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Green New Steel: Opportunities, Insight, and Barriers to Green Hydrogen Use in U.S. Steel Production

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Opportunities, Insight, and Barriers to Green Hydrogen Use in U.S. Steel Production

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Outline

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Abbreviations

Mmt = million metric tons
BF = blast furnace
BOF = basic oxygen furnace
EAF = electric arc furnace
DRI = direct-reduced iron
H2 = hydrogen
PEM = proton-exchange membrane
CO_2 = carbon dioxide
DOE = Department of Energy
RES = renewable energy sources
IEA = International Energy Agency

Definitions

Hot metal = liquid iron
Pig iron = solid iron
Sponge iron = direct reduced iron; alternative to pig iron, with higher iron content and lower carbon content
Coke = crushed coal combusts at high temperatures to form coke, a concentrated source of carbon
Clean hydrogen = the Infrastructure Investment and Jobs Act defines clean hydrogen as the process of producing hydrogen with less than, or equal to, 2 kilogram of CO2 equivalent per 1 kilogram of hydrogen at the site of production.
Green hydrogen = hydrogen produced from water, using renewable energy powered electrolysis
Gray hydrogen = primary method of hydrogen production; hydrogen produced from natural gas using steam-methane reform
Blue hydrogen = hydrogen produced from natural gas by steam methane reform with carbon capture and storage

Abstract

Steel production is a hard-to-abate, carbon intensive industry contributing 8-9% of global greenhouse gas emissions. Reducing greenhouse gas emissions from an expanding steel industry is a necessary step to attaining net-zero goals and limiting the impacts of global climate change. To achieve this goal, alternative energy carriers capable of direct reduction, high-temperature combustion and zero direct greenhouse gas emissions are under research to replace coal and natural gas for steel production. A potential alternative to traditional fossil fuels is green hydrogen (H_2), produced from water using renewable energy powered electrolysis. Currently, green H_2 is expensive, but the cost is declining in tandem with declining renewable energy and electrolyzer costs. Forecasts estimate green H_2 to play a progressively large role in international energy portfolios, with demand to grow and production costs to decline. Simultaneously, Section 813 of the Infrastructure Investment and Jobs Act supports the development of one or more green H_2 hubs with a specific end-use focus: transportation, electricity generation, residential heating, or industry. As a major importer and recycler of steel, the U.S. can benefit from increasing domestic steelmaking capacity and implementing green H_2 as an alternative energy carrier and reducing agent in steel production. To this end, a green H_2 hub ought to be considered for demonstrating end-use in the industrial sector.

Part I. Introduction/Overview

After months of delegation, H.R.3684: Infrastructure Investment and Jobs Act (IIJA), became law in November 2021. Among the $1.2 trillion dollar planned investments lie special provisions for an underrepresented energy carrier: clean hydrogen (H_2). IIJA delegates $9.5 billion dollars for projects that demonstrate the production, use, and recycling of clean H_2. This is the largest one-time federal investment in H2 in American history. Section 814: National Clean Hydrogen Strategy and Roadmap specifically mandates the DOE Secretary submit a strategy to facilitate a U.S. H2 economy. The roadmap will support economic incentives for clean H_2 production and utilization. Most notably, IIJA authorizes the creation of clean regional hydrogen hubs, which will validate at least four regions for co-localized production and use of low-carbon H_2. These initiatives and funding have potential to help realize a new pathway forward for clean H_2 production methods and its potential in U.S. decarbonization goals.

Hydrogen (H_2) has long been hypothesized as the energy of the future.[1] As a fuel substitute, it's versatile and emits primarily water vapor when combusted.[2] H_2 is abundant in natural compounds such as water, coal, and natural gas. H_2 must be removed, or produced, from these compounds in an energy-intensive process. As such, H_2 is similar to electricity: it acts as an energy carrier, not an energy source. H_2 production methods differ in their respective emissions intensity, feedstock, and overall cost. In the U.S, the traditional production method is gray H_2. Gray H_2 is produced from methane and emits greenhouse gas (GHG) at levels comparable to

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[1] The U.S. began passing federal H2 policy to support the development of the alternative energy carrier in the 1970's, with long-term plans for H2 fuel cell electric vehicles (FCEVs). U.S. H2 policy has since heavily favored FCEVs. In 2003, the Bush administration created a $1.2B initiative to support FCEVs and reduce American dependence on oil.

[2] Nitrous oxides (NO2) are emitted during the combustion of all fuels, hydrogen included. NO2 is a potent air pollutant and greenhouse gas.

the global aviation industry.[3] Clean H_2 may be produced with little to no carbon dioxide (CO_2) and methane (CH_4) emissions. For example, green H_2 may be produced via electrolysis powered by renewable energy. There are no direct GHGs emitted by green H2 production, however it is not yet cost-effective to replace gray H_2 with green.

Of the clean H2 investments included in the Infrastructure Bill, $8 billion is authorized for the creation of regional clean H_2 hubs. Clean H_2 hubs must demonstrate the viability of the entire H_2 value chain, overcoming economic, physical, and technical barriers. At least one hub must demonstrate production, delivery, and end use of green H_2. The green H_2 hub may focus end-use on residential heating, electricity generation, transportation, or industry.

One sector that stands to benefit from successful green H_2 demonstration is steel. Making steel is highly emissions intensive and accounts for 8-9% of global GHG emissions. The sector is hard-to-abate, with physical, technical, and economic barriers that inhibit substantial emissions reductions. However, green H_2 is capable of serving as a low-carbon reducing agent and energy carrier for steel production.

Steel is low-carbon iron, which may be recycled. However, to make new steel oxygen must be removed from iron ore in a process known as reduction. Traditional steelmaking uses coal as a source of carbon for iron ore reduction. The vast majority of global steel is produced in China by this method, known as blast furnace, coupled with basic oxygen furnace (BF-BOF). U.S. steel is primarily recycled or imported.

Steel is a necessary material for modern society, and, as the world builds the need for steel will increase. It’s estimated that global demand for steel will increase between 30-50% by 2050, in part due to growing demand for high-density housing, improved infrastructure, and renewable energy equipment, among other areas of opportunity. The revenue, jobs, materials, and national security provided by the steel industry make it difficult to restructure steel production, but in lieu of decarbonization goals, changes must be made.

In an attempt to reduce emissions from steel production, increase domestic steel output, reduce U.S. reliance on steel imports, a case emerges for the use of green H_2 in steel production.
H_2 is a relevant reducing agent in *one* steel production method: direct-reduced iron (DRI). In this process, H_2 acts as a reducing agent to remove oxygen from iron ore and form sponge iron. The sponge iron is then entered into an electric arc furnace (EAF) for processing into crude steel. H2-DRI is not commercially available in the U.S., but it has shown success in pilot projects, with plans for full-scale development for several countries.

I.I. U.S. Hydrogen Policy

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[3] Leigh Collins, “'So little attention' Emissions from current fossil hydrogen production on par with global aviation industry,” *Recharge News*, April 21, 2022, https://www.rechargenews.com/energy-transition/so-little-attention-emissions-from-current-fossil-hydrogen-production-on-par-with-global-aviation-industry/2-1-1204412.

The U.S. government has supported H_2 R&D at national labs since the 1970's, but federal policy has historically focused on fuel cell electric vehicle (FCEV) research and deployment. Prior to 2019, 80% of U.S. H_2 policies explicitly supported the use and expansion of FCEVs and H_2 refueling stations.[4] Subsidies, regulatory standards, credits, strategies, and mandates did not exist for clean H_2 outside of FCEV R&D.[5] Notably, after nearly 50 years of R&D funding, there are less than 7,000 H_2 FCEVs on the road today.[6]

In 2017, U.S. H_2 policy began to change. The U.S. initiated market studies for a national H_2 roadmap in 2017, soon after the EU, Argentina, Netherlands, Japan, and South Korea released their H_2 strategies.[7][8] In 2019, the IPCC report served as another wake-up call: hard-to-abate sectors must be included in decarbonization strategies to achieve 1.5℃. Perhaps in response to international H_2 pledges and mounting pressure to reduce emissions, the window for H_2 opened again.

The Hydrogen Fuel Cell and Technologies Office, of the DOE Office of Energy Efficiency and Renewable Energy (EERE), manages H_2 R&D activities. Its leading initiative, the Hydrogen Shot, was launched in July 2021 and aims to reduce clean H_2 production costs by 80% in ten years: $1/kg by 2031.[9] If clean H_2 production costs fall below $1/kg, it should unlock market potential to become competitive with gray H_2. To meet these goals, the EERE Office plans to accelerate R&D, de-risk demonstrations, and strategically scale-up production by co-locating clean H_2 production and end-use.[10]

The regional clean H_2 hubs, authorized by Section 813 of the IIJA, will demonstrate co-location of clean H_2 production and end-use. The bill authorizes $8 billion for the creation of *at least* four regional clean H_2 hubs. Each hub will be tasked to demonstrate the following:

1) Aid achievement of clean H2 production standard
2) Demonstrates full scale (production, processing, delivery, storage, end-use) of clean H2
3) Support a national clean H_2 network[11]

The four H_2 hubs must demonstrate use of green, blue, or pink H_2 in one of four end-uses: heating, transportation, electric power generation, or industry. States and industries are required

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[4] IEA, *The Future of Hydrogen Policy Dataset*, (Paris: IEA, 2019), https://www.iea.org/reports/the-future-of-hydrogen/data-and-assumptions.

[5] Ibid.

[6] Hydrogen and Fuel Cell Technologies Office, *Fact of the Month March 2019: There Are More Than 6,500 Fuel Cell Vehicles On the Road in the U.S*, March 2019. https://www.energy.gov/eere/fuelcells/fact-month-march-2019-there-are-more-6500-fuel-cell-vehicles-road-us.

[7] Korea, Japan, and the Netherlands all employed targets and financial incentives for H2 strategies, R&D, demonstration projects, and/or commercialization before the U.S.

[8] IEA, *The Future of Hydrogen Policy Dataset.*

[9] "Hydrogen Shot," Hydrogen and Fuel Cell Technologies Office, Department of Energy, 2022, Accessed March 5, 2022, https://www.energy.gov/eere/fuelcells/hydrogen-shot.

[10] Sunita Satyapal, "U.S. DOE Hydrogen and Fuel Cell Perspectives," (presentation, Office of Energy Efficiency and Renewable Energy, December 1, 2021), https://www.energy.gov/sites/default/files/2021-12/ghc-fall-meeting-2021.pdf.

[11] Infrastructure Investment and Jobs Act, H.R. 3684, 117th Cong. (2021).

to submit proposals for consideration as a H2 hub. The Office of Clean Energy Demonstrations, created by the IIJA, authorizes funding for the hubs and oversees an additional $1 billion for clean H_2 demonstration projects in rural areas and $500 million for demonstration projects in economically hard-hit communities.[12] The Infrastructure Bill's support for clean H_2, in collaboration with EERE's Hydrogen Shot Initiative, should help address physical, economic, and technical limitations of clean H2.

International H_2 policy is also developing at a rapid pace. As of 2021, at least 30 countries have established or are preparing H_2 strategies with committed funding for H_2 R&D and deployment. Governments have pledged $70 billion in funding, and global industries have announced over 200 projects. If carried to completion, these projects could invest $300 billion in the global H_2 economy by 2030.[13]

Part II. Hydrogen (H_2)

Hydrogen (H_2) does not exist outside of the compounds it inhabits. As such, H_2 is considered an energy carrier, rather than an energy source. H_2 can conveniently store and transport energy, but much like electricity, it is only as clean as the process used to produce it. Most of the world's H_2 is produced from fossil fuels. If H_2 is to be considered as a method for decarbonization, it must be produced in a less carbon-intensive manner.

Despite the limitations of clean H_2, its potential as an energy carrier has inspired international H_2 strategies, billions of dollars of investment, and research projects around the world. For H_2 to have potential in emissions reductions for hard-to-abate sectors, it must be produced using renewable energy, fossil fuels with CCS, nuclear energy, biomass, or waste. In lieu of the many shades in the H_2 rainbow, green H_2 has been chosen as the focus of this report.

Properties

H_2 is the lightest and most abundant element on earth. It is odorless, non-toxic, does not decompose, and emits no carbon dioxide (CO2) or methane (CH4) when burned. H_2 is unique in that it has high energy density by weight, and low energy density by volume. In other words, H_2 is an excellent energy carrier: there's more energy per weight than traditional fuels.[14][15] Simultaneously, H_2 takes up much more space than traditional fuels due to its low volumetric energy density, thereby creating storage and transportation hurdles.

H_2 must be removed, or produced, from the compounds it naturally inhabits. As such, H_2 is similar to electricity: it acts as an energy carrier, not an energy source. Methods for H_2

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[12] Department of Energy, *DOE Fact Sheet: The Bipartisan Infrastructure Deal Will Deliver For American Workers, Families and Usher in the Clean Energy Future*, November 9, 2021, https://www.energy.gov/articles/doe-fact-sheet-bipartisan-infrastructure-deal-will-deliver-american-workers-families-and-0.

[13] Hydrogen Council and McKinsey & Company, *Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness*, (Hydrogen Council, 2021), 4, https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021.pdf.

[14] 1kg of H_2 produces nearly three times as much energy (kWh) as natural gas.

[15] "Hydrogen Data," Ludwig-Bölkow-Systemtechnik, n.d., http://www.h2data.de/.

production vary for capital expenditures (CAPEX), levelized cost of electricity (LCOE), emissions intensity, and energy intensity.

II.I. H_2 Production, emissions

H_2 is commonly used to aid oil refining, ammonia production, and other petrochemical processes. Global H_2 production is roughly 90 $MmtH_2$/year, with the U.S. producing 10$MmtH_2$/year.[16][17]

The majority (>90%) of H_2 is called gray hydrogen; it is produced from fossil fuels, most commonly via steam methane reform (SMR) sourced from natural gas, resulting in CO_2, CO, and CH_4 by-products.[18] Alternative methods for H_2 production include:

> Pink: nuclear-powered electrolysis splits water
> Turquoise: pyrolysis transforms CH_4 from natural gas into H_2 and solid carbon.
> Brown: coal gasification.
> Blue: fossil fuels as feedstock; steam methane reform with carbon capture and storage (CCS)
> Green: electrolysis powered by renewable energy (solar, wind, biomass, geothermal, etc.)[19]

Emissions from H_2 production

Gray H_2's dominance in the H_2 market is a significant environmental concern. Global H_2 production emits roughly 830 $MmtCO_2$/year.[20] The U.S. H_2 industry emits 90 $MmtCO_2$/year, more than the country-wide CO_2 emissions from Norway and Finland, combined.[21]

Green, blue, and pink H_2 are considered clean, as the carbon intensity and overall life cycle assessments of these production processes are significantly lower than fossil-based H_2

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[16] IEA, *Global Hydrogen Review 2021*, (Paris: International Energy Agency, 2021), 5, https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf.

[17] Zhiyuan Fan et al. *Green Hydrogen in a Circular Carbon Economy: Opportunities and Limits.* (SIPA Center on Global Energy Policy, 2021). https://www.energypolicy.columbia.edu/research/report/green-hydrogen-circular-carbon-economy-opportunities-and-limits.

[18] Roughly 97% of global H_2 is produced from natural gas or coal.

[19] Though electrolysis is considered the default mechanism for green hydrogen, there are other methods still undergoing research, including thermal and photolytic splitting of water, pyrolysis and fermentation of biomass, and plasma reforming.

[20] IEA, *The Future of Hydrogen,* 17.

[21] Hannah Ritchie et al. "CO_2 and Greenhouse Gas Emissions," Our World in Data, August 2020. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions#co2-and-greenhouse-gas-emissions-country-profiles.

production.[22][23] Emissions factors for gray and brown H_2 production are 8.9kgCO_2/kgH_2 and 20.2kgCO_2/kgH_2, respectively.[24] The IEA estimates the direct emissions intensity of blue H_2 to be about 1kgCO_2/kgH_2.[25] However, the IEA's blue H_2 emissions intensity estimates fail to address the lifecycle emissions released from natural gas extraction, transportation, and distribution. Additionally, capture rates are highly variable, as CCS technology currently captures CO_2 directly from SMR plants, leaving CO_2 from on-site combustion processes unaddressed.[26] Green H_2 production produces no direct GHG emissions if the source used to power electrolysis is entirely renewable.[27] However, similar to lifecycle emissions for fossil fuels, the upstream, operational, and downstream processes that enable renewable energy to power electrolysis garner some emissions over their life cycles.[28] These values are still significantly less than lifecycle emissions from natural gas used to produce gray H_2. NREL estimates the lifecycle GHG emissions for onshore wind energy and solar PV is 10gCO_2/kWh, and 50gCO_2/kWh, respectively. If 45 kWh of electricity is required for 1kg green H_2, these values would total 0.45kgCO_2/kgH_2 and 2.25kgCO_2/kgH_2 for wind and solar PV, respectively.[29]

Transitioning to clean H_2 is difficult, as gray H_2 is cheap to produce, SMR infrastructure is readily available, and natural gas prices tend to be low in the U.S. To realize clean H_2 potential, economic barriers for renewable energy sources (RES) and electrolyzer technology must be overcome.

II.II. Production costs

Green H_2 technology is commercially available, but production costs prevent large-scale deployment.

The biggest cost component for H_2 production is fuel: natural gas, grid electricity, or renewable-sourced electricity. The levelized cost of renewable electricity (LCOE) accounts for 55% of green H_2 production costs, but may be as high as 70% depending on the region.[30]

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[22] Though blue H2 offers significant GHG emissions reductions compared to gray, it should be noted that only 1% of global H2 is produced using CCS. Most CCS capture rates are estimated to be about 55-90%, with 1.5-4% CH_4 leakage. Capture rates may differ in demonstration projects.

[23] Goldman Sachs, *Carbonomics: The Clean Hydrogen Revolution*, (New York: Goldman Sachs, 2022), 71,https://www.goldmansachs.com/insights/pages/gs-research/carbonomics-the-clean-hydrogen-revolution/carbonomics-the-clean-hydrogen-revolution.pdf.

[24] IEA, *The Future of Hydrogen Assumptions Annex,* 3.

[25] Ibid.

[26] Christian Bauer et al. "On the climate impacts of blue hydrogen production," (Sustainable Energy Fuels, 2022), 6, 66-75, https://pubs.rsc.org/en/content/articlehtml/2022/se/d1se01508g.

[27] If grid electricity is used to power electrolysis, the process releases more GHG emissions than using direct natural gas.

[28] Upstream emissions for renewable energy include raw materials extraction, materials production, construction of PV and wind turbines, etc. Operations emissions include system maintenance and operation. Downstream processes include plant decommissioning and disposal.

[29] Pareek, Alka, Rekha Dom, Jyoti Gupta, Jyothi Chandran, Vivek Adepu, and Pramod Borse, "Insights into renewable hydrogen energy: Recent advances and prospects," *Materials Science for Energy Technologies*, 3 (January 2020): 319-327. https://doi.org/10.1016/j.mset.2019.12.002.

[30] Fan et al. *Green Hydrogen in a Circular Carbon Economy: Opportunities and Limits*. 2021.

The levelized cost to produce gray H_2 ranges from \$0.50-1.70/kgH_2, depending on the price of natural gas. Adding CCS technology for blue H_2 increases the cost to \$1-2/kgH_2. Green H_2 prices, meanwhile, range from \$3-8/kgH_2 globally, though the U.S. range is closer to \$5-6/kgH_2.[31][32]

Electrolyzer capital costs (CAPEX) also influence the price of green H_2, though its impact varies with the electrolyzer technology. There are three primary technologies for electrolysis: alkaline electrolyzers, PEM electrolyzers, and solid oxide electrolysis cells (SOEC). Alkaline electrolyzers are fully mature, and most cost competitive to build and operate. There is limited production of PEM electrolyzers, and SOEC due to high CAPEX costs. However, each boasts higher efficiency and quicker response rates than alkaline electrolyzers.[33] PEM also appears to be safer, better performing, and capable of better integration with intermittent power generation than alkaline electrolyzers.[34]

Lastly, increasing the number of operating hours, or an electrolyzer's load factor, lowers the production cost of H2. As renewable electricity generation becomes more widely available, the load factor should benefit, but wind-solar hybrid systems are most promising to assure adequate capacity for electrolyzers.[35]

Narrowing the gap

Green H_2 must be produced at ~\$1/kgH_2 to be competitive with gray H_2. While LCOE for renewable energy sources (RES) have fallen drastically over the last decade, they are still not low enough to achieve cost parity for green H_2. The IEA's Global Hydrogen Review estimates RES electricity prices should be <\$20/MWh for green H_2 to achieve \$1/kg. Current grid-powered electricity ranges in price, between \$50-100/MWh.[36] U.S. regions with high-quality wind assume weighted-average LCOE around \$37/MWh, and \$31/MWh for U.S. solar PV.[37] Until the U.S. weighted-average LCOE falls significantly, it's important to co-locate green H_2 production with regions capable of strong RES potential.

Green H_2's cost competitiveness will further be supported by growth in electrolyzer capacity, stronger climate policy, and mounting industry alliances. Global capacity of electrolyzers is also growing, having doubled since 2016 to reach 300 MW in 2021. Boosting electrolyzer capacity

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[31] Ibid.

[32] \$5-6/kgH_2 reflect renewable electricity prices of \$50-70/MWh and electrolyzer CAPEX of \$1000-1,500/kW per (Vickers, Peterson, and Randolph 2020).

[33] Fan et al. *Green Hydrogen in a Circular Carbon Economy: Opportunities and Limits*. 2021.

[34] Chandrasekara, Aruna, Damian Flynn, and Eoin Syron. “Operational challenges for low and high temperature electrolyzers exploiting curtailed wind energy for hydrogen production.” *International Journal of Hydrogen Energy*, 46, no. 57 (2021): 28900-28911, https://doi.org/10.1016/j.ijhydene.2020.12.217.

[35] IRENA, *Hydrogen: A Renewable Energy Perspective*, (Abu Dhabi: International Renewable Energy Agency, 2019), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf.

[36] IEA, *Global Hydrogen Review 2021*, 123.

[37] IRENA, *Renewable Power Generation Costs in 2020*, (Abu Dhabi: International Renewable Energy Agency, 2021), 43, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020.pdf.

will improve its efficiency, lifetime, and learning rates for electrolyzer installation, further reducing CAPEX and OPEX costs.[38] Improvements in efficiency will also reduce the electricity required to produce each unit of H_2.

II.III. Forecasts

Many high-level technical reports attempt to predict H_2's future. The following forecasts analyze future scenarios for global H_2 integration and cost-parity: Hydrogen Council, BloombergNEF, Goldman Sachs, IEA, and IRENA. Each report assumes a significant role for clean H_2 in achieving net-zero emissions. Fundamentally, H_2 demand is expected to increase, and clean H_2 costs to decrease.

The reports predict cost parity of green H_2 with blue H_2 by 2030, and cost parity with gray H_2 by or before 2050.[39] Abundant RES, low RES LCOE, low or average natural gas prices, and carbon prices are assumed to support these estimates. The speed at which each is achieved and deployed will influence H_2's future.

Global H_2 demand estimates	2030 (Mmt)	2050 (Mmt)	Key assumptions
Goldman Sachs (Bear scenario)	115	220	Net-zero by 2070, 2℃ warming
IEA, Announced Pledges Scenario[40]	125	250	Existing projects with in-progress feasibility studies or final investment decisions. 1,350 GW capacity, 0.4 Gt CO_2/yr captured
Goldman Sachs (Base scenario)	125	368	Net-zero by 2060, <2℃ warming
IEA, Net-Zero Emissions Scenario[41]	212	530	$1.2T investments in low-carbon supply through 2030
IRENA, 1.5 degree scenario[42]	–	614	Annual addition of 160 GW electrolyzer

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[38] Automation in manufacturing, improvements in economies of scale, and greater deployment of electrolyzers will support cost reductions as well. Per (IRENA 2021)

[39] BloombergNEF, "'Green' Hydrogen to Outcompete 'Blue' Everywhere by 2030," *BloombergNEF,* May 5, 2021, https://about.bnef.com/blog/green-hydrogen-to-outcompete-blue-everywhere-by-2030.

[40] IEA, *Global Hydrogen Review,* 111.

[41] IEA, *Net Zero by 2050*, (Paris: International Energy Agency, 2021), 76, https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.

[42] IRENA, *World Energy Transitions Outlook: 1.5°C Pathway*, (Abu Dhabi: International Renewable Energy Agency, 2021), 81, https://irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_World_Energy_Transitions_Outlook_2021.pdf.

			capacity until 2050
H2Council[43]	–	660	H_2 to abate 7 GtCO2 in 2050; 3-4 TW electrolyzer capacity, 5 TW renewable generation capacity
BNEF, strong policy[44]	–	696	Net-zero climate targets legislated, regulatory barriers removed, standard harmonization, investment mechanisms, emissions standards

Table 1. Of the technical reports analyzed, each anticipates growing demand for H_2 by 2030 and 2050. The varied assumptions indicate significant uncertainty. Current pure H_2 demand in 2021 is 90 Mmt.

Each of the technical reports indicate at least a 2-fold increase in H_2 demand by 2050 to achieve net-zero. The variety in assumptions and estimates across technical reports showcase the degree of uncertainty in estimating H_2's demand in 2030 and 2050. The path forward is highly uncertain. However, it's clear that H_2 is a necessary addition to decarbonization portfolios, especially for hard-to-abate sectors.

Report	Cost parity: blue	Cost parity: gray	Key assumptions
Goldman Sachs[45]	2030	2030	RES LCOE: \$30-40/MWh Average gas prices (\$5/mcf) Global CO_2 price: \$45/tCO_2
Hydrogen Council[46]	–	2034	Abundant renewable resources, Gas prices: \$2.6-6/Mmbtu LCOE: \$13-37 MWh (2030), Global carbon price:

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[43] Hydrogen Council, *Hydrogen for Net-Zero: A Critical Cost-Competitive Energy Vector*, (Hydrogen Council and McKinsey & Company, 2021), v, https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero.pdf.

[44] BloombergNEF, *Hydrogen Economy Outlook Key Messages*, (Bloomberg Finance, 2020), 8, https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf.

[45] Goldman Sachs, *Carbonomics: The Clean Hydrogen Revolution,* 49.

[46] Hydrogen Council and McKinsey & Company, *Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness*, 13.

			\$50/tCO2
IEA[47]	2030	2050	Net-zero emissions by 2050 scenario
BloombergNEF	2030-2035	2050	Cost of production falls 85%

Table 2. Technical reports predict cost-parity of green hydrogen with blue by 2030, and cost-parity with gray by 2050.

Each report anticipates cost parity of green H_2 with gray H_2 by 2050. Significant policy, regulatory, and market changes are necessary to achieve quick adoption and deployment, especially in hard-to-abate sectors such as steel.

II.IV. Limitations

Storage and transportation

H_2 can be stored for later transport and use. However, its low volumetric energy density makes it difficult to store as a gas. The two most common methods for storage are liquefaction and gaseous compression, but H_2 may be stored as a sorbent, hydride, or high pressure solid as well. Liquid H_2 must be stored at incredibly low temperatures, and it is energetically inefficient to liquify H_2. To preserve efficiency and limit costs, H_2 is best stored and transported as a compressed gas.[48][49]

Transporting H_2 by pipeline risks H_2 embrittlement, as H_2 can crack and defect its containing metal. Over time these metals may break down and become more prone to corrosion and leaks. H_2 leakage, even in small increments, is a major safety concern. As H_2 is fourteen times lighter than air, it escapes easily in the presence of leaks. Its lack of odor, taste, and visibility adds difficulty to attesting leaks. Further R&D is needed to assure adequate detection sensors during transport.

Efficiency losses

When H_2 is separated from the compounds it naturally inhabits, some useful energy is lost in the process. To produce green H_2, renewable energy powers electrolysis to split water into H_2. Green H_2 may then be transported, stored, or put to use. Each of these steps experience efficiency losses, culminating in a round-trip efficiency that is inherently less than fossil fuels.[50]

NOx

H_2 can act as both a reducing agent and source of heat in H2-DRI steelmaking. As a source of heat, H_2 must undergo combustion. H_2 combustion, similar to fossil fuel combustion, releases NOx emissions when molecular nitrogen reacts with high temperature flames. Achieving stable,

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[47] IEA, *Net Zero by 2050*, 110.

[48] Dias, Véronique, et al. “Energy and Economic Costs of Chemical Storage.” *Frontiers in Mechanical Engineering* 2020. https://doi.org/10.3389/fmech.2020.00021.

[49] Liquid H_2 must be stored at temperatures lower than -253℃.

[50] The efficiency of alkaline electrolysis, the most common form of electrolysis, is roughly 72%. (Dias et al. 2020, 4)

efficient H_2 combustion while limiting nitrogen oxide (NOx) emissions is a difficult balance to strike. When flame temperatures rise above 1810 K, the rate of NOx formation increases significantly.[51] H_2 has a flame temperature of 2382 K. NOx emissions from H_2 combustion can negatively impact air quality and public health, and thus ought to be monitored and mitigated in line with National Ambient Air Quality Standards (NAAQS). Possible methods for reducing NOx emissions during H_2 combustion include reducing the combustion temperature, recirculating exhaust gas, and injecting water via dry low NOx combustion.[52]

Water consumption

Although water is decomposed in electrolysis, water demand is comparable between gray and green H_2 production. Water is required to cool feed gas and syngas in gray H_2 production, and much of it is lost to evaporation. For green H_2 production, the water consumption value varies depending on the source of electricity used to power electrolysis.

H_2 production process	Gray	Green (hydro; PEM)	Green (wind; PEM)	Green (solar PV; PEM)[53]
Water use (kgH_2O/kgH_2)	13.6	9	11	19

Table 3. Total water demand is not necessarily greater for green H_2 production.[54] Source: (Hydrogen Council 2021) and (Goldman Sachs 2022).

When electrolysis is powered by grid electricity, the water footprint becomes significantly higher.[55][56] Water demand is considered minimal in H_2 production when compared to natural gas extraction, which is extremely water intensive.

Part III. Steel.

Despite its physical, technical, and economic limitations, green H_2 is an excellent clean energy candidate for steel production. H_2 is the only non-fossil fuel capable of high-temperature combustion and iron reduction, two processes that are integral to steel production. While on the cusp of growing support for clean H_2 and falling RES prices, an opportunity has opened for decarbonizing steel.

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[51] He, Zhuohui, Clarence Chang, and Caitlin Follen, *NOx Emissions Performance and Correlation Equations for a Multipoint LDI Injector*, (NASA, April 2014), 4, https://ntrs.nasa.gov/api/citations/20140005329/downloads/20140005329.pdf.

[52] Kikuchia, Kenta et al, “Influence of nozzle design parameters on exhaust gas characteristics in practical-scale flameless hydrogen combustion,” *International Journal of Hydrogen Energy* 47, no. 49 (2022): 2. https://doi.org/10.1016/j.ijhydene.2022.04.230

[53] Solar PV panels require water to clean PV panels, cool equipment, and power towers.

[54] Goldman Sachs, *Carbonomics: The Clean Hydrogen Revolution,* 71.

[55] Truly green electrolysis (non-fossil fueled, i.e. not grid-electrolysis) performs best for life cycle environmental impacts, which includes water consumption potential.

[56] Andi Mehmeti et al., “Life Cycle Assessment and Water Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies,” *Environments* 5, no. 2 (February 2018): 24, https://doi.org/10.3390/environments5020024.

To achieve net-zero, steel must be included in decarbonization efforts. Steel significantly contributes to global warming: if the global steel industry was a country, it would rank third in greenhouse gas emissions.[57][58] Steel is hard-to-abate for several reasons. Physically, traditional steelmaking requires high temperature combustion and a strong reducing agent for iron ore. Economically, steel plants possess high capital costs and long lifetimes. For example, a U.S. steel plant built in 1810 still operates today.[59] Lastly, the majority of steel is produced in China, and the U.S. imports and recycles most of the steel it consumes.

III.I. Production processes

Steel is essentially low-carbon iron. As iron is one of the most abundant metals on earth, it's easy and cheap to obtain. To process iron into steel, iron ore (Fe_2O_3 or Fe_3O_4) must be reduced to remove the oxides. Depending on the steelmaking process, the reducing agent may be coke, carbon monoxide, unburned carbon, or hydrogen. Alternatively, steel can be recycled for new use.

The U.S. uses three methods to produce steel: integrated blast furnace/basic oxygen furnace (BF-BOF), electric arc furnaces (EAF), and direct-reduced iron (DRI). Each process differs in feedstock, energy sources, and GHG emissions.

Traditional steelmaking integrates a blast furnace (BF) with a basic oxygen furnace (BOF) to produce crude steel. Iron ore concentrate is pelletized and then fed into the hot BF at temperatures as high as 2000℃, where it is combined with a reducing agent, such as coke, to form pig iron. Pig iron, a solid, is then fed into the BOF along with oxygen, which removes carbon impurities and releases CO_2. The result is low-carbon steel, or crude steel. The most common by-products of integrated steel mills are heat, CO_2, and SOx, though SOx is recovered by desulfurization.[60]

BF-BOF is most commonly used in China, but 12% of U.S. steel making plants are integrated. Many integrated steel mills have closed in the U.S. due to operational costs, and the cost competitiveness of natural gas in modern production processes. Though the number of U.S BF-BOF plants is relatively low, these plants boast high output potential, and constitute 23% of U.S. steel making capacity.

Electric arc furnaces (EAF) recycle steel. In this process, electricity powers a furnace to temperatures just high enough to mold scrap steel for a new end-use. Passenger vehicles account for the bulk of scrap, with roughly 12 million cars recycled annually.[61] Natural gas is

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[57] Mark Peplow, "Can industry decarbonize steelmaking?" *C&EN*, June 13, 2021. https://cen.acs.org/environment/green-chemistry/steel-hydrogen-low-co$_2$-startups/99/i22.

[58] The steel industry emits roughly 3,000 MmtCO_2/year. In 2021, the U.S. emitted 4,600 MmtCO_2.

[59] Global Energy Monitor, "Global Steel Plant Tracker," 2022, accessed May 8, 2022, https://globalenergymonitor.org/projects/global-steel-plant-tracker/

[60] Energetics, Incorporated, *Environmental Profile of the U.S. Iron and Steel Industry*, DOE/EE-0229 (U.S. Department of Energy, 2000) https://www.energy.gov/sites/prod/files/2013/11/f4/steel_profile.pdf.

[61] Christopher Tuck, *Mineral Commodity Summaries, Iron and Steel*, (U.S. Geological Survey, 2021), https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-iron-steel-scrap.pdf.

used to power the furnace, and CO_2 is the major byproduct. Electric arc furnaces produce 72% of U.S. steel.[62]

EAFs are highly efficient, use cheap energy sources, and boast short manufacturing times. EAFs are also less energy intensive than BF-BOF; it operates using one-eighth the energy required for BF-BOF.[63] Both EAF and BF-BOF require significant amounts of water, but 95% of water used is recycled back to its original source. Surface water, desalinated sea water, and groundwater are all used in U.S. steelmaking mills.[64]

Direct-reduced iron (DRI) is gaining notoriety again after falling off the map centuries ago. DRI is similar to BF-BOF: it forms new steel from iron ore. Fundamentally, DRI is iron ore that has been directly reduced without melting the metal. Iron ore pellets enter a shaft furnace, heated to $1000^{\circ}C$. H_2 and CO, produced from reformed natural gas or syngas, reduce the iron oxide pellets to iron. CO_2 and water vapor is released. The result is DRI or sponge iron, another form of pig iron. The DRI is then fed into an EAF for processing and shaping into crude steel.

DRI is a potentially significant steppingstone to reducing emissions in the steel industry. Though most DRI processes use CO and H_2 sourced from natural gas as a reducing agent, green H_2 may be used as a sole reducing agent in H2-DRI processes.[65] The only by-products are H_2 and water vapor.

Emissions:

Steel production processes emit carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), sulfur dioxides (SO_2), and nitrous oxides (N_2O). There are strict production and emissions standards for CO, SO2, and N2O, but it is not mandatory for steel producers to report their CO_2 emissions. Standards documentation for reporting carbon and emissions intensities are provided by the International Organization for Standardization (ISO), a partner of the World Trade Organization (WTO). In 2013, the ISO released ISO 14404-1 to support BF-BOF plants in calculating their carbon intensity. Subsequently, ISO 14404-2 and ISO 14404-3 created standards for measuring the carbon intensity of EAF and DRI, respectively. Additional guidance passed in 2020 expands standards to quantify CO_2 emissions from by-product gases, stock, and electricity.[66]

Steel producers are incentivized to collect and report emissions as it offers a way to track their emissions relative to others and identify areas for improvement. Steel plants that fulfill CO_2 data

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[62] Global Energy Monitor, “Global Steel Tracker.”

[63] Stein, Jay, “Joe Biden's Green New Steel,” *Canary Media*, April 28, 2021, https://www.canarymedia.com/articles/clean-industry/joe-bidens-green-new-steel.

[64] Energetics, Incorporated, “Energy and Environmental Profile of the U.S. Iron and Steel Industry,” 2000.

[65] Bellona, “Hydrogen in steel production: what is happening in Europe,” (Bellona Europa, May 26 2021), https://bellona.org/news/industrial-pollution/2021-05-hydrogen-in-steel-production-what-is-happening-in-europe-part-two.

[66] ISO/TC 17 Steel, “ISO 14404-4:2020 Calculation method of carbon dioxide emission intensity from iron and steel production - Part 4: Guidance for using the ISO 14404 series,” (December 2020), https://www.iso.org/standard/77622.html.

collection are considered Climate Action members of the international trade body, World Steel Association.[67] 94 companies representing 53% of global steel capacity reported data in 2021.[68]

On average, for every ton of steel produced, 1.89 tCO_2 is emitted. This value is the global average factor, but there is significant variety between steelmaking processes:[69]

Process	Emissions intensity (tCO2/t steel produced)
BF-BOF	2.03
DRI	0.78
EAF	0.58

Table 4. The emissions intensities of steel production.[70]

BF-BOF is the biggest threat to climate within the steel industry. The most emissions and energy-intensive step in BF-BOF processes is the blast furnace, with an energy factor of 8.2-10.4 GJ/ton pig iron.[71] The blast furnace releases 70% of process emissions.[72]

III.II. Steel capacity

The greatest players for steel production are as follows: China, India, Japan, and the U.S. Though the U.S. is the fourth largest producer of steel, there is little competition between the U.S. and China in steel output. China owns roughly 55% of global steelmaking capacity. In 2021, China produced 1,032 Mmt of crude steel, followed by India (118 Mmt), Japan (96 Mmt), and the U.S. (86 Mmt).[73] Most Chinese steel is produced by BF-BOF.

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[67] World Steel Association, "Worldsteel CO_2 Data Collection & reporting," (EFDB, IPCC/IEA, December 13-14 2018), https://iea.blob.core.windows.net/assets/imports/events/243/18_WSA_H.Reimink.pdf.

[68] World Steel Association, "Sustainability Indicators," (World Steel Association, November 2021), https://worldsteel.org/steel-by-topic/sustainability/sustainability-indicators/.

[69] Producing iron ore, a precursor step to steelmaking, also has a high emission factor: 1.85 tCO_2/t iron.

[70] World Steel Association, "Worldsteel CO_2 Data Collection & reporting."

[71] R. J. Fruehan, O. Fortini, H.W. Paxton, and R. Brindle, "Theoretical Minimum Energies To Produce Steel for Selected Conditions," (Pittsburgh: Carnegie Mellon University, May 2000), 20, https://www.energy.gov/sites/prod/files/2013/11/f4/theoretical_minimum_energies.pdf.

[72] Peplow, "Can industry decarbonize steelmaking?"

[73] World Steel Association, "PRESS RELEASE December 2021 crude steel production and 2021 global crude steel production totals," (Brussels, worldsteel, 2022), 4, https://worldsteel.org/wp-content/uploads/December-2021-crude-steel-production-and-2021-global-crude-steel-production-totals-4.pdf.

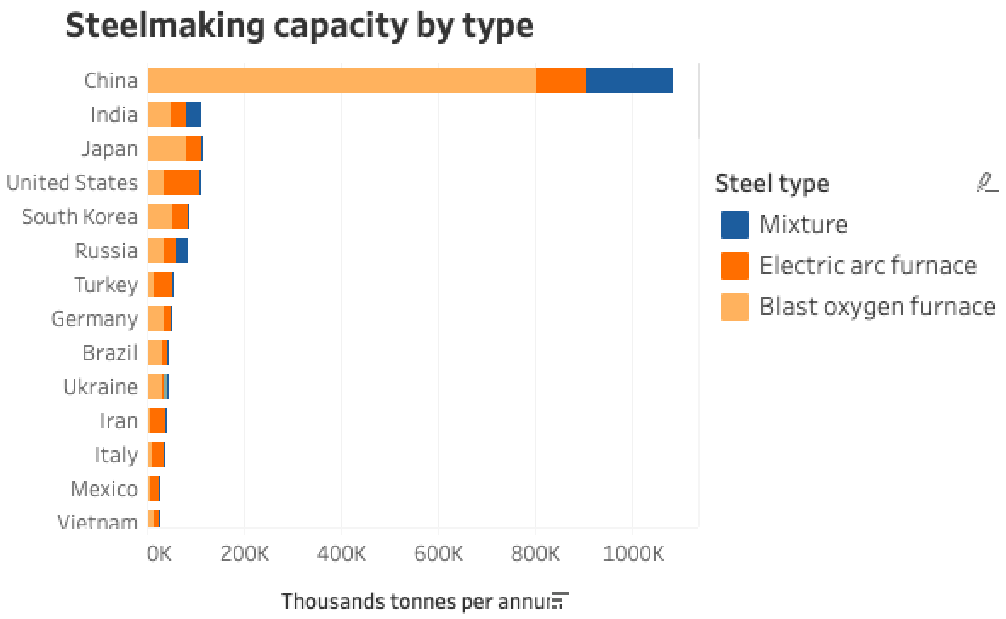

Figure 1. Steelmaking capacity by type, country.[74]

China is the world's leading exporter of steel, trading 51.4 Mmt in 2020, but most of the steel produced in the country is internally consumed.[75] Despite its primary stake in global production, steel plants in China face overcapacity. In 2020, steel output reached a record national high. Due to overcapacity concerns, the Chinese government issued a production cap in 2021, forbidding any year-on-year increase.[76] Subsequently, production fell 3% in 2021. If steel production continues to fall in China, other countries will have to onshore capacity to accommodate growing demand.

The majority of domestic U.S. steel is produced in Indiana (27%), Ohio (11%), and Pennsylvania (5%), though there are nearly 100 steel mills scattered across the continental U.S.[77] Of these, 6 companies own 50% of U.S. steelmaking capacity.

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[74] Global Energy Monitor, "Global Steel Plant Tracker."

[75] World Steel Association, *2021 World Steel in Figures*, (Brussels, worldsteel, 2021), 27, https://worldsteel.org/wp-content/uploads/2021-World-Steel-in-Figures.pdf.

[76] Zhong, Frank, "Blog: China's drive towards a low-carbon future and challenges ahead," World Steel Association, 28 January 2022, https://worldsteel.org/media-centre/blog/2022/blog-chinas-drive-towards-a-low-carbon-future-and-challenges-ahead/.

[77] Tuck, *Mineral Commodity Summaries.*

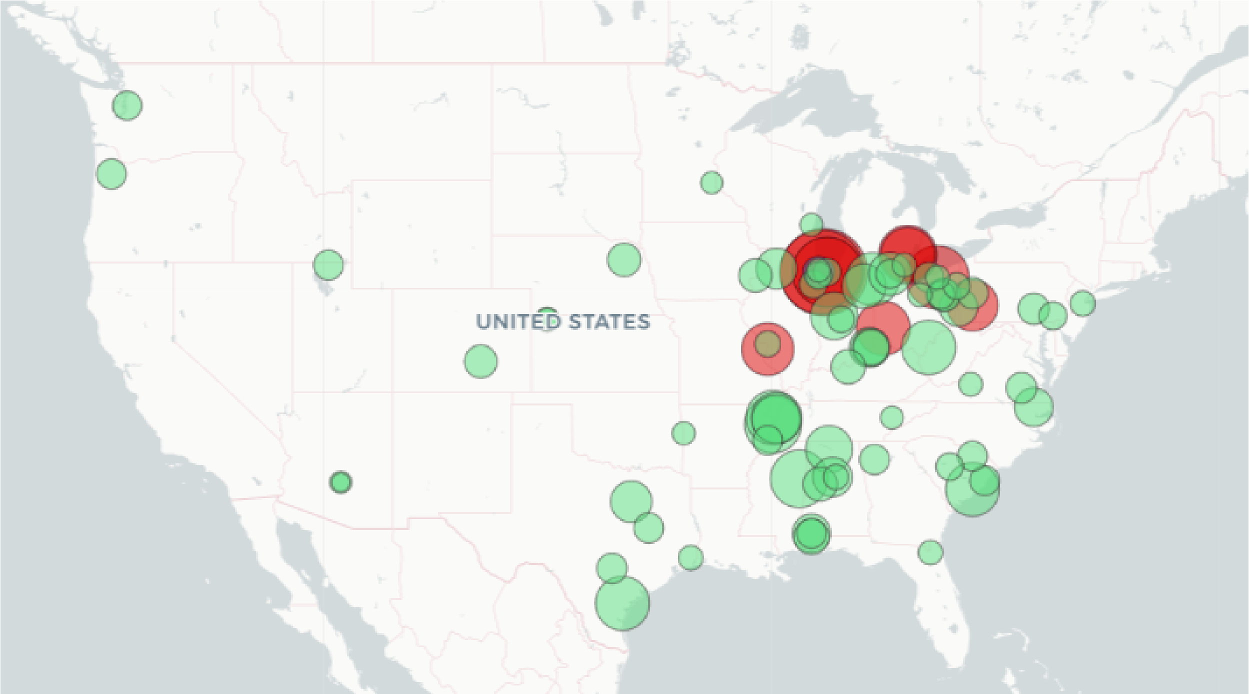

Figure 2. Steel production in the U.S., depicted by steel plant capacity.[78]

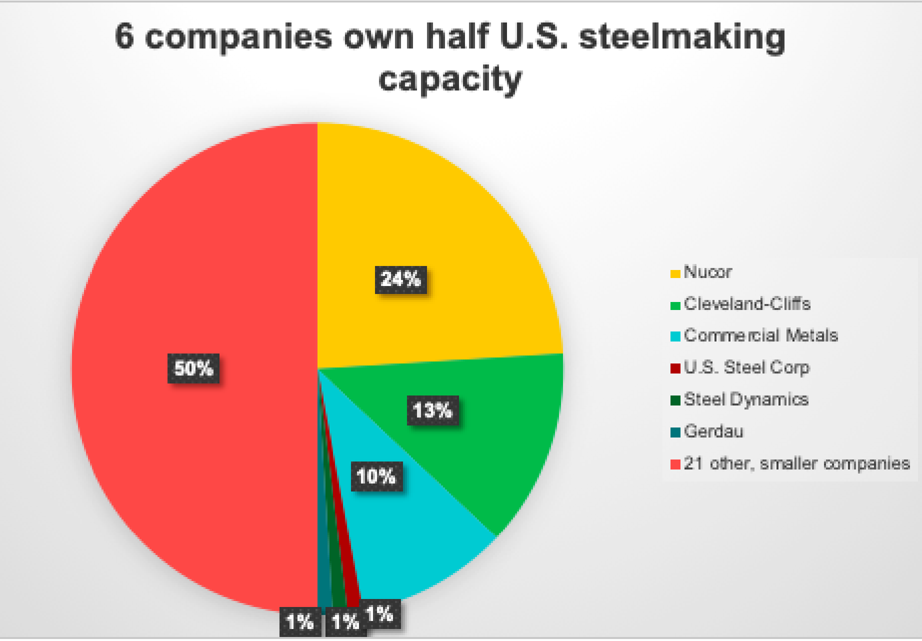

Figure 3. Steelmaking capacity is concentrated among big players*. Data received from Global Energy Monitor.*[79]

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[78] Global Energy Monitor, “Global Steel Plant Tracker.”

[79] Ibid.

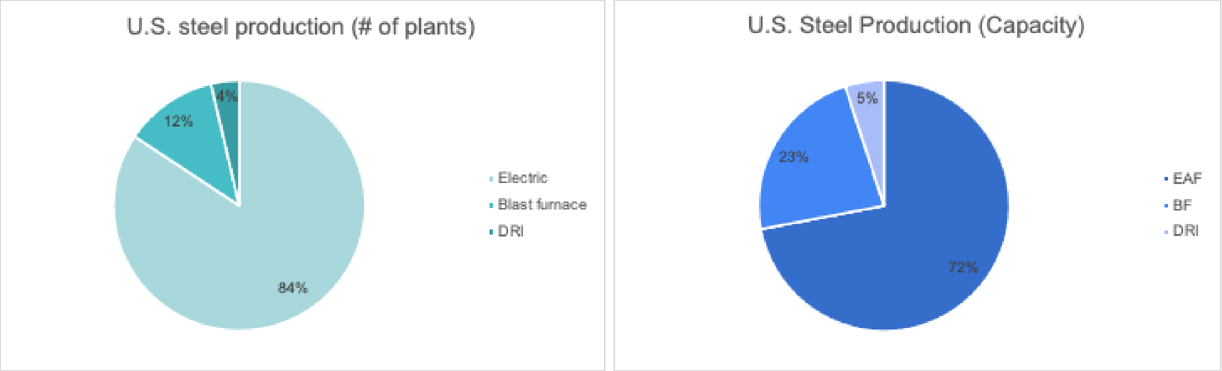

Figure 4. U.S. steel production. *Data received from Global Energy Monitor.*[80]

The U.S. primarily produces steel from scrap via EAF. Though only 12% of U.S. plants are BOF-BF, these mills produce 23% of U.S. capacity. Approximately 5% of U.S. steel capacity operates with DRI. The U.S. started employing DRI at scale in the 2010's, largely in response to low shale gas prices. DRI production in the U.S. has steadily increased from 1.8 Mmt in 2016 to 3.5 Mmt in 2020.[81]

Steel demand

Steel demand has more than doubled since 2000, likely in response to rising human population growth, global GDP, and emerging economies.
Global steel demand in 2021 was around 1,795 Mmt.[82] Worldsteel, the international trade body for iron and steel, reports a 4.1% worldwide increase in steel demand between 2019-2021.
To accommodate demand, global crude steel output in 2021 was 1,950.5 Mmt, an increase of 3.7% from 2020.[83]

The U.S. ranks third for apparent steel use. In 2020, despite the COVID-19 pandemic, U.S. demand for steel reached 80 Mmt of finished steel products. China's apparent steel use ranked first at 995 Mmt, and India second at 88.5 Mmt.[84]

U.S. Dependence on Steel Imports

Despite its rank as a major steel producer, the U.S. imports a significant amount of steel. In fact, the U.S. is considered the world's greatest net importer of steel, according to worldsteel.[85]

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[80] Ibid.
[81] World Steel Association, *2021 World Steel in Figures*.
[82] Ibid.
[83] World Steel Association, "PRESS RELEASE."
[84] World Steel Association, *2021 World Steel in Figures.*
[85] Ibid.

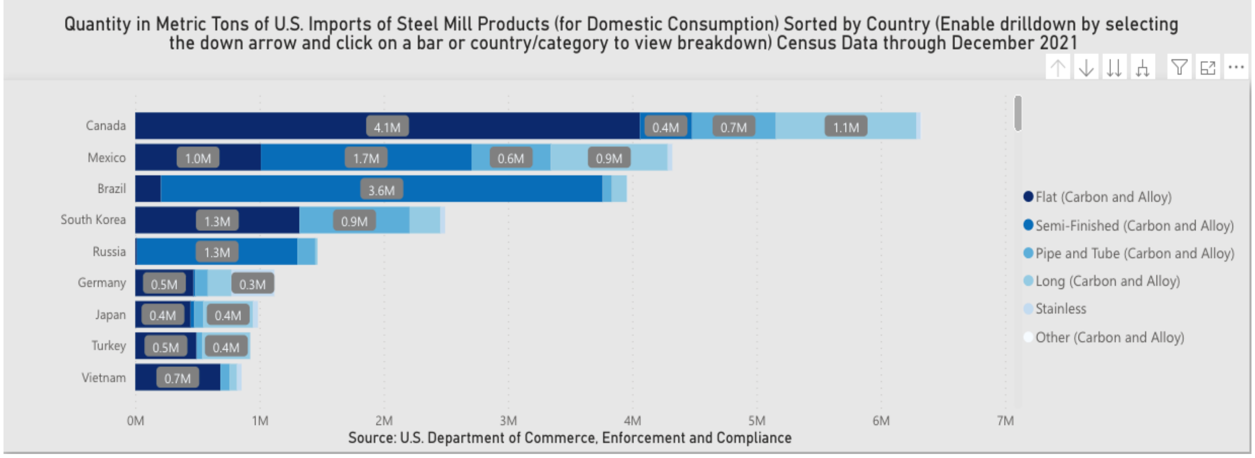

Figure 5. The majority of U.S. imports come from Canada, Mexico, and Brazil*. Chart retrieved from International Trade Administration. Data sourced from U.S. Department of Commerce, Enforcement and Compliance*[86]

Trade partners for steel help supplement high domestic demand. In 2021, steel imports primarily arrived from Canada (22%), Mexico (15%), Brazil (13%), South Korea (8.7%) and Russia (5%).[87] In total, the U.S. imported 29.6 Mmt in 2021, a 47% increase from 2020.[88]

The U.S. is the third greatest importer of steel; in 2020, 19.9 Mmt were imported, while 6.3 Mmt were exported. China (37.9 Mmt) and the European Union (32.6 Mmt) were the primary importers.[89] However, net imports (imports - exports) are highest for the U.S. than any other country, standing at 13.6 Mmt/year.[90] The U.S. is also the biggest importer of indirect steel goods. Indirect steel imports symbolize the amount of steel required to meet the total, or true, steel demand of a country.[91][92] The major importers within the U.S. are Missouri, Louisiana, Connecticut, and Maryland.[93]

In 2018, the U.S. Secretary of Commerce declared U.S. reliance on steel imports a national security threat, per Section 232 of the Trade Expansion Act. At the time, global overcapacity and

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[86] U.S. Department of Commerce, Enforcement and Compliance, "U.S. Steel Import Monitor," International Trade Administration, 2022, https://www.trade.gov/data-visualization/us-steel-import-monitor.
[87] Ibid.
[88] United States Census Bureau, *FT-900A Supplement Final: U.S. Imports for Consumption Of Steel Products, December 2021*, CB 22-14, U.S. Department of Commerce, February 8, 2022, https://www.census.gov/foreign-trade/Press-Release/steel/steelf_2112.pdf.
[89] World Steel Association, "Worldsteel CO2 Data Collection & reporting."
[90] Ibid.
[91] Molajoni, Pierluigi and Adam Szewcyk, "Indirect Trade in Steel," (World Steel Association, 2012), https://worldsteel.org/wp-content/uploads/Indirect-trade-in-steel-Definitions-methodology-and-applications-April-2012.pdf.
[92] Ibid.
[93] McCarthy, Niall, "The U.S. States Most Reliant On Steel Imports." *Forbes*, March 9, 2018, https://www.forbes.com/sites/niallmccarthy/2018/03/09/the-u-s-states-most-reliant-on-steel-imports-infographic/?sh=1db280b6323d.

excessive steel production caused imports to be cheaper than U.S. steel. Trade sanctions were imposed on steel imports from all countries except Mexico and Canada.[94]

It's unclear if the policy move was justified as a genuine national security threat, or a liberal translation of Section 232 in order to support domestic steel industries.[95] Regardless, three years later, the Biden Administration made exclusions to the tariff due to a lack of domestic availability to meet demand.[96]

III.III. Reducing emissions

There are several opportunities to mitigate emissions in the steel sector, through technological innovation and policy.

The steel industry has pledged to reduce its carbon footprint, but its plans are weak and non-comprehensive. The World Steel Association (worldsteel) recommends a three-track approach for mitigation: substantially improving process efficiency, maximizing scrap use via EAF, and developing breakthrough technologies.[97] In tandem, U.S. Steel pledged net-zero goals by 2050, though their plans mostly include increased EAF and DRI capacity, improving efficiency at steel plants, and CCS. Carbon-free technologies, including H_2, are among U.S. Steel's plans to achieve emissions reductions, though the steel giant has only formally committed to assessing H_2 potential.[98]

Increasing EAF capacity is an important piece to the puzzle, but it is not sustainable in the long-term. As mentioned, steel demand has doubled since 2000, and it is expected to increase at least 25-30% by 2050.[99] Recycling steel is not a direct substitute for BF-BOF, and it's unlikely the rate at which we recycle steel will meet growing demand.[100] As a major recycler of steel, the U.S. is at a turning point: boost imports or accept alternative methods of production.

Two potential carbon-free technologies intended to reduce steel sector emissions include direct electrolysis and H2-DRI. Direct electrolysis, or molten oxide electrolysis (MOE) has not yet been demonstrated beyond research, though its efficiency and flexibility suggest potential for success in the future.[101] H2-DRI, meanwhile, is more advanced.

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[94] The White House, *A Proclamation on Adjusting Imports of Steel into the United States*, December 27, 2021, https://www.whitehouse.gov/briefing-room/presidential-actions/2021/12/27/a-proclamation-on-adjusting-imports-of-steel-into-the-united-states/.

[95] Chinn, Menzie, "What is the National Security Rationale for Steel, Aluminum and Automobile Protection?" (University of Wisconsin-Madison: Robert M. La Follette School, 2018), https://econofact.org/what-is-the-national-security-rationale-for-steel-aluminum-and-automobile-protection

[96] The White House, *A Proclamation on Adjusting Imports of Steel into the United States*.

[97] World Steel Association, *2021 World Steel in Figures*.

[98] United States Steel, "Roadmap to 2050." (U.S. Steel, n.d.), Accessed May 20, 2022, https://www.ussteel.com/roadmap-to-2050.

[99] Peplow, "Can Industry Decarbonize Steelmaking?"

[100] Blank, Thomas K, *The Disruptive Potential of Green Steel*, (Rocky Mountain Institute, 2021), https://rmi.org/wp-content/uploads/2019/09/green-steel-insight-brief.pdf.

[101] Boston Metal plans to launch a demonstration project for MOE in 2024.

H2-DRI, as an alternative to BF-BOF, is promising to reduce emissions from virgin steel production in the long-term, should it utilize green H_2 as the sole reducing agent. If renewable-sourced electricity is used to power the iron ore pelletization step, H2-DRI achieves 92 - 96% emissions reductions, compared with NG-DRI and BF-BOF processes, respectively.[102][103] The emission factor for 100% green H2DRI-EAF is roughly 0.1 tCO_2/t crude steel.[104]

The leading developer of H2-DRI is Sweden's HYBRIT. This joint venture includes an iron ore producer, steel manufacturer, and electricity utility company. The project utilizes wind-powered electrolysis at its pilot plant, and its demonstration plant will be operational by 2026. Based on successes, and learning-by-doing from the pilot project, HYBRIT projects 100% fossil-free steelmaking by 2035.[105] The EU's cap-and-trade system has likely contributed to the project's cost-competitiveness with traditional steel processes.

Although H2-DRI is not yet deployed at commercial scale, its success in pilot projects has spurred international action. Since 2018, nine countries have planned projects for green H_2 in steelmaking. Full-scale H2-DRI projects have been announced in Sweden and Germany.[106]

In the short-term, the U.S. can take a proactive approach to limit future CO_2 emissions. These may include mandating new steel capacity be DRI or EAF, requiring EAF be powered with renewable electricity, and increasing R&D funding to address the limitations of green H_2.[107] Though it's much more difficult to achieve bipartisan federal climate action, a carbon tax or price on carbon should always be considered.

Part VI. Recommendations

- *The DOE's Clean Energy Demonstration Office should prioritize green H_2 hub proposals that would demonstrate industrial end-use.*

The U.S. has yet to invest in H2-DRI, and there are no pilot projects for low-carbon steel production in the U.S. The IIJA and Hydrogen Shot created opportunities to lower the cost of clean H_2, but it's still unclear when green H_2 may become cost-competitive with gray H_2.

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[102] This assumption does not factor in all upstream and downstream CO2 emissions. I.e. transport, storage, and construction of steel infrastructure.

[103] Yadav, Deepak, Ashish Guhan and Tirtha Biswas, *Greening Steel: Moving to Clean Steelmaking Using Hydrogen and Renewable Energy*, (New Delhi: Council on Energy, Environment and Water, 2021), 20, https://www.ceew.in/sites/default/files/ceew-study-on-clean-and-carbon-neutral-hydrogen-based-steel-production.pdf.

[104] Campbell-Davis, Rob, Alasdair Graham, Maaike Witteveen, Chathu Gamage, and Laura Hutchinson, *Net-Zero Steel Sector Transition Strategy*, (Mission Possible Partnership, 2021), https://www.energy-transitions.org/wp-content/uploads/2021/12/MPP-Steel_Transition-Strategy.pdf.

[105] Ibid.

[106] Vogl, V., F. Sanchez, et al. "Green Steel Tracker," Dataset, (Stockholm: November 2021), www.industrytransition.org/green-steel-tracker.

[107] Stein, "Joe Biden's Green New Steel."

Designating the green H_2 hub for industrial end-use creates a foundation for demonstrating the viability of green H_2 in U.S. steel production.

❖ *The green H_2 hub should be co-located with regions of high potential for renewable energy sources (RES)* ***and*** *existing steel plants.*

A H2-DRI demonstration project should be coupled with an existing EAF facility in a region with high renewable energy capacity potential to power electrolysis and EAF electrification. Middle America has strong potential for wind energy resources. Texas, Kansas, Nebraska, and Minnesota possess strong wind energy resources and are home to existing steel plants. The American West and Southwest, including Arizona, Colorado, and Utah, show strong solar PV potential. Should a hybrid option be considered, Kansas has strong solar and wind RES potential, and two EAF plants. Figures x and y indicate regions with high potential RES capacity and existing steel plant locations.

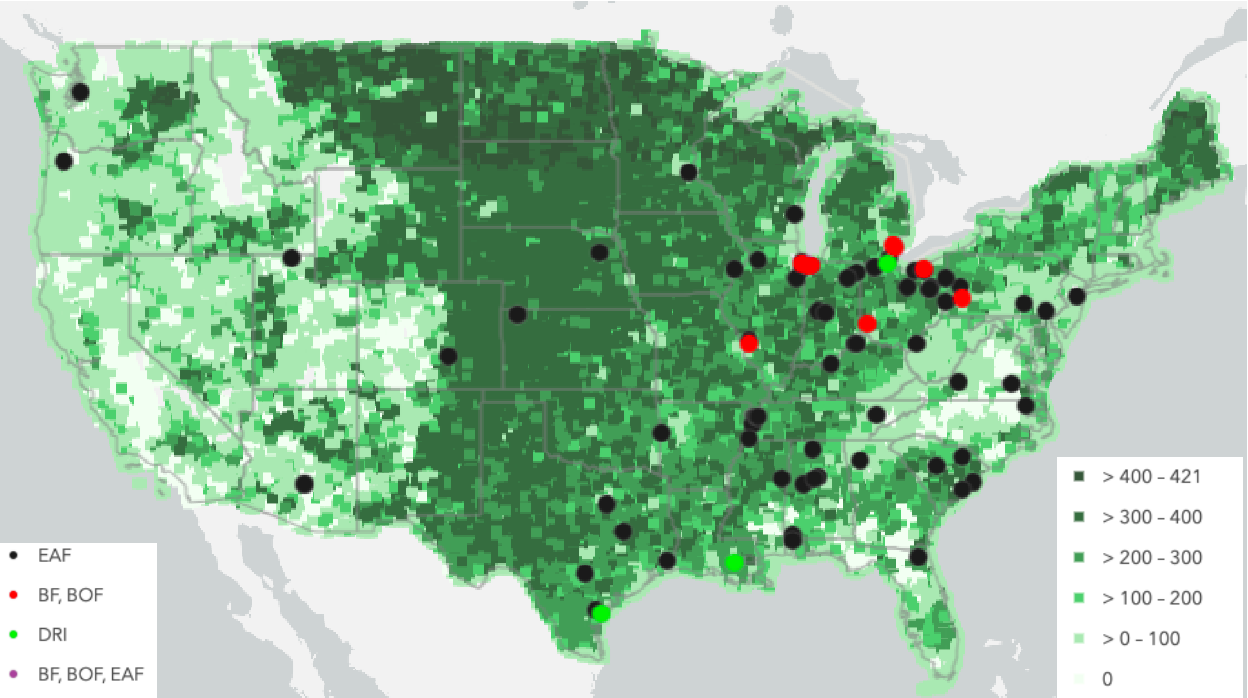

Figure 6. U.S. potential capacity for wind energy (MW), and existing steel plants*. Wind capacity potential shows potential rated capacity (MW) that may be installed on available land. Steel plant data collected from Global Energy Monitor; wind energy data collected from NREL.*[108][109]

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[108] Global Energy Monitor, “Global Steel Plant Tracker.”

[109] National Renewable Energy Laboratory, Alliance for Sustainable Energy, and U.S. Department of Energy, “NREL Wind Prospector,” NREL, Accessed May 10, 2022. https://maps.nrel.gov/wind-prospector/?aL=F6SWs_%255Bv%255D%3Dt%26F6SWs_%255Bd%255D%3D1&bL=clight&cE=0&lR=0&mC=54.77534585936447%2C-145.37109375&zL=3.

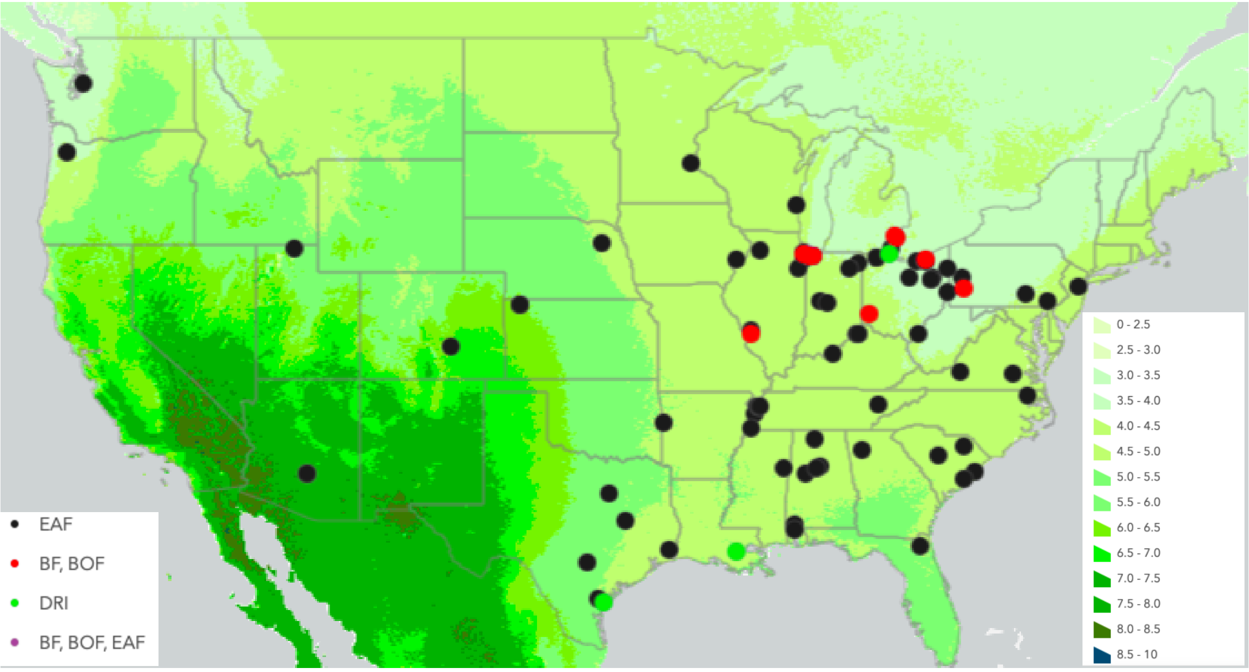

Figure 7. U.S. potential solar capacity, represented by normal direct irradiance, and existing U.S. steel plants*. Steel plant data collected from Global Energy Monitor; solar capacity data collected from North American Cooperation on Energy Information.*[110][111]

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[110] Global Energy Monitor, "Global Steel Plant Tracker."

[111] North American Cooperation on Energy Information, "Solar Resource, NSRDB PSM Direct Normal Irradiance," Natural Resources Canada, 2016. https://open.canada.ca/data/en/dataset/9554ed18-6ab2-477f-9545-da091eba762f

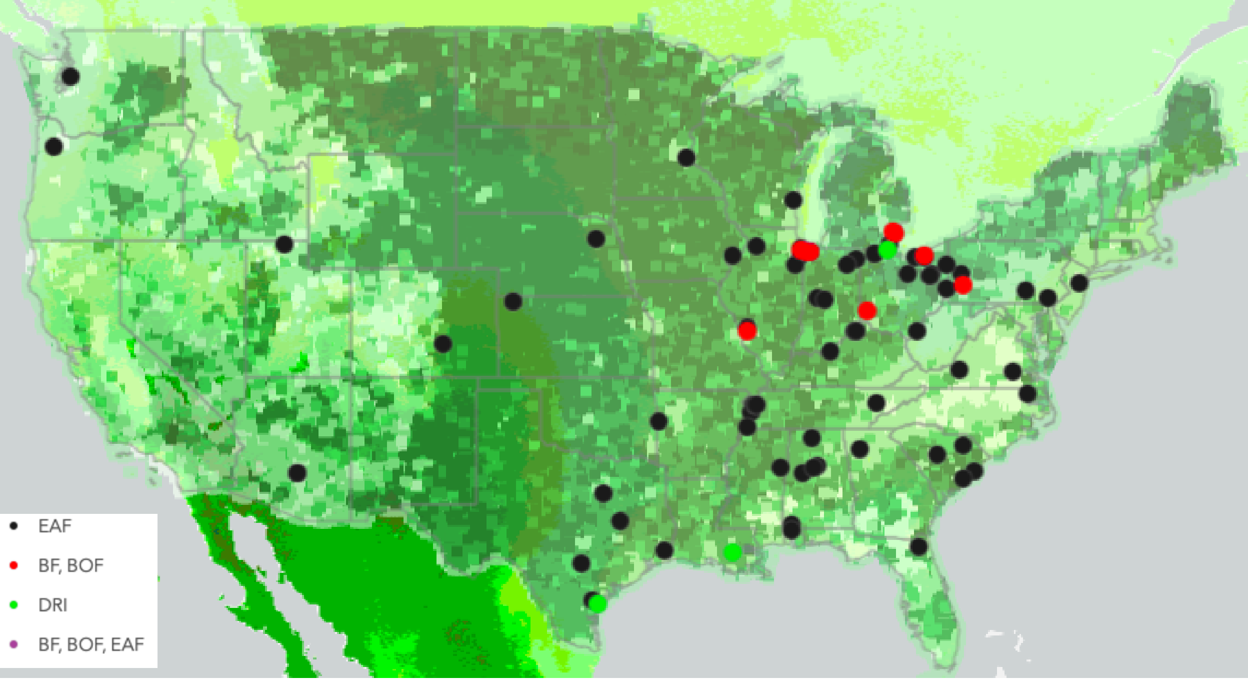

***Figure 8. Overlay of potential wind and solar capacity**. Dark green regions in middle America indicate strong potential for hybrid solar and wind generation.*[112][113]

Conclusion

The United States' reliance on steel imports and recycling has created material security, if not national security concerns in the past. Growing demand for steel will further exacerbate this issue, but it's unwise to build new BF-BOF. It is simply too carbon-intensive. Should H2-DRI prove to be commercially viable, the U.S. would not only achieve emissions reductions in the long-term, but growth in:

- ❖ *Job creation.* H_2 hubs will expand job creation for working Americans. Proposals for H_2 hubs are given special consideration should they demonstrate significant job creation.
- ❖ *Reduce U.S. reliance on steel imports.* Onshoring steel production would lessen U.S. dependence on other countries to fulfill U.S. steel consumption demands.
- ❖ *Revenue from H_2, steel.* As global H_2 and steel demand grows, the U.S. could export domestically produced steel and H_2.
- ❖ *Emissions reduction.* Supporting domestic H2-DRI would achieve direct emissions reductions, and lessen U.S. demand on foreign imports, which are primarily produced using coal and natural gas as a fuel and reducing agent.

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[112] Ibid.
[113] Ibid.

Demonstration projects must showcase the viability of H2-DRI in the U.S. before these gains may be achieved. The IIJA and Hydrogen Shot have created a window of opportunity for affordable clean H_2 in diverse end-use, but stronger policy measures will be needed to ensure wide-scale adoption. While R&D continues to address the limitations of clean H_2 transport, storage, and production, the green H_2 hub should be used to demonstrate risky, yet necessary alternatives for steel production.

Limitations of this report

- Alternative RES: maps did not report on potential hydropower, geothermal, or biomass capacity.
- Alternative technologies: MOE (molten oxide electrolysis) was not considered for its potential in reducing steel emissions
- Environmental justice implications of H_2 deployment: EJ should be a priority when choosing clean H_2 hubs, and local communities should be incorporated in decision-making (i.e. community task force, board seats, etc.)
- H_2 regulation: Regulations surrounding clean H_2 use, delivery, and storage are premature. A comprehensive regulatory code does not yet exist for H_2 at the federal level, and it will be necessary to include as H_2 becomes a realistic energy carrier in the U.S.
- Clean H_2 production tax credits: To facilitate greater deployment of RES and assist with CAPEX, RES production tax credits (PTC) should be passed, standalone from the Build Back Better bill.

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