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DE-FOA-0002564: Request for Information on Establishing a New Manufacturing Institute

September 2021

Changing the World's Energy Future

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Idaho National Laboratory

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Topic: (2) Decarbonization of Metal Manufacturing
Submitted to: Decarb-Institute@ee.doe.gov

General Questions

Category 1: Institute Scope

The objective of this category is to solicit information on the scope of a potential Institute, as a public-private partnership, to advance industrial decarbonization. Responses should focus on the contributions that an Institute could make beyond that of private industry alone.

C1.1 What are key obstacles and/or challenges facing the development and deployment of technology supporting the proposed topic areas and how can the utilities of a Manufacturing Institute address these issues?

Key obstacles/challenges facing the development/deployment of technology for decarbonizing Metals Manufacturing include:

- High CapEx and long asset turnover times put the net-zero 2050 goal in jeopardy; facilities such as blast furnaces have lifetimes of 30 years and upwards of 50 years if they are relined.
- Clean electricity costs more than coking coal; The large energy scale and capital investment inhibits change unless there is a price on carbon and high confidence in both the future technology and the economics. For example, a small steel plant of 2 million tonnes of output per year would require approximately 1GW of power at 90% capacity factor (assumes 4 MWh per tonne of steel whether it is hydrogen or electrolytic). If carbon-free energy can be produced at \$30-\$40/MWh, with coking coal costs savings of \$15/MWh[1], this difference adds up to \$100 to the cost of steel. Thus, support of \$50/tonne CO_2 would be required since 2 tonnes CO_2 are emitted (avoidance potential) per tonne steel produced (primary steelmaking). The economics align with the DOE hydrogen earthshot mission.
- FERC would have to facilitate long-term contracting for electricity (energy markets) where metals manufacturers have price predictability. Price fluctuation through volatile energy markets adds significant financial risks to manufacturer's OpEx.
    - Lab testbeds can also be a platform for advancing process digitalization through AI/ML to speed up throughput and increase efficiency and quality.
    - If green hydrogen is used to decarbonize steel, more R&D is necessary to reduce hydrogen production costs towards the Earthshot goal of \$1/kg.

[1] See https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_prices/total/pr_tot_US.html&sid=US

- Given the energy and investment scale of metals manufacturing, it's recommended that AMO start with a broad portfolio of Technology Readiness Levels (TRL) 2-4 technology options and adopt a long-term vision towards net-zero metals manufacturing by 2050. The community is cognizant that some technologies will be beneficial to specific markets or applications and fail for other markets. A portfolio approach is required to achieve national goals.
- With steelmaking as an example, see the necessary timeline in Table 1. As shown, a first phase of RD&D with down-select(s) in 2025 timeframe, followed by engineering-scale test beds and digital engineering to reduce technical risks and to optimize process integration could be accomplished by 2030. Upon successful completion of this phase, commissioning of a first-of-a-kind net-zero steel plant by 2040 puts industry in a position to make the capital investments to transform the industry. Technical and economic operating data from this first-of-a-kind net-zero plant provides industry the assurance it needs to make capital investments that lead to net-zero carbon steelmaking by 2050.

Table 1. Timeline estimate for scaling sustainable, net-zero carbon steelmaking (example).

Major Phases	2020	2025	2030	2035	2040	2045	2050
Research, design integration & subscale demonstration (Testbed) reinforced by digital engineering		Down-Select	Techno-economic data, mat'ls performance, heat integration, etc. Leverage NE, FECM, HFTO, and other investments				
Full-scale, First-of-a-Kind net-zero steel plant with predictable energy contract		Regulatory/Energy Contract Approvals			First Plant Operating Data		
New investment decisions and scaling of net-zero carbon steelmaking				Construction Complete enabled by DOE loan guarantee?			

<u>Utilities of a Manufacturing Institute to address Metals Manufacturing Issues</u>:

- Given the energy/carbon scale and timeline for Decarbonization of Metals Manufacturing, the Institute model of five years of Federal support at 50% cost share would likely not provide the level of technical and financial de-risking necessary to catalyze the significant CapEx and OpEx changes necessary to decarbonize the sector. While substantial productivity and carbon reductions could be made under the 50% cost share, 5-year Institute model, it's likely that greater Federal share and a much longer time frame is needed if the goal is net-zero by 2050.
- Metals decarbonization is one of the most challenging components in the plans for widespread transformation because: 1) high CapEx, 2) long plant service life and slow replacement cycle, and 3) lack of flexible / distributed replacement options. In comparison, large, centralized coal power plants could be replaced by distributed assets including modular nuclear reactors, wind or solar. With the transportation sector, typical vehicle replacement cycles are ~15 years, facilitating transformation of the fleet to electrification and other clean technologies.
- In addition, the DOE Institute model serves mid-stage TRL 4-7 technologies. This provides for some innovation and assists industry in commercializing what they are already working on. For instance, the Institutes facilitate technology transfer and validate manufacturing processes for potential customers. The Institute model is unlikely to promote the higher risk innovation

and pre-competitive R&D necessary to accelerate solutions in time for economy-wide 2050 net-zero solutions.

- A major assumption of the Institute model is that it can be sustainable after 5 years. If AMO's vision is net-zero metals manufacturing, a Federally supported effort requiring more than 5 years is necessary to advance TRL 2-4 technologies and to de-risk the systems integration challenges through testbeds and digital engineering. If the Institute model is chosen by DOE-AMO for industry collaboration on net-zero metals manufacturing, there are two recommendations:
  - Signal in the FOA that a second and third five-year period could be awarded based on performance; and
  - Establish a complementary consortium or innovation hub for universities and national laboratories to collaborate with the Institute. The hub would not be subjected to minimal cost share and would investigate higher risk, higher impact research providing technology options that enable Institute to develop net-zero solutions. The hub, if based at a DOE National Lab would also provide the independent technical and economic data to the broader industry/investors from test beds and digital twin simulations. The test beds and digital twins are critical because of the process integration challenges related to metals manufacturing. Specific issues TRL 2-4 issues to be addressed include material science in harsh environments, electrochemistry, manufacturing research, digital simulation with AI/ML tools, and laboratory testbed validation.

C1.2 Is Industry sufficiently engaged and interested in the topic to invest?

- Industry is engaged in deploying natural gas-based syngas solutions (see Cleveland-Cliffs Toledo[2] direct reduction of iron plant) that reduce carbon emissions compared to coke ovens and blast furnaces. However, there are still significant carbon emissions associated with these processes. Start-ups and ventured-back companies are exploring early-stage R&D to electrify metals manufacturing (see Boston Metal molten oxide electrolysis[3]). These concepts while revolutionary, would need time to scale.
  - In addition, as reported by the Wall Street Journal on September 13, 2021, car companies are trying to reduce their carbon footprint by developing a more environmentally friendly manufacturing process.[4].
  - In addition to transportation, lowering the embodied carbon in steel manufacturing cascading impact in lowering the carbon footprint in the buildings, power sector, and industrial sectors where steel is used for structures, equipment, and components.
- Other companies are acquiring abandoned facilities and assets with the intention to use investments and Federal support (e.g., iFOA). The goal is to minimize CapEx in redeploying old facilities with state-of-the-art technologies to meet decarbonization goals. With the land, infrastructure, utilities, and transportation in place, the developer can focus on the technology. These projects, while limited in overall market transformation, could be first adopters and seed a broader market transformation

[2] See https://www.clevelandcliffs.com/sustainability/environment/producing-high-quality-hbi-in-toledo.

[3] Boston Metal molten oxide electrolysis See https://www.bostonmetal.com/.

[4] See https://www.wsj.com/articles/green-steel-becomes-a-hot-commodity-for-big-auto-makers-11631525401

What key knowledge or capability is missing that prevents the private sector from adequately addressing the industrial decarbonization strategy in the absence of public sector investment?

- Deep decarbonization of major industries such as metals manufacturing requires extensive process integration and controls to manage feedstocks, side reactions, heat, water, and waste streams. The scale of the energy and capital investment requires that process integration be validated to a high level of confidence with no bias. Industries such as steel production have very thin profit margins. Therefore, lack of confidence in process integration, product quality, and economics is a major deterrence to changes in manufacturing capital investment. Public sector investment in reconfigurable pilot testbeds and a first-of-a-kind plant would be necessary to de-risk technical and financial barriers prior to industry-wide buildout. DOE should consider a National Lab-led hub for the testbeds. Lab testbeds could be utilized in campaigns and allow multiple industrial partners to evaluate and validate technologies prior to making major capital investments.

If industry is currently not investing in this area, how might an Institute bridge the gap between the current state of technology and what industry is willing to invest?

- The Institute model at 50% cost share could help advance TRL 4 (and higher) decarbonization solutions already in the pipeline. However, given the significant private investment necessary to reach TRL 4 or higher, there may be an unwillingness for companies to share background IP amongst themselves. If this happens, the Institute model could enable companies to advance their individual technologies by providing Federal support. Given that revolutionary changes are required for decarbonizing metals manufacturing, broad industry collaboration on pre-competitive R&D is required to de-risk decarbonized metal manufacturing. The Institute can bridge some gaps related to transferring later technology, but it is unlikely to produce breakthroughs at a 50% industry cost share model. The 50% cost share model is highly effective at driving point solutions that incrementally decrease carbon emissions by ~10 % but will not result in transformative solutions that achieve national decarbonization goals.

C1.3 What investments are currently being made to develop technology for a given topic area and can any of them be advanced by an Institute?

- There are investments in carbon-free hydrogen production necessary to reduce oxide in ores for various metals (iron, titanium, etc.). In addition, investments are being made for electrolysis of ores to separate and refine metals. Institutes would be challenged to try to advance these technologies unless there was a parallel effort to build the pre-competitive testbeds where national laboratories and universities could be more open around publicizing low TRL, but potentially transformative solutions and data.
    - Given the interest of original equipment manufacturers (OEM) in lowering their embodied carbon, OEM participation and leadership can help establish requirements and focus the efforts while bringing potential cost share.
    - Cost share requirements for small businesses should carefully be evaluated. DOE should consider making this 100% Federal share for small businesses.

Are there sufficient early TRL technologies to advance and develop through an Institute? Are the technologies in pre-competitive space or at a TRL appropriate for an Institute to advance?

- There are some early TRL technologies that can start the industry on the decarbonization pathways. There are gaps in the early TRL technologies (e.g., utilization of carbon-free syngas for exothermic reactions) and significant integration challenges in the pre-competitive space. Without a more robust early-TRL program, the Institute model risks driving the industry towards incremental performance improvements that lock the industry in another investment cycle dependent waiting for a generation of facilities to reach end of life. This is not commensurate with pre-competitive R,D&D required to achieve the full decarbonization goals. DOE should consider a parallel effort to any Institute, such as a hub, to advance pre-competitive R&D for the benefit of the entire metals manufacturing industry.

C1.4 Would an Institute be a more effective mechanism for reducing GHG emissions, advancing the energy efficiency, environmental stewardship, productivity, and competitiveness than other methods of technology development?

- The Institute model could be effective for industry to collaborate on incremental advancements to reduce carbon emissions and increase energy efficiency and productivity. At 50% cost share, the cost to companies is too high for higher risk, pre-competitive R,D&D necessary for deep carbon reductions. To be fully effective, the Institute should be linked to a pre-competitive hub and testbeds to realize decarbonization goals.
  - For a carbon-intensive industry such as metals manufacturing, more disruptive approaches (e.g., ARPA-E model) should be considered as part of the institute's portfolio.

Category 2: Institute Organization

The objective of this category is to solicit information on the potential for strategic structuring and organization to foster collaboration through a Manufacturing Institute.

C2.1 What stakeholders or collaborators should the Manufacturing Institute engage with and what are their roles?

- U.S.-based industry metal manufacturers throughout the supply chain including those upstream who first process ores through downstream that produce the final metal. This should include companies that perform secondary separations and processing of mine tailings which are a source of other metals such as rare earths, etc. There should be a concentration of collaborators that represent the largest CO_2 emissions which is often the fossil-based reduction of oxides (i.e., iron ore, etc.) to pure metal.
- At the periphery, industry Associations such as AISI, Aluminum Association, can bring value related to early deployment policies.
- Technology providers in small to medium sized companies (e.g., electrolyzer manufacturers), specialty alloys, process controls, high temperature equipment providers (e.g., Midrex, etc.), industrial systems integrators and EPCs (e.g., Fluor).
- A separate National Laboratory and university consortium should be established in parallel to the Institute. This consortium would provide pre-competitive R,D&D and systems integration expertise through digital engineering and physical testbeds. This model is successful in AMO in other sectors including critical materials and water desalination.

C2.2 How should the scope of the Institute be focused to maximize its impact? What are the appropriate bounds of the scope?

- The AMO institutes are focused on later stage TRLs where industry is more incentivized to cost share at the 50% level. This can yield measurable advances in decarbonization but not the deep decarbonization which require more revolutionary and earlier stage TRL research. A risk of this approach is that capital investments are made based on incremental improvements, locking facilities at partial decarbonization for the life of the asset.
  - Thus, a complementary "hub-like" effort should focus on more disruptive TRL 2-4 approaches by universities and national labs so that net-zero carbon can be achieved.
  - As typical for institutes, workforce development and inclusion of minority businesses needs to be a priority.

C2.3 What would be the most effective manner to structure an Institute to ensure the highest impact?

- An Institute in conjunction with a separate and parallel "hub-like" effort should be established by AMO to seed and grow more novel ideas from universities and national laboratories. Because of their independence and FFRDC responsibilities, National laboratories would be ideal to set up process integration testbeds where technical and economic data needs to be openly published.
- AMO should make a commitment of up to 15 years for the institute which should be run by a private entity, where the initial 5-year investment can be renewed for a second and third 5-year cycle. The Institute should be subject to a rigorous review at between cycles to ensure that to Institute remains productive and aligned with AMO priorities. The "hub-like" effort should be led by a DOE national lab with support from other labs and universities.
  - As part of the first year technology roadmap, a sustainability plan should be integrated into the overall scope with carbon intensity of the entire supply chain baselined and evaluated for improvements.

Provide any information on specific regional approaches that effectively merge innovation, economic activity, and high-skill jobs at all levels of the supply chain, as appropriate.

- Regions need to be selected that affiliate themselves with metals manufacturing. This will enable greater support and more potential cost share for facilities, equipment, and workforce development programs. The Institutes already have established a track record of regional and/or State collaboration/support that supplements Federal funding. Factors include in deciding regional selection include access to primary and recycled feedstocks, clean energy, water, and product markets. If a region lacks a well-trained regional workforce, the Institute should partner with regional universities to implement a workforce development plan.
  - As previously discussed, the energy requirement for decarbonizing metals such as iron and steelmaking is large. Therefore, ideal regions would be iron/steelmaking can take advantage of carbon-free nuclear power and heat. Regions such as Ohio, Michigan, Indiana, Pennsylvania and Illinois should be considered since iron/steelmaking is important to their economies.

C2.4 How could this topic area benefit from cross-discipline collaboration and what would be the impact?

- Cross-discipline collaboration and solutions for carbon-free processing of ores to metals across steel, titanium, other critical minerals, and rare earth metals would help build greater domestic supply chain for metals used in clean energy technologies (EV/stationary batteries, lightweighting, permanent magnets/motors, semi-conductors (PV, inverters, electronics, etc.)). Standardized, life-cycle sustainability analyses would also be a cross-cutting discipline that would inform sustainable metal manufacturing and reuse/recycling from a CO_2, energy, and waste stream perspective.

- Another cross-discipline opportunity is to have a common testbed managed and operated by a National Laboratory. Advantages of a testbed include:
  - Development of a common digital engineering simulation platform or digital twin enable "soft" integration of various technologies and their corresponding technical and economic performance).
  - Independent results/data.
- A third cross-discipline opportunity is to develop a suite of standard analysis tools to benchmark pathways, risks, and impact. Develop and implement standard analysis tools including life cycle analysis (LCA), techno-economic analysis (TEA), and supply chain analysis (SCA). SCA, the least mature analysis platforms, is becoming more critical as climate, international trade, and pandemics impact production and transportation. Standard platform tools and methods should be made available across the Institute stakeholders.
  - Given that decarbonizing metals will involve internet-based process controls, smart manufacturing, and life cycle analysis of embodied carbon, cross-coordination with other Manufacturing Institutes such as CyManII, CESMII, REMADE and others will better leverage AMO resources.

What are the barriers to cross-discipline collaboration in this area?

- The barrier to cross-discipline collaboration is IP protection. Since DOE Institutes require 50% cost share, technologies being pursued tend to be mid to late stage TRLs where companies already made their own significant investment. This investment and protection of corresponding IP make it difficult to collaborate on R,D&D.
- Cross-cutting LCA and SCA would not have major IP hurdles and would benefit DOE in evaluation decarbonization options across multiple metals refining iron/steel, titanium, critical minerals/rare earth metals.

C2.5 How would an Institute attract sufficient private sector investments and what metrics would provide short-term indicators of success within the first 5 years? Please include a discussion on long-term operations and the technical achievements needed to remain relevant to industry. Discuss the value proposition to the private and public stakeholders/members.

- If the Institute is established only at the TRL 4-7 level, longer-term Federal support would bring more industry interest and investment. Institutes could attract more private investment if DOE built in a go-no/go for Federal support for a second/third five-year phase based on the previous five-year performance. Even with Institutes pursuing TRL 4-7 at 50% cost share, further technology development, tech transfer and commercialization takes longer than the 5-7 year run time of existing institutes. As discussed early, expecting research Institutes to generate significant income within 5 years and be self-sustaining is not realistic. Without Federal support, there is some incentive for companies to share their internal research dollars with other entities, but not enough to open new areas of research and sustain Institute management and operations.
  - Private investment can be incentivized if metal manufacturers (e.g., steelmakers, etc.) and OEMs (customers) have first access to IP generated under the institute.

- Metrics of success should be based on a standardized life cycle analyses around sustainability.
- Other metrics could be based on the number of technologies that graduate from the Institute into demonstrations, funded by either corporate for venture capital
- Major metrics shown in Table 2 should be established for each metal and baselined for state-of-the-art processes. Given DOE's past record of only providing five years of funding support at 50% cost share, gains against the baseline will not be enough to enable net-zero by 2050. Expectations for advancing TRL 4-7 in 5 years should be around 30%.

Table 2. Recommended technology metrics.

Primary Success Metric	Units	Baseline SOTA	5-year target (30% improvement)
Carbon emissions	Tonnes CO_2/tonne metal	W	W'
Avoided carbon cost	\$/tonne CO_2 avoided	X	X'
Process energy intensity	MJ/tonne of metal	Y	Y'
Change in metal mfg. cost	Δ \$/tonne metal or %	Z	Z'
Underrepresented persons trained/upskilled	# per demographic categories	0	N
Jobs created in disadvantaged areas	#	0	J
Technology transfer	# of new commercial applications	n/a	a
IP: New licenses/patents	#	0	b
Overall persons trained	#		
Overall jobs created			
Non-Federal funds	\$	50%	50+%
Management & operating costs	\$/year	First year	15% of total R&D throughput

Category 3: Institute Benefit

The object of this category is to solicit information on the potential benefits of establishing an Institute, as a public-private partnership, to advance industry topics of importance to the DOE Mission. Responses should focus on the impact that an Institute could have beyond that of private industry alone.

C3.1 What are potential quantitative impacts of a Manufacturing Institute targeting a given topic area? Consider impacts on energy efficiency, life-cycle energy benefits, U.S. productivity, U.S. manufacturing base, economy, energy infrastructure, greenhouse (GHG) emissions, and/or related environmental impacts in manufacturing or use.

- Over the long term, investment in R&D will address climate and result in new economic opportunities for businesses and create jobs for people. If the U.S. businesses create new technologies, it can lead to greater domestic capacity to produce technologies and metals with lower embodied energy and reduced criteria and GHG emissions over the lifecycle. If carbon intensity becomes an international trade metric, this could lead to greater global market share for U.S. manufacturers.
  - Decarbonization solutions should target \$50/tonne of CO2 avoided.

- By developing cleaner, potentially more distributed technologies, the Institute could enhance environmental justice. By partnering with regional universities and schools on workforce development, the Institute could enhance economic justice.

What impact can an Institute have in 5 years, and beyond?

- In 5-years, the Institute can be up and running with some technology development progress and new facility/equipment capabilities. However, it is not realistic to expect that many economically competitive solutions can be commercialized in 5 years. Even if the Institute focuses on TRL 4-7, investment in adopting new technologies and subsequent job creation will take decades. There could be potential for 30% reduction in particular industries/applications. Development of net-zero carbon solutions for applications such as the steel industry will require earlier stage TRL technology, long-term decadal commitment and focus on high-risk systems integration to provide industry the confidence to make large infrastructure investments for net-zero by 2050.
- A more appropriate goal is for the Institute to shift the focus of the sector to consider new technologies and have several technologies or processes under review for piloting and validation.
    - Beyond 5-years, impact metrics can include employment, worker wage/income levels, productivity, share of national GDP, and global market share.

C3.2 Industry uptake is critical to realizing the impacts of a Manufacturing Institute. What is the potential for industry to adopt innovative technologies developed through a Manufacturing Institute?

- Further Federal support through the Institute model for later stage TRL technologies, such TRL 6-7, the potential for industry adoption can be good. It is unlikely that lower TRL technologies, such as TRL 4-5, can be adopted within the 5-7 Institute timeframe. Therefore, DOE should signal a second and third five-year Federal commitment if performance metrics are achieved.

What are the R&D breakthroughs/milestones necessary to integrate specific decarbonization strategies at the industrial level?

- The big breakthroughs needed are cost related. Given that industry is dependent on high-carbon, low-cost coke and natural gas for thermal energy, electricity and carbon feedstock, new decarbonized solutions will find it difficult to be competitive with $4/MCF[5] industrial gas.
- DOE should establish a threshold where decarbonization solutions stay below a certain carbon avoidance cost of $50 - $100/tonne carbon avoided to be viable since this is in the policy range being discussed.
- An example of a potential breakthrough is based on replacing coke with hydrogen for iron ore reduction. When coke is used to the coke is converted to syngas, a mixture of hydrogen and carbon monoxide. Syngas reduction of iron ore is an exothermic process (excess heat is generated). If hydrogen is used, then the process is endothermic (heat must be added) reactor/furnaces might need to be reconfigured to make up for the heat deficit. If a net-carbon-zero process to make syngas was developed, then existing blast furnace technology could be more readily adapted. Net-carbon-zero syngas could be produced by co-electrolysis of water and carbon dioxide using carbon-free electricity. Co-electrolysis is not a mature technology.

[5] See EIA https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm

The carbon dioxide could be supplied from the exhaust gas from the blast furnace or an exogenous source such as an ethanol biorefinery.

What factors ensure U.S. manufacturing derives sustained benefits from a Manufacturing Institute beyond the five planned years of Federal funding?

- Continued Federal support for minimum of management and operations beyond 5 years would be a start.
- In addition, Federal support for R,D&D beyond 5 years (contingent upon fully successful performance) would sustain industry commitment necessary to further technology development and collaboration necessary for commercial adoption.
- Provide flexibility to the Institute to test technologies and make decisions to sunset unsuccessful projects and reallocate resources to alternative pathways or processes. Using a "fail-fast" mode could accelerate development of commercially viable technologies.

C3.3 How could an Institute in this topic area provide opportunities for advancing environmental justice and Equitable Economic Opportunity?

- Institutes could provide opportunities for environmental justice and Equitable Economic Opportunity if the model has a longer life cycle. One five-year cycle is too short to deliver on a commitment of environmental justice and Equitable Economic Opportunity. Longer time frames allow for deployment planning where brownfield sites or closed mills can be selected for model net-zero plants.
- Aligning an Institute's theme (e.g., steel) in a region impacted by that industry's downturn (e.g., plant closures, layoffs, etc.) would likely garner more local and State support, thus improving an Institutes success probability.

How could an Institute in this topic area benefit their community and communities they serve, particularly underrepresented communities?

- Institutes can provide benefit to the community by providing generic upskilling and job training to unemployed or underemployed persons. Certifications programs, such as in machine tools, would provide a more fungible benefit to job seekers.
- Require that minority-serving academic institutions and minority-owned companies in the community be part of the Institute.
- Replacing facilities with low-environmental performance with cleaner, new facilities could retain jobs while improve local air, water, and land quality.

How can an Institute engage with local leadership and organizations?

- Through workforce development programs.
  - Collaboration with state and regional economic development agencies to create a more enduring role for the institute
- Cooperation on regional water, power, and transportation needs

How can diversity and inclusivity be leveraged as a source of strength while Manufacturing USA Institutes establish their science and technology communities?

- Require that minority-based companies and institutions be part of the Institute and hire unrepresented persons as part of the management and operations of Institute. Establish K-12 STEM programs in the communities.

What is the potential that an Institute in each topic area could have to lessen overall environmental impacts and to ensure those impacts are experienced more equitably in the community and across the nation?

- Potential is high if the Institute becomes an enduring institution. Decarbonization will take decades, not 5-years. If the Institute is around for only 5 years, then it is less likely to have major impact.
- Replacement of old dirty facility with modern clean facilities will enhance regional air and water quality.

What diversity, equity, and inclusion efforts can be incorporated into RD&D investments to foster a productive and inclusive environment, support people from underrepresented groups in STEM, and advance equity?

- Require plans that a certain percentage of the RD&D be carried by underrepresented groups and that Institute membership have underrepresented institutions and businesses. Establish FOA evaluation criteria and score proposals on whether Institutes have incorporated diversity, equity and inclusion in its membership.
- Ask for diverse Institute management and operations leadership and staff to be inclusive of underrepresented groups. Establish FOA evaluation criteria and score proposals on this.
- Require a community STEM program for K-12 with Federal and non-Federal matching funds.
  - Establish free skills training and host job fairs for disadvantaged communities.
  - Consider requiring the Institutes to show how at least 40 percent of the overall benefits of the investment will benefit disadvantaged communities, in accordance with the President's Justice 40 commitment.

-Category 4: Education and Workforce Development

The objective of this category is to solicit information on education, workforce development, and training needs of the new and incumbent workforce facing each topic area. The deployment of any new technology and the growth of any manufacturing industry requires a supply of workers skilled in the unique aspects for producing, installing, and using that technology. This includes developing a diverse and inclusive pipeline in education and workforce. To ensure that any new innovations are not hampered by workforce needs, we seek input from stakeholders on the most important workforce challenges and the most promising education and workforce developments that could address them.

C4.1 Describe the workforce gap facing the specific industrial decarbonization strategy. How large is the gap? What training and education resources are needed to fill the gap? Who is the target audience? What other workforce needs are not currently addressed?

- The workforce gap is likely more generic than specific. Community college training, education and certification for skilled manufacturing jobs would fill most needs.
- A notable potential gap is that traditional manufacturing regions have a workforce that is highly skilled in mechanical functions. New facilities will require significantly higher skills in automation, controls, and digital design. The Institute should work with the local schools and developing and implementing programs to train the workforce of the future.
- The Institute should recruit veterans into the training programs. Their service will have prepared them to adapt to a rapidly changing work environment.

- The Institute should recruit people with disabilities. In a modern facility, performance will not be limited by the physical strength that drove employment decisions at traditional manufacturing facilities only consider able-bodied men

What organizations/programs exist to strengthen workforce pipeline in the specified area?

- Existing Institutes (such as IACMI) provide a good model for emulation. More funding is needed for AMO to network together all six Institute workforce development programs.
- LEAD (Leveraging and Enhancing All Diversity): To promote an inclusive environment that embraces the vision, furthers the value, and aligns with the Inclusion and Diversity strategy of U. S. Steel. This will be accomplished by leveraging the mix of diverse thought, personal background, and professional education in order to enhance employee engagement and positively impact business goals.
- SteelABILITY: To foster an environment that supports employees with disabilities and their caregivers in bringing 100% of themselves to work by advocating for and empowering the individual, increasing awareness and understanding of disability related issues and promoting inclusion, trust and respect throughout the organization and in our communities.
- SteelPARENTS: Supporting working parents and caregivers at U. S. Steel by providing resources, access, and opportunities to strengthen social networks within the community.
- SteelPRIDE: To create awareness and promote a work environment that is inclusive and safe, where people feel they can reach their maximum potential and have confidence in a work environment where they will be fairly evaluated.
- WIN (Women's Inclusion Network): To cultivate an inclusive environment that enables women to maximize their professional success at U. S. Steel through networking, education, recruitment, leadership opportunities and community involvement

What role can a Manufacturing Institute have in workforce development to maximize long-term impact?

- DOE can require that Institutes create partnerships with community colleges to establish workforce development programs with Federal assistance. The Federal assistance could be contingent on a commitment by the State or county to sustain and evolve the programs.

C4.2 How can Institutes encourage the participation of underserved communities and underrepresented groups in clean energy education and manufacturing jobs?

- Locate Institutes in underserved communities. Institutes could offer technician apprenticeships and summer jobs to targeted high school students interested in trades.
- The Institute should recruit and retain a diverse workforce at all levels to ensure that new hires see themselves in a career at a manufacturing facility

Questions Addressing Decarbonization of Metal Manufacturing

Category 8: Productivity and Competitiveness

The objective of this category is to solicit information on the challenges/opportunities in the metals industry, as they relate to productivity and global competitiveness. Responses should focus primarily on technical aspects of the topic and how establishing an Institute would address the topic; however, relevant supporting information should be included when applicable.

C8.1 What are the greatest opportunities for increasing productivity, without increasing energy consumption or carbon emissions? Provide a detailed description of the opportunities and challenges. How would a public-private Institute effectively address these opportunities/challenges to increase the productivity of the U.S. metals industry?

- Incremental productivity gains in metals manufacturing can be achieved in an Institute model through better heat integration and smart process controls. As stated, coordination with other Institutes such as CyManII, RAPID, REMADE and CESMII can increase productivity and resiliency of industrial processes. For electrically driven systems, national lab resources and capabilities in grid simulation and microgrids could be tools utilized to improve resiliency (and maintain productivity) during power disruptions. These activities are commensurate with the TRL 4-7 activities at 50% cost share. The impact will be less energy and carbon intensity and more cost-competitive products. However, productivity gains alone will not lead to net-zero carbon.

Elimination or significant modification of established processing routes (e.g., robotics/automation, sensors, industrial controls, legacy systems/equipment). Again, existing AMO institutes can be leveraged here.

- An Institute model could effectively address these leading to incremental productivity gains.

Incorporation of new processing routes and methodologies (e.g., hybrid processing, machine tools, near net shape processing, flexible/adaptable processing systems).

- An Institute model could effectively address these leading to incremental productivity gains.

Improved testing, experimental capabilities, and predictive capabilities (e.g., prototyping capabilities, empirical data sets, computational tools, design tools, material-process-structure relationships, visualization tools, artificial intelligence / machine learning (AI/ML)).

- An Institute model could effectively address these leading to incremental productivity gains.

What is the highest technical priority for the metals industry related to productivity?

- Highest technical priorities would revolve around decreasing labor and energy costs and reducing wastes. Smart controls and processing can reduce OpEx and wastes. Energy storage may decrease energy costs where time of use pricing is used. Switch to natural gas from coke for primary steel mills can reduce costs and decrease carbon emissions and other pollutants incrementally.

C8.3 Are there technology areas where international competitors are outpacing or have the potential to outpace the domestic metals industry? How would a public-private Institute effectively position the U.S. metals industry to close this technology/competition gap?

- Europe is outpacing the U.S. in green hydrogen production and transitioning to direct reduction of iron ore with hydrogen.
  - Application of blockchain-based transactions could present energy savings and improve data and cybersecurity in areas such as process controls.

Category 9: Energy Efficiency and Energy Intensity

The objective of this category is to solicit information on the challenges/opportunities in the metals industry, as they relate to energy efficiency and energy intensity. Responses should focus primarily on technical aspects of the topic and how establishing an Institute would address the topic; however, relevant supporting information should be included when applicable.

C9.2 Are there significant opportunities to reduce the embodied energy of metals using secondary feed stocks? This includes the quality of scrap and recycling (upcycling).

- There are significant opportunities to reduced embodied energy using secondary feedstocks. The U.S. is one of the most advanced nations in scrap recycling. The technical challenge is eliminating metal contaminants in the recycle. One example is copper from wiring in construction steel recycling. As the number of cycles of steel grow, the risk of contamination also grows.

C9.3 Are there opportunities to increase energy efficiency by collocating metals manufacturing facilities with other industrial facilities. This includes manufacturing and nonmanufacturing facilities (e.g., water treatment, infrastructure). How would a public- private Institute help the metals industry to realize these energy efficiencies?

- Yes, there are opportunities to increase energy efficiency. For example, co-locating near a nuclear reactor could enable offtake of high temperature thermal resources to enhance hydrogen electrolysis efficiency. Another example, is to co-locate near an ethanol biorefinery or other agriculture facility to provide a carbon source for metals manufacturing/

Category 11: Decarbonization and Environmental Justice

The objective of this category is to solicit information on the challenges/opportunities associated with the decarbonization of the metals industry. Responses should focus primarily on technical topics but also include social aspects when applicable.

C11.1 What are the greatest opportunities for decarbonizing the metals industry? How would a public-private Institute effectively facilitate the metals industries transition to carbon neutrality?

- The greatest opportunities for decarbonizing the metals industry is to directly electrify processes (electrolytically), generate hydrogen from carbon-free electricity for ore reduction, and/or apply carbon capture and sequestration to fossil fueled processes. Implementation of carbon capture processes will require diligence in reducing fugitive methane emissions to achieve carbon reduction goals.
- An Institute model could achieve incremental gains in five years at 50% cost share, but a much more long-term, comprehensive foundational R&D effort involving universities and national labs would be required for net-zero carbon emissions. A National Lab parallel effort using an Energy Innovation Hub model that includes early stage TRL 2-4, digital engineering and physical testing capabilities such as reconfigurable testbeds, could provide the foundational

R&D and systems integration expertise through digital engineering and testbeds to meet net-zero carbon emissions by 2050. The Innovation Hub would be dedicated to supporting the Institute which would focus on TRL 5 and higher to transfer technologies. Both the hub and the Institute would require more than 5 years to make an impact on net-zero carbon goals. Therefore, DOE should establish cooperative agreements for an initial 5 years but build in a second 5-year phase and possibly a third phase based on performance.

What are the largest technical challenges to decarbonizing the metals industry? It is recognized that these challenges will vary across the industry depending on the alloys and processing routes.

- To enable cost-competitive sustainable metals manufacturing such as steelmaking, focused R&D and systems integration and demonstration are needed for de-risking the chemical processing and plant economics. The slow asset turnover (e.g., blast furnaces, basic oxygen furnaces, etc. in the case of steel) and large capital infrastructure requires high confidence before industry decisions can be made to invest in new technology pathways. The following **four key challenges** need to be addressed over the next 5 years.

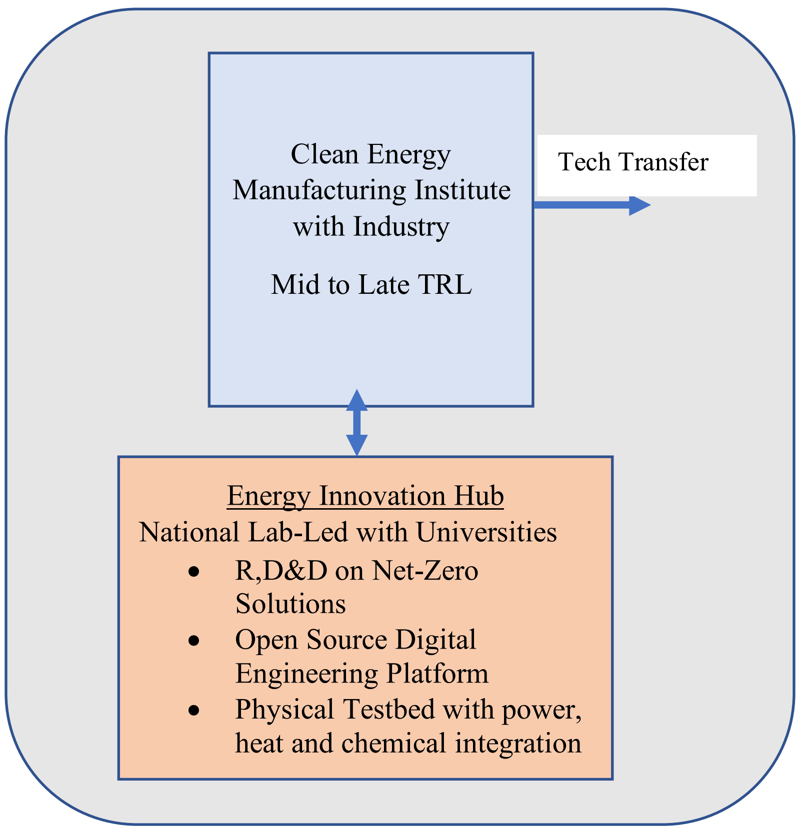

Figure 1. Public-private partnership model.

1. Materials Science and Electrochemistry – Some carbon-free approaches (e.g., hydrogen direct iron reduction) require high temperature, harsh environment (reducing atmosphere, abrasive particles, etc.) 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 ore reduction. This materials science potentially applies to reduction

of iron ore, other critical metal oxides/ores including titanium. Electrolytic production of steel would require significant advancements in electrochemistry.

2. Manufacturing R&D – New process development such as iron ore processing, unwanted competing chemical reactions, impurities, process yields and selectivity, process control and automation including AI, and other variables affecting product quality need to be optimized for decarbonized iron/steelmaking. Digital twins could help in the configuration, evaluation, and integration of a portfolio of new manufacturing processes.

3. Digital Engineering and Simulation – Integrated energy systems modeling establishes the digital design basis (e.g., digital twins) for seamless integration of nuclear/renewable generation with electrolysis/co-electrolysis, thermal management, and other unit operations (condensers, etc.) and ensures optimum heat and mass balances. Digital engineering will accelerate process design and enhance the experimental productivity. Detailed technical and economic modeling determines the optimum unit operations design and impact with respect to hydrogen stoichiometry, reaction temperatures, unsteady operations, bio-based CO sources for reductants, and other variables. In addition, digital engineering/simulation software represents a digital twin of the laboratory hardware for theory validations, optimization, and new AI-based digital process controls.

4. Laboratory and Testbed Validation – Operating experience at the laboratory-scale verifies the materials performance/durability, process design and operations and techno-economic performance. This information and data under real operating conditions is critical prior to scale-up to the plant level with industry equipment manufacturers, sensor and controls developers, and others. Testbed plant validation would be needed before industry would invest in a first-of-a-kind production-scale plant. Given the large capital investment in ore reduction and steelmaking, high confidence is required before replacing major steelmaking facilities such as blast furnaces.

What are the most viable approaches to decarbonization of the metals industry and what approaches will have the greatest impact?

- The Institute model has the potential to make near-term gains in decarbonization of metals manufacturing. With the Institute's 50% cost share model, incremental gains can be applied with relatively small infrastructure investments. To achieve net-zero carbon, major innovation, followed by large infrastructure investments need to be made and implemented over decades. New innovations can be accelerated under a National Lab-led "hub-like" model that includes universities at no or low cost share. Implementation of these potential net-zero solutions would require a very high degree of confidence which is validated through digital engineering and testbeds. A portfolio approach should be undertaken to decarbonize integrated metals manufacturing. Figure 2 shows an example approach for integrated steelmaking. As shown, productivity improvements can be pursued using the Institute model while net-zero approaches requiring much more infrastructure investment should be pursued using a hub-like model.

What are the opportunities to significantly reduce or eliminate the use of carbon- based fuels/energy in the metals industry?

- Revolutionary approaches involving carbon-free electricity and/or hydrogen are the best opportunities to eliminate carbon-based fuels (for heat and reductant) in the metals industry.

C11.2 What are the challenges/opportunities related to utilizing onsite carbon-free power generation (e.g., solar, wind)? What are the challenges/opportunities to collocating metals manufacturing facilities with carbon-free power generation stations (e.g., hydroelectric, nuclear, geothermal)?

- On-site power is not necessary if challenges can be solved with bilateral contracting in energy/capacity markets. FERC would need to govern these purchases.[6] With nuclear, power and heat can be provided and collocation within a few miles would be optimal to retain high thermal quality. Given the scale of steelmaking, 1 GW reactor would be necessary for a small 2 million tonne per year steel plant at 4 MWh/tonne of steel (electrolytic or hydrogen-based). Geothermal power and heat are unlikely to meet this scale. Small modular reactors and geothermal energy with high utilization factors could be used for power and heat needs in other metals manufacturing processes (e.g., titanium ore reduction and metals refining).

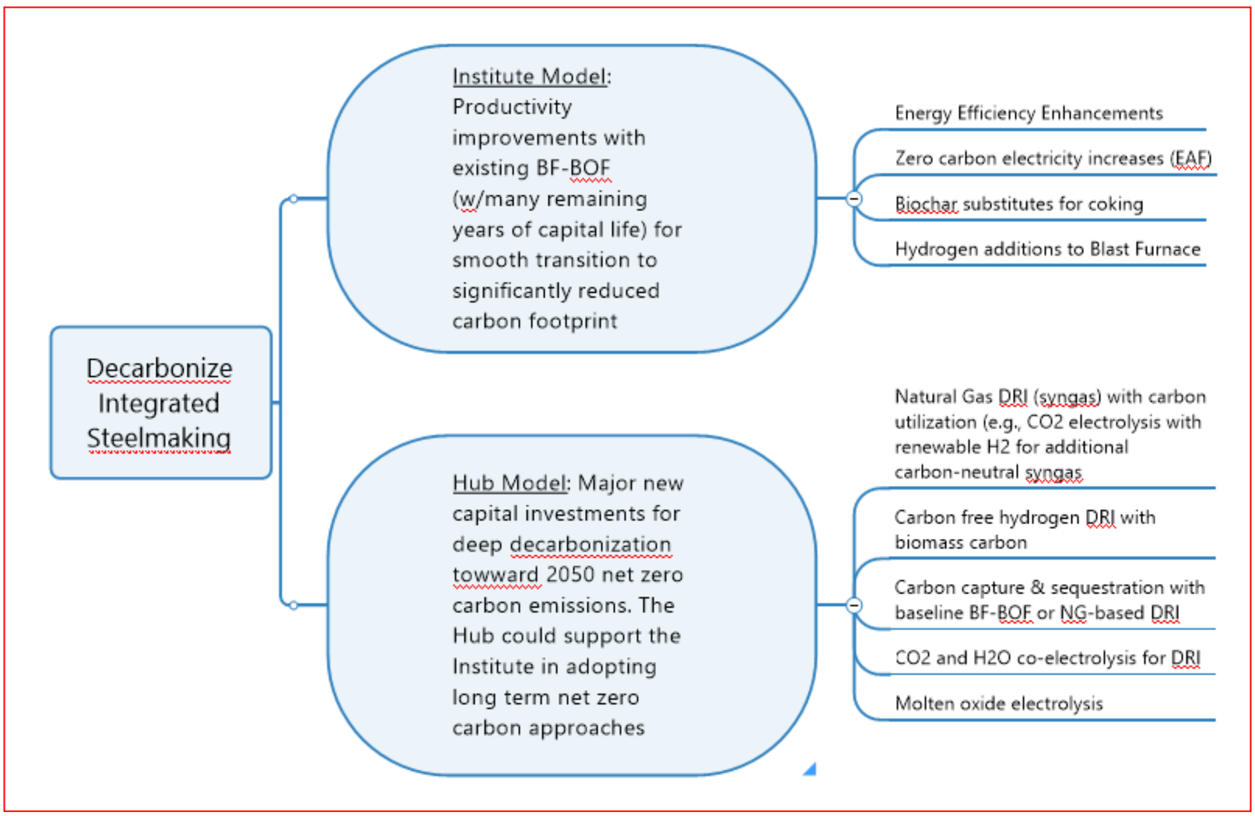

Figure 2. Example approach for integrated steelmaking.

C11.3 What role does electrification have in decarbonizing the metals industry? What specific opportunities/applications are there in the metals industry for electrification.

[6] https://www.bricker.com/industries-practices/energy/insights-resources/publications/us-supreme-court-decision-may-undercut-recent-puco-decisions-approving-ratepayer-subsidized-power-purchase-agreements-for-ohio-utilities.

- With the Administration's 2035 carbon-free grid target and likelihood of an EPA clean power rule, direct electrification or electricity-based hydrogen production can play a major role in decarbonizing metals industry. Direct electrification through electrolytic processes such as electrowinning are under development. Electrolysis of water (using carbon-free electricity) can provide the hydrogen for process heat and reductant necessary to covert ores to metals. In addition, carbon-free electricity can be used to split CO_2 (recycled from the blast furnace stack or from other industrial processes such as an ethanol biorefinery) and make carbon-neutral syngas when reacted with carbon-free hydrogen. For example, in iron ore reduction, syngas can be advantageous over pure hydrogen because it is exothermic. Carbon-neutral bio-based syngas can also be provided.

C11.4 What is the greatest opportunity for reducing or eliminating environmentally harmful by-products or co-products? This question is focused on technical solution to avoid the creation of harmful co/by-products, not finding alternative uses for the co/by-products.

- For critical minerals and rare earths, developing electrolytic or alternate ore separation and reduction techniques can eliminate acid leaching processes where there can be ground/water contamination. Obviously, carbon-free electricity for power and heat can eliminate many air emissions (oxides of carbon, nitrogen, sulfur, etc.).
- Replacing coke as a carbon and energy source in industrial metal processes with carbon-free power and biomass or CO_2 derived carbon.

C11.5 What is the greatest opportunity for advancing environmental justice[7], as it relates to the metals industry? How would a public-private Institute effectively advance environmental justice, as it relates to the metals industry.

- Revitalization of shuttered mills previously polluted by the steel industry (e.g., Zug Island, MI) with clean iron and steelmaking technologies can right some wrongs. As DOE strives to accomplish environmental justice objectives, it is doubtful that this can be incentivized through the 50% cost share, 5-year Institute model. A much longer-term, higher Federal-share effort would be necessary.

C11.6 Provide any additional information relevant to the environmental stewardship opportunities/challenges of the metals industry that do not fit into the previous questions in this Category. This could include various industry data (e.g., equitable economy opportunities), references, or technical information (e.g., clean energy technologies or innovations).

- Environmental justice and advancing STEM in underrepresented demographic categories can be advanced through combining AMO programs with State Energy Programs that may be funded in the Bipartisan Infrastructure Bill. In addition, a "hub" model that co-exists with an Institute model can better promote STEM opportunities through internships, post-doc fellowships, temporary research appointments and other opportunities available through a university/National Lab-based hub.

Category 12: Transition and Adoption of New Technologies

[7] What is Environmental Justice? U.S. Department of Energy. 2021. https://www.energy.gov/lm/services/environmental-justice/what-environmental-justice.

The objective of this category is to solicit information on barriers to transitioning and adopting new technologies into full rate production or low-rate initial production. New technology includes, but is not limited to, new materials, advanced processes, modeling/simulation tools, and testing/inspection methodologies.

C12.2 What additional facilities or equipment resources are needed to accelerate technology adoption? How would the metals industry benefit for shared resources such as testbeds, prototypes, pilot scale equipment, and/or demonstration facilities.

- A publicly access testbed that could reconfigured for novel unit operations, technologies, or systems would accelerate progress. The facility shall be well equipped with sensing and analytical tools enable evaluation of LCA and TEA. It is important to support a testbed that could provide operational performance data on a useful timeframe (e.g., hundreds of hours)

C12.3 Provide any additional information relevant to the opportunities/challenges associated with the transition and adoption of new technologies to the metals industry that does not fit into the previous questions in this Category. This could include various industry data, references, or technical information.

- AMO should consider the role of testbeds in complementary programs. For example, the Geothermal Program supports testbed in the FORGE Consortium. From our experience in FORGE, we report:
  What works
  - The test site is an actual EGS (Enhanced Geothermal) Reservoir (pressure, temperature, chemistry, rock type, etc.). So, the data is useful and does not need to be extrapolated to some idealized environment.
  - Collaborative environment - there are not winners or losers based on institutions connection
  - Anybody can work at FORGE, providing they meet the review boards criteria. That is, there are projects on site that are funded by DOE, private sector, and other DOE offices (ARPA-E).
  - Tens of millions of dollars invested in infrastructure including boreholes, sensors, network, are available for research. Without DOE's investment in infrastructure, it is unlikely any researchers could access the level of funding that would be required to field test EGS technologies.

  What doesn't work
  - Contracting between DOE and host has delayed implementation
  - Liability waivers challenge progress
  - Too much oversight of FOAs delays progress
  - DOE is so extremely risk adverse that there have been projects withdraw rather than deal with the bureaucracy
  - Universities are not set up to manage complex projects of this nature. If a National Lab has the infrastructure to host testbeds.

AMO has managed the Critical Materials Institute (CMI) for nearly a decade. The progress in CMI should guide AMO.

- During the first 5 years the TRL level of CMIs research projects spanned the range from TRL 2 – 5 with modest industry engagement and adoption of de-risked technologies. During the second 5 years of CMI a new Federal administration pushed R&D emphasis onto lower TRL projects. Consequently, the level of industry engagement in CMI settled at a lower level. In FY22, after 9 years, the Energy Innovation Hub – Critical Materials will again be opened to a Funding Opportunity Announcement and CMI administrators have already been looking forward to proposing a more refined CMI consortium R&D management model which has been dubbed the evolved CMI model.

- The evolved CMI model retains the financial resources of the Energy Innovation Hub and a consortia research approach, but instead of a higher number of diverse R&D projects spanning a wide range of critical material topics, the new model will involve more coordinated R&D along targeted (focused) topical areas within the critical materials genre. By way of example, conversion of REE ions to metallic forms is a significant technical challenge, yet a crucial technological need in the overall REE lifecycle. The evolved CMI model focuses staff from several CMI partners on the metallization task with different institutions working in concert on the development of metallization technology from low TRL through to higher TRL. To attract industry engagement, and to enhance hand-off of a suitably de-risked technology to industry, the evolved CMI model has incorporated a technology testbed approach. The vision of the technology testbed is a location (National Lab) where industry partners can engage the testbed's staff/resources/capabilities and conduct tests on CMI "product technologies" to determine how well CMI developed technologies suit their needs. Techno-economic and lifecycle process economic data are acquired at the testbed scale as supporting evidence of technology suitability and adaptability to industry's needs.

Category 13: Disruptive Technology

The objective of this category is to solicit information on disruptive technologies and how to prepare the metals industry to benefit from them. If the technology was discussed in an earlier response, identify the technology again with additional information, as appropriate.

- Carbon-free syngas by co-electrolysis of water with carbon dioxide capture from the furnace stack is a disruptive approach. The stack gas would have heat, water, and CO_2. The iron ore reduction process would become circular where the inputs are iron ore and clean electricity. The water and carbon would be continuously recirculated through hundreds of cycles.

References

Coking coal costs see
https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_prices/total/pr_tot_US.html&sid=US

Boston Metal molten oxide electrolysis See https://www.bostonmetal.com/