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# An industrial policy framework for transforming energy and emissions intensive industries towards zero emissions

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**ABSTRACT**

The target of zero emissions sets a new standard for industry and industrial policy. Industrial policy in the twenty-first century must aim to achieve zero emissions in the energy and emissions intensive industries. Sectors such as steel, cement, and chemicals have so far largely been sheltered from the effects of climate policy. A major shift is needed, from contemporary industrial policy that mainly protects industry to policy strategies that transform the industry. For this purpose, we draw on a wide range of literatures including engineering, economics, policy, governance, and innovation studies to propose a comprehensive industrial policy framework. The policy framework relies on six pillars: *directionality, knowledge creation and innovation, creating and reshaping markets, building capacity for governance and change, international coherence,* and *sensitivity to socio-economic implications of phase-outs*. Complementary solutions relying on technological, organizational, and behavioural change must be pursued in parallel and throughout whole value chains. Current policy is limited to supporting mainly some options, e.g. energy efficiency and recycling, with some regions also adopting carbon pricing, although most often exempting the energy and emissions intensive industries. An extended range of options, such as demand management, materials efficiency, and electrification, must also be pursued to reach zero emissions. New policy research and evaluation approaches are needed to support and assess progress as these industries have hitherto largely been overlooked in domestic climate policy as well as international negotiations.

## Key policy insights

- Energy and emission intensive industries can no longer be complacent about the necessity of zero greenhouse gas (GHG) emissions.
- Zero emissions require profound technology and organizational changes across whole material value chains, from primary production to reduced demand, recycling and end-of-life of metals, cement, plastics, and other materials.
- New climate and industrial policies are necessary to transform basic materials industries, which are so far relatively sheltered from climate mitigation.

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- It is important to complement technology R&D with the reshaping of markets and strengthened governance capacities in this emerging policy domain.
- Industrial transformation can be expected to take centre stage in future international climate policy and negotiations.

## 1. Introduction

The Paris Agreement has implications for the development of not only energy and transport systems but also the industrial sector. In 2019, the industrial sector accounted for about 9 Gt of direct $CO_2$ emissions, plus another 7 Gt in indirect emissions from energy used – adding up to almost half of all energy related $CO_2$ emissions – with energy and emission intensive industries, such as steel, chemicals, cement, and aluminum, accounting for more than 70% of direct industrial emissions (IEA, 2020). The latest information from global models considered by the Intergovernmental Panel on Climate Change (IPCC) to advise the United Nations Framework Convention on Climate Change (UNFCCC) negotiations shows that $CO_2$ emissions from the industrial sector must be reduced by 58–93% by 2050 compared to 2010 levels for developed countries, to fall within the broad scope between the 10th and 90th percentile of all 1.5°C scenarios (Huppmann et al., 2018; Masson-Delmotte et al., 2018). This will require 'herculean efforts' in the coming decade (Rockström et al., 2017). The requirement to rapidly decarbonize the economy, together with the large negative effects of failing to do so, and the large uncertainties involved in any potential approach to allocate remaining emissions, makes it imperative to strive for zero emissions across all sectors, including industry. The highly aggregated characterization of the industrial sector in the computational models underpinning the latest IPCC report provides little detail about the opportunities and barriers for mitigation specific to industry (e.g. Edelenbosch et al., 2017). A high reliance on negative emission technologies (NETs) in these scenarios also obscures the need to discuss further (Smith et al., 2016) or to discuss alternative means (van Vuuren et al., 2018) to rapidly reduce industrial emissions and eventually approach zero.

Transforming global industrial systems to zero emissions will require significant changes across and between existing value chains, economic sectors, and policy domains (Bataille, 2020; Rissman et al., 2020). As systems of production and consumption of materials, products, and services are closely intertwined in modern economies, there is no single silver bullet to transform energy and emission intensive industries. These industries and their challenges are characterized by the high energy and emission intensity of production processes, a strong and continued lock-in due to large capital investments in carbon-intensive technologies and infrastructures, and long investment cycles which only provide opportunities for major process changes every few decades. Further challenges include their historical embeddedness as well as both symbolic and economic value to local communities, and global competition in commodity markets in which largely undifferentiated products are traded (IEA, 2020; Seto et al., 2016; Wesseling et al., 2017). Therefore, several complementary solutions, relying on technological, organizational and behavioural change, must be pursued in parallel throughout value chains. For example, decarbonization will require improved energy efficiency, materials efficiency, reduced demand, circular material flows, electrification, fuel switching, and carbon capture for utilization or storage (Bataille et al., 2018). Short term emission reductions in existing processes are often possible through energy efficiency improvements and fuel switching but major process changes are needed to reach zero emissions. This will require much more strategic action by firms active in energy and emission intensive industries, many of which have been late to adopt strategic carbon management practices (Dietz et al., 2018), as well as pro-active governments to identify and develop geographically specific and structured pathways towards zero emissions (Waisman et al., 2019).

To deliver these solutions, industrial policy – here defined inclusively as all policy initiatives affecting industrial development – must acknowledge that zero emissions is a key objective of the policy domain (Aiginger & Rodrik, 2020). Modern industrial policy, however, grew out of an ambition to protect industries representing key state interests in the post-war era with policy instruments such as state ownership, direct subsidies, or tax breaks, but also using trade policy related instruments such as tariffs (Grabas & Nützenadel, 2014). Later, industrial policy focused primarily on promoting high-tech growth sectors such as ICT and biotechnology, as well as supporting small- and medium-sized enterprises.

Environmental policy, emerging in the 1970s, aimed mainly for end-of-pipe solutions to reduce local and regional pollution. Only recently has the interest in industrial policy turned towards the transformation of modern economies for sustainable development (Aiginger, 2015; Rodrik, 2014; Warwick, 2013), arguing that to achieve this, industrial policy must be systems oriented instead of growth focused. This turn follows similar developments in innovation policy, which has shifted from aiming to support all types of economic development to taking up more challenge driven and transformative objectives (Schot & Steinmueller, 2018). Given that the aim of such policies is not merely to support the development of innovations, but to instigate and proliferate specifically directed changes of the systems that deliver key services in society, such as transport, housing or food, there is a need for considering strategic policymaking that includes a portfolio of policies rather than singular instruments (Edmondson et al., 2019; Grillitsch & Hansen, 2019; Rogge & Reichardt, 2016). Although carbon pricing is an important part of climate policy, it is insufficient to drive the transformative change needed (Ball, 2018; Rosenbloom et al., 2020; Tvinnereim & Mehling, 2018).

Earlier approaches to green industrial policy and clean technology innovation have not paid explicit attention to the necessity of zero emissions or to the profound changes in production, use, and recycling of emissions intensive basic materials that this entails. This challenge has gained increasing attention since the adoption of the Paris Agreement and in the past few years, several policy briefs and recommendations on low-carbon industrial development have been published by NGOs, industrial actors, and academic scholars (Busch, Foxon, & Taylor, 2018; Material Economics, 2019; University of Cambridge Institute for Sustainability Leadership, 2019).

While these present important contributions to the debate, we argue that an industrial policy for transforming energy and emission intensive industries towards zero emissions must take a structured and comprehensive approach. We build on the recent insights that effective climate policy must use a diverse set of instruments and initiatives (Meckling & Allan, 2020) implemented strategically both in combination and sequentially (Meckling, Sterner, & Wagner, 2017). We thus draw on a broad range of literatures including economics, political science, and innovation studies to propose a framework for industrial policy that builds on six pillars: **directionality**, referring to the ways that the state can express and emphasize the direction of development accepted and needed; **knowledge creation and innovation**, referring to support for low-carbon innovation and learning throughout value chains; **creating and reshaping markets**, as markets are not natural entities but indeed political products policy must both create new markets and reshape existing ones; **building capacity for governance and change,** which will be needed as the challenges for industrial climate solutions are different from the ones mainly addressed by agencies for energy and transportation that have thus far taken the lead; **international coherence**, referring to the growing need for international coordination on the topic in addition to global agreements on climate and trade; and the need to take responsibility for **phase-outs and socio-economic implications** of the foreseen development, which for some households and regions will be negative and significant. Several of the pillars are closely related and must support each other, but for the purpose of clarity we present them here as fully separate and do not specify all areas where there are interconnections.

## 2. Towards industrial policy for zero emissions

### *2.1. Directionality*

Future industrial policy must shift from its current narrow focus on economic efficiency and development to wider aims that combine efficiency with a sense of direction that leads to the fulfilment of both environmental and socio-economic goals. Public policies, directly or indirectly, play a key role in defining not only the rate of change and development, but also its direction by creating specific incentive structures. Embracing directionality as a key pillar of industrial policy is to acknowledge that it is necessary to generate innovations not just as efficiently as possible, but also in ways that contribute to development in the desired direction (Weber & Rohracher, 2012). An industrial policy with a strong sense of direction does not simply call for top-down state-centered projects (Mowery et al., 2010). Instead, it requires bottom-up partnerships between private and state actors (Aiginger & Rodrik, 2020) to support the development not only of new technologies, but of new techno-economic paradigms (Mathews, 2013; Perez, 2010). Setting the direction of travel is not limited to tilting the playing field in the desired direction. It also limits the room to maneuver for competing, less sustainable solutions. Consequently, the policy mix should include both creation and destruction policies (Kivimaa & Kern, 2016; Rogge & Johnstone, 2017). The combination of creation and destruction creates winners and losers and may require various forms of reskilling, job creation and compensation to maintain legitimacy and acceptance (see 2.6).

Overarching policy frameworks, such as climate laws that define the policy ambition, are important starting-points to set the direction of development (Eskander & Fankhauser, 2020). However, more detailed plans must also be developed, closer to the realities and specifics of different industries. Both trade associations and individual firms play important roles in developing roadmaps that map out possible development options that are available to reach zero emissions. Directionality can also be materialized through infrastructure investments, a domain in which governments have opportunities to make investments that allow for system-building and acceleration of the transformation (Cass et al., 2018). To achieve the direction of travel, a wide policy toolbox of direct and indirect policy measures is necessary (Andersson & Karpestam, 2012; Rogge & Reichardt, 2016). A key concern for such a policy mix is then to ensure alignment and coherence across the domains – alignment both with the targeted direction and within the policy mix employed.

### 2.2. Knowledge creation and innovation

Studies of innovation processes have highlighted the importance of government interventions for ensuring sufficient – from a societal perspective – investments in research, development and innovation (RDI) and the possibilities for firms to profit from these investments by establishing intellectual property rights systems. Since the late 1980s, systemic perspectives on innovation processes have dominated in research and policy practice (Godin, 2009; Schot & Steinmueller, 2018). These perspectives emphasize the interactive nature of innovation processes encompassing not only the 'usual suspects' of firms, universities and research institutes for creating knowledge and innovating, but also the role of public sector actors and intermediary organizations as well as actors on the demand side (Edquist, 1997). Further, they underline the influence of formal and informal institutions connected to specific industries on innovation processes. Recent contributions focus on the possibilities of innovation policy to contribute to systemic change and transformation (Grillitsch et al., 2019; Grillitsch et al., 2021).

Most energy intensive industries are characterized by large dominant actors on the primary production side of the value chain with low investments in RDI, typically below 1% of the annual turnover (Wesseling et al., 2017). The industries are shaped by high capital intensity and incremental development focused on processes and only limited opportunities for product innovation. New technologies typically need to fit into existing processes, and high capital utilization is necessary for recovering investment costs leading to increasing returns and path dependency (Arthur, 1994). Many radical innovations that are necessary for industrial transformation are hence perceived as risky, hard to integrate and uncompetitive compared to established technologies (Sood & Tellis, 2005). Thus, firms that attempt to commercialize emerging technologies will likely incur substantially higher production costs with few immediately monetizable co-benefits. Public RDI policies reduce the cost for firms to engage in innovation and are therefore needed in order to overcome this barrier. This may include public funding of basic research, pilot and demonstration plants, as well as support for education and training (Nemet, 2009; Schot & Steinmueller, 2018). Such policies may also be justified by knowledge spill-overs where other firms capture part of the benefits of this new technology without paying for the development cost (Nemet et al., 2018). Other forms of innovation, e.g. regarding organizational structures and business models throughout the value chains, may also be needed (Olivetti & Cullen, 2018), although the demand and scope for such innovations also depends on the pathways followed to zero emissions (Axelson et al., 2021).

Developing and diffusing innovations for zero emissions in the industrial sector is more likely to succeed with collaboration along the value chain since this enables combining knowledge held by different actors and collective learning (Rissman et al., 2020). Traditionally specialized engineering firms have had an important role for technological development in the energy and emission intensive industries, since many industry companies outsource or collaborate intensively with them on process development (Arora & Gambardella, 2010; Wesseling et al., 2017). Furthermore, collaboration across sectors that complement each other's knowledge and capabilities is considered to be necessary in some cases, such as the upscaling of forest biorefineries, although it has proven to be difficult to engage a diverse group of actors in such collaborations (Bauer et al., 2018; Karltorp & Sandén, 2012). Governments can promote collaboration and knowledge exchange in their design of pilot and demonstration programmes (Hellsmark et al., 2016) and by catalyzing heterogeneous actor networks (Mossberg et al., 2018; Söderholm et al., 2019), which they may also participate in via research institutes and universities.

A systems perspective, which recognizes the interdependencies with other sectoral developments, is necessary for governance to be effective in any effort to achieve zero emissions. The need for such an approach is particularly evident for two key pathways that require systems innovation: electrification of industrial processes (directly or via hydrogen) and carbon capture and storage (CCS) (Lechtenböhmer et al., 2016). These pathways require access to low carbon electricity through power systems with sufficient transmission and distribution capacities, $CO_2$ and hydrogen distribution networks, and storage – which in turn rely on rapid adoption and diffusion of other innovations. Investment in this infrastructure requires long-term planning and a common vision, shared between government, industry and civil society. Such a common vision could evolve via stakeholder-oriented pathway development processes. Such processes could include co-development of scenarios, roadmaps, and action plans and be important tools for learning, communicating and coordinating transitions (Lechtenböhmer et al., 2015).

### 2.3. Creating and reshaping markets

The creation of industrialism required a far-reaching transformation of economies through political interventions to create and shape modern markets (Polanyi, 1944/2001). Contemporary markets for industrial products are not naturally occurring phenomena but are co-created outcomes of decades of economic development, political processes, and institutionalization – shaped and supported by (often state-owned) enabling infrastructure. This in turn, provides states with a key role in deciding the rules of access to such markets. Consequently, introducing a new political goal – near zero emissions in the industrial sector – necessitates support for the development of new social practices, technologies, and products, but also their introduction to and the reshaping of existing markets – in evolutionary terms, changing the selection environment to allow for new growth (Ayres, 1991; van den Bergh et al., 2006). Creating and shaping niche markets – protective spaces in which new technologies can mature – for new, green technologies and products, has been part of national environmental policymaking for some time. However, the notion that existing markets can and must also be reshaped to conform with climate targets, including new ways of providing services in different ways or with a lower material use, has received less attention (Mazzucato, 2016).

The scale-up of small-scale green niches is hampered by fossil energy subsidies and supportive market architectures, such as through codes and standards that hamper innovative solutions. Decarbonized industrial production systems are often at a competitive disadvantage due to both higher risk associated with novel technologies and the high degree of lock-in of present systems (Seto et al., 2016). Higher production costs are a major barrier to deep decarbonization in the energy intensive industries, which puts green technologies at a disadvantage. Examples include steelmaking with hydrogen-based direct reduction, cement production with oxyfuels and CCS, or electrification and the methanol-to-olefins route in chemicals, all of which have production costs ranging from 38% to 277% higher than conventional, GHG emission intensive production methods (Agora Energiewende & Wuppertal Institut, 2019). A plethora of specific policy instruments are available for market creation, which typically take the form of positive economic incentives or supportive requirements, such as subsidies or quota obligations. Instruments for the reorientation of markets to eliminate the disadvantage typically takes the form of negative economic incentives or restrictions, such as taxes or regulatory standards. Market shaping can target the supply side, such as production subsidies, or market demand through standards, quota obligations or public procurement.

Direct subsidies will be needed to bridge the gap from demonstration to the commercialization of large first-of-a-kind industrial plants – such as the ones required to decarbonize steel or cement making – before proper markets for such products exist (Hellsmark & Jacobsson, 2012). Setting up such markets for industrial products relies on information instruments, such as carbon footprint tracing or tradable certificates for green materials. In turn, this facilitates the introduction of product requirements and quota obligations, and allows private and public actors to procure green products (Vogl et al., 2020). Demand-side policies aiming to establish markets for greener materials are emerging around the world, e.g. in France where a new building energy code has been adopted including life cycle analysis (LCA) derived metrics to encourage the use of low-carbon building materials (Schwarz et al., 2020).

Tilting the playing field through market shaping requires a series of choices regarding the policy process and design (Mazzucato et al., 2020). Negotiating eligibility for support with the incumbent industry, through both demand- and supply-side market policies, bears a high risk of deepening existing carbon lock-in if regulators are disadvantaged in terms of information and knowledge (Okereke & McDaniels, 2012). Furthermore, collection of information about real environmental performance, and about implementation costs of changes to processes and methods in globalized value chains, is far from trivial and requires significant bureaucratic capacity as well as transparency. Finally, the creation of markets for green products will likely produce spill-overs outside the jurisdiction that has created the lead market. Lead markets can in this way serve as a source from which low-carbon industrial production can diffuse internationally.

### 2.4. Building capacity for governance and change

The need for fully decarbonizing industry is a new policy challenge for governments and thus the managerial and bureaucratic capacity for governing this transformation must be developed. As long as emission reduction targets were short term and incremental (e.g. as in the Kyoto Protocol), industrial emission reductions could be achieved through low cost and marginal measures, such as energy efficiency and fuel shifts from coal to gas, supported by conventional energy efficiency policies. As the idea of near term and marginal solutions with low abatement costs is being replaced with the notion of zero emissions and a transformational change of industry, new challenges require the attention of governments, industry, and other actors and innovation in the policy processes (Upham et al., 2014).

Climate policy has been a part of energy and transport policies for decades. As a result, there has been a build-up of institutional capacity in these fields, including the creation of directionality, policy learning, government expertise in ministries and agencies, as well as academic research. Albeit, in these sectors much focus has also been on near-term marginal changes with less attention to strategies and capabilities for more long-term transformation (Johansson et al., 2020). That said, reducing industrial emissions to zero is a new and underdeveloped field for policy and governance. Plastics is a case in point, where initial policy efforts have been piecemeal and not addressing the key dependence on fossil feedstock, energy, and associated greenhouse gas (GHG) emissions (Nielsen et al., 2020). Moving forwards, there is a dire need to also consider the structural challenges facing the integrated oil, gas, petrochemical, and plastic industries and their mutual dependence on fossil resources (IEA, 2018). Building new and comprehensive institutional capacity to understand the specificities of such interconnections is important for dealing with challenges emerging in the process. Separate, independent organizations, such as the UK Climate Change Committee, can provide increased transparency, reflect broader perspectives and the political accountability.

Stable conditions reduce the risk for businesses to invest in new technologies, and these need to be combined with an ability to adapt and tailor policies to future changes in technologies, demand patterns, or external conditions on a geopolitical scale. This policy reform process is a difficult balancing task, as there is a risk for both regulatory capture by strong businesses aiming to preserve *status quo* in all instances and that suggested policies generate unfair conditions among businesses, or excessive profits for some actors. For example, the EU ETS has led to large extra profits for several of the most emission intensive industries who have received over-allocation of free emission rights (de Bruyn et al., 2013). Creating long-term stable investment conditions may also have democratic implications, if this severely restricts options available to future policymakers (and voters) to adapt their policies according to new knowledge and priorities.

In pursuing transformational change, policy coherence is often argued as important for efficient policies and something that might require institutional reforms (Bocquillon, 2018; Nilsson & Weitz, 2019). A coherent policy approach to industrial transformation will cut across many traditional policy domains, particularly if the future is much more material-efficient, circular, and electrified with new sectoral couplings. It may cut across building codes, waste handling, product standards, electricity market design, resource security, environmental permitting, trade, CCS infrastructure and regulation, and much more, in addition to RDI and market creation as discussed above. This highlights the need for a more systems-oriented policy for sustainable development and less growth focus (Aiginger, 2015; Rodrik, 2014; Warwick, 2013). In addition to the need for building knowledge about industry and industrial transformation, more systems-oriented policy approaches will also require capacity development.

Systems for continuous monitoring and evaluation will be important parts of the institutional setting as they contribute to learning and political accountability (Mickwitz, 2003). The learning effect can reduce the risk for the asymmetric knowledge that may exist between the regulator and industry. Monitoring and evaluation can be organized next to existing governmental structures through an independent observatory and advisory function like the UK Climate Change Committee, which has inspired similar bodies around the world (Weaver et al., 2019). It can also be organized as part of the existing government structure, e.g. in existing agencies and ministries. Objectives, mandate, resources, independence and organization may vary between countries depending on political and institutional traditions, but the task of institutional learning remains crucial. The need for developing an internationally effective system for tracking and evaluating progress for industry is a further challenge.

### 2.5. International coherence

Most emission intensive industries are both carbon and trade intensive, making them sensitive to different national carbon pricing schemes and other policies. As a result, global governance is needed to achieve zero emissions in the industrial sector, but the potential for this is yet largely under-developed (Oberthür et al., 2020). The UNFCCC has as a core principle that the responsibility for mitigating GHG emissions is 'common but differentiated according to respective capabilities' between countries. In the Kyoto Protocol, this principle meant that industrialized countries such as the EU, US, and Japan should implement stricter carbon policies than countries such as China, South Africa, or India. This core principle of the UNFCCC created an institutionalized 'uneven playing field' for global industries such as steel, cement and aluminum producers and has been criticized by industrialized countries for leading to decreasing competitiveness and carbon leakage. Industrialized countries have responded by sheltering domestic industries from the costs that stem from climate policy (Åhman et al., 2017). The strategy has worked, at least for the EU, and so far no real evidence of carbon leakage has yet been seen (Åhman & Nilsson, 2015; Branger et al., 2017).

The differentiation in climate ambitions between rich and poor countries is still relevant but has been played down in the new Paris Agreement. This is partly due to developments in the global economy over the past 20 years. Reality on the ground has changed with the rapidly industrializing BASIC countries becoming major emitters. Industrializing countries need capacity for producing steel, cement and other materials for their development, but the narrative has shifted from these countries being allocated 'extra' GHG emissions to instead getting technical and financial assistance to leapfrog past carbon intensive solutions (Bataille, 2020). The issues of fairness and climate justice are still very present within the global framework for climate action.

Introducing Border Carbon Adjustments (BCAs) is an increasingly discussed policy response. Correcting for the unpriced embodied carbon of products at the border might seem like a quick fix, but it is anything but (Monjon & Quirion, 2011; Wood et al., 2020). Disadvantages for industries do not just come from higher carbon prices, but also from domestic subsidies and other advantages (Haley & Haley, 2013). Such subsidies are all part of a broader industrial policy for development that fast growing and industrializing countries such as China and India have as a key political priority. An effective trade policy response to carbon leakage would thus need a broader approach, including agreements on fair levels of subsidies, competition and market access.

A future approach must take into account that industry needs to transform itself in a context where it competes internationally at the same time. The conflict between international trade and industrial and climate policies is especially sensitive for industries competing on global markets. The alignment of industrial, climate, and trade policies and BCAs urgently needs to be resolved within both the UNFCCC and the WTO, and other trade agreements (Åhman et al., 2017; Oberthür et al., 2020).

The Paris Agreement calls for and depends on initiatives that are taken outside, but supportive of, the UNFCCC. Several initiatives have been launched including the Mission Innovation[1] and Energy Transition Commission[2] that focus more on innovation and transformation, partly including emission intensive industry. Emerging and industry focused international initiatives include the Leadership Group for Industry Transition[3] and the Clean Energy Ministerial Industrial Deep Decarbonisation Initiative.[4] Another avenue of increasing cooperation is to develop the idea of 'climate clubs' with a specific focus on basic materials (Keohane & Victor, 2016). Climate clubs are often linked to using the threat of BCAs as the stick, inducing more members to join the club. BCAs imply that governments lead these clubs. However, recent research suggests that a complementary focus on clubs for innovation, development, and access to green niche markets could be a more fruitful development in line with the spirit of the Paris Agreement (Victor et al., 2019). This approach is more open to leadership from non-state actors e.g. industry coalitions and financial market initiatives for non-financial disclosure.

### *2.6. Phase-outs and socio-economic implications*

The Paris Agreement target implies the discontinuation and phase-out or repurposing of existing fossil fuel and feedstock infrastructure (e.g. coal power plants, gas pipelines, and blast furnaces). Lessons can be learned from the ongoing phase-out of coal and nuclear, e.g. in Germany (Johnstone & Hielscher, 2017; Rogge & Johnstone, 2017; Stegmaier et al., 2014). Any major techno-economic transformation in the industrial sector is likely to have economic and political effects, and create winners and losers among firms, workers, regions as well as countries.

Firms will be affected in different ways depending on their position in the value chain. Jobs in the extractive fossil fuel industries, i.e. coal, oil and gas extraction and processing, are most threatened in the short term. The effects on jobs in steel and chemicals may be small if these industries can eliminate emissions while retaining production. There may be fewer blast furnaces and steam crackers, but relatively few jobs may be affected, and new ones will be created elsewhere e.g. with more circular material flows. For cement, smaller and older plants that are not suited for CCS, may be phased-out and affect local economies (Andersson, 2020). Most studies point towards basic materials becoming costlier to produce when fossil fuels and feedstock are phased out, or when applying CCS. This may suggest that such cost increases will spread through the economy, reducing economic welfare. However, for carbon intensive materials, such as steel and cement, the cost of materials is only a minor share of the price of the final products in which they are used; thus even substantial increases in the cost of primary materials are likely to have only negligible impacts on the price of final products (Rootzén & Johnsson, 2016, 2017). In addition, downstream industries, facing high levels of competition, are likely to absorb most of the cost increase through new products combined with new and more efficient production technologies (Andersson, 2020). Due to these moderating mechanisms, the effect on consumers and thus economic welfare is thus likely negligible.

New skills are needed to take up jobs in new or other sectors, which may hinder a transition of workers from old to new sectors. Technological change will lead to fewer jobs in some industries but it will be hard to attribute such effects to emission reductions in the larger context of continuous industrial restructuring, automation and digitalization. Criticism has been raised that a focus on increasing international competitiveness and cheaper exports could depreciate real wages and lead to higher income insecurity and precarity (Standing, 2012; Wigger, 2019). Calls for an industrial policy that acknowledges the vulnerability of workers and communities have crystallized under the demand for a 'just transition for all'. It is a concept dating back to the 1970s, but it has since been mainstreamed beyond the confines of labour unions and broadened in its meaning (Stevis & Felli, 2014). An industrial transition will have a more concentrated impact on some regions than others. Workers are vulnerable in the process of industrial restructuring, such as the consolidation to fewer and larger plants or plant closures in 'one-company-towns'. A consequence of low carbon development might be, for example, that the trend towards electrification will put regions with limited access to inexpensive renewable energy at a disadvantage (Lechtenböhmer et al., 2016).

Governments can respond to this with transitional assistance policies that provide monetary assistance, public goods and services, or tailored local or regional assistance (Green & Gambhir, 2020). A commitment to both procedural and distributional justice of phase-outs and industrial development is key in order to earn public support for transition (Newell & Mulvaney, 2013). Structural policies that promote flexible labour markets may contribute to easing the transition, while preserving key objectives such as social balance and equity (Andersen et al., 2015). Labour market and welfare policies for well-functioning retraining and reinvestment are needed in regions that will lose industries.

## 3. Conclusions and outlook

Given the necessity of aiming for zero emissions across all sectors, the energy and emission intensive industries can no longer be the emitters that remain and rely on other sectors to carry the burden of climate change mitigation. Green industrial policies are needed, but a green industrial policy for targeting the transformation of the typically slow moving, incumbent and socially embedded energy and emission intensive industries is still a relatively unexplored field. The discussion has started in the EU and the UK. Other regions aiming for carbon neutrality by mid-century, e.g. China, Japan, and South Korea, must also engage with this important but difficult topic. As a result, we expect that industrial transformation will take centre stage in future international climate policy and negotiations.

Carbon pricing has been a primary climate policy instrument in some jurisdictions so far but has been insufficient to induce more than marginal emission reductions in energy and emissions intensive industries – if these industries have been affected by the pricing mechanisms at all. We argue that a comprehensive industrial policy framework for zero emissions is needed to tackle this in the emission intensive subsectors of industry. Drawing on a wide range of literatures including engineering, economics, policy, governance, and innovation studies, we propose a framework built on six pillars: ensuring directionality in policy; supporting knowledge creation and innovation; creating and reshaping markets; building capacity for governance and change; international policy coherence; and addressing socio-economic implications of phase-outs. Policy strategies covering these pillars must address all mitigation options, ranging from materials demand management to electrification and CCS.

For governments, this means taking initiative and a more active role to create directionality through roadmaps and clear policies, including the reshaping of markets, extending the scope of research and innovation policies to zero emission solutions for industry, developing its own capacity and knowledge on industrial transformation and, finally, raising this issue in international climate and trade negotiations. Such a strategy must also be dynamic as technologies, systems, and socio-cultural norms develop and evolve over time. The mitigation options, value chains, market characteristics, and industrial structures vary widely across industries, for example, the cement, chemicals, and steel industries. Industrial policy strategies may therefore be more effective if they are tailored to specific sub-sectors. They may also be adapted to different national and regional contexts, where access to specific cleaner feedstocks and energy forms, for example, and local versus global perspectives will contribute differently to the six pillars. Strategies, interventions, and instruments must thus be developed, designed, and implemented with sensitivity to the specific context, e.g. in terms of level of economic development, governance tradition, resource availability, and industrial landscape. As 2050 is only one or possibly two investments cycles away for major process changes in the most implicated sectors, the time is now to rethink industrial development.

## Notes

1. www.mission-innovation.net.
2. www.energy-transition.org.
3. www.industrytransition.org.
4. www.unido.org/IDDI.

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