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Sustainable, Net-Zero Carbon Steelmaking Utilizing Nuclear and Renewable-based Integrated Energy Systems

April 2021

Changing the World's Energy Future

Steve Chalk, Seth W Snyder

Idaho National Laboratory

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Sustainable, Net-Zero Carbon Steelmaking

Utilizing Nuclear and Renewable-based Integrated Energy Systems

AIChE: **2nd Competitive Energy Systems Symposium**

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Decarbonized Steelmaking

Administration priorities

- *Decarbonization*
- *Domestic manufacturing*
- *Gigatonne scale*

Emissions Background

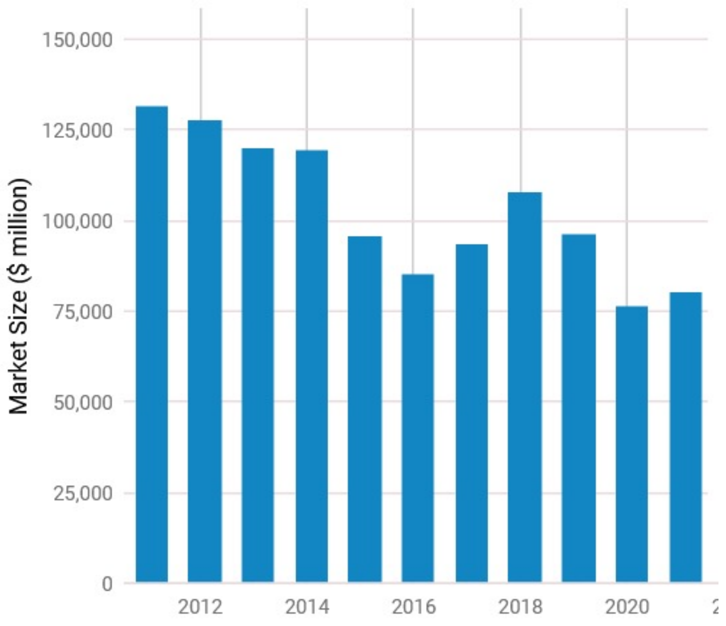
- Industrial processes (including power) account for 28% of global CO_2 emissions dominated by steel, cement, NH_3, ethylene
- Steel accounts for 7% of global CO_2 emissions (25% of Industrial)
  - *2-3 Gigatonnes annually*

- ***U.S. steel industry:***
  - Two-thirds secondary (scrap) steelmaking – 600 kg CO_2 per tonne raw steel (determined by carbon intensity of the grid powering EAF)
  - One-third primary (iron ore) steelmaking – 1.8 tonnes CO_2 per tonne raw steel (fossil-based blast furnace)
  - Recent Progress: Cleveland Cliffs NG-based reduction (HBI plant in Toledo)

Steel Economics

- **U.S. Iron & Steel Industry**
  - $520B in economic output in 2017 [AISI]
  - 2 million jobs (direct, indirect and induced) in 2017 [AISI]
  - 87 million metric tonnes (MMT) steel produced in 2018
- **National infrastructure vulnerability:**
  - U.S. is largest steel importer by country (net ~23 MMT/yr)
  - U.S. steel industry continues to lose market share
- **Opportunity**
  - Globally, one-third increase in demand 2050 [IEA 2020]
  - Flexible steel production improves competitiveness
  - Increase scrap utilization
  - Sustain manufacturing jobs

U.S. Iron & Steel Manufacturing (IBIS*World*)



National infrastructure & decarbonized transportation require domestic, decarbonized steel

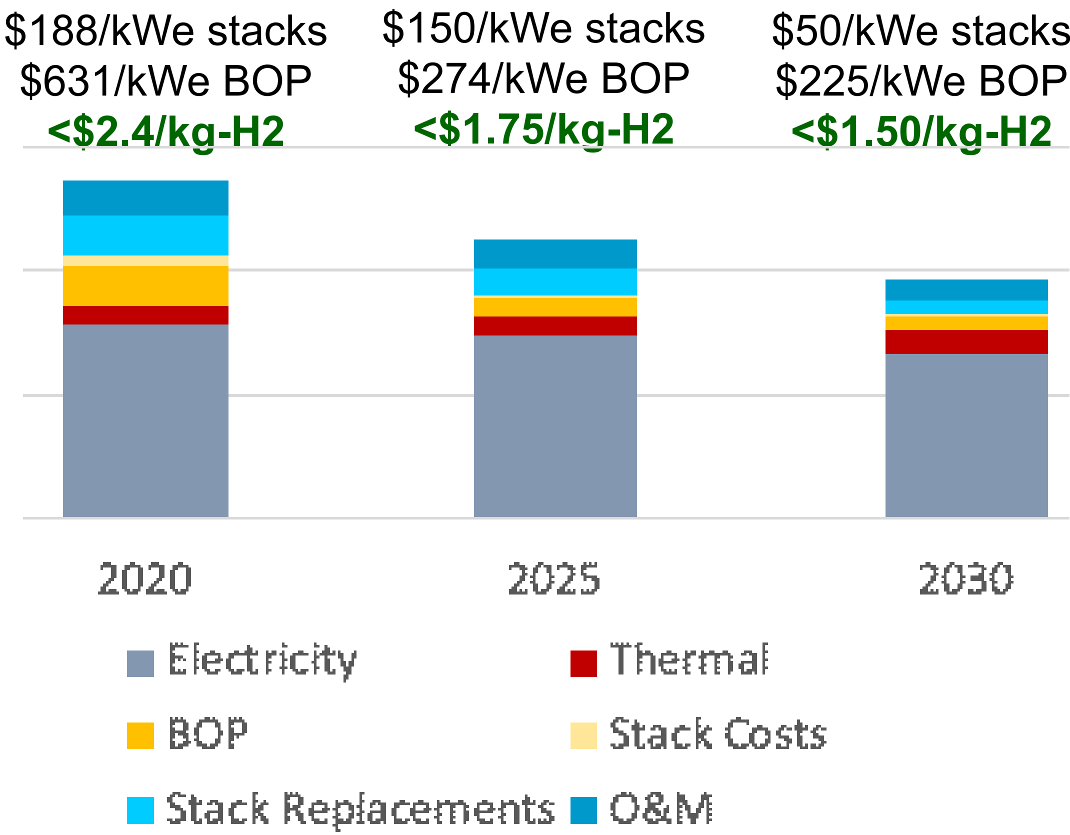
Opportunity

Leveraging low-cost carbon-free electricity

- Nuclear/renewable generation
- Advances in electrolyzer – low-cost hydrogen
- Integrated with electrification / energy storage
- Non-fossil carbon sources

Why now?

- **Availability of low-cost renewable / nuclear electricity***
- **Advancement in Electrolyzers**
  - Scaling of electrolyzers (20 MW with plans for 100 MW+)
  - Low-cost hydrogen (~$2/kg heading to $1.5 (at scale))
- **Integrated Energy Systems**
  - Progress on thermal integration
    - (Tri-Lab Consortium: INL, NREL, NETL)
- **Waste carbon sources**
  - CO_2, plastics and other wasters



→*$30 MWH carbon-free electricity*
→*$1.5 kg H_2*
→*@ Steel plant scale*

*Source: : Nuclear Energy Institute for 2019, see https://www.powermag.com/u-s-nuclear-industry-shaved-generating-costs-by-7-6-compared-to-2018/ accessed 12/21/20.

Green hydrogen is at scale

- Industrial 20 MW facilities are coming online
- Decarbonizing manufacturing is in play

SUSTAINABILITY

Ineos to build green hydrogen hub in Norway

by Alex Scott

MARCH 19, 2021

Inovyn, Ineos's polyvinyl chloride business, has unveiled plans to build a zero-carbon hydrogen production hub at its site in Rafnes, Norway. The project will feature a 20 MW electrolyzer powered by renewable electricity to split water into hydrogen and oxygen. Inovyn estimates that the project will reduce its carbon dioxide emissions by at least 22,000 metric tons per year. Inovyn will use the green hydrogen itself and may sell it as transport fuel in Norway.

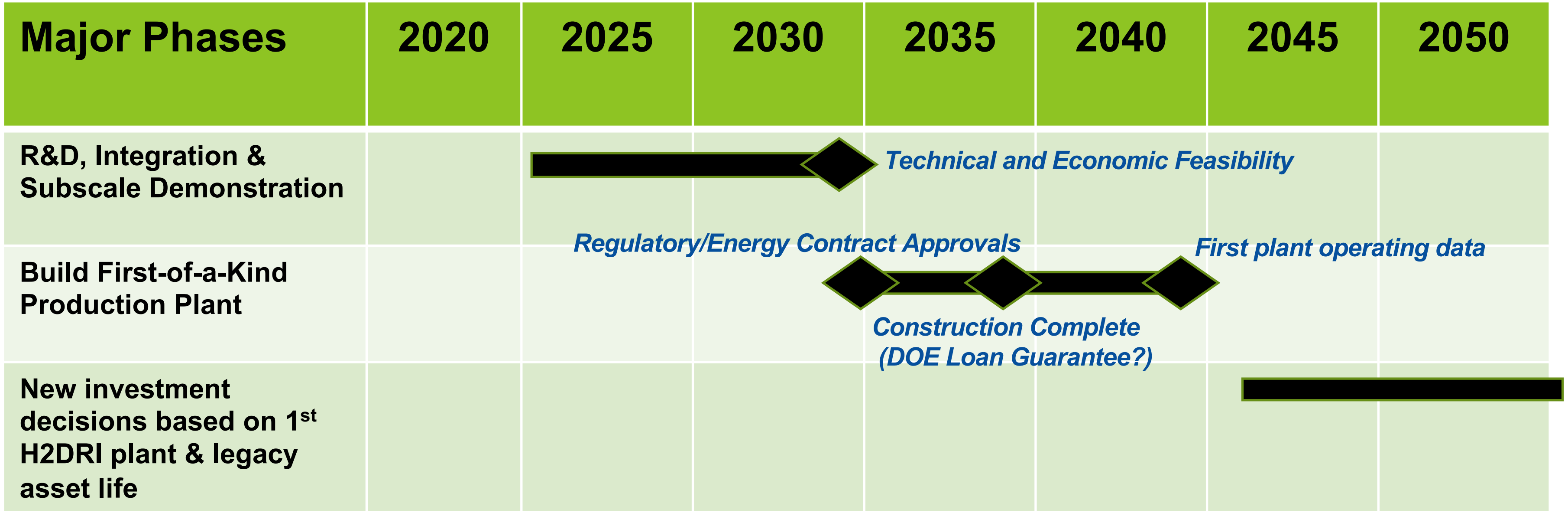
Chemical & Engineering News
ISSN 0009-2347

Inovyn

Inovyn's site in Rafnes, Norway

Timeline to Net-Zero Carbon by 2050 Requires Research Now because of Steelmaking's Scale and Long Investment Cycles

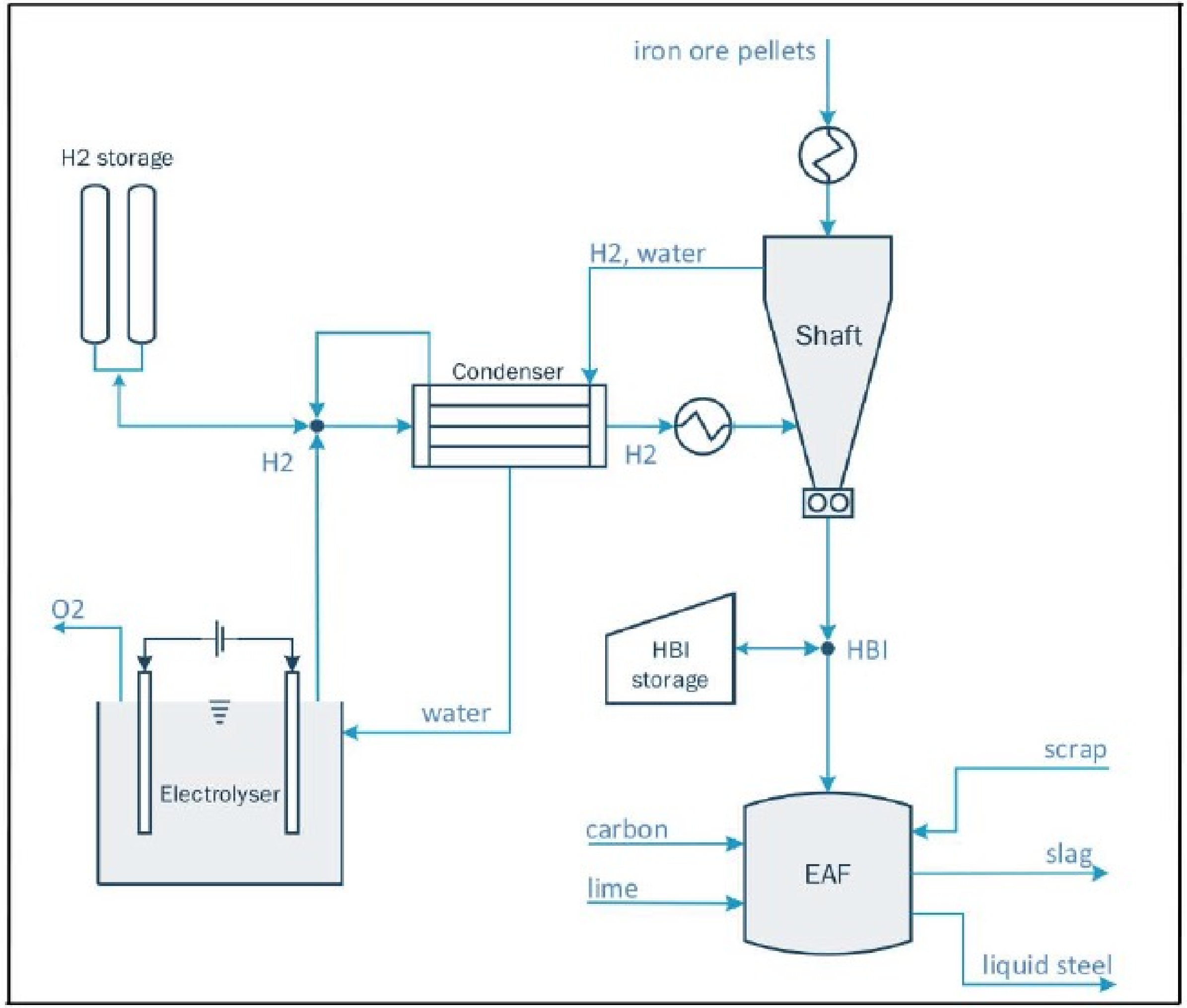
- **NAS "Decarbonization" Report:** "Although technology exists to decarbonize all parts of the energy system, some sectors remain at precommercial or first-of-a-kind demonstration stages and will require significant improvement in cost and performance to become commercially viable. These include aviation, shipping, and industrial subsectors such as steel, cement, and chemicals manufacturing." (Summary, p. 3)
- Typical **steel investment cycles are 25 yrs** with blast furnaces / other major equipment lifetimes up to 40 yrs (IEA)
- Europe is moving out: ArcelorMittal Hamburg demonstration with NG-based hydrogen (100% H_2 @ 100Kt yr demo)



Need a coordinated R&D and pre-pilot program to meet net-zero by 2050

Hydrogen Direct Reduction of Iron (H2DRI) Process

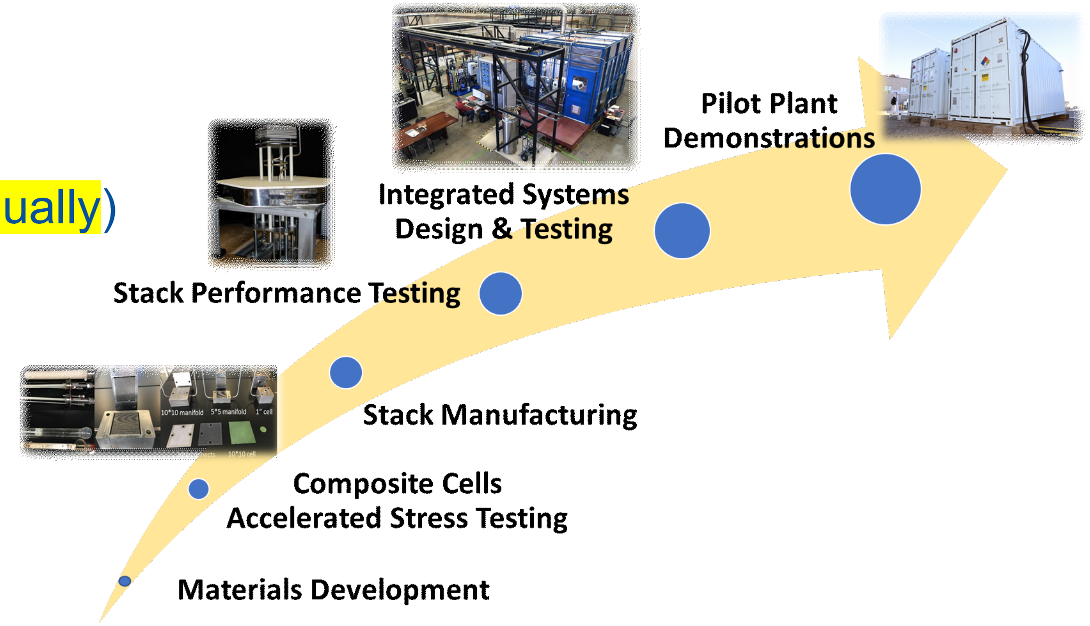
- **Requires 4 MWh/tonne raw steel (100% H2DRI)**
  - 70% of electricity required for water electrolysis (64% efficient electrolyzer/rectifier)
  - 30% for electrical heating of iron ore, shaft furnace pre-heat, EAF
- **Detailed Process Requirements**
  - 54 kg H_2 per tonne steel (H2 for all primary steel = 18% of today's H_2 production)
  - H_2 costs at-scale $2/kg
  - Water costs are negligible at $0.01/kg H_2 (4 gal. H_20/kg H_2)
  - Water resource availability not issue in current steel plant locations
  - Scrap lowers electricity requirements but not all grades of steel can be produced with scrap



Source: V. Vogl

H2DRI Scale and Economic Analysis

- **Small 2 MMT/yr H2DRI steel plant requires 8 TWh**
  - ~ 1 GW at 91% CF
    - Current grid 1100 GW (2005-9, 40 TWh gen. added annually)
  - Includes ~ 700 MW for H_2 production
    - Mfg plans for 100 MW electrolyzers (e.g., Siemens)
- **$30/MWh yields raw steel at $470/tonne**
  - Assuming non-energy costs of $350/tonne including capex*
  - Various electricity prices included in analysis
  - Fleet-wide nuclear electricity costs $30.4/MWh (NEI 2019)
  - Renewable costs as low or lower
- **Steel can be cost neutral with carbon abatement ~ $50/tonne CO_2**
  - **@ 100% H2DRI with $30/MWh**
  - Lower if scrap mixed in EAF
  - 45Q tax credit for carbon sequestration is $50/tonne in 2026 (CRS)



* Source: Vogl for non-energy costs, note iron ore prices can vary

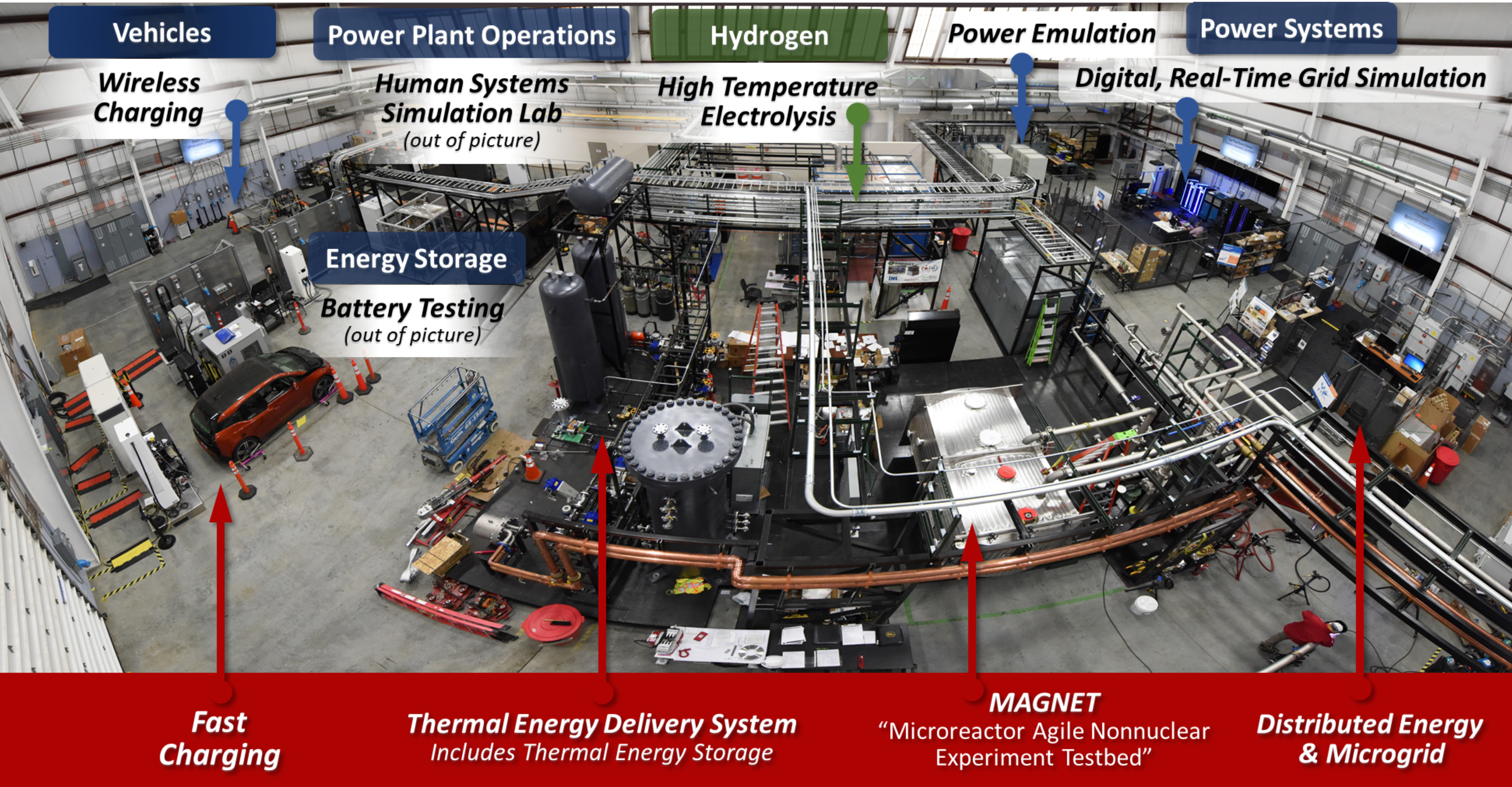
R&D Challenges* with H2DRI

R&D focus to de-risk the chemical processing and plant economics to reduce iron ore to steel utilizing carbon-free hydrogen

- **High-Temperature Materials Research** – Need for furnace linings and other components to maintain structural and mechanical properties under high, pure hydrogen concentrations and elevated temperatures required for iron ore reduction
- **Thermal Management and Integration** – Understand heat transfer required for pure hydrogen chemical conversion processes can drive new furnaces designs and unit operations. Optimal heat integration amongst major components can lower overall energy costs to ensure steel costs stay market competitive. CO from bio-based or waste-derived CO_2 or plastics can lower thermal requirements for iron ore reduction
- **Operating Experience and Process Optimization** – Obtain laboratory/pilot-scale data for techno-economic analysis before production-scale designs and plant investments can be made to replace major steelmaking facilities such as blast furnaces

** For details on R&D challenges see: Lalena, J. Nick, Fox, Robert V, and Snyder, Seth W., Material For Harsh Environments : 2020 Virtual Workshop Summary Report. United States: 2021. Web. doi:10.2172/1772461.*

INL’s Integrated Energy Systems Laboratory



Technology Investment Now to Deliver Future U.S. Economic Benefits

Given long asset life and large investments in steel industry, recommend:

- *Detailed analysis, materials R&D and pre-pilot technology integration required by 2030 to position U.S. industry for an investment decision for building first net-zero integrated steel plant:*
  - *INL Energy Systems Laboratory, thermal/grid integration expertise, electrolysis/H_2 testing, harsh materials development*
- *Net-zero carbon steelmaking, including winning back import market and becoming net exporter;*
  - *Use domestic supply chain for building domestic infrastructure*
- *Electrolysis technology enables markets to decarbonize other industrial sectors (incl. CO_2 electrolysis, NH_3 synthesis, etc.)*

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