DEEP DECARBONIZATION PATHWAYS

CLIMATE AMBITION BEYOND EMISSION NUMBERS

Taking stock of progress by looking inside countries and sectors

INDUSTRY

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Disclaimer

How is this document relevant to the Global Stocktake?

This document is part of a collective report that assesses the evolution of climate ambition in 26 countries and 3 hard-to-abate sectors through a granular and context-specific analysis of trends and progress of national and sectoral transformations.[1] This approach allows identifying what hinders and spurs action in countries and sectors, and understanding the conditions that can support enhanced ambition, which could be political, social, economic, governance.

These insights are directly relevant to four overarching functions of the Global Stocktake in support of its desired outcome, i.e. "to inform Parties in updating and enhancing, in a nationally determined manner, their actions and support in accordance with the provisions of the Paris Agreement, as well as enhancing international cooperation for climate action" (Article 14.3 of the Paris Agreement):

- Create the conditions for an open and constructive conversation on global cooperation (on e.g., technology, trade, finance, etc.), based on an in-depth understanding of the international enablers of enhanced country ambition.
- Organize a process for knowledge sharing and collective learning, based on concrete examples of actions already in place or being discussed, including best practices.
- Create space for open dialogues across different stakeholders to support better coordination of actions, based on a detailed understanding of the levers to be activated to enhance ambition in national and sectoral transitions
- Facilitate ownership by decision-makers of the climate challenge and the risks and opportunities of the low-emission and resilient transition, based on context-specific and granular analysis of barriers and enablers.

More specifically, the collective report in general – and this document in particular – can contribute to address some of the key guiding questions for the Global Stocktake[2], notably:

- What actions have been taken to increase the ability to adapt to the adverse impacts of climate change and foster the climate resilience of people, livelihoods, and ecosystem? To what extent have national adaptation plans and related efforts contributed to these actions (Decision 19/CMA.1, paragraph 36(c))?
- How adequate and effective are current adaptation efforts and support provided for adaptation (Article 7.14 (c) Paris Agreement)?

1 The full report « Climate ambition beyond emission numbers - Taking stock of progress by looking inside countries and sectors" can be found at: https://www.iddri.org/en/publications-and-events/report/climate-ambition-beyond-emission-numbers-taking-stock-progress

2 Draft Guiding Questions for the Technical Assessment of GST1 (version 20th October 2021), available at: https://unfccc.int/sites/default/files/resource/Draft%20GST1_TA%20Guiding%20Questions.pdf

- What are the barriers and challenges, including finance, technology development and transfer and capacity-building gaps, faced by developing countries?
- What is the collective progress made towards achieving the long-term vision on the importance of fully realizing technology development and transfer in order to improve resilience to climate change and to reduce greenhouse gas emissions referred in Article 10.1 of the Paris Agreement? What is the state of cooperative action on technology development and transfer?
- What progress been made on enhancing the capacity of developing country Parties to implement the Paris Agreement (Article 11.3 Paris Agreement)?
- To achieve the purpose and long-term goals of the Paris Agreement (mitigation, adaptation, and finance flows and means of implementation, as well as loss and damage, response measures), in the light of equity and the best available science, taking into account the contextual matters in the preambular paragraphs of the Paris Agreement:
  - What are the good practices, barriers and challenges for enhanced action?
  - What is needed to make finance flows consistent with a pathway towards low GHG emissions and climate-resilient development?
  - What are the needs of developing countries related to the ambitious implementation of the Paris Agreement?
- What is needed to enhance national level action and support, as well as to enhance international cooperation for climate action, including in the short term?
- What is the collective progress made by non-Party stakeholders, including indigenous peoples and local communities, to achieve the purpose and long-term goals of the Paris Agreement, and what are the impacts, good practices, potential opportunities, barriers and challenges (Decision 19/CMA.1, paras 36(g) and 37(i))?

Foreword

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Country commitments as reflected in enhanced Nationally Determined Contributions submitted to the UNFCCC are insufficient to put the world on track to achieve the collective objective of the Paris Agreement to hold temperature increase below 2 °C or 1.5 °C above pre-industrial levels. Furthermore, concrete policies and actions adopted by countries on the ground are often not sufficient to achieve these NDC targets. These conclusions highlight the need to increase ambition and to provide convincing evidence to accelerate action in the immediate and short term to give effect to this ambition. Yet these assessments are not sufficient to effectively guide the progressive increase of ambition, as organized by the cyclical process of the Paris Agreement.

APPROACH

With this imperative in mind, this report adopts a different, complementary, perspective on climate ambition. It seeks to open the box of emission pathways, by considering multiple dimensions of the conditions that will make these pathways possible. These are technical, economic, political, social and governance considerations in need of attention to enable the required far-reaching and systemic transformation towards the long-term goal. On the one hand, the revision of emission targets needs to be directed by an assessment of how drivers of emissions should change to trigger transformation. On the other hand, converting emissions' targets into pertinent concrete implementation requires well-designed policy packages and investment plans that are also informed by a clear and detailed understanding of the starting point, priorities and interplays between the available levers of transformation.

This bottom-up assessment aims at contributing to the process of collective learning in support of the progressive increase of collective ambition, as inserted at the core of the Paris Agreement paradigm. Approaching climate ambition through the lens of underlying transformations calls for reflecting the heterogeneous nature and the multi-faceted aspects of transitions in different sectors and countries. This forces a move away from a purely global perspective to a more granular approach based on country- and sectoral perspectives. Thus, the report explores trends and progress on these transformations, as locally observed over the past years, notably since the Paris Agreement. This 'backwards looking' approach can help identify where developments are going in the right direction, where they should be accelerated and where major tensions remain that should be addressed as a priority to avoid undermining the transition. The picture of the state of the ambition discussion, firmly embedded in the country and sectoral realities, can provide means for reflection and action within the international climate community, particularly to inform focus areas for advancing the collective ambition agenda.

STRUCTURE OF THE REPORT

This sectoral report highlights a selection of the main recent advances and remaining barriers for a far-reaching sectoral transformation towards, and where relevant beyond, net zero sectoral emissions. It examines relevant scientific and academic debates, as well as relevant sectoral- and climate policy influencing the climate- and environmental impact of the sector.

This report is part of a full series of 26 country chapters and three sectoral chapters. The full report includes a "summary for decision-makers" to present 10 cross-cutting messages emerging from the country and sector analysis, as a guide to the selection of priorities for collective action in the post-COP26 period.

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You will find the full report at: https://www.iddri.org/en/publications-and-events/report/climate-ambition-beyond-emission-numbers-taking-stock-progress

A narrative of climate ambition in key hard-to-abate sectors

Industrial decarbonization ambition in the post-Paris context

This chapter has been written thanks to the support of the International Climate Initiative (IKI) of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

SUMMARY

The Paris Climate Agreement's objective for net-zero CO_2 emissions shortly after mid-century has completely transformed the climate policy debate for heavy industry. Prior to Paris, the steel, cement, chemicals and other materials sectors were expected to be the last sectors emitting in a -80% reduction world, and much of their emissions were exempted or given free allowances. After Paris, these sectors now have to face both transforming rapidly and paying for any necessary permanent, additive and verifiable negative emissions. This has set off an intense global debate on demand and supply technological options, induced innovation, capital investment needs, policy packages, and potential uprooting of old supply chains to move the most intensive emitting parts of production either where there is geology for carbon capture and storage (CCS) or inexpensive low carbon electricity for electrification. A major shift is needed, from contemporary industrial policy that mainly protects industry to policy strategies that transform. There is a vigorous debate on the key enablers, but a common set of components for a policy framework is emerging: clear policy directionality towards net-zero, knowledge creation and innovation, creating and reshaping markets for sustainable materials, building capacity for governance and change, international coherence, and sensitivity to the focussed cost of sectoral phase outs and the communities where they happen.

INTRODUCTION

Prior to the Paris Agreement (PA) at COP21 in December 2015, heavy industry was largely exempted from most climate change efforts. A 50% chance of maintaining +2°C from pre-industrial temperatures was the usual high-level objective, which most climate modelling of the time showed requiring roughly 80% reduction in emissions by 2050. The integrated assessment models which proved that -80% was possible mainly squeezed the emissions out of electricity production combined with negative emissions, leaving buildings, transport and industry less touched. Heavy industry was considered hard if not impossible to abate, mainly using CCS & bioenergy, and would mostly carry on emitting as part of the last 20%. The PA's more ambitious 66% chance of 2°C, towards 1.5°C target, requires a smaller carbon budget, however, one consistent with net-zero CO_2 emissions by 2050-'70. Complicating this, existing and planned investments in electricity and heavy industry with current technology would exceed the +1.5°C budget (Tong et al., 2019).

The days of partial reductions for heavy industry, i.e. -40%, -50%, or -80% GHG targets, are over; the PA goal demands that all energy using sectors reach near zero to negative emissions as soon as demand, technology and stock turnover allow. This requires a fundamental transformation in most sectors. Before the ink was dry on the Paris Agreement, industry participants, system modellers, direct stakeholders, and other interested observers began debating what this meant for industry (Bataille et al., 2018). It reawakened largely dormant interest in several mitigation pathways: circularity through more and better quality recycling; material efficiency; fuel switching to electrification, hydrogen, bioenergy & feedstocks; 90%+ carbon capture and storage, especially the parts of it that had been proven to work with existing technology (e.g. storage of formation gas CO_2 or from methane based hydrogen production); and small and large nuclear for power and heat (Bataille, 2019; Rissman et al., 2020).

THE PHYSICAL PATHWAYS TO NET-ZERO INDUSTRIAL EMISSIONS

Industry emitted 31% of CO_2 from the energy supply and demand system in 2016. Of this, a nominal 9.7% was light industry (manufacturing, food, etc.). Of the "heavy industry" sectors 8% was iron and steel, 6.4% cement & lime, and 5.2% chemicals (Bataille, 2020). The numbers fluctuate each year, but not in fundamental relative size to each other or the rest of the economy. Reducing these emissions will be challenging. First, the standard technologies in use for these sectors are currently highly GHG intense processes for whom low GHG options typically cannot be bought off the shelf, e.g., for making zero emissions primary steel or cement. Lab and pilot level technological options exist, but most are far from fully commercialized. Second, steel, chemicals and potentially clinker are all highly traded, leading to the potential for carbon leakage in a multispeed climate policy world. Finally, unlike coal, oil & gas, steel, cement & chemicals are fundamental to basic development needs for larger buildings, transport and energy infrastructure, and water and sanitation systems.

In terms of demand, several major independent forecasts have shown that while North America and Europe are in their "renovate and replace" phase of demand for concrete, steel and other heavy materials for buildings and infrastructure, and China's infrastructure demand is tailing off, demand is rising fast in India, Africa and other developing regions, leading to a roughly constant level of global production for these materials (Bataille, 2020). Even after incorporating rigorous demand management "sufficiency" policies and education (recent IEA analysis shows a 26% drop in cement end-use intensity and 40% drop in steel end-use intensity is possible with transformational supply changes (IEA, 2020, 2019)), the need for key infrastructure (e.g. ports, railways and urban transport) and housing development to reach all the SDGs in Agenda 2030 will contribute to a steady and possibly rising demand for concrete and steel (UN Environment et al., 2018; Wang et al., 2021).

While intense efforts to improve **energy efficiency** have always prevailed because of the large cost component of energy in steel, cement, chemicals and other sectors, while it will continue to be important it will never be enough for net-zero - this requires a transformative change in production. Where there is perhaps more potential is in **material efficiency**; we currently use more than is necessary steel and especially concrete for crafting buildings and infrastructure. Concrete is especially overused because it is so cheap and durable, but we only really need it where we need compressive strength and corrosion resistance. Steel is only needed where we need torsional, shear and tensile strength. New computer aided design tools potentially allow architects and civil engineers to use steel and concrete only where necessary, and to blend in other lower GHG intensity materials where appropriate. For this to happen, however, material intensity with respect to GHGs needs to become not only part of architectural, engineering, and trades education, but be allowed and mandated under building codes.

The use of cement in concrete, as well as its production, can also be much less GHG intense. Cement is the glue in concrete, holding together the sand, gravel and small stones that give concrete its strength; better mixed concrete, that more carefully disperses and "packs" the aggregates can be stronger while using less cement. The most emissions intensive part of making cement and concrete is the initial calcination process for making clinker, a cement precursor. Clinker can be safely replaced in cement up to specific levels for given end-uses by both active cementious material substitutes and passive limestone filler if allowed and encouraged under local building code. But again, education for architects, engineers and trades is necessary.

In sum, while demand reduction through sufficiency as well as energy and material efficiency can significantly reduce the challenge, production decarbonization is unavoidable. In the following, working sector by sector, we will identify: the core technical challenges and progress towards production decarbonization; the economic, organisational, institutional and social challenges; enablers to overcome these challenges; and signs of progress.

STEEL

Core challenge

75% of steel production is new primary as opposed to recycled secondary production. Almost all primary production is based on using coal as the iron ore "reductant" (to strip the oxygen off the elemental iron so it can be melted) and heat source. The production facilities are long lived, profit margins are low, and steel is highly traded.

Signs of technical progress

For iron and steel production, several technological pathways for largely eliminating GHG emissions are being considered (Fischedick et al., 2014): more recycling, which is limited by the availability of high quality, uncontaminated scrap; the traditional blast/basic oxygen furnace combined with CCS, perhaps using biocharcoal to reach negative emissions (Fan and Friedmann, 2021); advanced coal based iron reduction & smelting that produces concentrated CO_2, more amenable to CCS; direct iron ore reduction (DRI) using low GHG hydrogen instead of coke followed by an electric arc furnace for smelting (Vogl et al., 2018); and perhaps eventually direct aqueous or molten oxide electrolysis of iron ore to metal, followed by an electric arc furnace run on low GHG electricity. Several regions, including China, are working to increase the amount of recycled steel. The most progress in primary production decarbonization has been made on low GHG hydrogen DRI, using both CCS on syngas (H_2+CO) DRI (a facility has been operating since 2016) and electrolysis based hydrogen DRI (Spanish and Swedish full scale facilities are due to begin operation in 2025 & 2026). At time of writing, there are 10 electrolysis hydrogen DRI plants announced to start before or on 2030, and two CCS DRI plants.[1]

Critical economic, organisational, institutional, and social transition barriers & enablers

While most technical progress is being made in Europe under the aegis of its tight overall GHG targets, most new steel demand will be in the developing world, requiring the technology is adopted there much faster than usual. This will require mechanisms for technology sharing and finance.

The proposed EU carbon border adjustment mechanism (CBAM) is controversial. Without strong developed country ambition, which CBAM enables, there

1 https://www.industrytransition.org/green-steel-tracker/

will be no effective technology transfer mechanism. But CBAM risks being penurious for developing countries in the early stage of industrialization, when the most steel and concrete is needed. To get around this conundrum, some form of global technology accelerator is needed (Bataille, 2020). It would be fully paid for by the historically GHG culpable, to commercialize needed tech for all. Then pooled, risk diversified enabling finance, again largely enabled by the culpable, is needed to deploy this technology in developing countries.

Signs of organizational, institutional and social transition progress

There has been huge progress in steel decarbonization efforts in the last few years, far more than expected as late as 2017. There have been announcements by several steel firms to reach net-zero by 2050, with a focus on UK & European operations. The Canadian steel association has pledged to net-zero by 2050, and Nucor in the US has now also pledged to dramatically reduce their emissions intensity. HBIS in China has stated it will begin large scale experiment with syngas & CCS and electrolysis hydrogen DRI EAF steel production.

On June 1st 2021 there was a Clean Energy Ministerial agreement (United Nations Industrial Development Organization (UNIDO), 2021) to jointly pursue steel and cement decarbonization, the first time steel and cement decarbonization has seen this level of political commitment.

In terms of carbon pricing policy, the EU has announced it will impose a partial CBAM for steel, cement and aluminum in January 2023, fully phased in by 2026. In terms of lead market creation, Volvo and Daimler Benz have agreed to contract with SSAB and H_2 Steel for green steel (Daimler-Benz., 2021; Green Car Congress, 2021) and Salzgitter AG will start allocating existing low GHG EAF steel making to Mercedes Benz this year.

Where progress is missing is a clear direction for how steel decarbonization technology will be transferred to developing nations, and how the extra costs will be justified and paid for until low GHG technologies cost less than standard high GHG technologies.

CEMENT & CONCRETE

Core challenge

Concrete is the most widely used material in human civilisation. The sand, gravel and stones in concrete are held together with cement, of which calcium oxide is a key constituent. CaO is made by heating limestone (CaCO3), and CO_2 is released – this represents ~60% of all cement and concrete emissions. The other 40% come mainly from heat for the limestone calcination and then clinker baking, where CaO is combined with mainly iron and aluminum silicates.

Signs of technical progress

As mentioned previously, clinker can be safely replaced in cement up to specific levels for given end-uses (most up to 50%) by both active cementious material substitutes and passive limestone filler (Habert et al., 2020; UN Environment et al., 2018).

While there are some long term potential replacements for Portland cement, it will be decades before they are available in any amount. CCS will be required for the Portland cement limestone calcination process CO_2 emissions, and progress is ongoing. There are several multi-company projects to master key technologies: 90-95% capture CCS at the Heidelberg Lehigh plant in Edmonton; the LEILAC process gas CSS kiln retrofit project in Belgium (Hills et al., 2017); and the Brevik CCS project in Norway.

For the heat requirements, mixes of biomass or hydrogen-based fuels may be useful for decarbonization. There is also a project linked to LEILAC to electrically heat the calcination kiln.

Critical economic, organisational, institutional, and social transition barriers & enablers.

CCS technology needs to be proven for at least process gases, and it will be helpful if it can be used for all heat needs. As with steel, this production decarbonization technology must be made available globally, with the necessary finance and incentives for its adoption – CCS does not add value to cement products, it only adds capital and energy costs. Alternative heat sources must be trialed and their use proven for where CCS cannot be used for the entire flue gas stream.

Material efficiency efforts will be complicated, as they encourage less use of cement and concrete. This may or may not be welcome by construction companies, but will not be welcomed by cement companies unless they are compensated somehow. The business model of cement, in conjunction with construction regulation, must be adapted to level the playing field for all cement firms, possibly through building design regulations, which are hard if not impossible to enforce in developing countries.

Signs of organizational, institutional, and social transition progress

On the negative side, unlike steel, very few global cement companies have announced net-zero goals. On the positive side, as with steel, a Clean Energy Ministerial agreement was announced in June 2021, likely to be followed by green procurement commitments at COP 26. Again like steel, the EU has announced a partial CBAM for steel, cement and aluminum in 2023, fully phased in by 2026.

There is virtually no movement towards decarbonizing cement production in developing country contexts.

CHEMICALS

Core challenge

Chemicals demand, and especially for plastics, is growing rapidly globally. Ammonia fertilizers, usually made from methane for its hydrogen and as an energy source, are currently critical to global food production. Most chemicals are composed of primarily carbon, nitrogen, hydrogen and oxygen. The chemicals industry, with over 20,000 products produced using 7-8 main feedstocks (hydrogen, carbon monoxide, methane, methanol, ethylene, benzene, toluene, xylene) is currently designed to use coal, crude oil and methane as the primary feedstocks. Production facilities are long lived, profit margins are low, and feedstocks are highly traded.

Signs of technical progress

Plastics recycling e.g., for ethylene products, and deposit and return systems to encourage this, are a first key step to reducing chemical emissions. Regional progress in this varies from very high rates of recycling to none, but the global average is only about 5%.

In the chemicals industry, alternative heat sources, low GHG hydrogen (either from low fugitive methane based production with CCS or electrolysis using low GHG electricity), electrocatalytic processes, and net-zero or negative carbon feedstocks (e.g., incorporating forestry or pulp and paper biomass or carbon from direct air capture) are key to reducing the sector's emissions (Bataille, 2020; Rissman et al., 2020). The pulp and paper industry, for example, can contribute biogenic carbon feedstock for chemicals and negative emissions through CCS.

Critical economic, organisational, institutional, and social transition barriers & enablers.

A key barrier organization and institutional barrier to decarbonizing chemical production emissions is that carbon is the key "construction material", or lattice upon which most chemicals are built. The industry has argued vociferously that even though most chemicals get combusted to atmosphere as waste if not fuel, that they are not responsible, instead the end emitter is – this matches with standard GHG accounting practices. A key institutional principle needs to be applied somehow that all carbon that leaves the ground and becomes a net emission to atmosphere must be accounted for, and be eliminated or offset using additive, verifiable and permanent offsets.

Chemical feedstocks are also highly traded, without certification of their highly varying production GHG intensity – most of the basic feedstocks are made from coal, crude oil, natural gas liquids or methane. Methane in turn can be fossil or biogenically sourced commercially today. The long run goal is to recycle chemical feedstock carbon or source it biogenically or from direct air capture.

Signs of organizational, institutional, and social transition progress

Plastics recycling is almost non-existent globally, and is probably the fastest way to reduce large amounts of GHG emissions from the chemicals sector. Ammonia has been made with electrolysis based hydrogen in the past, and could be again in relatively short order if enough clean electricity can be purchased. Otherwise low GHG chemical production decarbonization is at a very early stage. BASF, the largest German chemical company, is actively considering electrification and green hydrogen options in cooperation with the RWE (BASF, 2021).

LIGHT INDUSTRY

Core challenge

Light industry, whose emissions mainly come from combustible gases and heating oil, mainly requires electricity, steam and small amounts of heat in various ranges from 50-1000°C. The relative cost of coal (very low), natural gas (low) and electricity (high) in most regions and the noncentrality of energy costs to most light industry operations are the biggest challenges.

Signs of technical progress

Light industrial energy needs are mostly highly electrifiable today, directly or with heat pumps. Local solar or biomass is also useful on a site-specific basis. Direct electric methods to produce low grade heat and steam through industrial heat pumps (possibly farming from waste heat sharing systems) and electrothermal heating for higher heat needs have been considered (Lechtenböhmer et al., 2016; Madeddu et al., 2020). Low GHG hydrogen and bioenergy can be used for process heat above 150°C, but it is expensive and limited by local demand and supply of hydrogen and bioenergy.

Critical economic, organisational, institutional, and social transition barriers & enablers.

Most small and medium sized firms are focussed not on their energy cost but sales and production of their product, and will simply use the cheapest and most reliable energy form that meets their needs. Electrification through heat pumps is capital intense, and while fully commercialized, knowledge of it is at a fairly low state. Information programs that suit the industry, lifetime cost education, and targeted low interest loans would help alleviate some of the key challenges.

Signs of organizational, institutional, and social transition progress

While options like industrial heat pumps and solar heating systems are becoming more commonly available, there is little or no progress beyond carbon pricing systems (which struggle against the electricity gas spread, i.e. the carbon price would need to be very high to induce a switch) to address decarbonization of these sectors.

In summary, there is no one magical, simple solution (such as demand management, energy efficiency or material efficiency, or carbon capture and storage (CCS)). In each and every sector there is a fundamental technological challenge that must be faced for which one has to dig into the details of each sub-sector to identify the solutions.

POSSIBLE POLICY PACKAGE COMPONENTS

Thinking in terms of transformation, rather than the historic mode of pricing and protection (which is a necessary but insufficient condition for transforming heavy industry), the following **key enablers of ambition** emerge from the physical pathways above

The first most important element is **national governments and the global community need to demonstrate ironclad policy directionality towards net-zero. Decarbonization is very risky and costly for industry (producing decarbonized materials will cost more for the foreseeable future), and it needs to be sure the world is serious before it will act.** Arguably, there's been lots of progress with this. All the above, combined with regional climate policy pressures such as the EU commitment to net-zero and the Green Deal, including an EU general industrial strategy (European Commission, 2020a) and hydrogen strategy (European Commission, 2020b), has led to regional and global firm and sector commitments to net-zero in the various industrial sectors. Most of these commitments, given the very real risks of long-term industrial investments, come with requests for financial help and demands for competitiveness protection, such as from border carbon adjustments (BCAs). While simple in conception, BCAs beyond very simple, undifferentiated bulk products will be very difficult to implement practically, and if applied clumsily could have adverse legal, political and climate effects. Ascertaining the GHG intensity of individual products is a nascent organisational and logistic science that needs development. This calls for more nuanced, subtle and staged policy packages to enable the transformation

Basic materials industries are so far relatively sheltered from climate mitigation. Given the Paris Agreement goals, new climate and industrial policies are necessary for transforming the basic materials industries. **A gradual end to industrial process emission exemptions & free allowances is needed, combined with competitiveness protections.** While full material carbon pricing will eventually be needed, gradually rising maximum GHG intensity standards for simpler (easier to measure in terms of GHG intensity) and then more complex products, designed to weed out the most emitting foreign and domestic supply (with compensation and transition support) could help send short term signals to industry until stronger carbon pricing is possible. Given the long-lived nature of industrial facilities, just applying simple carbon pricing and border carbon protections will likely slowly boil these industries alive inside the carbon pricing bubble, imposing broader costs on the economy given the need for steel, cement, chemicals etc. in a low carbon economy. A transformative approach is needed.

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. Complementary solutions relying on technological, organizational, and behavioral change must be pursued in parallel and throughout whole value chains. **This requires clear, full supply chain lifecycle emissions accounting rules that take account of current differences in GHG** intensity (e.g. primary steel can vary from 0.7 to 3.0 tonnes CO_2 per tonne made with existing commercial technologies). While there are many possible GHG efficiencies in current technologies, **to reach near zero emissions new technologies are required** (e.g., electrification, hydrogen and post combustion carbon capture and storage). This requires multistage support, from research and development through piloting and early commercialization. Arguably, enough R&D has been done to mostly decarbonize most heavy industry – what is required is intensive early commercialization support so that all new facilities are near zero emissions by the early 2030s (International Energy Agency (IEA), 2021). For this to happen, **following research and development, we need lead or niche markets for low GHG commodities (creating and shaping markets) to allow steel companies to invest in the first 10-20 plants to fully commercialize low GHG steel technology,** i.e., via government green procurement or private buyers' clubs. This will allow firms to build experience with the new technologies and supply chains in a less risky environment. These could include financially supported lead markets through public procurement and private buyers' clubs actualised through contracts for difference (Sartor and Bataille, 2019) for low GHG production. Volvo and Daimler Benz have already committed to absorbing early green steel production from Sweden.

Given existing GHG intensity differences, and the potential for new supply sources, we need **trade policy with flexibility to allow reformulation of supply chains to minimize the costs of decarbonization**. In the long run, it is quite feasible that the supply chains for currently intense products will separate into pieces, with the most GHG intensive parts (e.g. clinker and iron ore reduction) being done in regions with ample CCS geology or potential for clean electricity production, e.g. from wind & solar. For this to happen efficiently and equitably, however**, international trade rules and regulations will need to be revisited**, including common GHG intensity measurement rules and a "level playing field" for all parties, which could have material implications for the Paris Climate Agreement's Article 6 negotiations.

It's far from good enough to decarbonize basic materials production in the developed world. Most new steel demand will be in the developing world, requiring the technology is adopted their much faster than usual. This means **we will require mechanisms for technology sharing while maintaining innovation**. Developing nations in particular may need educational, logistic and financial support adopting initially more expensive low carbon technologies.

In particular, finance, due to risk, is structurally more expensive in developing countries, i.e., the weighted cost of capital is higher for the same project. Some mechanism for pooling these risks to allow portfolio diversification and allow developed country finance rates to apply for a climate

related project to proceed are needed. The risk premia will be lower with each successive successful project. Developed country enabling finance to "leverage" private market finance will likely be required.
Finally, **some long lived, non-retrofittable facilities will need to be shut down, which in some cases will have large impacts on local and regional economies and communities**. Regions and communities will need help exploring options, aid for worker re-education, and in some cases early retirement funds will be required for labourers. Amongst others, these 'just transition' strategies should be reflected in nations' long-term strategies and Nationally Determined Contributions under the Paris Agreement.

THE UPSHOT

Industrial decarbonization is technically possible, and would not cost the greater economy much (less than 1-2% for most materials for most final end uses), but because heavy industry, unlike transport, buildings and electricity, tends to be highly traded and is currently very GHG intense it poses strong investment and carbon leakage risks in a multispeed climate policy world. This has been largely ignored in global climate negotiations to date. We must also build global, national and sectoral capacity for governance and change in this sector; this is broad component that stretches from teaching all key stakeholders about the need for netzero to identifying the key emissions intense components and use structured research, development and fast commercialization policies (e.g., government procurement and private buyers clubs/contracts) to build economies of scale and bring the key technologies to market. Regulations and carbon pricing can then be used to enable their uptake. In summary, heavy industry decarbonization will need to take center stage in future international climate policy and negotiations.

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The DDP is an initiative of the Institute for Sustainable Development and International Relations (IDDRI). It aims to demonstrate how countries can transform their economies by 2050 to achieve global net zero emissions and national development priorities, consistently with the Paris Agreement.. The DDP initiative is a collaboration of leading research teams currently covering 36 countries. It originated as the Deep Decarbonization Pathways Project (DDPP), which analysed the deep decarbonization of energy systems in 16 countries prior to COP21 (deepdecarbonization.org). Analyses are carried out at the national scale, by national research teams. These analyses adopt a long-term time horizon to 2050 to reveal the necessary short-term conditions and actions to reach carbon neutrality in national contexts. They help governments and non-state actors make choices and contribute to in-country expertise and international scientific knowledge. The aim is to help governments and non-state actors make choices that put economies and societies on track to reach a carbon neutral world by the second half of the century. Finally, national research teams openly share their methods, modelling tools, data and the results of their analyses to share knowledge between partners in a very collaborative manner and to facilitate engagement with sectoral experts and decision-makers.
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