U.S. Department of Energy
Advanced Research Projects Agency – Energy (ARPA-E)

Request for Information (RFI)
DE-FOA-0002536
on
Steel Made via Emissions-Less Technologies (SMELT)

OBJECTIVE

The purpose of this RFI is to solicit input for a potential future ARPA-E-funded research program focused on novel **technical approaches to produce iron metal (Fe) from iron-containing ores**, which can create **new** technology pathways to enable future **net-zero GHG emissions steelmaking at global scale.**

BACKGROUND

Global steel production – 1,700 million tonnes (Mt) of crude steel[1] annually, of which 2/3 is primary production from ores and 1/3 is secondary scrap recycling[2] – accounts for ~7% of world energy use[3] (over 38 EJ) and ~7% of global GHG emissions[4] (3.5 Gt CO_2e). The most widespread primary steelmaking pathways are: (1) blast furnace ironmaking-basic oxygen furnace steelmaking (BF-BOF) which emits ~2.2 t CO_2/t steel, and (2) natural gas direct reduced ironmaking-electric arc furnace (NG DRI-EAF) steelmaking, which emits ~1.4 t CO_2/t steel. Annual domestic steel production (~80 Mt steel) accounts for ~4% of U.S. emissions and 2% of U.S. energy use; the remainder of annual U.S. steel demand (~43 Mt steel) is imported. Global steel production is expected to almost double, reaching ~2,500 Mt steel per year by 2050 as GDP per capita increases in developing nations.[5] Despite steel's role in achieving sustainable development goals, these increasing emissions must be abated to avoid the most disastrous effects of climate change**.**[6] The most emissions-intensive stage in the value chain from ore to steel products is ironmaking (see ARPA-E Iron & Steel Webinar[7] overview). There are no zero-emissions ironmaking technologies yet available at scale to replace these routes. Accordingly, this request for information (RFI) focuses on **novel zero-emissions ironmaking processes with a credible future path toward enabling zero-emissions steelmaking at global scale** (~2 Gt steel/yr).

A dominant medium-term strategy toward this goal is to retrofit carbon capture systems (CCS) onto blast furnaces, which will increase the levelized cost of crude steel; the estimated premium is ~$130/t steel,[a] as shown in Figure 1. A dominant long-term strategy for many global steel companies is water electrolysis to produce hydrogen followed by hydrogen direct reduced ironmaking (H_2 DRI).[8–11] H_2 DRI is currently more expensive than CCS retrofit given today's electrolyzers and electricity prices, but may approach a cost-competitive range if electrolyzer R&D is successful and electricity prices drop (Figure 1).

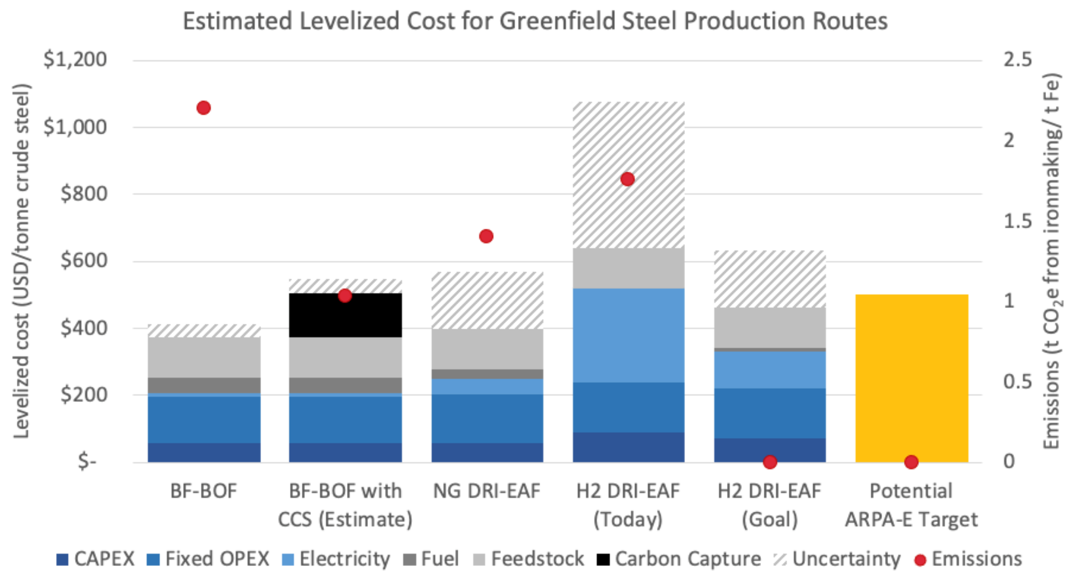

Figure 1. Levelized crude steel cost for commercial routes (BF-BOF and NG DRI/EAF) and pilot routes (CCS and H_2) as U.S. greenfield deployments.[12;b]

POTENTIAL TECH-TO-MARKET PATHWAY

Current ironmaking and steelmaking technologies benefit from economies of scale, economies of mass production, and already paid-off capital equipment. The so-called "valley of death" for any alternative technology to deploy large enough scale to achieve cost parity with incumbent technologies is wide. ARPA-E hypothesizes that this valley of death may be bridged by first targeting small-scale production of higher-value steels and ferrous alloys as a market entry strategy, as shown in Figure 2. In the long term, it will be essential to ultimately target commodity steel production that can be implemented at the gigaton scale in order to achieve meaningful GHG emissions reductions. ARPA--E is interested in targeting ironmaking processes that have **both**: (a) a clear **near-term value proposition** – the production of high-value steels or ferrous alloys – and (b) a credible path to **long-term commodity iron and steel production**.

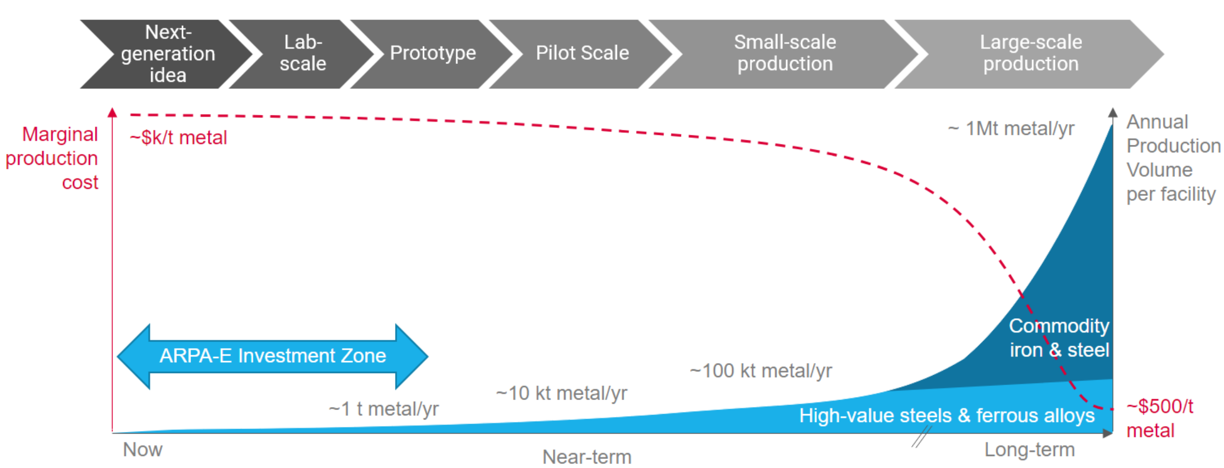

Figure 2. A proposed pathway to clean steel production at scale via high-value ferrous alloy market entry.

CRITERIA OF INTEREST

ARPA-E is interested in zero-emissions technology concepts to **produce iron metal from ores**. In particular, they must provide a new learning curve for a credible technology pathway to zero GHG emissions of steelmaking at global scale (Figure 2). **Responses to the RFI should discuss how technology concepts could meet the following four criteria at scale**:

	Criterion	*Target Value (ARPA-E Hypothesis)*	*Incumbent Value*
1.	**Energy Use**	9.3 GJ/t Fe (s)	11-13 GJ/t Fe (s)[12,14]
		12 GJ/t Fe (l)	13-19 GJ/t Fe (l)[12,14]
2.	**GHG emissions** from ironmaking process*	0 t CO_2/t Fe[c]	1.4-3 t CO_2/t Fe[15]
3.	Annual **scalability** of **inputs** needed for process# (tons/yr)	Enough to enable ~2Gt/yr steel production	Gigatons of iron ore, coking coal, slag, and process water
4.	Could produce a pig-iron replacement at cost parity with BF-BOF-CCS route	>= 95 wt.% pure Fe at ~$500/ton	95 wt.% pure Fe at ~$400/ton

Table 1. Hypothetical criteria for zero-emissions ironmaking technologies of potential interest.

***Criterion 2 Description**: This criterion includes Scope 1 emissions for the process's ongoing operations and Scope 2 emissions for energy sources. For example, if electricity, heat, or steam used, their emissions should be included. (Future 3c/kWh zero-emissions electricity may be assumed, or narratives describing other future prices may be discussed.) Embodied emissions from one-time capital expenditures may be omitted. Upstream emissions from mining ores may be omitted if expected to be substantially similar to state-of-the-art ore mining. Upstream emissions from pre-processing of ore (e.g. pelletizing, sintering) should be discussed if possible, but these emissions are not included.

#**Criterion 3 Description**: RFI responses should describe the current and potential future availability of any required inputs if the process route scaled to global 2 Gt of future steel production (e.g., global production in mass per year). Current production technologies for the inputs (and associated CO_2e) as well as any potential future technologies needed to scale-up or cleanly produce these inputs, should be described.

ARPA-E would also welcome feedback on the target values for these four criteria and especially any information about why it may not be feasible to achieve one or more of them.

QUESTIONS

ARPA-E is seeking responses describing ***any*** approaches that meet the above criteria. The technology categories below are meant to be **illustrative**, and are not intended to be limiting.

Instructions: Several potential technology routes appear below. Please respond to any and all of the ***route-specific questions***, and please evaluate technology concept(s) against the **four target criteria** above. If possible, please also describe the current knowledge gaps and technological barriers to the successful development and/or deployment of the technology concept(s).

Those without specific technology concepts are still encouraged to respond to the questions below.

ARPA-E does not expect any single respondent to answer all, or even many, of these questions. Please provide responses to any of them, indicating the question number in your response. You are encouraged to provide references to supplementary information.

A. Novel Iron Ores and Ore Processing

1. Are there one or more alternative (non-traditional) iron-containing ores with significant potential for ironmaking via extractive metallurgy in the US? Which ones, and why?
    - Please include composition, costs, and, if applicable, value proposition for their use in ironmaking as opposed to presently-used hematite/limonite/magnetite/taconite.
2. What technical opportunities exist to decarbonize or completely eliminate the pre-processing (sintering, pelletizing) of ores?

B. Electrometallurgical Ironmaking Routes

1. What are the current technology barriers to deployment of low-temperature electrolysis (electrodeposition) to produce iron?
2. What are the current technology barriers to deployment of high-temperature molten electrolysis to produce iron?
3. What are the major energy losses in electrochemical metal extraction systems, and what makes them difficult to reduce or mitigate?
4. What is the lowest overpotential (highest energy efficiency) that is practically achievable today, and what are the R&D barriers to moving beyond today's state of the art? Could >70% energy efficiency be achieved, and if so, what enabling R&D is needed?
5. What is the state of the art of inert anodes to produce iron electrolytically under molten conditions (e.g., composition of the anode, cost to manufacture the anode, material loss rate under operating conditions)? What R&D, if any, is needed to improve inert anodes to the point of commercial viability?
6. Are there electrolytes (e.g., ionic liquids, molten salts) that would overcome critical technology barriers for Fe extraction? If so, please describe such electrolytes, their current production scale, and the potential to scale up production (see especially Criterion 3 above). If not, why not?

C. Pyrometallurgical Ironmaking Routes

Hydrogen-Based Ironmaking Routes

1. What are transformational H_2-based ironmaking concepts which could create new learning curves, leapfrogging beyond the existing and planned H_2-based ironmaking pilots/demonstrations?
2. What currently limits H_2 plasma-based ironmaking from becoming commercially adopted?
    a. If any of the limitations are fundamentally technical or technoeconomic in nature, please explain what R&D is needed to move beyond today's state of the art.

Biomass-Based Ironmaking Routes

3. Are there any biomass feedstocks for use in ironmaking that may result in net-zero emissions when the full lifecycle and land-use change are considered? If so, please specify the feedstock, current TRL, and sourcing pathway. If not, why not?

Thermochemical reductants

4. Especially given that syngas-based DRI is presently deployed and H_2 DRI is in pilot to demonstration phases, should any other potential synthetic feedstocks should be considered which may be able to compete with or complement these technologies?
    a. If so, please compare any alternatives to these incumbent/pilot technologies (DRI) with respect to: availability of the reductant, cost, technical risks, time needed to develop the technology, and any strategic benefit to the U.S.
5. What is the potential for emerging renewably synthesized feedstocks[16] (e.g. carbon monoxide (CO), methane (CH_4), formic acid (HCOOH), methanol (CH_3OH), ethylene (C_2H_4), ethanol (CH_3OH)) to be used in ironmaking?
6. Would any reducing agents used in the chemicals industry[17,18] be compelling candidates for zero-emissions ironmaking at scale, whether as direct reactants or as mediators? (See especially Criteria 2 and 3 above.)

Metallothermic reduction

7. Are there scenarios in which metallothermic reduction to produce iron or iron alloys from ores would be preferable to other reductants? If so, please indicate the features of such scenarios and which metal reductants might be employed. (See especially Criterion 3 above.) If not, why not?

Drop-in approaches

8. Are there opportunities to retrofit existing thermochemical furnaces (e.g., blast furnaces, shaft furnaces) for zero-emissions reductants? If so, what technology barriers must be addressed?
9. Are there opportunities to retrofit electrically powered furnaces (especially induction furnaces and electric arc furnaces) for ironmaking via zero-emissions reductants? If so, what technology barriers must be addressed?

D. Enabling Technologies for Novel Ironmaking

1. What opportunities exist for ironmaking to benefit from technical insights or specific technologies from other fields with analogous technical challenges (for example, corrosion science, AI/ML, electrochemistry, nuclear engineering, or ICME)?

E. Iron & Steel Product Markets

Due to the potential initial cost premium of zero-emissions approaches, ARPA-E is interested in learning about **high-value iron-based alloys/steel compositions** that could provide a near-term value proposition on the path to ultimate bulk iron/steel production. Examples might include: electrical steels (i.e. silicon steels), magnetic steels, stainless steels, high-purity iron alloys, advanced high-strength steels, high-entropy alloys, and/or powder forms of such steels.

1. What other high-value steels materials, products, or specialty alloys should we consider and why?
    - For each product/market class, what scale and cost point would be needed to enable cost-effective production?
    - Would any of these products would be well-suited to make use of "green" ironmaking technologies? If so, how and why?
2. What steel materials/products have a very high cost to produce today (e.g., tailored compositions, composition gradients, powders)? What are opportunities to produce them via a new, cheaper process?
3. Are there desired quality improvements in iron and steel products that are limited by current blast furnace technology (E.g., elimination of residual/tramp elements like S or P)?
    - If so, please describe the properties and specifications that "holy grail" iron and steel materials would have, and cost points that would enable interest in such materials.
4. What technical and market challenges must be considered and overcome to produce metals/alloys from ores via a new process with fewer intermediate steps than the current steelmaking value chain?

F. Scaling & Demonstration

1. What parameters of a lab-scale novel ironmaking technology are needed to make a compelling case for further investment?
    - Our hypotheses are: 99% pure target product (metal or alloy), a batch or continuous process that can make ~1 kg/day at lab-scale, and a clear value proposition (e.g., whether better materials properties; >~30% lower cost for an existing material).
    - Are these parameter values correct? What should be added, eliminated, or changed?

Please carefully review the REQUEST FOR INFORMATION GUIDELINES below for written responses. Please note, in particular, that the information you provide will be used by ARPA-E solely for program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME.**

Purpose and Need for Information

The purpose of this RFI is solely to solicit input for ARPA-E consideration to inform the possible formulation of future research programs. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use information submitted to this RFI without any attribution to the source. This RFI provides the broad research community with an opportunity to contribute views and opinions.

REQUEST FOR INFORMATION GUIDELINES FOR WRITTEN RESPONSES

No material submitted for review will be returned, and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E may contact respondents to request clarification or seek additional information relevant to this RFI. All responses provided will be considered, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. **Respondents shall not include any information in the response to this RFI that could be considered proprietary or confidential**.

Responses to this RFI should be submitted in PDF format to the email address **ARPA-E-RFI@hq.doe.gov** by **5:00 PM Eastern Time on 6/14/2021**. Emails should conform to the following guidelines:

- Please insert "Response to RFI on Iron and Steelmaking - <your organization name>" in the subject line of your email;
- In the body of your email, include your name, title, organization, type of organization (e.g. university, non-governmental organization, small business, large business, federally funded research and development center (FFRDC), government-owned/government-operated (GOGO), etc.), email address, telephone number, and area of expertise;
- Responses to this RFI are limited to no more than 5 pages in length (12-point font size);
- Responders are encouraged to include non-proprietary data and figures that describe their potential innovations.

REFERENCES

(1) World Steel Association. *Steel Statistical Yearbook 2018*; World Steel Association, 2018.
(2) Cullen, J. M.; Allwood, J. M.; Bambach, M. D. Mapping the Global Flow of Steel: From Steelmaking to End-Use Goods. *Env. Sci Technol* **2012**, 8.
(3) Allwood, J. M.; Cullen, J. M. *Sustainable Materials without the Hot Air*; UIT Cambridge: Cambridge, 2015.
(4) Bloomberg New Energy Finance. *New Energy Outlook 2020*; 2020.
(5) International Energy Agency. Iron and Steel Technology Roadmap - Towards More Sustainable Steelmaking. 190.
(6) Committee on Accelerating Decarbonization in the United States; Board on Energy and Environmental Systems; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine. *Accelerating Decarbonization of the U.S. Energy System*; National Academies Press: Washington, D.C., 2021; p 25932. https://doi.org/10.17226/25932.
(7) *ARPA-E Dives Deep on Iron & Steel*; OPEN 2021; 2021.
(8) The Use of Hydrogen in the Iron and Steel Industry. *IRON STEEL Ind.* 13.
(9) Sortwell, M.; Sohn, H. Y.; Boy, G.; Green, E.; Li, D. *A Novel Flash Ironmaking Process*; EE0005751, 1485414; 2018; pp EE0005751, 1485414. https://doi.org/10.2172/1485414.
(10) Koch Blank, T. Technology Disruption in the Global Steel Industry.
(11) Hasanbeigi, A.; Arens, M.; Price, L. Alternative Emerging Ironmaking Technologies for Energy-Efficiency and Carbon Dioxide Emissions Reduction: A Technical Review. *Renew. Sustain. Energy Rev.* **2014**, *33*, 645–658. https://doi.org/10.1016/j.rser.2014.02.031.
(12) IEA. The Future of Hydrogen. **2019**, 203.
(13) EIA. Monthly Energy Review https://www.eia.gov/totalenergy/data/monthly/.

(14) Cavaliere, P. *Clean Ironmaking and Steelmaking Processes: Efficient Technologies for Greenhouse Emissions Abatement*; Springer International Publishing: Cham, 2019. https://doi.org/10.1007/978-3-030-21209-4.
(15) Fan, Z.; Friedmann, S. J. Low-Carbon Production of Iron and Steel: Technology Options, Economic Assessment, and Policy. *Joule* **2021**, S2542435121000957. https://doi.org/10.1016/j.joule.2021.02.018.
(16) De Luna, P.; Hahn, C.; Higgins, D.; Jaffer, S. A.; Jaramillo, T. F.; Sargent, E. H. What Would It Take for Renewably Powered Electrosynthesis to Displace Petrochemical Processes? *Science* **2019**, *364* (6438), eaav3506. https://doi.org/10.1126/science.aav3506.
(17) Vanysek, P. Electrochemical Series. In *CRC handbook of chemistry and physics: a ready-reference book of chemical and physical data*; CRC Press: Boca Raton, Fla., 2011.
(18) Connelly, N. G.; Geiger, W. E. Chemical Redox Agents for Organometallic Chemistry. *Chem. Rev.* **1996**, *96* (2), 877–910. https://doi.org/10.1021/cr940053x.

---

[a] A cost of ~\$60/t CO_2 captured is modeled in Fan and Friedmann, Joule, 5, 1-34, 2021, on pgs 22-23. Blast Furnace ironmaking produces ~2.2 t CO_2 / t steel, yielding a premium of \$60 x 2.2 = \$132 / t steel.

[b] Underlying assumptions are: current U.S. industrial fossil energy prices[13] and 7 c/kWh electricity prices (first 4 stacks) or a future electricity price of 3 c/kWh (final 2 stacks).

[c] This value **does not** include **ore mining and transportation** emissions or upstream **ore processing emissions**, though information about them and how they may be reduced is welcome. These ore processing emissions are roughly 0.3 tCO_2/t steel. In the BF-BOF route, ores are processed via pelletizing (~ 35 kg CO_2) and sintering (~ 260 kg CO_2), whereas in the NG DRI-EAF route, pretreatment of fines is conducted (~ 307 kg CO_2). (Fan and Friedmann, Joule, 5, 1-34, 2021.)