



Midwest Nuclear-based Net-Zero Carbon Steelmaking Demonstration

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Changing the World's Energy Future

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Concept: Midwest Nuclear-based Net-Zero Carbon Steelmaking Demonstration

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- **Regional Hydrogen Production, Resources, and Infrastructure**

Globally, the iron and steel industry accounts for around a quarter of GHG emissions from the manufacturing sectorⁱ, which is about 7% of the 33 gigatonnes (Gt) of global CO₂ emissionsⁱⁱ. Thus, globally, the steel industry is a 2-3 Gt CO₂ per year emissions challenge. The steel industry is important to the U.S. economy with output equal to \$0.5 trillion and domestic production capacity is critical to national defense, infrastructure, energy production, and transportation. President Biden's executive orderⁱⁱⁱ on climate identifies actions and policies to put the Nation on a path to achieve net-zero carbon emissions, economy-wide, by no later than 2050. To achieve this, deep carbon reductions in the power, transportation, buildings and capital-intensive industrial manufacturing segments such as steel, cement and chemicals need to be addressed. In its recent "Accelerating Decarbonization of the U.S. Energy System" report^{iv}, the National Academy of Sciences (NAS) stated that, "while technology exists to decarbonize all parts of the energy system, some sectors remain at precommercial or first-of-a-kind demonstration stages and require significant improvement in cost and performance to become commercially viable." The NAS goes on to state that these hard to decarbonize sectors include "aviation, shipping, and industrial subsectors such as steel, cement, and chemicals manufacturing^v."

The Administration has proposed a timeline to decarbonize energy, transportation and then industry and manufacturing. From a life-cycle approach, decarbonizing steel and other large industrial inputs are necessary to decarbonize transformations in energy and transportation.

DOE's TRI-Lab Consortium's Integrated Energy Systems (IES) program is a collaboration amongst DOE's three applied energy laboratories: the National Energy Technology Laboratory; National Renewable Energy Laboratory and Idaho National Laboratory. The IES approach looks at more tightly integrating low-carbon nuclear energy, renewable electricity, energy storage, load/demand balancing, and biomass (including plastics and other wastes) with one or more industrial processes that utilize heat and/or power from these clean and waste energy sources to produce a low-carbon commodity-scale product.

According to the Nuclear Energy Institute, fleet average nuclear power in 2019 was \$30.4/MWh^{vi}. Nuclear power is predictable and almost always on with a capacity factor greater than 93%^{vii}. Integration of nuclear power and heat with steelmaking would create an opportunity for more competitive sustainable steel production with near, net-zero carbon emissions. In addition, with such large, predictable energy required for steelmaking, matching it with existing nuclear plants or dedicated new nuclear reactor technology (e.g., small modular reactors (SMRs) specifically sized for steel production or micro-nuclear reactors on the order of 5-20 MW designed for specialty mini-steel mills.) would help grow nuclear energy's contribution to the Nation's carbon-free electricity portfolio and to decarbonizing the industrial end-use sector.

This concept focuses on the integration of nuclear energy to produce carbon-free hydrogen for direct reduction of iron ore (DRI) and steelmaking. Direct electrical conversion of iron ore (e.g. electric arc furnaces) offer an alternative. This concept primarily targets reducing GHG emissions from steelmaking by reducing iron ore with carbon-free hydrogen (or electricity) instead of coke. Emissions associated with secondary steelmaking (i.e., using recycled scrap) would also benefit from carbon-free nuclear power but this process is already substantially electrified.

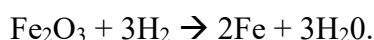
Toledo, Ohio and Detroit, MI are two areas where integrated steel mills are in proximity (30 miles) to nuclear reactors. While this distance is too long to integrate high quality heat from the reactor to the steel plant, there could be bilateral agreements for carbon-free electricity pricing. Demonstrations in these distressed communities would show the potential of how integrated energy system demonstrations can decarbonize the steel industry and set the stage for new investments which would create jobs.

- **End Users for Hydrogen in the Region, Cost, and Value Proposition**

Integrated steelmaking mostly occurs in the Midwest in States such as Michigan, Ohio and Indiana. In Toledo, Ohio, Cleveland-Cliffs recently opened their advanced, hot briquetted iron (HBI) plant which uses natural gas-based CO and H₂ (syngas) instead of coke to reduce iron ore to metal which significantly decreases GHG emissions. The next step is to nearly eliminate CO₂ emissions from iron ore-based steelmaking by using carbon-free hydrogen. However, in addition to electrolyzers substituting for steam methane reformers (or coke ovens in conventional plants), pure carbon-free hydrogen (as opposed to syngas) changes the iron reduction reaction from exothermic to endothermic and changes heat management.

Therefore, integrated demonstrations are required to validate performance and cost of net-zero steelmaking so that the steel industry can make informed investment decisions regarding new plant infrastructure which have long turnover times of 30 years and more.

For the Hydrogen Direct Reduction of Iron (H₂DRI) process where carbon-free, nuclear-based hydrogen is used, the quantity of hydrogen required would be primarily^{viii} in accordance with the following reaction:



Stoichiometrically, this reaction implies that 54.1 kilograms of hydrogen would be required for every tonne of raw iron produced. Hydrogen would be produced through nuclear-based water

electrolysis at 52.2 kWh/kg^{ix} which represents an electrolyzer stack efficiency of 70% (LHV), system efficiency of 65% and a rectifier^x efficiency of 98.4%.

Compared to today's carbon-intensive, integrated steelmaking processes, it is likely that initial overall operating costs and capital costs for state-of-the-art hydrogen direct iron reduction will increase steel prices. As subscale demonstrations help validate technoeconomics and operating experience is gained, potential pathways for operating and capital costs minimization can be identified and pursued. After first-of-a-kind plants are built, costs can be further lowered by learning curves. Since steel costs would be very sensitive to electricity costs, new nuclear plants would need to match the competitive electricity price of \$30/MWh being provided by existing plants. Approximately 70% of the electricity is due to the electrolyzers to make hydrogen, capex and efficiency of electrolyzers also need to continue to improve.

The table below shows the electricity requirement of 4 MWh of electricity are required for pure H2DRI per tonne of liquid steel (no finishing operations included).

H2DRI and EAF Process Electricity Requirements	Electricity Requirement (MWh/tonne liquid steel)
Electric heating of iron ore pellets to 800 C	0.44 ^{xi}
Pre-heating H2 to shaft furnace	0.16 ^{xii}
Electricity for water electrolysis to produce H2	2.80 ^{xiii}
Electricity for electric arc furnace (EAF)	0.5 ^{xiv}
Subtotal	3.9
Total accounting for 2.5% hydrogen/heat losses	4.0

Thus, for every 1 million metric tonnes (MMT) of steel produced, 4 TWh of electricity are required which equates to a 491 MW nuclear plant at 93% utilization. Thus, even a small integrated steel plant at 2 MMT per year would consume most of the energy of a typical 1 GW nuclear reactor. The nuclear capacity factor of 93%^{xv} demonstrates another advantage of nuclear energy versus variable sources. If direct solar and/or wind with lower capacity factor were utilized, more upfront capital expense to oversize the electrolyzers would be necessary to achieve the same net-zero carbon impact. Furthermore, since the direct hydrogen reduction reaction is endothermic, nuclear heat integration is advantageous compared to additional electricity needed for electrically-generating the heat. As an alternative, biomass-based syngas, bio-derived fuels (e.g., ethanol) and recycled CO₂ (air capture or point sources followed by reduction) could provide sources for the CO to make the iron ore reduction reaction more exothermic while maintaining carbon-neutrality. The table below show the sensitivity of electricity prices on the cost of steel and carbon abatement.

Electricity rate (\$/MWh)	Cost of Steel (\$/tonne liquid steel) – not including finishing		Electricity Cost in \$ per tonne liquid steel (Electricity cost as percentage of steel cost)		Carbon Abatement Costs (\$/tonne CO ₂)	
	100% H2DRI ⁱ	50% H2DRI/50% Scrap ⁱⁱⁱ	100% H2DRI @ 4 MWh/tLS	50% H2DRI/50% Scrap @ 2.25 MWh/tLS	100% H2DRI compared BF-BOF ⁱⁱⁱ	50% H2DRI/50% Scrap ^{iv}
20	430	427	80 (19%)	45 (11%)	27	24
30	470	450	120 (25%)	68 (15%)	50	44
40	510	472	160 (31%)	90 (19%)	73	63
50	550	495	200 (36%)	112 (23%)	96	83

ⁱbased on non-energy H2DRI/EAF steelmaking costs of \$350/tLS and 4 MWh/tLS, see references ^{xvi}, ^{xvii}

ⁱⁱbased on non-energy EAF scrap steelmaking costs of \$414/tLS and 0.5 MWh/tLS, see references xvi, xvii.

ⁱⁱⁱbased on the H2DRI steel production cost at the electricity rate minus BF-BOF steel production cost of \$382/tonne liquid steel (reference 39) divided by 1.75 tonnes CO₂ avoided/tonne liquid steel

^{iv}based on 50% H2DRI compared to 50%BF-BOF and 50% scrap with electric grid at 550 kg CO₂/MWh (average of IN, OH, PA and MI grid carbon intensities (EIA)) x 0.5 MWh/tLS for EAF. Electricity prices constant.

The carbon abatement cost represents the subsidy necessary so plants don't lose money. Thus, certainty around a value on carbon is necessary to stimulate long-term investment. At competitive wholesale electricity cost of \$30/MWh, similar to the nuclear fleet generation in 2019, a subsidy of \$50/tonne is in-line with the IRS tax credit of \$50/tonne CO₂ in 2026^{xviii} for geologic sequestration. In this case, carbon-free nuclear energy obviates the need for sequestration and receiving the same value for the CO₂ avoidance makes the H2DRI steelmaking cost-competitive. The Biden Administration FY 22 Budget proposal includes up to a \$3/kg hydrogen production tax credit to catalyze decarbonization of industry and transportation. This level of tax credit would make carbon-free steelmaking cost-competitive with conventional coke-based steelmaking.

After first-of-a-kind plants are built, costs can be further lowered by learning curves. The learning curves will include improvement in materials, especially under extreme environments, better process technologies, development of resilient supply chains, and integration across the supply chains. These are all areas of expertise for the U.S. Department of Energy.

- **Greenhouse Gas and Pollutant Emissions Reduction Potential**

A large integrated steel mill such as Burns Harbor produces 5 million short tons per year^{xix}. Integrated steel plants vary in annual capacity from about 2 million short tons (Dearborn Works^{xx}) to 7.5 million short tons (Gary Works^{xxi}).

A small-sized plant for direct iron reduction of 1 million metric tonnes (MMT) per year is roughly the capacity of a typical blast furnace that the H2DRI equipment would replace. For instance, Granite City's Blast Furnace A is approximately 0.9 MMT and Gary Works Blast Furnace No. 4 is 1.3 MMT per year^{xxii}. However, more modern plants are now designed for over 2 MMT.

On average, integrated BF-BOF steelmaking in the U.S. emits 1.8 tonne CO₂ per tonne of liquid steel^{xxiii}. Not all of this CO₂ can be avoided with the H2DRI/EAF process because there are CO₂ emissions associated with calcination of limestone to promote slag, EAF graphite electrode consumption and since carbon needs to be added for alloying. These sources amount to approximately 0.05^{xxiv} tonnes CO₂ per tonne liquid steel reducing the carbon emissions avoided with H2DRI/EAF process to 1.75 tonnes per tonne liquid steel.

So, a typical 2 MMT/year steel plant operating as an H2DRI plant would avoid 3.5 MMT annually of CO₂. Nationwide with approximately 30 MMT/year of primary steelmaking, the CO₂ avoidance would be 52.5 MMT annually.

- **Diversity, Equity, Inclusion (DEI), Jobs, and Environmental Justice**

Potential demonstration site options:

1. Zug Island, Michigan is a heavily industrialized area and home to a closing U.S. Steel plant. The University of Michigan assessed Zug Island as the most polluted area in Michigan. In its heyday, over 15,000 people worked there; today they are down to 500. According to eig.org, River Rouge community is severely distressed (see <https://eig.org/dci/interactive-map?path=zip/48218>) with more than 40% of the people living below the poverty level and 40% of the adults unemployed. Revitalization of Zug Island with a carbon and pollution-free steel plant could revitalize the area if combined with clean-up of contaminated areas as part of an overall environmental justice initiative. Nuclear power for carbon-free hydrogen can be supplied by Fermi 2 reactor in nearby Newport, MI for the demonstration project. Over the long-term, the unbuilt, already NRC-licensed Fermi 3 reactor at 1.5 GW would be large enough for 3 MMT per year of carbon-free steel production.
2. Toledo, Ohio is home to the most modern iron-ore based steel plant in the U.S. with Cleveland-Cliffs installing a natural gas-based iron reduction process to replace conventional coke processes. A nearby demonstration to take the next step to nearly eliminate carbon emissions could be feasible. The University of Toledo could potentially be involved and carbon-free electricity could be supplied by Davis-Besse nuclear power station in nearby Oak Harbor, Ohio. According to eig.org, Toledo, Ohio community is severely distressed (see <https://eig.org/dci/interactive-map?path=zip/43605>) with more 38% of the people living below the poverty level and 38% of the adults unemployed.

As an example, the Energy Systems Laboratory (ESL) at Idaho National Laboratory can support the demonstration-scale carbon-free steelmaking. It has the electrolysis stations, thermal management systems, hydrogen delivery systems and grid simulators to facilitate flowsheet modeling, hardware-in-the-loop simulation and other validation and risk reduction activities necessary prior to field demonstrations.

- **Science and Innovation Needs and Challenges**

Focused research and development (R&D) is needed for de-risking the chemical processing and plant economics to reduce iron ore to steel utilizing carbon-free hydrogen. The following R&D is required:

- High-temperature materials research to ensure that furnace linings and other components maintain structural and mechanical properties under high, pure hydrogen concentrations and elevated temperatures required for iron ore reduction.
- Materials and manufacturing R&D to further reduce the capital cost of electrolyzers and critical components to ensure low-cost hydrogen can be produced for competitive steelmaking.
- Integration of thermal energy from nuclear plants and other sources needs to be simulated and demonstrated at laboratory scale so that the heat transfer required for pure hydrogen chemical conversion processes can drive new furnaces designs and unit operations. Optimal heat integration can also lower overall energy costs to ensure steel costs stay market competitive.
- Operating experience at the laboratory and demonstration-scale is needed before commercial-scale designs and investments can be made to replace major steelmaking facilities such as blast furnaces.

An integrated demonstration would need to happen by 2030 so that a first-of-a-kind production plants can follow and subsequent infrastructure investments could be planned and implemented to support President Biden's goal of net-zero carbon emissions by 2050.

ⁱ Global Efficiency Intelligence, "How Clean is the U.S. Steel Industry? An International Benchmarking of Energy and CO₂ Intensities," November 2019, p. 30.

ⁱⁱ International Energy Agency, <https://www.iea.org/articles/global-co2-emissions-in-2019>. Accessed 12/21/20.

ⁱⁱⁱ See <https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/>, accessed 2/12/21.

^{iv} The National Academies Board on Energy and Environmental Sciences, Committee on Accelerating Decarbonization in the United States, 2021, p. 3.

^v Ibid, p. 3.

^{vi} 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.

^{vii} Ibid.

^{viii} Production of FeO is small and was neglected

^{ix} DOE Hydrogen and Fuel Cells Program Record 19009, Hydrogen Production Cost from PEM Electrolysis – 2019, dated February 3, 2020.

^x Source for AC to DC conversion is NREL, see

<https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiB2se68LTtAhWks1kKH TX4BB8QFjABegQIBBAC&url=https%3A%2F%2Fwww.nrel.gov%2Fdocs%2Ffy19osti%2F73520.pdf&usg=AOvVaw1BN7JgAY7WIWFHsT-hkoiX>

^{xi} Bhaskar, A., Assadi, M., Somehsaraei, H.N., "Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen, Energies 2020, Vol. 13, 758, doi:10.3390/en13030758, pp. 11.

^{xii} Ibid, p. 11.

^{xiii} Based on 54.1 kg H₂/tonne of Fe and 52.2 kWh/kg H₂.

^{xiv} Bhaskar, A., Assadi, M., Somehsaraei, H.N., "Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen, Energies 2020, Vol. 13, 758, doi:10.3390/en13030758, pp. 12. EAF of 0.445 MWh/tonne increased to 0.5 MWh/tonne to account for impurities. See also reference 23 Niloofar and reference 24 (Hornby).

^{xv} Average capacity factor reported by Nuclear Energy Institute. See <https://nei.org/fundamentals/nuclear-provides-carbon-free-energy> accessed 1/4/21.

^{xvi} Vogl Supplementary Data information to Vogl paper, reference 23. Table "a" shows coking costs 55.66 EUR/tLS = \$67/tLS and BF-BOF costs of 318 EUR/tLS = \$382/tLS with EURO to \$ conversion of 1.2. See <https://ars.els-cdn.com/content/image/1-s2.0-S0959652618326301-mmc1.docx>, accessed on 12/4/20.

^{xvii} Vogl Supplementary information to Vogl paper, reference 23. Table "a" shows H₂DRI/EAF liquid steel cost without electricity, Calculation (431 EUR/tLS – 40 EUR/MWh x 3.48 MWh) x 1.2 conversion of EURO to USD = \$350/tonne liquid steel. Also 50% scrap/50% DRI costs = 401 EUR with energy at 40 EUR/MWh and 0.667 MWh/tLS EAF leads to \$414/tonne for scrap steel after accounting for 50% H₂DRI at 431 EUR/tLS. See <https://www.sciencedirect.com/science/article/pii/S0959652618326301#appsec1>, accessed on 12/4/20.

^{xviii} Congressional Research Service, The Tax Credit for Carbon Sequestration (Section 45Q), dated March 12, 2020.

^{xix} Cleveland-Cliffs Burns Harbor 2020 data sheet, see

<http://www.clevelandcliffs.com/English/Operations/Steelmaking/Burns-Harbor/default.aspx>. Accessed on 12/10/20.

^{xx} See <https://www.spglobal.com/platts/en/market-insights/latest-news/metals/042920-cleveland-cliffs-idling-aks-michigan-hot-strip-mill-sources>. Accessed on 12/10/20.

^{xxi} See https://www.nwintimes.com/business/local/enterprise-of-the-year-resurgent-u-s-steel-investing-big-in-gary-as-it-undergoes/article_647000da-07c4-529e-958e-e961556151fe.html. Accessed on 12/20/20.

^{xxii} See <https://www.argusmedia.com/en/news/2091252-coronavirus-forces-us-steel-to-idle-blast-furnaces>. Accessed on 12/10/20.

^{xxiii} Ibid, Figure 16, p. 22.

^{xxiv} V. Vogl, M. Ahman, L. Nilsson, "Assessment of hydrogen direct reduction for fossil-free steelmaking," Journal of Cleaner Production 203, 2018, p. 741.