New frontiers in research on industrial decarbonization

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Substantial advances toward global decarbonization have been made in areas such as electricity generation and the electrification of building heat and road transport, yet the decarbonization of energy-intensive industries remains a formidable but crucial challenge. Decarbonization of the industrial sector, whose direct emissions account for about 25% of global CO_2, is essential for transitioning the world economy towards a sustainable growth path. With current technologies and policies, such decarbonization appears technically possible, but difficult and costly. This article highlights the pressing need for a new line of research on two emerging frontiers: The first quantifies how industrial decarbonization technologies and policies interact with the broader economy. The second builds on growing data availability and policy experience with industrial decarbonization to provide broad-scale ex-post quantifications of its impacts as an essential empirical complement to a largely modeling-based literature to date.

A growing literature aims to address the critical challenge of industrial decarbonization (see supplementary materials). One foundational strand of this literature explores technical pathways for deep decarbonization, such as alternatives to coal as reductant in steel production (*1*). A second strand proposes policy options – ranging from carbon pricing to demand guarantees - and governance structures to achieve industrial decarbonization (*2,3*). A third strand provides qualitative frameworks to consider social issues such as just transitions (*4*) or the role of social dynamics in decarbonization (*5*).

While research along the two new lines we propose has begun to emerge in the broader climate policy context, industrial decarbonization presents unique data and modeling challenges. This is due to factors such as the critical importance of production networks, for which data are typically scarce, and the presence of oligopolistic competition between limited numbers of firms with market power (e.g., Airbus and Boeing), which is often overlooked in macroeconomic modeling. Other challenges include complex geographies of competition that may vary from regional markets for goods such as cement to globalized competition for steel, high fixed costs that complicate dynamic modelling and are frequently excluded in mitigation cost estimates, and the importance of process-based emissions, which cannot be eliminated through changes in energy inputs. Addressing these research questions in the context of industrial decarbonization will require new suites of models and datasets. For example, the models must combine sufficient industry detail with macro-level spillovers across broad sectors of the economy. This article lays out the nascent research frontiers for economists, political scientists, and engineers that seek to bridge these gaps and give a broader and empirically-based perspective on industrial decarbonization. Governments as well as international organizations, such as WTO, OECD, and the World Bank, are best positioned to provide further data and research support needed, allowing the research community to lay the groundwork for much-needed further guidance for future decarbonization.

Implications of the Broader Economic Context for Industrial Decarbonization

While a growing literature has studied industrial decarbonization from the perspective of specific industries or technologies, new evidence highlights that spillovers across industries, countries, and segments of the overall macroeconomy may be of first-order importance for the effects of emissions-reducing industrial policies (*6, 7*). For example, some industrial decarbonization policies can be rendered ineffective by supply chain linkages. A case in point are upstream subsidies for clean hydrogen production which, as new research has shown, have not lowered prices sufficiently to incentivize the development of hydrogen-using technologies downstream (*8*). As another example, emerging research indicates that so-called “general equilibrium” or macroeconomic feedback effects - such as changes in wages - may render pollution taxes less effective. To illustrate, while increases in environmental regulations and concerns reduced US manufacturing pollution by 19 percent over the past two decades, wage adjustments offset the cumulative pollution decline by 7 percentage points (*9*). While important interactions with the broader economy have been established for a variety of environmental policies in the past, there is a need for more research on these interlinkages specific to industrial decarbonization and with the unique features of heavy industries in mind.

It also has long been known that the impacts of environmental policies on trade patterns and technological specialization across countries can influence and potentially undermine the overall global effectiveness of these policies. For example, stricter environmental regulations can shift the production of polluting goods to less regulated countries or regions, resulting not only in carbon leakage (see supplementary materials) but also in weakened incentives to innovate in cleaner production methods for those goods (*10*). An important new research frontier is to quantify these spillovers in the context of heavy industries, new technologies, and a new policy environment, which includes measures such as Europe’s Carbon Border Adjustment Mechanism. Both the high levels of trade exposure and the need for innovation (*2*) render this interaction especially pertinent for industrial decarbonization as trade policies can substantially alter incentives for innovation in clean industrial technologies.

Understanding policies that can support industrial decarbonization thus requires a unique combination of both detailed industry-level analyses and macro-level analyses that account for a wide range of spillovers across markets and industries. Examples may range from production network models featuring industry-specific details on technology choices, costs, and market structure, to empirical evaluations of policy spillovers across connected firms and markets.

Implications of Industrial Decarbonization for Broader Economic Outcomes

Quantitative evaluations of industrial decarbonization in a broader economic context are essential not only to ensure the effectiveness of proposed policy levers, but also to understand how these policies and technologies affect a wider set of economic outcomes.

Consider labor markets. The impacts of conventional climate policies on outcomes such as workers’ wages and employment disruptions are increasingly being studied. Emerging empirical research on the clean energy transition highlights that, while clean energy firms may provide comparatively high paying and stable jobs, opportunities to transition into these jobs have historically been limited for many individuals with experience in fossil fuel extraction, processing, distribution, and power (*11*). Prior work has also found substantial transition costs for manufacturing workers affected by certain environmental regulations, such as lost wages for workers displaced by the US Clean Air Act Amendments (see Supplementary Materials and literature discussion (*11*)). However, less is known about the impact of climate policies on workers' wages and career progression in heavy industries. Fundamental questions remain about the impacts of specific industrial decarbonization efforts on workers, including how these will interact with broader economic trends such as automation and trade and how costs to workers who lose their jobs can be reduced.

A related pressing research need is to better understand and quantify the distributional impacts (i.e., who are the winners and losers) of industrial decarbonization technologies and policies. Ignoring economic and environmental justice concerns, as well as the need to compensate those who stand to lose under an otherwise cost-effective policy measure, can fuel political opposition capable of slowing down or even blocking its implementation. Recent work across multiple fields has begun providing insights, but there are many industrial sectors and contexts where these impacts have not yet been quantitatively explored.

Quantification at a broad scale is also vital for outcomes that may be conceptually understood to be related to industrial decarbonization, but where the link has thus far been challenging to quantify. As illustrated by recent emerging literature, examples range from air pollution to firms' market power and consumer pricing.

Broad-Scale Empirical Assessments

Many insights from the industrial decarbonization literature to date are based on conceptual frameworks or quantitative ex-ante modeling. Whether real-world policy impacts and technology dynamics play out as envisioned at the broad-scale across the economy thus remains one of the most pressing open research questions in the field. The confluence of climate policy experience and improved data availability is increasingly putting researchers in a position to provide such econometric or broad-scale quantitative assessments.

For example, policymakers around the world are increasingly adopting carbon taxes or emissions trading schemes as core tools to combat climate change. New research using detailed firm-level data has enabled ex-post econometric assessments of these policies' impacts, demonstrating their real-world ability to decrease industrial emissions at a comparatively low cost (*12*). Related work, which connects to our first research theme, has empirically demonstrated the importance of supply-chain spillovers of climate policy (*7*).

Broad-scale empirical assessments can also inform our understanding of critical potential roadblocks to industrial decarbonization which are conceptually well-understood but remain quantitatively uncertain. For example, model-based estimates can generate a range of technological "lock-in" effects depending on their parameter assumptions. However, new research using firm-level data across the US manufacturing sector over a 40-year period has econometrically quantified the extent to which energy prices at the time new firms enter the market affect their subsequent energy and resource choices, documenting "lock-in" effects that last for decades (*13*). These findings highlight the importance of timely policy actions to avoid further lock-in, a concern that may be especially relevant in emerging market economies more dependent on fossil fuels.

Of course it is not always possible to conduct broad-scale ex-post quantifications of industrial decarbonization tools' impacts. Innovative new work has often found other ways to empirically test core conceptual predictions. For example, decarbonization measures such as carbon dioxide removal technologies may require specific policy tools, such as auctions, to operate at scale. New research tests these auctions experimentally (*14*).

Some of the world's largest economies have recently introduced targeted green industrial policies such as the Inflation Reduction Act in the United States, the European Green Deal Industrial Plan, and similar efforts such as China's 1+N Policy Framework and Implementation Plan for Carbon Peaking for the Industrial Sector. Empirically quantifying the impacts of these policies is thus a foundational research priority for industrial decarbonization.

The Need for Interaction Between Researchers and Stakeholders

Tackling the above questions, and ensuring that the results are applied in practice, requires genuine interaction between researchers, policymakers, industry experts, and community leaders, and will rely on new datasets and tools that allow for a deeper understanding of broader economic impacts. Partnerships between industry, government, and researchers are already playing a leading role in many industrial decarbonization efforts, for example, the Hydrogen Breakthrough Ironmaking Technology (HYBRIT) low carbon steel plant projects in Sweden which bring together multiple private sector entities with support of the government and in collaboration with researchers at several universities, and similar initiatives in other countries such as the Hebei Iron & Steel Group (HBIS) H2-Direct Reduced Iron (DRI) project in China. However, understanding the broader economic impacts of these efforts may require both continued and additional collaborations. For example, understanding spillovers across supply chains requires collecting data on the production networks in which firms are involved, which only some governments or industry associations collect, and only rarely have been shared with research partners.

A lack of reliable greenhouse gas emissions data for industrial plants outside the largest firms has often hampered quantitative policy evaluation to date. Fortunately, progress has already begun: Academic researchers have started to build better networks to consolidate and extend existing data sources (*15*) and are helped by increasingly binding greenhouse gas emissions disclosure mandates by financial regulators. These better networks and data can lead to better policymaking, for example by refining our knowledge base of how the design of industrial policy influences environmental outcomes and the longer-run effects of industrial innovation policies. This could potentially change the focus of industrial policies, e.g., towards approaches with the greatest spillovers.

Governments and international organizations are uniquely positioned not only to facilitate better data collection and support critical research collaborations, but also to act as customers for such data to inform their own policymaking. For example, governments could share information on applicants of competitive grant programs designed to promote innovation to allow for analysis of the causal effects of such programs. At the same time, finance ministries are also increasingly eager to quantitatively evaluate decarbonization policies but often cite the need for more expertise and data to do so. Cross-cutting research partnerships and data sharing could vastly improve our understanding of and inform the critical new frontiers in industrial decarbonization that cover a broad economic context.

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SUPPLEMENTARY MATERIALS

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