WORKSHOP ON ACCELERATING GREEN STEEL

CARNEGIE MELLON UNIVERSITY | PITTSBURGH, PA
TUESDAY, OCTOBER 3, 2023

RAPPORTEUR'S REPORT

DR. VALERIE KARPLUS, PROFESSOR, ENGINEERING & PUBLIC POLICY, WORKSHOP CO-CHAIR
DR. CHRIS PISTORIUS, PROFESSOR, MATERIALS SCIENCE & ENGINEERING, WORKSHOP CO-CHAIR
DR. DANIEL TKACIK, EXECUTIVE DIRECTOR, WILTON E. SCOTT INSTITUTE FOR ENERGY INNOVATION

EXECUTIVE SUMMARY

The Wilton E. Scott Institute for Energy Innovation hosted a Research Workshop on Accelerating Green Steel at Carnegie Mellon University, which gathered experts on iron and steelmaking from around the globe on October 3, 2023. The workshop was co-hosted by the Center for Iron and Steelmaking Research (CISR) with support from Schmidt Futures. The workshop brought together representatives of sixteen companies (see Appendix A) with iron and steel production spanning six continents and representing roughly a quarter of global steel production.

The three goals of the Workshop were to:

01 Share the goals, actions, and experiences to date across the industry to reduce greenhouse gas emissions.

02 Engage in a frank dialogue about challenges encountered and priorities for R&D and demonstration.

03 Build new connections and collaborations involving the diverse group of attendees.

At the Workshop, participants discussed insights from research and practice, their organization's climate targets and actions to implement them, and opportunities to accelerate the development of green steel in line with global climate goals.

A few of the major insights were:

01 Most companies from nearly every global region participating in the Workshop had adopted commitments to reducing carbon dioxide (CO_2) emissions by 20-30% by 2030 and many pledged to achieve CO_2 neutrality by mid-century, suggesting that CO_2 emissions intensity will increasingly be a differentiator in the industry.

02 Demand for ore-based metallics in steelmaking will continue to grow but the ironmaking step remains the most CO_2 emissions intensive. Mechanisms are needed to clearly incentivize and potentially fund greater deployment of a wide array of promising pre-commercial technologies—including carbon capture, utilization, and storage (CCUS) for both blast furnace and direct reduced iron (DRI) production, H_2-DRI, and electrolysis pathways—to reduce CO_2 emissions reductions from the ironmaking step.

EXECUTIVE SUMMARY

03 Beyond the ironmaking step, there is an urgent need to expand and decarbonize the electricity system to support industrial loads (e.g., DRI, electric arc furnace (EAF) operation, remelting) and examine the potential of electricity and hydrogen to provide a low or zero CO_2 source of high-quality process heat.

04 Participants were enthusiastic about tax credits for steel produced with low CO_2 emissions using a broad range of technologies. Current incentives, such as the U.S. Inflation Reduction Act tax credits for hydrogen and CCUS, favor specific decarbonized steelmaking routes. Broadening these incentives to include all decarbonization routes would create a dynamic incentive for innovation. Several participants suggested that a CO_2 emissions-based fee would similarly create a strong, technology-agnostic incentive and could raise revenue to support the transition.

05 Common or at least compatible CO_2 accounting framework(s) across nations and producers that can reflect CO_2 reductions due to a broad range of actions, from process efficiency improvements to retrofits of existing facilities to new capital projects, is needed as a basis for domestic and trade policy, including a carbon border adjustment mechanism (CBAM).

The Workshop was carried out in four sessions. In Session 1, Dr. Valerie Karplus and Ph.D. student Elina Hoffmann gave a stage-setting presentation about the current state of steel technologies and presented an assessment of the cost and greenhouse gas (GHG) emissions of future steelmaking pathways. In Session 2, Dr. Chris Pistorius moderated a discussion of each participating company's decarbonization pathways and strategies. In Session 3, Dr. Karplus moderated a discussion focused on the current challenges in accelerating green steel, and in Session 4, Drs. Karplus and Pistorius jointly moderated a discussion about potential solutions that could be pursued by the industry.

The Workshop was held under the Chatham House Rule, meaning that no comments would be directly attributed to attendees or the organizations they represented. A summary of presentations and discussions is provided in this Rapporteur's Report.

BACKGROUND

Reducing greenhouse gas (GHG) emissions while ensuring steel meets quality demands and remains affordable is a monumental technical, organizational, and policy challenge. Iron and steelmaking accounts for roughly 7% of global energy- and process-related scope 1 emissions of carbon dioxide (CO_2), a major GHG. Steel is an essential input to many industries, including construction, automotive, and appliances. Demand is expected to remain strong to meet the needs of developing countries and build clean and renewable energy and infrastructure projects to meet mid-century climate goals. The long lifetimes of capital investments in the industrial sector and increasing risk of catastrophic climate change as GHG emissions rise increase the importance of action now to accelerate the transition.

SESSION 1: STATE OF THE TECHNOLOGY: ASSESSING THE COST AND GHG EMISSIONS OF FUTURE STEELMAKING PATHWAYS

Moderator: Dr. Valerie Karplus (Workshop Co-Chair), Professor of Engineering and Public Policy and Associate Director of the Scott Institute

In the first half of Session 1, Dr. Valerie Karplus shared results from an anonymous survey participants were asked to complete prior to the Workshop about their company's activities and views related to decarbonizing iron and steelmaking processes. A summary of key results from that survey follows.

The steel industry comprises a diverse group of companies employing various operations and GHG reduction pathways. Most companies focus on measuring GHG emissions at the production process or product level, with significant emphasis placed on operational efficiency. Reporting standards differ widely across participants, including those set by various associations and protocols.

Over half of the respondents consider green steel production tax credits, buyer pledges, investment tax credits, and hydrogen (H_2) production tax credits effective in promoting green steel production. Multiple factors, including regulatory requirements, shareholder expectations, and financial considerations, influenced organizations' decarbonization strategies.

One issue that emerged here and throughout the day was the urgency—as well as the difficulty—of developing a standardized accounting framework for CO_2 emissions from iron and steelmaking. A challenge emerged that everyone agreed on the value of a common standard but wanted it to be their preferred standard. Participants generally favored a standard that reflects and rewards a broad range of CO_2 emissions reduction options. Most companies indicated that they had already developed or were developing CO_2 measurement systems that could support product-level or in some cases even heat-level CO_2 emissions accounting.

A closely-related issue concerns how “green steel” or “greener steel” should be defined, e.g., based on a specific CO_2 intensity threshold or at the crude steel or product level. This topic was not discussed in detail, but it was noted that definitions were usefully discussed separately from emissions measurement approaches. During discussions, participants debated the merits of using the word “green steel,” suggesting the term “low carbon” or “decarbonized” to refer to processes and advocating for standardized measurement systems to clarify product sustainability and sourcing.

Sound, globally-recognized CO_2 emissions measurement approaches will grow in importance given anticipated developments in climate and trade policy, including the European Union (EU)'s Carbon Border Adjustment Mechanism (CBAM). Other regions like China and Korea may employ separate accounting systems or accounting boundaries, posing challenges when trading with the EU. These complexities highlight the need for cohesive international standards and a comprehensive approach to measuring and reporting GHG emissions of steel production.

In the latter half of Session 1, a CMU Ph.D. student gave an overview of CMU’s international collaborative research, performed under the U.S. National Science Foundation-funded Industrial Decarbonization Analysis, Benchmarking, and Action (INDABA) Partnership, on the cost and CO_2 emissions of future iron and steelmaking pathways. A summary of that overview follows.

The overview first showed evidence of the importance of considering options for reducing CO_2 emissions through efficiency and materials substitution in blast furnace operations. Second, the presentation highlighted variable costs and CO_2 emissions by scope for various production pathways, revealing the limitations of certain strategies, like increased Direct Reduced Iron (DRI) usage, which can increase CO_2 emissions if it is being used to replace scrap in the EAF. The source of electricity impacts the CO_2 emissions associated with DRI and EAF production, with considerations for the variability of the US grid based on location.

Third, the presentation showed that current tax credits for CCS (45Q, $85 per ton CO_2 emissions avoided) and hydrogen (45V, $3/kg H_2) under the U.S. Inflation Reduction Act (IRA) create advantages for certain pathways over others, especially today’s precommercial electrolysis options. Survey results suggested broad support for a technology-neutral production tax credit for green steel as a mechanism for accelerating the deployment of advanced, low CO_2 emissions technologies in the steel industry. The CMU analysis found that the credits effectively reduce costs for H_2 pathways to a greater extent than does the tax credit for CCS. Participants expressed that a technology-neutral green steel production tax credit or a CO_2 emissions fee would help to create much-needed certainty to support industry investments.

One participant pointed out that modeling projections tentatively suggest that currently precommercial electrolysis technologies might dominate steel production in net-zero scenarios by 2050, followed by CCS, but uncertainties persist regarding the availability of low-cost electricity produced with zero CO_2 emissions.

Key uncertainties affecting CO_2 emissions reductions cost and potential for the steel industry worldwide included the cost of inputs especially high-quality ore, scrap, and energy, the capital cost of carbon capture, utilization, and storage, the ore quality and processing requirements for DRI, heating and fuel requirements, the type and availability of reductants (natural gas or hydrogen) for DRI, the cost and availability of zero or low-carbon electricity, ability of CO_2 emissions measurement standards to reflect the impact of various interventions, and future policy incentives and available financial resources and mechanisms to fund a transition. CO_2 emissions per ton of crude steel depended on many of the same factors, including incentives for continuous decarbonized operation due to the fuel and reductant flexibility of many candidate production routes.

SESSION 2: PROSPECTS FOR AND CHALLENGES FACING GREEN STEEL

Moderator: Dr. Chris Pistorius (Workshop Co-Chair), Professor of Materials Science and Engineering

Dr. Pistorius moderated Session 2, during which representatives from each participating company spoke for 5-7 minutes about their iron and steel decarbonization strategies. A summary of the collection of presentations follows.

Across the steel industry, companies are actively pursuing diverse strategies to achieve their CO_2 or GHG reduction targets, mostly set for 2030 and 2050. Companies from every global region participating in the Workshop had adopted commitments to reducing CO_2 emissions by 20-30% by 2030 and many pledged to achieve CO_2 neutrality by mid-century, suggesting that CO_2 emissions intensity will increasingly be a differentiator in the industry. While blast furnace efficiency, hydrogen DRI, shifting from BF-BOF to scrap/DRI-EAF production, and CCUS were common strategies across multiple companies, there were many unique, site-specific strategies shared. One company's approach involved optimizing Basic Oxygen Furnace (BOF) operations through innovative techniques such as Inductive Gas Atomization Refining (IGAR), relying on both green and blue hydrogen, and integrating downstream CCS and sustainable biomass utilization.

Numerous companies are focusing on incorporating renewable energy sources, such as solar power, and transitioning from conventional blast furnaces to more environmentally friendly EAF. Some face challenges in adopting CCS and hydrogen technology due to the operational complexities, prompting a concentration on operational efficiency and eco-friendly resource procurement as an interim solution while technologies are developed and proven further.

Several companies are exploring a spectrum of solutions, including the adoption of biocarbon and green charcoal, investment in nuclear generators and fusion power, as well as the integration of electric smelting furnaces (ESF), fluidized bed reactors, and green hydrogen production technologies. Very few steelmakers expressed an intention to produce green hydrogen themselves but instead had formed partnership

for development and offtake. Circular production processes and the implementation of EAFs and DRI-compatible iron ore grades were important considerations and challenges for others.

Additional efforts involve collaborations with electricity suppliers to reduce emissions. Several shared a special focus on nuclear energy as a low-carbon option. Others emphasized the potential for biomass for "green pig iron" production when regionally available and appropriate. Routes being pursued differed markedly on their reliance on complementary infrastructure developments, e.g., for clean electricity and hydrogen or CO_2 offtake. Operational optimization through modeling and a positive attitude towards nuclear energy are evident in the approaches adopted by certain companies. The fossil fuel industry's influence on the steel sector's growing interest in CCS technology was acknowledged.

Overall, participating companies are collectively pursuing a broad range of technologies, procurement strategies, and other approaches to align their operations with decarbonization goals.

SESSION 3: WHAT WOULD IT TAKE TO ACCELERATE PROGRESS ON GREEN STEEL?

Moderator: Dr. Valerie Karplus

Dr. Karplus moderated two rounds of breakout conversations that then brought attendees together to share summaries of their small discussions with all participants. Breakout groups were asked to discuss potential challenges to accelerating green steel, such as:

- Technological readiness
- Production cost
- Enabling infrastructure (e.g. clean electricity, hydrogen, carbon capture and sequestration)
- Buyer demand
- Policy and border adjustment mechanisms
- Community and workforce

A summary of those discussions follows.

Some companies believe that the electricity grid will be the most important bottleneck in decarbonizing the industry. There is uncertainty about bringing renewable electricity to steel plants, as the companies acknowledged an abundance of grid congestion. In the US and EU, companies expressed that expanding the power grid is not easy, leaving them with a lot of uncertainty when considering investments in decarbonizing steel.

Technological readiness was deemed essential to many companies, with suggestions ranging from the implementation of nuclear energy to the development of other climate-friendly energy sources like wind and solar for producing green hydrogen. However, uncertainties persist regarding the viability of 100% H_2 DRI and H_2-based technologies to deliver equivalent products without overcoming technical hurdles on multiple fronts, including the performance of 100% H_2 in furnaces, as well as H storage and transmission facilities. As one participant noted on the current state of hydrogen infrastructure, "we'd have to put it in tanks and truck it in."

Some companies expressed concern about the potential cost implications of various decarbonization strategies. The issue of buyer demand loomed large, as companies expressed that assessing true demand for green steel was challenging due to the mismatch between the aspirations and willingness-to-pay of some potential buyers. Many companies shared that balancing the drive for decarbonization with local community considerations is crucial, as businesses navigate the potential impacts on employment, community dynamics, and societal backlash against these changes. However, in the survey, very few companies expressed that community or workforce concerns constituted a major barrier to decarbonization.

Additional concerns regarding potential environmental implications of the decarbonization leading to the increased mining tailings or solid waste generation to yield OBMs suitable for steelmaking, via either DRI and/or smelting were expressed. It was pointed out that if the goal of decarbonization is to limit environmental impact from industrial processes like steelmaking, the solutions being developed and implemented should not come at the cost or increase of other environmental impacts, such as waste burdens or tailings dams.

Multiple participants underscored the need for transparent and coordinated GHG accounting principles that would be reliably and consistently applied in national, regional, and international policy. They noted the complexity of GHG accounting, the mismatch in accounting boundaries across policies, and the need for localized monitoring and enforcement. They highlighted the challenges associated with creating a unified international framework for emissions control while acknowledging the role of individual governments in enforcing regional regulations. Nearly every participating company said they would support a unified GHG accounting standard, but those same companies also acknowledged a major roadblock is that every company wants the standard to best suit their own specific needs and practices.

SESSION 4: OPPORTUNITIES AND NEXT STEPS

Moderators: Dr. Chris Pistorius and Dr. Valerie Karplus

Drs. Pistorius and Karplus moderated two rounds of breakout conversations that then brought attendees together to share summaries of their small discussions with all participants. Small groups of participants were asked to discuss the following potential strategies to address challenges identified in Session 3, such as:

- Common industry GHG accounting and certification practices
- Climate change policies
- Opportunities for R&D collaboration on specific pathways
- Potential to collaborate on enabling infrastructure
- International collaboration
- How to create and grow demand for green steel
- Others

A summary of those discussions follows.

The group discussions in Session 4 underscored that decarbonizing the iron and steel industry involves grappling with a wide array of challenges. One prominent issue involved in the disparities in reporting boundaries and rules for accounting GHG emissions, emphasizing the need for different countries to work together on the principles and methods of accounting. For example, some companies must report GHG emissions at the firm level in their own country, but when exporting to other countries, they are reporting emissions at the product level.

One company shared that they calculated their GHG emissions “six or seven different ways” in a recent year, and they acknowledged “that’s problematic. They’re all different numbers, and they’re all correct according to different standards.” This disparity in reporting underscores the importance for industry-wide collaboration and consensus on a singular model and system.

On increasing demand, some companies suggested engaging in a “climate club” spanning multiple stages of the supply chain. They noted some steel buyers are

already participating in such arrangements, driven by a desire to provide lower-carbon products to customers, demonstrate progress on climate change to shareholders and stakeholders, and influence buyer preferences towards greener steel or to streamline their sourcing practices. One notable suggestion included a standardized "nutrition label" system for steel to provide clarity and credibility to consumers about the GHG emissions of various steel pathways using a transparent and well-documented accounting procedure that can be interpreted by multiple audiences. A potential solution to the multiple standards problem is an "exchange table" that clearly delineates which CO_2 emissions are included or not included. It was discussed that methodologies that distort or weight CO_2 emissions measurements using factors other than current-year CO_2 footprint are ungrounded and may conflate priorities in ways that obscure true impacts and tradeoffs.

When it comes to setting thresholds to define "how green is green enough," several participants suggested that differentiated standards by end-product category (e.g., exterior automotive versus rebar), similar to the approach taken in the U.S. Corporate Average Fuel Economy standards, might help to ensure that decarbonization does not encourage dilution or undermine production of specific steel grades for more or less demanding applications. Improvements within "benchmark" product categories would be rewarded. This would further help to ensure innovation is directed toward maintaining quality while decarbonizing processes.

Participants believed that effective policies are required to incentivize the production of green steel, while ensuring that implementation supports, and does not inadvertently discourage, investments in green production globally, especially in locations with favorable resources, e.g., abundant renewable energy and iron ore.

To promote fair competition and avoid bias toward specific technologies, many companies voiced that policies and incentives should adopt a technology-agnostic approach, understanding the potential consequences of their implementation on various production methods. This requires transparent and coordinated approaches to the design of measurement and definition of green steel anchored to the fundamental removal of CO_2 emissions as a byproduct, irrespective of the nomenclature used.

Some companies called for an international steel association or alliance comprised of both technical and strategy representatives of decarbonization efforts akin to the International Maritime Organization (IMO). The goal of such an organization could be to foster aggressive decarbonization policies similar to those in the aviation and shipping industries. Standards that are coordinated and interoperable are vital.

Several participants reinforced the need to create dynamic incentives for CO_2 intensity reduction within product category to ensure that product integrity and quality are not compromised – for instance, via a tradeable credit program, again suggesting the U.S. CAFE standards as a model. Additionally, understanding the co-benefits of decarbonization, such as reduced air pollutants like NOx and SOx, should be considered as an input to the design of policy frameworks.

Establishing a global carbon price and a common standard for accounting and reporting, akin to currency exchange mechanisms, may be an effective way to streamline the industry's efforts, some companies shared. The massive capital investment required for the transition poses a challenge for many in the industry and sources of financing are largely unclear. Finally, inquiries about the proportion of steel purchased by governments and the likelihood of governments setting independent policies for themselves remain important to shaping effective decarbonization strategies for the industry.

CONCLUSIONS AND FUTURE OUTCOMES FOR THE INDUSTRY

The Workshop and its deliberations were widely acknowledged by participants as an invaluable exercise in pinpointing the key obstacles and opportunities for accelerating the global transition to green steel. The participants forged new relationships, expressing an interest in maintaining the dynamism and momentum of the discussions. To this end, they unanimously requested a list of attendees, along with their contact information, aiming to perpetuate the dialogue, explore avenues for collaboration, and propel “green steel” forward.

FOR MORE INFORMATION, PLEASE CONTACT:

Dr. Valerie Karplus, Professor, Engineering & Public Policy, Workshop Co-Chair
Dr. Chris Pistorius, Professor, Materials Science & Engineering, Workshop Co-Chair
Dr. Daniel Tkacik, Executive Director, Wilton E. Scott Institute for Energy Innovation

APPENDIX A

PARTICIPATING IRON AND STEELMAKING COMPANIES

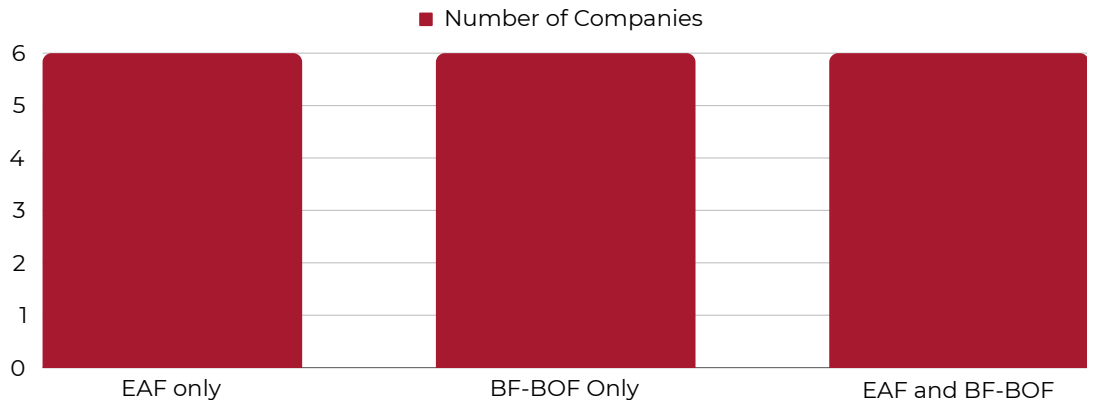
- ArcelorMittal
- ATI
- BlueScope
- Cleveland-Cliffs
- Electra
- HBIS Group
- Hyundai Steel
- Nanjing Iron and Steel Group
- Nippon Steel
- Nucor
- POSCO
- SMS Group
- Tata Steel
- US Steel
- Universal Stainless
- Vallourec Star

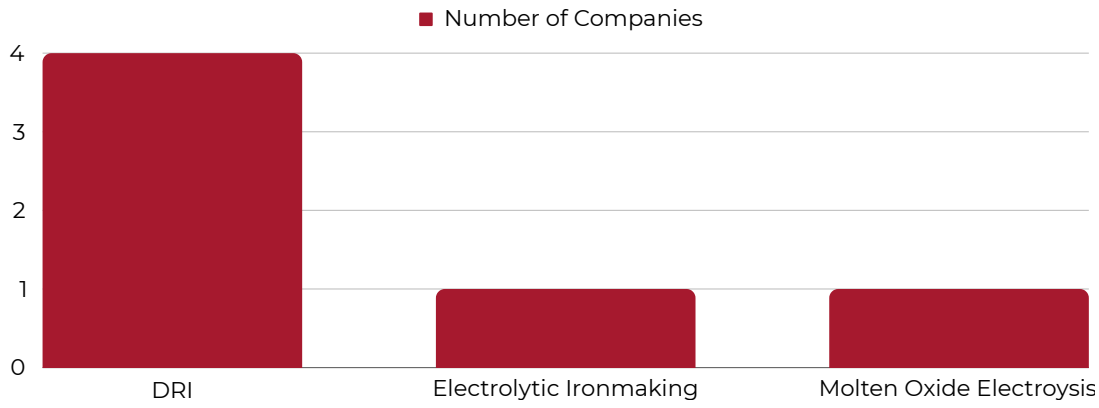
APPENDIX B

SURVEY RESULTS

Prior to the Workshop, participants were asked to complete a brief, anonymous questionnaire about their company's activities and views related to decarbonizing iron and steelmaking processes. The results of that questionnaire were presented at the Workshop and are shown below.

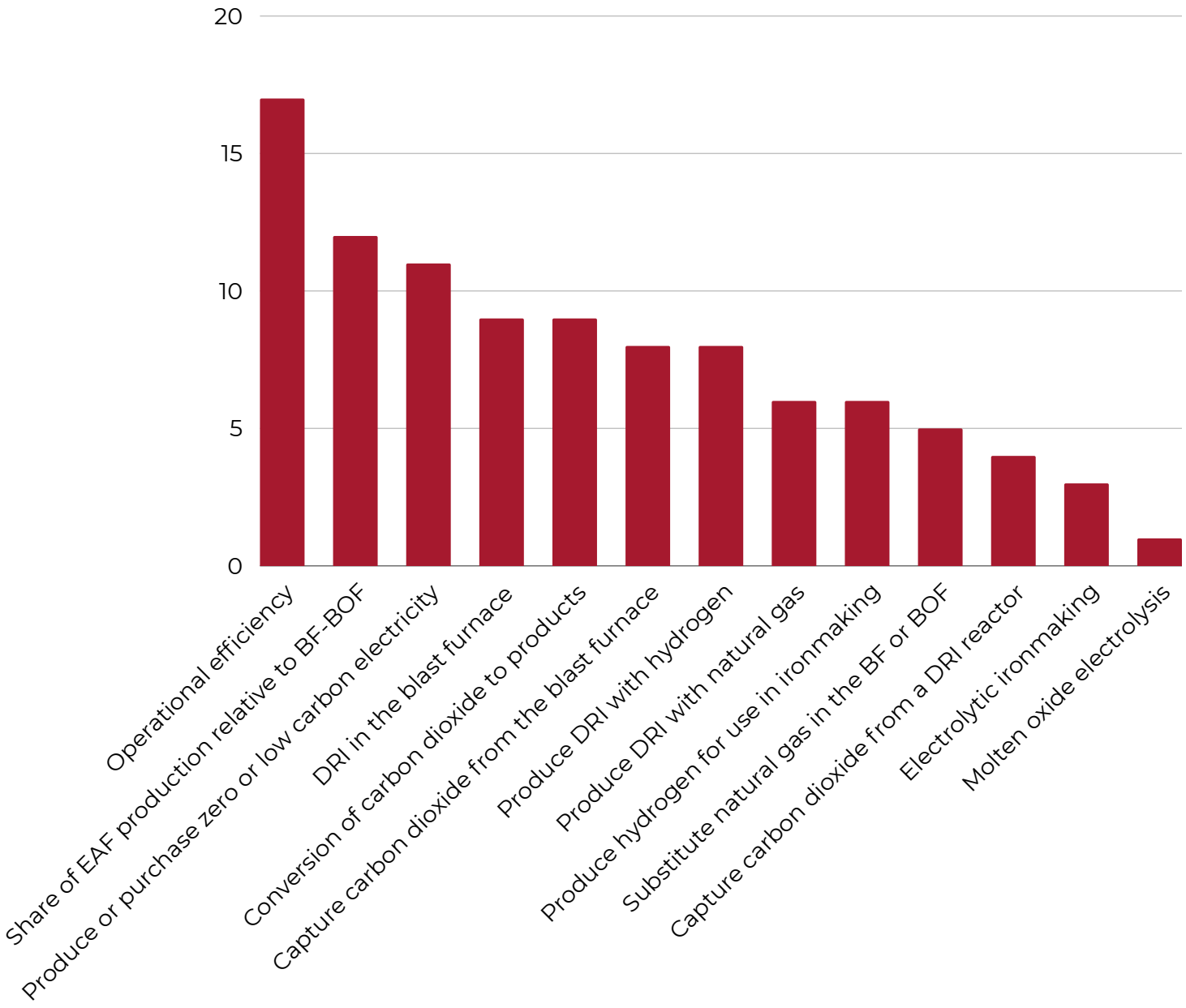
1. WHICH TECHNOLOGIES DOES YOUR ORGANIZATION USE TO MAKE IRON AND/OR STEEL?





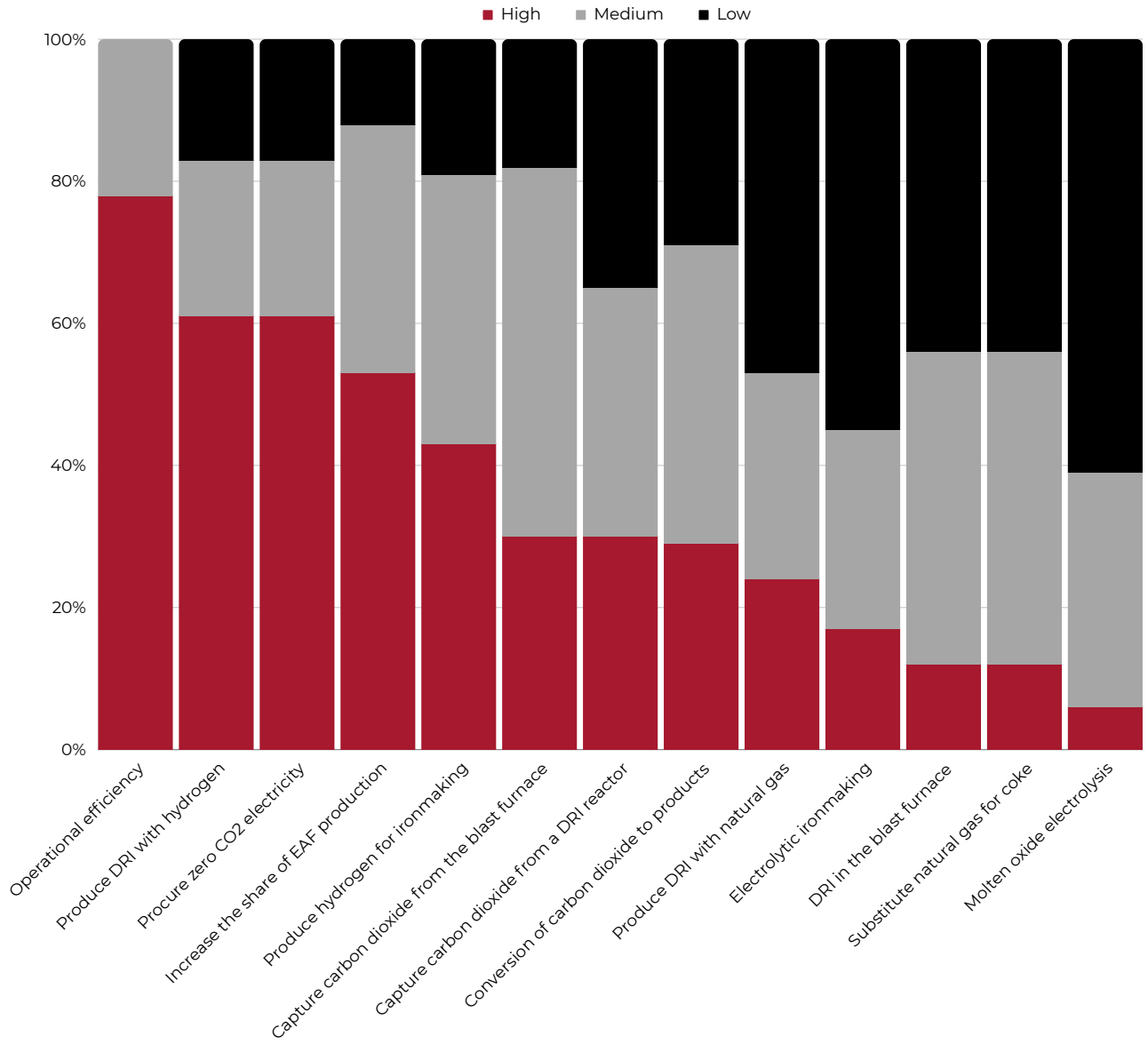
Top graph includes each respondent only once and does not include ironmaking companies
Bottom graph is number of companies producing with each technology

2. WHICH OF THE FOLLOWING TECHNOLOGIES OR STRATEGIES IS YOUR ORGANIZATION PURSUING TO REDUCE GREENHOUSE GAS EMISSIONS FROM YOUR OPERATIONS?



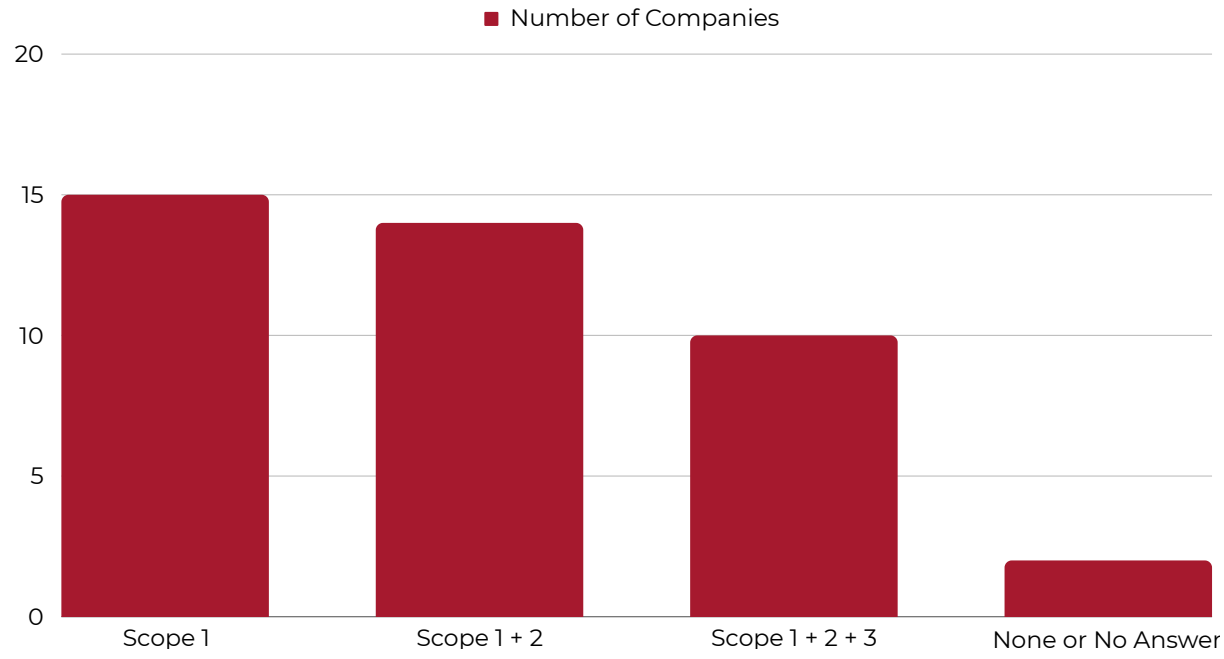
Other strategies identified by respondents: Electrification of Process Heating, Biomass, Hydrogen replacement of natural gas in furnaces, Energy efficiency measures, Digitalization of process controls, Carbon capture from reheat operations, Use of hydrogen for billet reheating

3. AT THE INDUSTRY LEVEL, HOW WOULD YOU PRIORITIZE RESEARCH AND DEVELOPMENT FUNDING ACROSS THE FOLLOWING TECHNOLOGIES OR STRATEGIES?

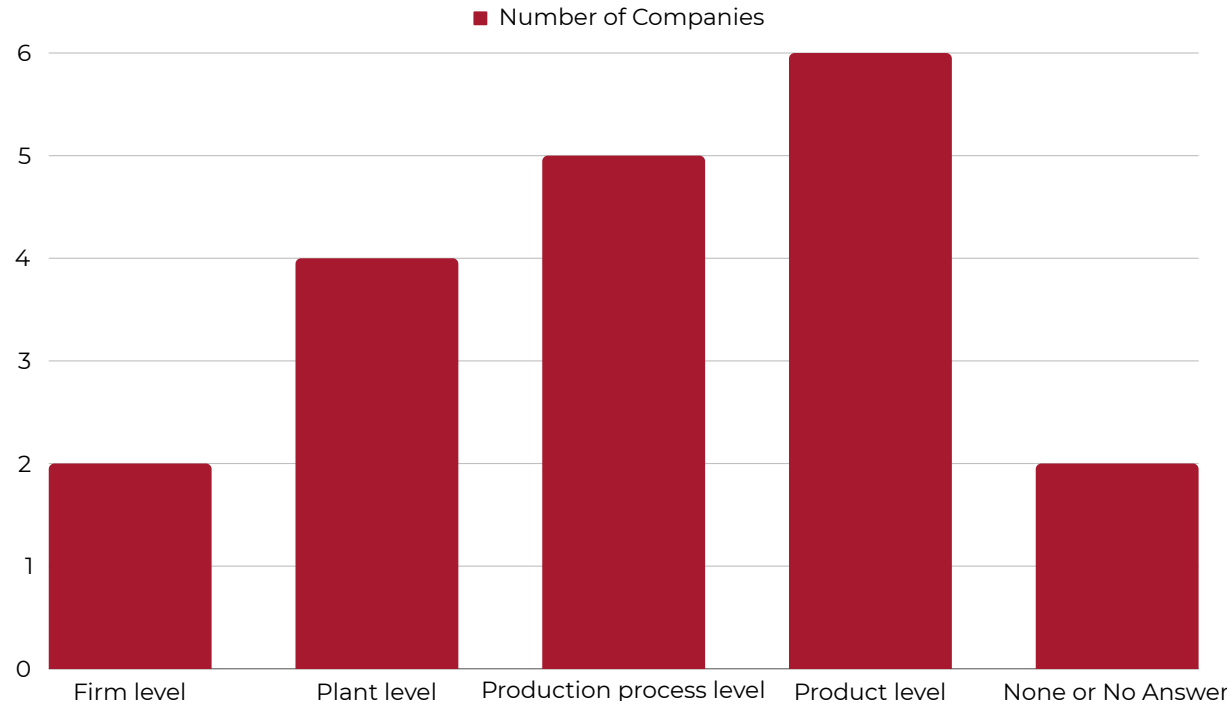


Other strategies identified by respondents: Supply green hydrogen at a competitive price, decarbonizing process heat, impact of hydrogen on product, scrap recycling, use of hydrogen in billet reheat process, raw material optimization, produce high quality steel from scrap, integrate renewable energy, options for process heat beyond natural gas and electric.

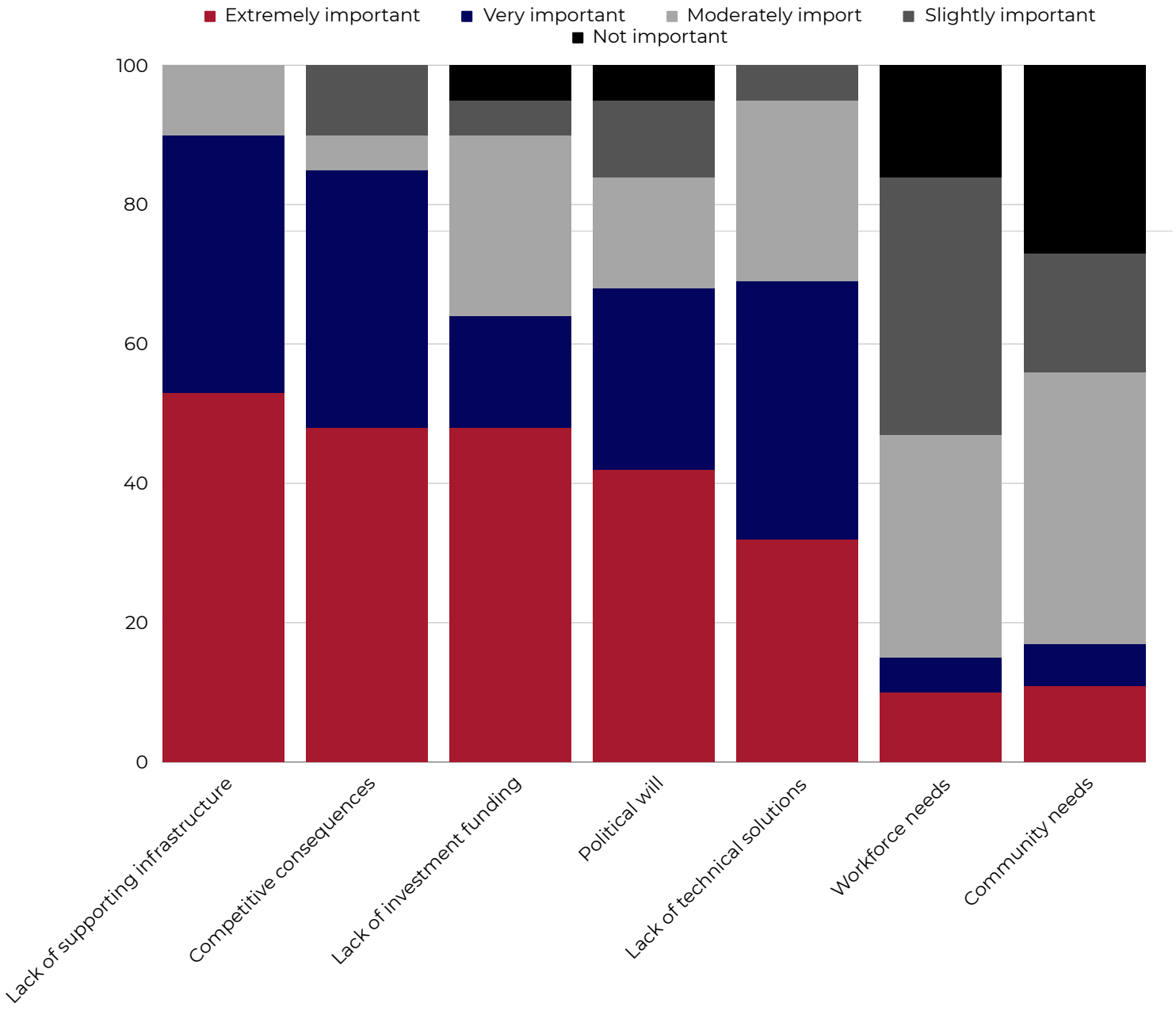
4. WHICH OF THE FOLLOWING SCOPES ARE INCLUDED IN THE COMPANY'S GREENHOUSE GAS EMISSIONS REPORTING?



5. WHAT IS THE MOST GRANULAR LEVEL AT WHICH YOUR COMPANY MEASURES GHG EMISSIONS?

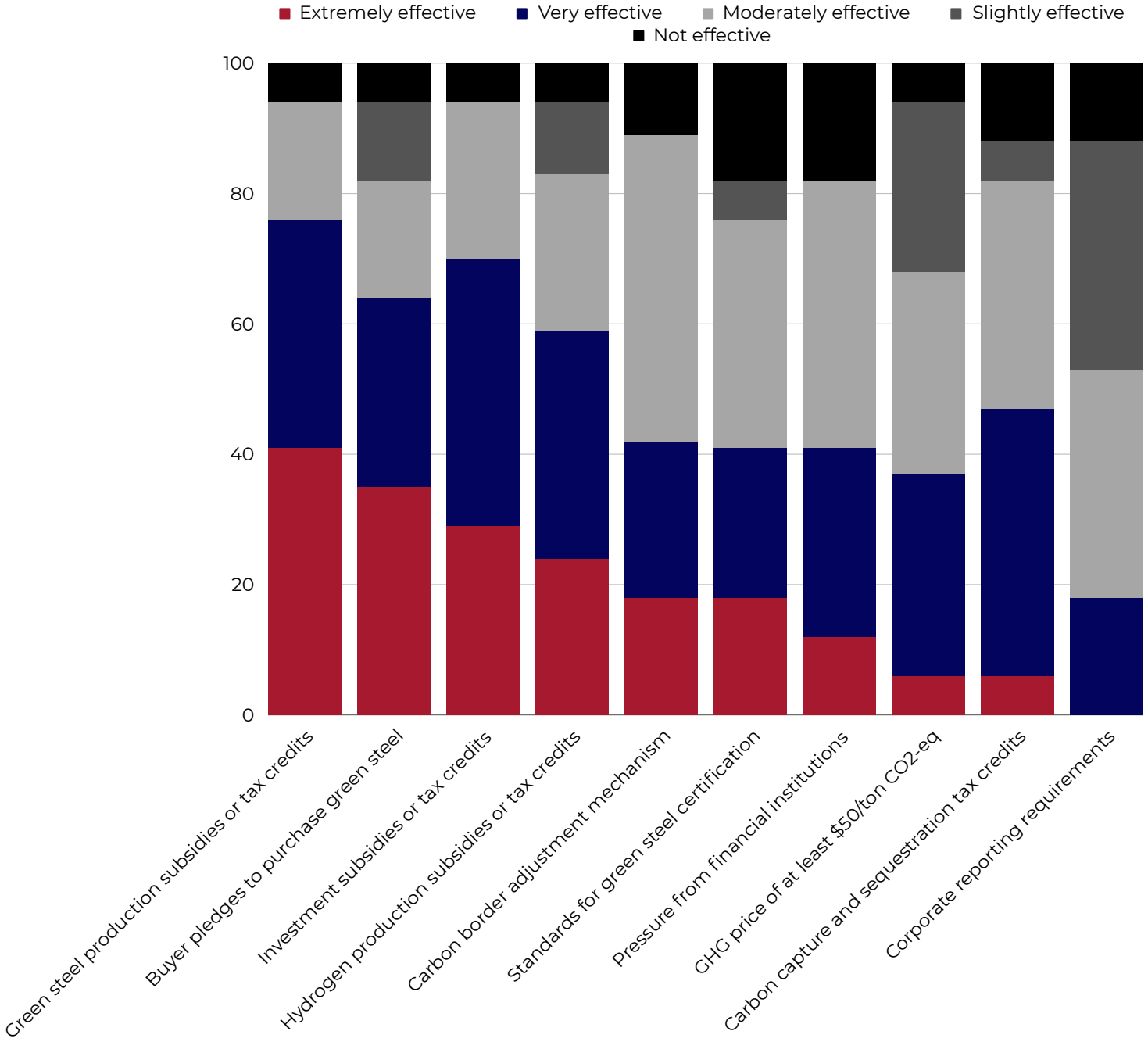


6. HOW IMPORTANT ARE EACH OF THE FACTORS BELOW IN LIMITING INVESTMENTS IN GREEN STEEL PRODUCTION TODAY?



Other factors identified by respondents: Future steel demand uncertainty, lack of buyer willingness to pay, lack of engineering/construction support and limited supply base, profitability, lack of financial incentive, focus on short return on investment, lack of developmental funding and grants, lack of clarity on qualification criteria for green products, global trade and climate change (carbon tax) policy, availability and cost of green/renewable energy, ability to forecast cost-benefit

7. HOW EFFECTIVE DO YOU BELIEVE THE FOLLOWING POLICIES OR OTHER MECHANISMS WOULD BE IN ACCELERATING GREEN STEEL PRODUCTION BY YOUR ORGANIZATION?



Other mechanisms identified by respondents: EU carbon border adjustment mechanism, OEM's Scope 3 reduction plans, shareholder expectations, decision points on reinvesting in existing assets versus building something new and lowering GHG emissions, corporate requirements, political pressure and financial institutions, investor pressure and greenhouse gas price, competitors' decarbonization moves, government funding, and internal company business strategy

ACKNOWLEDGEMENTS

The Wilton E. Scott Institute for Energy Innovation and the Center for Iron and Steelmaking Research at Carnegie Mellon University would like to acknowledge Schmidt Futures for their support of the Workshop on Accelerating Green Steel. The organizers of the Workshop would also like to recognize the students and staff members who volunteered as notetakers, the output of which is reflected in this Rapporteur's Report. Those students and staff include:

- Tarik Ahmad
- Anthony Cheng
- Katelyn Haas-Conrad
- Elina Hoffmann
- Annabel Hu
- Cody Januszko
- Simon Kammerer
- Jillian Miles
- Joanna Slusarewicz
- Quantum Zhuo

Carnegie Mellon University
Wilton E. Scott Institute
for Energy Innovation

CISR
Carnegie Mellon University
Center for Iron and
Steelmaking Research

SCHMIDT FUTURES