A Vision for *Zero Emissions Ironmaking & Sustainable Steel*

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August 31, 2021

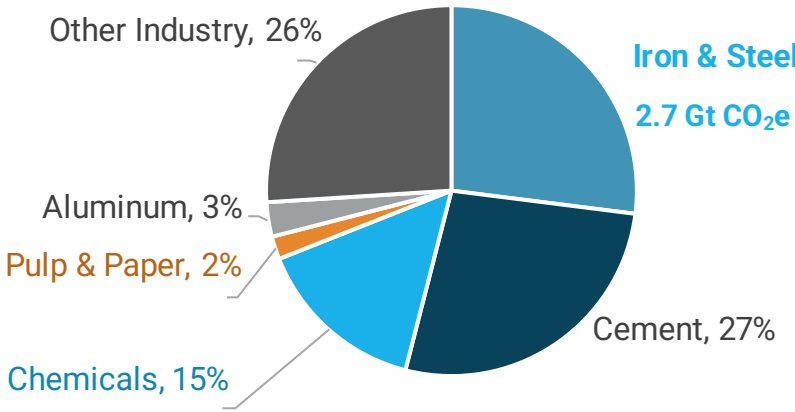
Meet our Workshop Mascot - “Ferri”

Executive Summary

Central Goal & Hypothesis

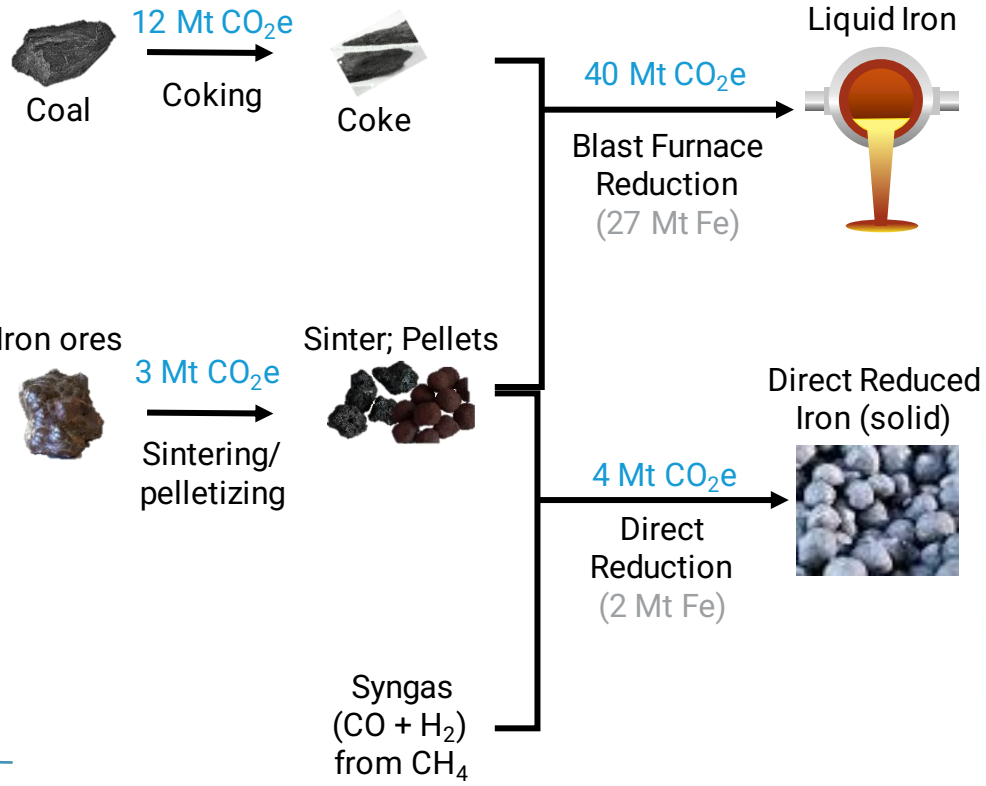
Zero-emissions ironmaking needs to ***occur as soon as possible*** and will require multiple technical approaches for ***rapid deployment***

Global Industrial Emissions (~10 Gt CO_2e)



Zooming into front of U.S. portion

U.S. Ironmaking Emissions



Next step

Are we crazy?!

DATA: National Bureau Of Economic Research, 2019; Center for Strategic and International Studies, 2020; Worldsteel, 2021; https://phys.org/news/2019-11-climate-impacts-world-trillion.html

Why ARPA-E?

Goal 1: To enhance the economic and energy security of the United States through the development of energy technologies that—

Goal 2: To ensure that the United States maintains a technological lead in developing and deploying advanced energy technologies.

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CHANGING WHAT'S POSSIBLE

The Team

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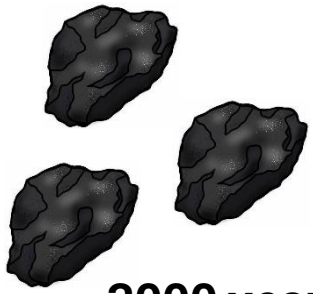
We want to learn from YOU!

Factors impacting vision direction

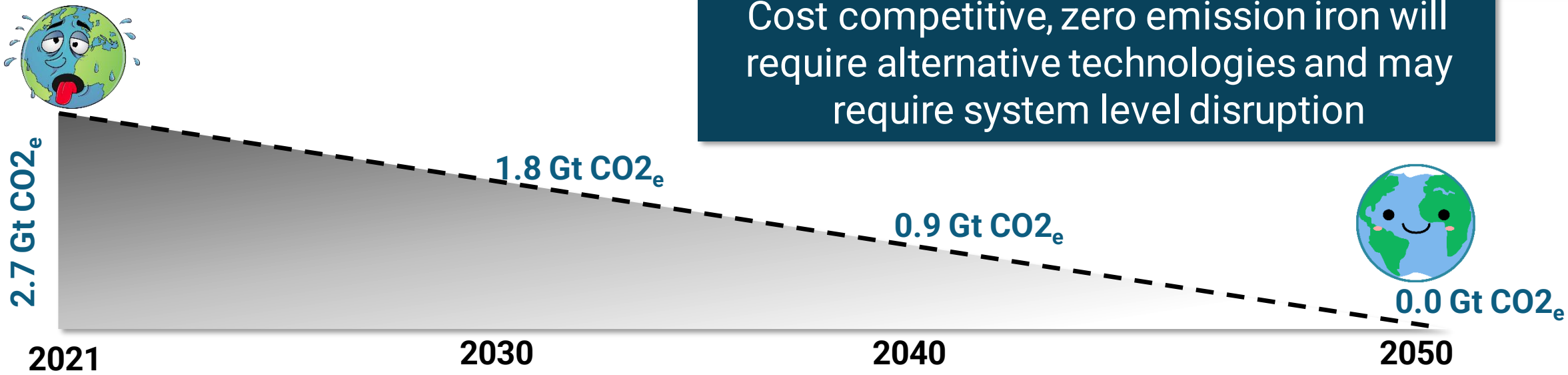
Steel is **inextricably** tied to quality of life, and we need **zero emissions** ironmaking



3000 years ago

Tomorrow

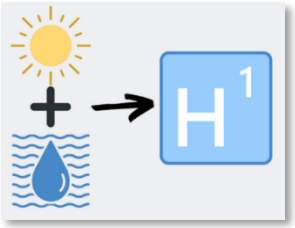
Cost competitive, zero emission iron will require alternative technologies and may require system level disruption



Current Route to Decarbonation & Limitations

The current roadmap to zero emission iron may only be a piece of the puzzle…

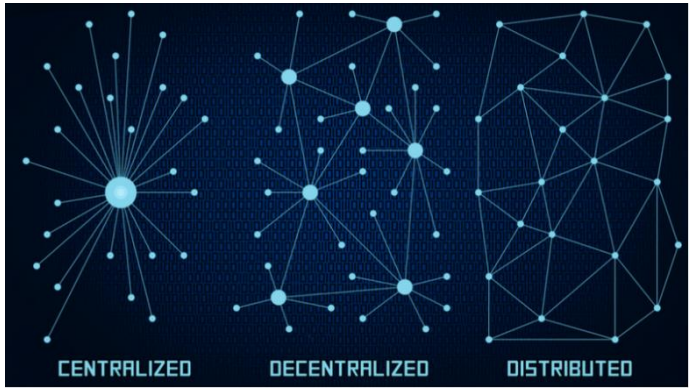
1. Electrolyzers for hydrogen production will probably go to petroleum industry first



2. Carbon capture doesn't get us to zero emissions

The current industry has significant inertia, but is not necessarily optimized for today's world

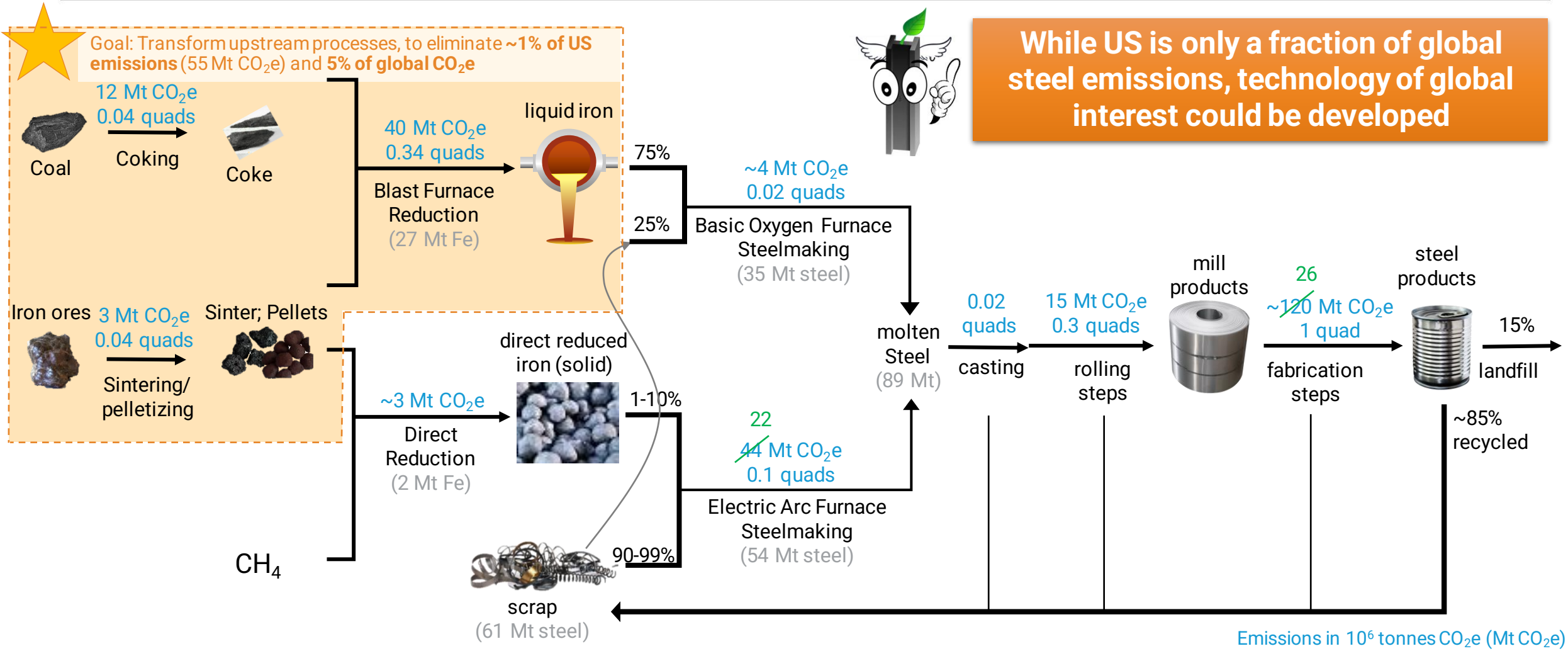
Steel is the basis for many products, but none of them require pig iron



A variety of iron and steel production paths might be viable and necessary

US iron & steel industry process map today

Annual US steel demand (138 Mt steel) is 8% of global demand (1800 Mt = 1.8 Gt steel).



Acknowledgements – 80+ Outreach Conversations to Date

Industry

CLIFFS
CLEVELAND-CLIFFS INC.
USS
ArcelorMittal
HELIOS
Berry METAL COMPANY
BST SYSTEMS, Inc.
MIDREX
NUCOR
ElectraSteel
Form energy
D BLOCK METALS, LLC
UTILITY
SORTERA ALLOYS
nel
BOSTON METAL
SKYRE
voestalpine
tenova
Otherlab CHANGING WHAT'S POSSIBLE
ARCANUM ALLOYS

Academics & National Labs

MIT
ASU
Carnegie Mellon University
OAK RIDGE National Laboratory
MISSOURI S&T
BOSTON UNIVERSITY
PURDUE UNIVERSITY NORTHWEST
UB
CLEMSON UNIVERSITY
Argonne NATIONAL LABORATORY
COLORADO SCHOOL OF MINES
Tufts UNIVERSITY
THE UNIVERSITY OF UTAH
GT GEORGIA TECH
NREL
CASE WESTERN RESERVE UNIVERSITY
Northwestern University
Pacific Northwest NATIONAL LABORATORY
AMES LABORATORY
WPI

Broader Stakeholders

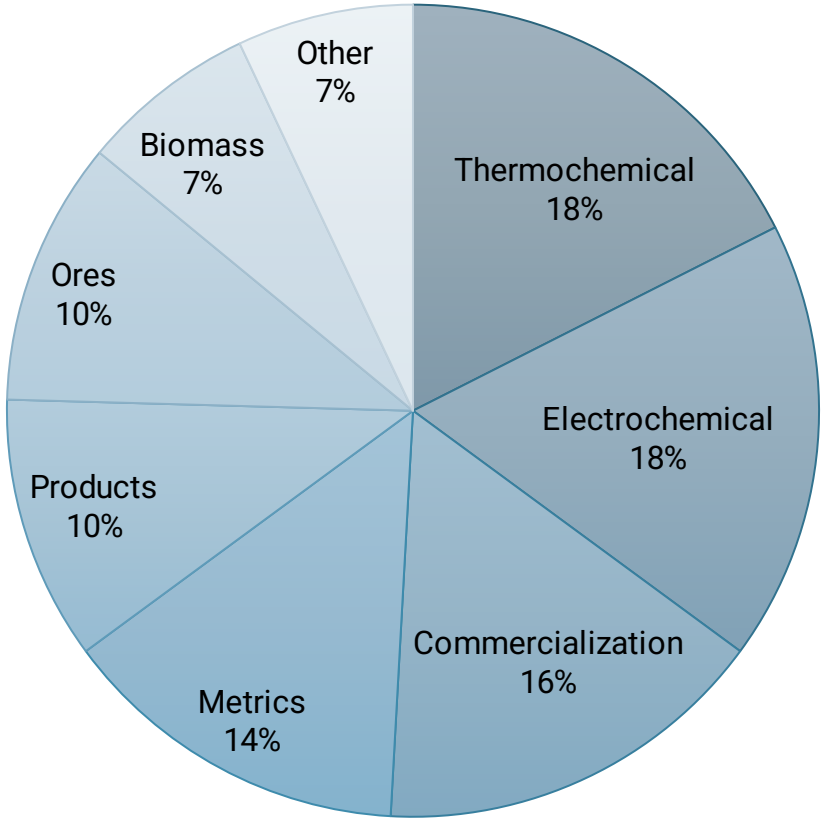
Breakthrough Energy VENTURES
Steel Founders Society
Prime Impact Fund
ROCKY MOUNTAIN INSTITUTE
WILLIAM + FLORA Hewlett Foundation
climateworks FOUNDATION
NATIONAL SLAG ASSOCIATION
American Iron and Steel Institute
CLEAN ENERGY VENTURES
Metals Service Center Institute 100 YEARS STRONG
HATCH
U.S. DEPARTMENT OF ENERGY

Program Development / RFI

The 36 responses were varied, creative, positive, and useful

The responses indicated broad interest …

… and provided input on a range of topics

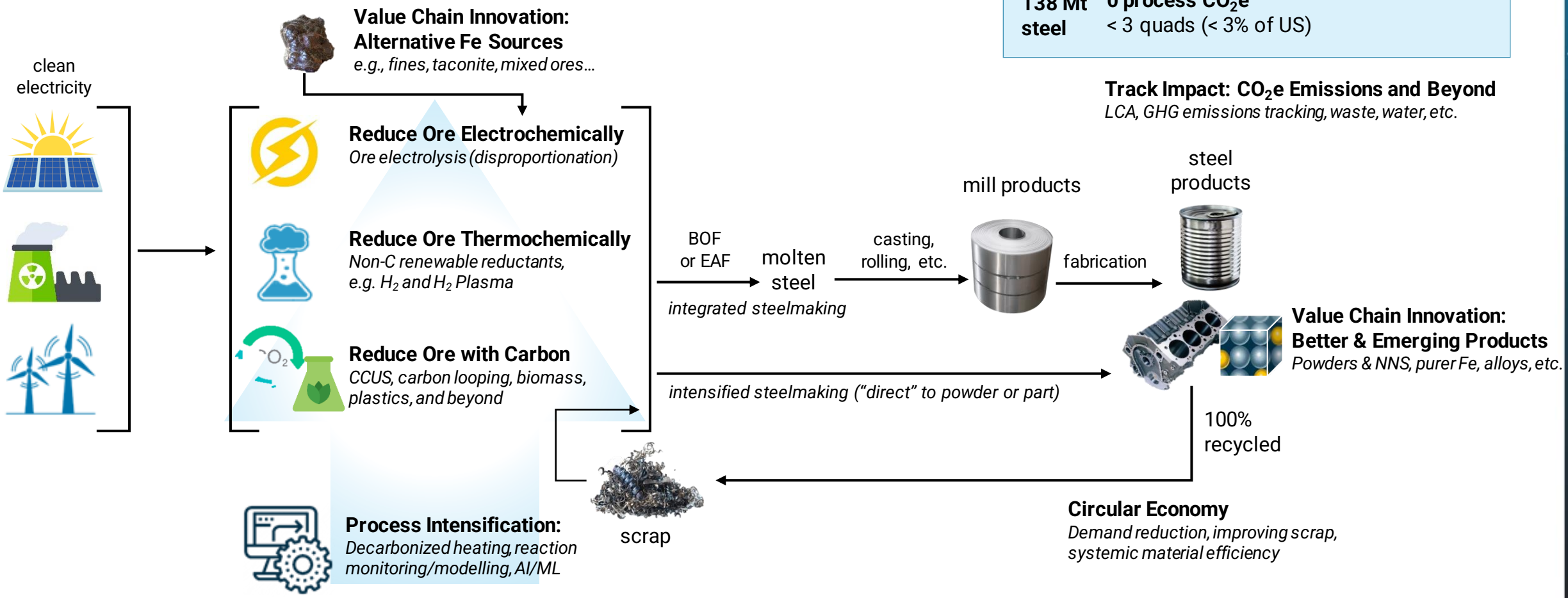


Steel industry map of tomorrow?

US annual **steel demand** ~ 138 Mt

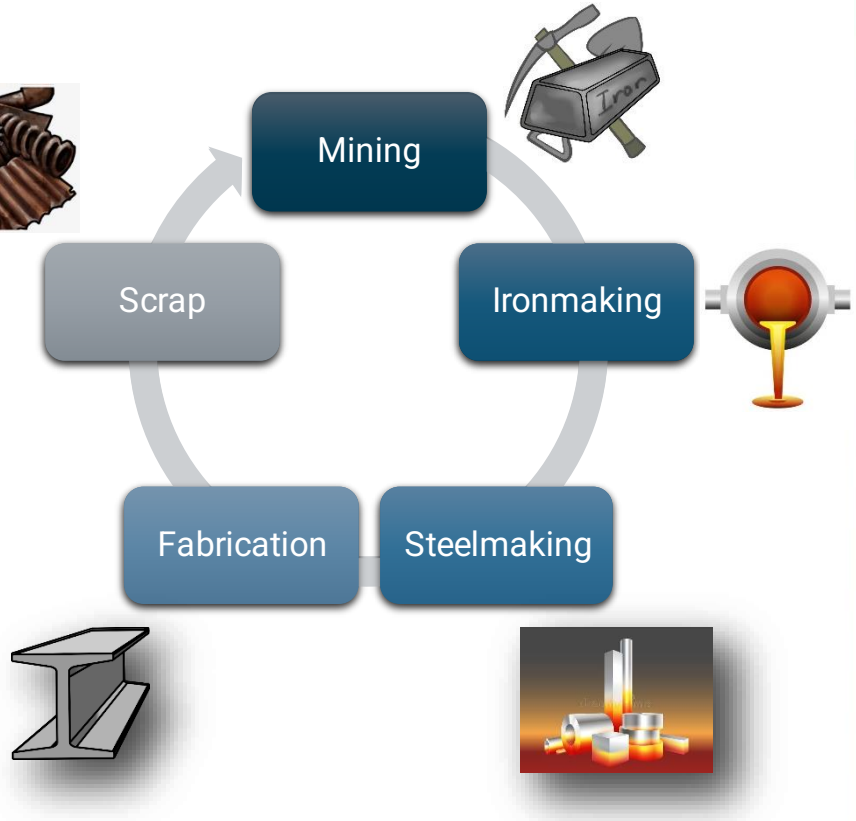
Domestic steel production

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



Track Impact: CO_2e Emissions and Beyond
LCA, GHG emissions tracking, waste, water, etc.

What we want to learn from you!



Identify technical R&D areas

Identify opportunities for process intensification

Estimation of potential R&D impact

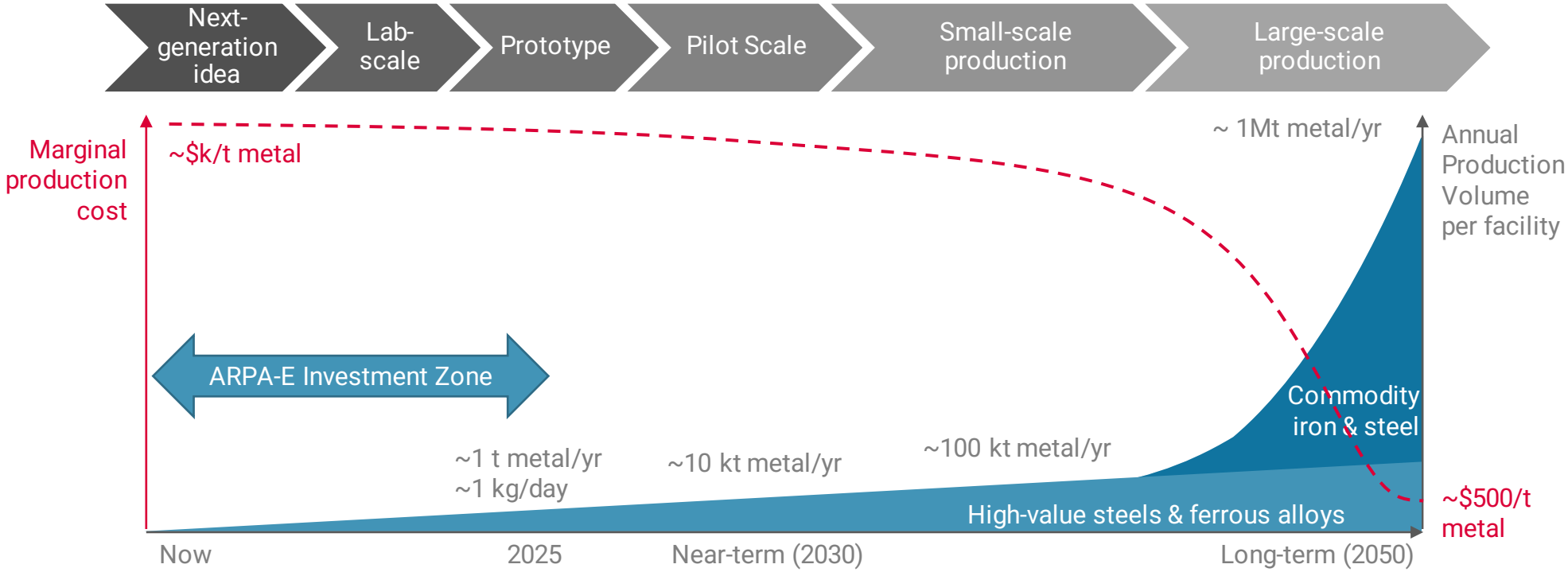
Prioritize R&D needs

$1-5M High Risk/High Reward Projects

Hypothesis - Potential Roadmap for Deployment

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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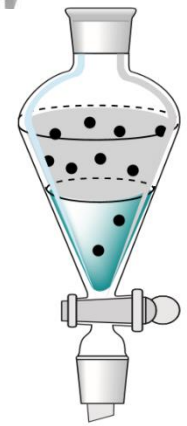
Hypothesis – Process Intensification is Possible & Necessary

Solvent extraction could provide a pathway to removing pig iron and handling more complicated ores

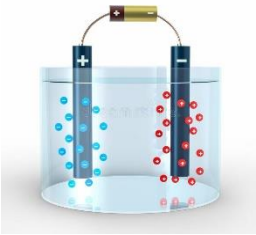


Solvent Extraction

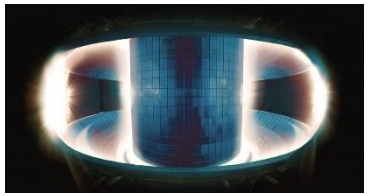
Other valuable products

Iron Oxide

Electrolysis



H_2 Plasma



Near Net Steelmaking

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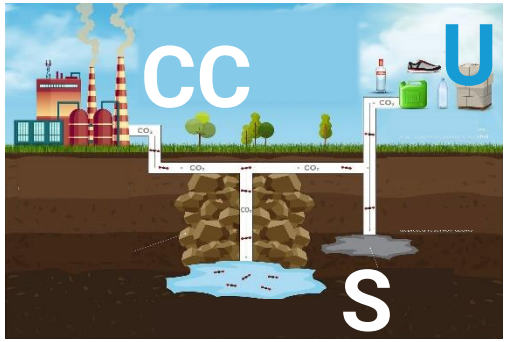
Steelmaking

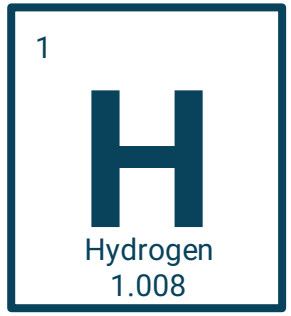
Near net parts could be leveraged more substantially

Hypothesis – a portfolio approach will be the best strategy

- Currently, two **conflicting** narratives are paralyzing climate action in the steel industry:



CCUS "versus" **Hydrogen**



- This narrative overlooks the several drawbacks of picking a single strategy:
  - Lack of Flexibility
  - Deterministic
  - Fit with just 1 endgame
  - Not robust to black swans
  - Law of Diminishing Returns with any 1 tech

- Recommended: ***a portfolio approach, to capitalize upon system-wide potential efficiencies***

Metrics

Should the metric be transition parity? (~$200/tonne crude steel)

	Incumbent	Our Metric now
1. Levelized Cost of Fe-based product	$400/tonne crude steel	>99.99% pure Fe, enabling <$400/tonne crude steel
2. Process Emissions	1.4-3 t CO_2e/t HRC steel	0 t CO_2e/t HRC steel*
3. Lifecycle Emissions (A1-A3)	>> 3 t CO_2e/t HRC steel	0.5 t CO_2e/t HRC steel*
4. Other envt'l impacts (H_2O, waste, land use, etc.)	A lot	Minimized
5. Future annual production volume possible, given the process's inputs	Per-facility: 1-12 Mt steel/yr Global: 1.2 Gt steel/yr (Gigatons iron ore, coking coal, slag, H_2O)	Per Facility: ~1Mt steel/yr Global: >=100 Mt steel/yr

Feedback on specific metric values and the general metric categories is desired!

*For integrated steelmaking, the example 'final product' considered is hot-rolled coil
For any other form of steelmaking, final product may vary

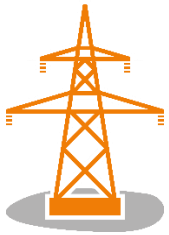
Potential Built-In Assumptions

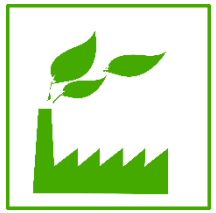
Current thinking: We will NOT assume a fixed cost of energy input

Teams will show how their technology meets the **overall levelized cost of steel** target

Will tell us what energy carrier & energy price they had to **assume** to get there

- U.S. 2022 grid is **~450 g CO_2e/kWh**[a]
  - We assume 2050 grid emissions factor is **~32 g CO_2e/kWh**[b]
  - Other emissions assumptions from GREET 2020 model
- EAF cost is approximately **$200/t** crude steel
- Equipment lifetime ~**25 yrs**
- Cost of capital **~8%**
- Iron Ore Assumptions (open to change if alternate ores are assumed)
  - **~$60/t** Fe
  - **~58 wt.%** Fe
- Scrap **~$250/t** Fe





a) EIA AEO's projections b) 2050 grid value is lifecycle emissions from manufacturing and installing the equipment for a grid that is 100% renewable, nuclear, and hydro

Parting thoughts

- We will continue to coordinate closely with relevant stakeholders in DOE and elsewhere
  - FECM, AMO, HFTO, National Labs

- Feel free to send us any ideas after the workshop.

- We need to start by dreaming as big as we can, *then* refining the idea

ADVISE: No one should say "we can't do that because":

"It has never been done"

"We tried that and it didn't work (technology has evolved!)"

"It is not covered by existing regulations"

- Many stakeholders are here to keep us grounded… please listen and keep an open mind