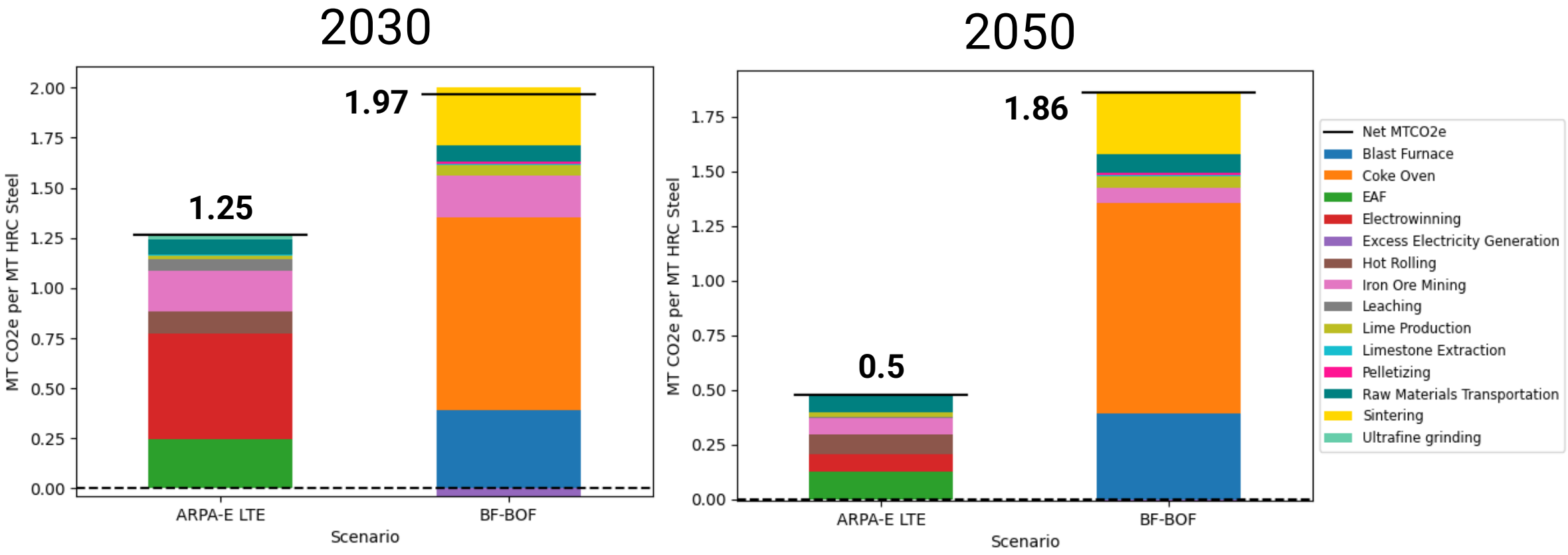


Worldsteel, 2015

Analysis Boundary
Functional Unit (end product) = 1MT
Hot Rolled Coil Steel

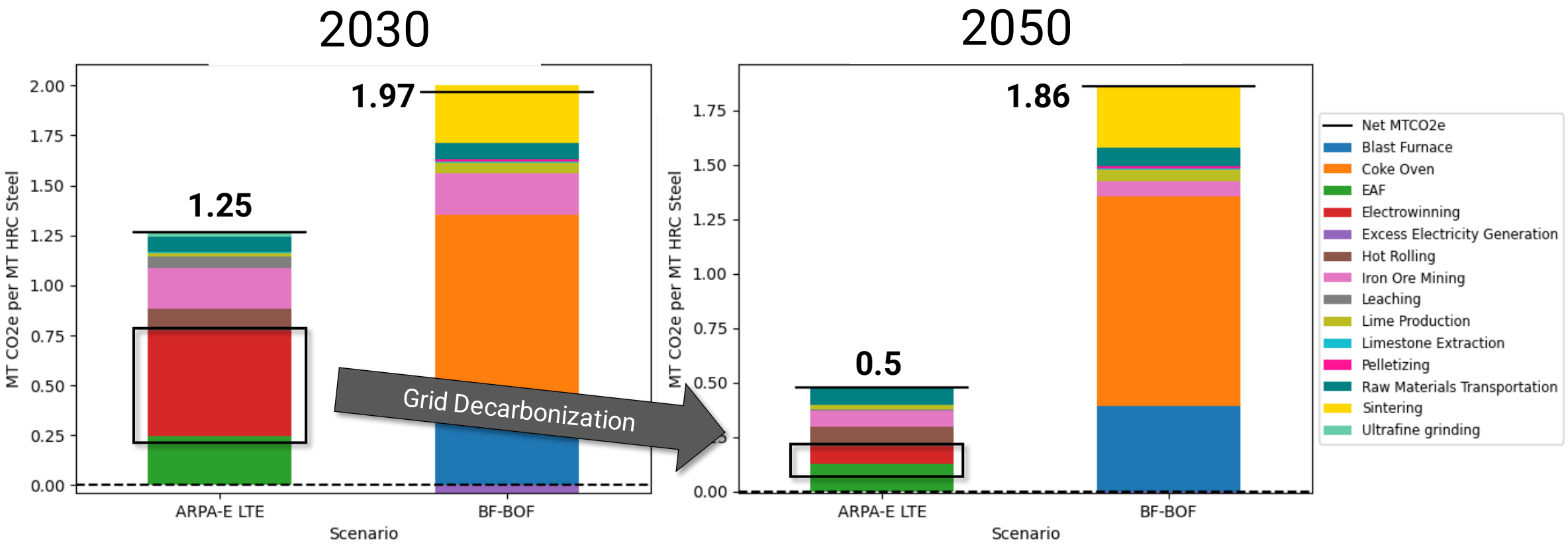
HGB Industrial

LTE Example: Review Outputs, Emissions by Stage



Process diagram adapted from SIDERWIN D7.4 Environmental life cycle assessment final report, https://www.siderwin-spire.eu/content/deliverables

LTE Example: Review Outputs, Emissions by Stage



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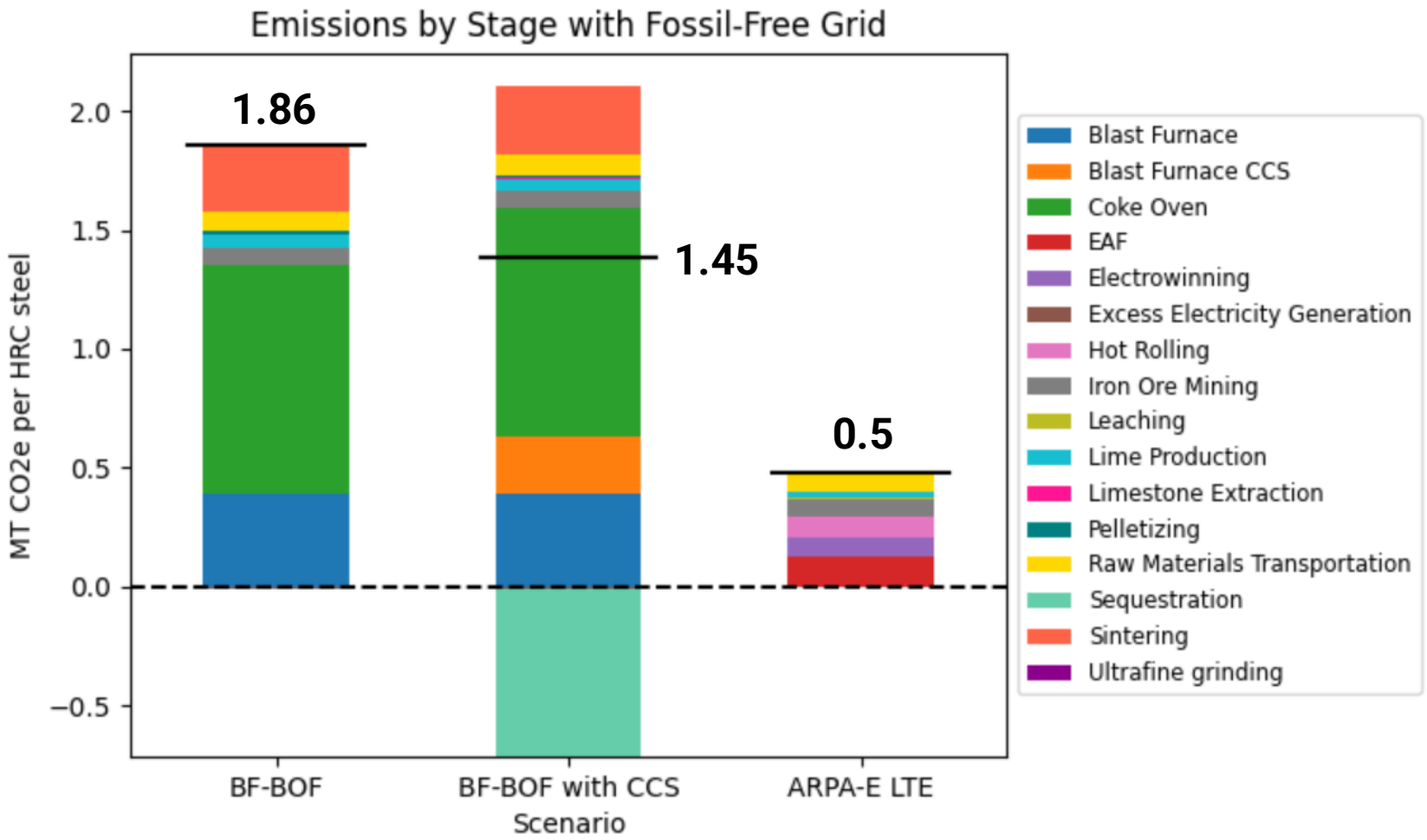
Comparing Three Steel Pathways – LTE v BOF-CCS

2050

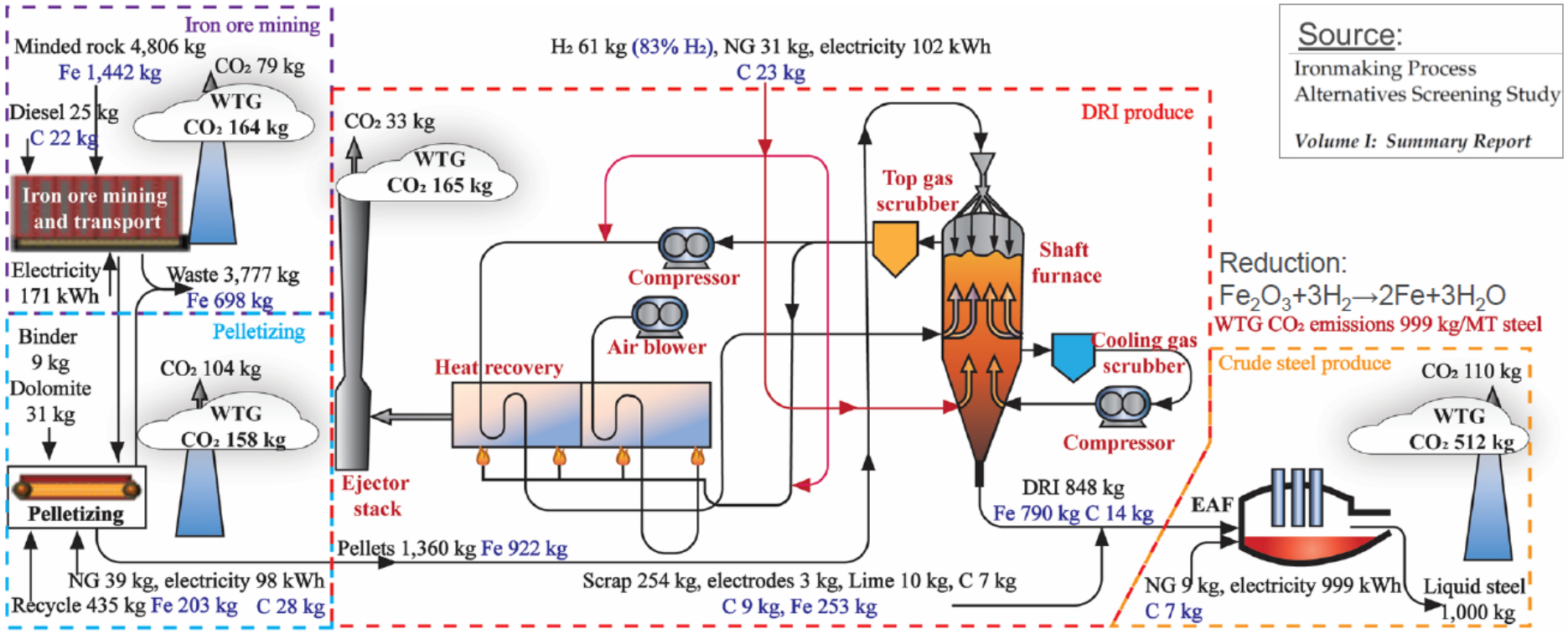


Process diagram adapted from SIDERWIN D7.4 Environmental life cycle assessment final report, https://www.siderwin-spire.eu/content/deliverables

Process and Data Considered

Accomplishments

MIDREX_EAF_H_2 mass and energy balance (with 25% scrap to EAF)



Source:
Ironmaking Process Alternatives Screening Study
Volume I: Summary Report

Reduction:
$Fe_2O_3+3H_2 \rightarrow 2Fe+3H_2O$
WTG CO_2 emissions 999 kg/MT steel

DRI-direct reduced iron https://doi.org/10.1002/srin.202000110 MT-metric ton

- 100% MIDREX-EAF is rebalanced by using information for EAF process to represent the same feedstock as BF-BOF (75% iron ore: 25% scrap)
- NG is the common feedstock, but renewable H_2 can be used to reduce CO_2 emissions

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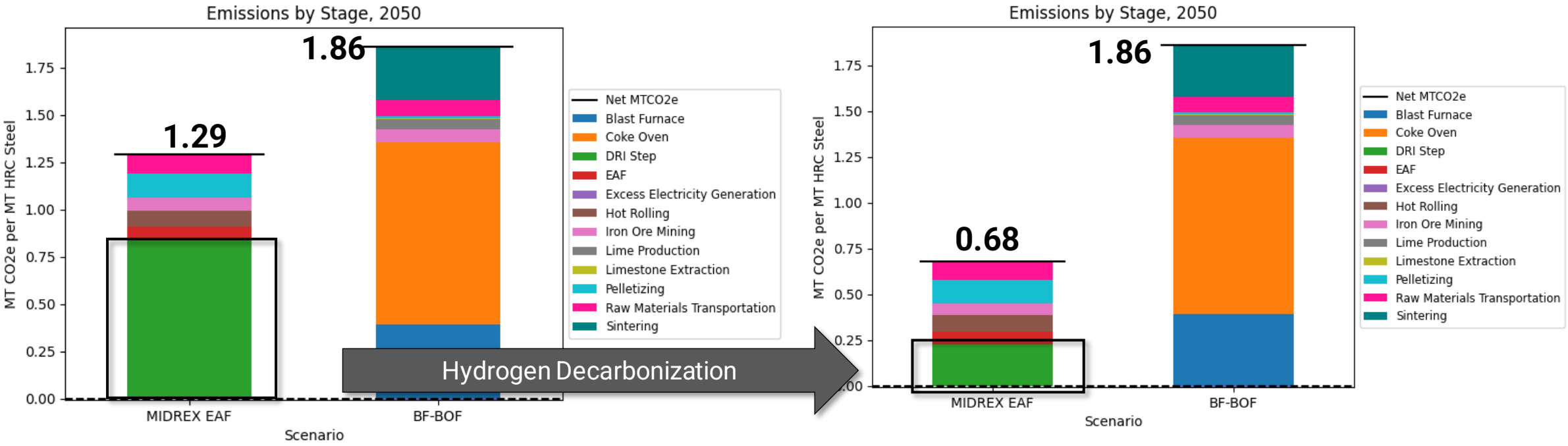
Example Two: EAF Grey v. Green Hydrogen



Two different cases were considered for the MIDREX technology (as shown on slide 13 of the "2021 DOE Hydrogen and Fuel Cells Program Annual Merit Review, Technoeconomic and Life Cycle Analysis of Synthetic Fuels and Steelmaking" presentation given by Amgad Elgowainy on June 8, 2021

Grey H_2 (NG primary feedstock for H2, 93% renewable grid by 2050)

Green H_2 (mix of solar and wind H2, w/93% renewable grid by 2050)

We are evaluating a Portfolio of Tech-to-Market Approaches

- Building on ARPA-E METALS lessons, testing to specifications must be incorporated throughout R&D with clear value proposition and market fit

Funding, partners, buyers
for follow-on R&D and pilot

Government & Industrial Partners

- Large U.S. Steel Incumbents
- Department of Energy Program Offices
- ARPA-E SCALEUP

Investor Partners

- Strong signal that patient capital is very interested in zero-emissions steel companies
- How can we get VC capital interested in this space? Through partnerships?

Customers

- Partner with midstream "clean" steel producers
- Partner with downstream buyers of zero-emissions steel

How do we differentiate products
in emerging steel landscape?

- Produce ~95% solid iron, sell to electric arc furnace companies who then make steel

- Sell Fe powders to additive manufacturing market

- Produce steel "mill products" at small annual scale (~1 Mt/yr)

The Workshop's 8 Breakout Sessions

US annual **steel demand** ~ 138 Mt

Domestic steel production

138 Mt steel — **0 process CO_2e**, < 3 quads (< 3% of US)

Legend:
- Tuesday Breakouts
- Wednesday Breakouts
- ARPA-E Breakout Facilitators
- External speakers

Dr. Doug Wicks, Prof. Brajendra Mishra


4 **Value Chain Innovation: Alternative Fe Sources**
e.g., fines, taconite, mixed ores…

Dr. Jack Lewnard, Dr. Vincent Chevrier


1 **Reduce Ore with Carbon**
CCUS, carbon looping, biomass, plastics, and beyond

Dr. Halle Cheeseman, Prof. Antoine Allanore


2 **Reduce Ore Electrochemically**
Ore electrolysis (disproportionation)

Prof. Zak Fang & Dr. Joe King, Dr. Martin Pei



3 **Reduce Ore with Hydrogen & Hydrogen Plasma**
Non-C renewable reductants, e.g. H_2 and H_2 Plasma

Dr. Peter de Bock, Prof. Chenn Zhou, Prof. Tyamo Okosun



5 **Process Intensification**
Decarbonized heating, reaction monitoring/modelling, AI/ML

Dr. Joe Marriott, Dr. Jack Lewnard

7 **Tracking Impact: CO_2e Emissions and Beyond**
LCA, GHG emissions tracking, waste, water, etc.

BOF or EAF → molten steel → casting, rolling, etc. → fabrication

integrated steelmaking

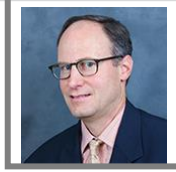

intensified steelmaking ("direct" to powder or part)

4 **Value Chain Innovation: Better & Emerging Products**
Powders & NNS, purer Fe, alloys, etc.

Cross-cutting: Dr. Doug Wicks & Dr. Peter de Bock

Cross-cutting: Dr. Vincent Chevrier & Dr. Katie Daehn

Dr. Joe King & Dr. Dave Tew, Dr. Katie Daehn




6 **Circular Economy**
Demand reduction, improving scrap, systemic material efficiency

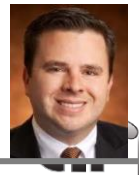
8 **Tech to Market**
Markets, metrics, partnering, investment, deployment, etc.

Patrick Finch, Prof. Mark Johnson, Traci Forrester, Ben Kowing, Pedro Prendes-Arias, Dr. Kevin Zeik, Dr. Dave Miracle









Acknowledgements – 80+ Outreach Conversations to Date

Industry

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AMES LABORATORY
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Metals Service Center Institute 100 YEARS STRONG
HATCH
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