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Low and zero emissions in the steel and cement industries

Barriers, technologies and policies

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This issue note was prepared for the 2019 GGSD Forum to steer discussion around the theme of Session 2 on "*Driving innovation for greening heavy industries*". This paper discusses the main barriers and possible solutions to the decarbonisation of steel and cement industries. First, the paper details the economic, regulatory, technological and political economy barriers that impede a low carbon transition. Then, it addresses the role of material efficiency and enhanced recycling in greening these industries, and reviews the emerging and near commercial low- and zero- emissions production technologies. Finally, the policy packages that could contribute to trigger demand and supply decarbonisation of steel and cement are discussed.

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Table of Contents

Tables

Figures

Boxes

Executive Summary

The iron & steel and cement & concrete industries are essential elements of the global economy and development aspirations. They provide key materials for buildings, infrastructure, and industry that can be used more efficiently but are also irreplaceable for key needs for the foreseeable future**.**

These sectors are significant and growing emitters of CO_2. Iron & steel represents 6-8% and cement & concrete 6% of global energy system combustion and industrial process CO_2 emissions (International Energy Agency, 2018[1]; International Energy Agency, 2018[1]; Lehne and Preston, 2018[2]). Global cement demand is projected to grow by 12-23% by 2050 compared to 2014 (International Energy Agency; Cement Sustainability Initiative, 2017[3]), and global steel demand by 15-40% by 2050 (Accenture Strategy, 2017[4]). In one scenario, absent new climate policies, both sectors are projected to double by 2060 (OECD, 2019[5]).

The Paris Agreement climate goals to stabilise global temperatures at "well below 2°C, and towards 1.5°C" require energy system and industrial process CO_2 emissions either become net negative by 2050-2070 or be compensated with land use or technological negative emissions (Edenhofer et al., 2014[6]; Masson-Delmotte et al., 2018[7]). This applies to all sectors, including steel and cement.

Reaching net-zero CO_2 emissions for these sectors will require increasing material efficiency to reduce the primary demand of these materials, more and higher value recycling, as well as decarbonising production. This requires that we change how we design and build structures and machinery, and develop very low or zero emissions production technologies by 2030-2040 to allow for the replacement of older facilities as they wear out (Bataille et al., 2018[8]). Retrofitting and early retirement may also be required.

The most effective way to reduce steel and concrete emissions is to use them only for necessary applications in new products, vehicles and structures (-25 to -50% emissions reduction potential) (Allwood and Cullen, 2015[9]; International Energy Agency, 2019[10])**.** This requires innovation in design for: material substitution; longer lifetimes for final products and structures; ease of deconstruction, component reuse; and high value recycling when their useful life ends. This will require engagement with national institutions responsible for a wide range of topics, including architecture, design, civil engineering, construction, trades, and building code formation and enforcement.

Appropriately sizing and mixing aggregates, and reducing the clinker content of cement are key short-term strategies to reduce CO_2 emissions of existing plants (UN-Environment et al., 2018[11])**.** The building material concrete familiar to most people is a mixture of cement glue holding together various sizes and mixtures of gravel and sand aggregates. How well this mixture is mixed, and the appropriate sizing and packing of the aggregates, is key to the final strength of concrete. This argues for professional mixing and pouring, and a movement away from bagged cement and ad-hoc mixing. The most GHG intense part of cement production (~60% of total emissions) is limestone calcination to produce clinker. It is already common to partially replace some of the clinker with blast furnace slag, coal fly ash, bauxite, and natural pozzolanic materials, but use of all these products may be constrained by available volume. While not yet common, clinker can be substituted (up to 40-50% by mass) with a mixture of limestone and heat treated clays, which are common materials globally.

In the medium term, all cement plants should be retrofit to existing best available technology, and the use of alternative lower carbon fuels (e.g. biomass and waste) for process heat should be maximized. All facilities should be using dry kilning with preheating of the ground limestone entering the calciner using the waste clinker production heat; this is retrofittable in most cases. Hydrogen or ammonia are possible zero emissions fuels to be considered for retrofitting for process heat needs.

New cement emissions reduction technologies that are currently being tested could also play an important role in the longer term (International Energy Agency; Cement Sustainability Initiative, 2017[3]; Lehne and Preston, 2018[2])**.** Waste CO_2 from other sectors via carbon capture and utilisation (CCUS) can be added to the concrete. A pilot is underway to concentrate the CO_2 emissions of limestone calcination from clinker production (i.e. the EU LEILAC project). The technology used for LEILAC will be retrofittable in most cases, and the geologic disposal of highly concentrated CO_2 emissions (>=80-85%) has already been commercially proven by the oil and gas industry. Carbon capture and utilisation (CCUS) for CO_2 in dilute flue gases, i.e. from process heating to make cement, is at a lower technology readiness level. Finally, there are several potential alternative chemical pathways to make cement with much lower emissions, some of which may allow negative emissions, but most are at a low technology readiness level.

The first step to reducing emissions from steel is to maximise the volume and quality of recycling (25% of current production is secondary steel). Using roughly half the energy of primary steel production, steel recycling is mostly done with electric arc or induction furnaces powered by electricity, which must also be decarbonised. For recycled steel to be used for all purposes, however, contamination with copper and to a lesser extent other metals must be minimised through intentional design and post-use deconstruction.

Very low or zero emissions primary iron & steel and production can be achieved through two main pathways: advanced coal based methods using CCUS (e.g. HISARNA), or CO_2-free hydrogen and electricity based methods (e.g. HYBRIT) (Fischedick et al., 2014[12]; Vogl, Åhman and Nilsson, 2018[13])**.** There are several retrofittable and new build methods for both pathways with widely varying levels of technological readiness. Some could be commercially available by 2030 with concerted effort.

While technological innovation policy is a key priority, policy to address market conditions, behaviour and political economy challenges will be equally if not more important. Steel and cement production are both highly competitive with low profit margins (i.e. they have difficulties passing on costs) and steel is highly traded, facilities last a long time, new facilities are capital intense, and installations are often keystone elements of local supply chains with substantial indirect capital and employment value added (e.g. ~$1000 of steel is essential to making a $25,000-100,000 car). There is also no existing market ready to pay a premium for low emissions steel.

At present, despite the overarching net-zero CO_2 emissions goal of the Paris Agreement, iron & steel and cement & concrete firms face a lack of global and national clarity regarding what actual policies they will face. This results in an investment limbo: carbon-intensive choices are incompatible with the Paris Agreement and face risks of more stringent climate policy, while climate-friendly choices lack a clear investment case in the currently uncertain policy regime.

To break this impasse clear long term policy signals are needed, followed by comprehensive strategies incorporating all key actors and addressing all key challenges, actualised by policy packages to incentivise all actors to play their parts (Neuhoff et al., 2018[14]; Wesseling et al., 2017[15]; Bataille et al., 2018[8]; Wyns et al., 2019[16]; Material Economics, 2019[17]; UK Energy Transitions Commission, 2018[18])**.** The first thing required is an initial policy commitment to eventual net-zero emissions and appropriate interim targets that reflect reasonable stock turnover and investment operations dynamics. Then a transition plan needs to be formed that includes participation, input and buy-in from all key stakeholders, including governments, sector associations, firms, product consumers, unions, communities and other impacted and concerned parties. Practically speaking, the national and global steel and cement firms and associations need to enter into a long term technical pathways and policy planning process with appropriate governmental institutions that are engaged in the low-carbon agenda, at appropriate regional (e.g. California), national (e.g. the UK, Netherlands, France, Germany, China, Canada), supra-national (e.g. the EU) and international levels.

The policy packages would likely need to include many elements: 1) Material use design and standards to reduce demand, implemented through engagement with architectural, transport, civil engineering, design, and construction institutions. 2) Promotion of R&D, including strategic demonstration pilot projects. 3) Lead market demand creation for early 'green' commercial plants through guaranteed markets that reflect the higher production costs and investment risk, for instance via green public procurement (e.g. preferred or minimum market shares for green materials), low emissions material "feed-in-tariffs" (or "contracts-for-difference", a.k.a CFDs) or private buyers coalitions (e.g. Apple's role in the Elysis green aluminium project). 4) Removal of energy subsidies combined with an initially low but rising carbon price. The role of carbon competitiveness protection measures (e.g. border carbon adjustment or standards) may need to be considered. 5) Harmonisation of process and product standards and removal of barriers (e.g. for clinker substitution). 6) Infrastructure planning and support for high voltage electricity transmission, CO_2 capture and hydrogen production, including consideration of potential industrial clusters. 7) Supporting institutions, including for workforce adjustment and for assessment of life cycle emissions of given materials and derivative products.

In sum, very low and zero emissions from the iron & steel and cement & concrete sectors is a technically and economically reasonable challenge, but given the physical, economic and political challenges, this must be done with well-designed policy packages and careful consultation with all parties involved and affected. The main technical and policy knowledge gaps to be addressed and discussed include:

- How to engage with architectural, transport, civil engineering, design, and construction institutions in a systematic way to implement materially efficient, reusable and recyclable design for vehicles, machinery, buildings and infrastructure.
- When, where, and how to create publically and privately driven lead markets and business models for new low emission steel and concrete. This would be essential to prove the technologies for wider mainstream use before they can become the new commercial standards around which the market builds.

- When, where and how retrofits can be made to reduce the emissions of the existing long lived plants to very low or zero emissions.
- Whether "sunset" decommissioning regulations may be needed for high GHG facilities that are not retrofittable and don't wear out, and how could these be designed to minimize disruption for firms, workforces and communities
- How can the key stakeholders be involved in the transition, and what are possible sequencings of actions that could build trust and enable the planning of a long-term low-carbon transition strategies in developed, in-transition and developing country contexts (Bataille, 2019/2020[19])? This should look at the role governments, multinational steel and cement firms, national and global sector associations, and big steel and cement users like vehicle and construction companies. Are there key trusted convenors, like the OECD, the International Energy Agency, the European Commission, or the Intergovernmental Panel on Climate Change, that can help start the dialogue?

1. Introduction

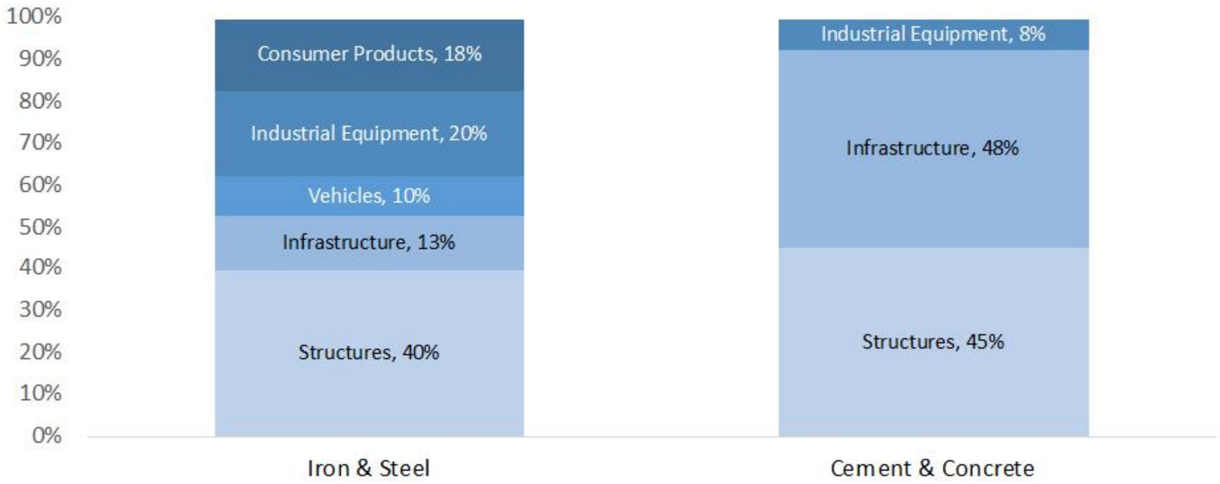
In light of the Paris Agreement objectives to stabilise global temperatures at "well below 2°C, and towards 1.5°C", anthropogenic emissions of greenhouse gases must fall substantially. CO_2 emissions in particular must fall to net-zero by 2050 (or earlier) for 1.5°C and by 2070 for 2°C, and to probably net-negative levels thereafter (Edenhofer et al., 2014[6]; Masson-Delmotte et al., 2018[7]). This is applicable to all sectors, including steel and cement production.

The objective of this issue paper is to review the literature on the main barriers and possible solutions to the decarbonisation of heavy industries, with a focus on the two largest by CO_2 emissions, iron & steel and cement & concrete production. The following section will establish some basic background, e.g. what steel and concrete are used for, how they are made, what the prospects are for their demand, and what fundamental economic, regulatory, technological and political economy characteristics of these industries may impede a low carbon transition. Section 2, **Reducing demand for steel & concrete,** will address the role of material efficiency and enhanced recycling in reducing demand for steel and cement. Section 3, **Technologies for decarbonising production of steel & concrete,** will examine available emerging and near commercial low and zero emissions production technologies. Section 4, **Policies to decarbonise steel and cement**, will discuss policy approaches to trigger demand and supply decarbonisation in a way that recognises and works with the political economy challenges that have already been identified. Section 5, **Main takeaways**, will summarise the main lessons.

What are steel and concrete used for?

The global iron & steel and cement & concrete industries are essential elements of the global economy and industrial development, as they provide key materials for buildings, infrastructure, industry and almost all structures (Figure 1). While there is significant room for improving material efficiency in buildings and infrastructure (as will be discussed), and to substitute aluminium, recyclable plastics in vehicles and wood in buildings, concrete and steel are currently irreplaceable for larger structures, infrastructure and industrial equipment.

Figure 1.1. End-uses for iron & steel and cement & concrete, as a volume proportion of all use



Source: (Material Economics, 2019[17]; Allwood and Cullen, 2015[9])

Demand is growing for both cement and steel (OECD, 2019[5]). Global cement demand grew from about 1.2 Gt per year in 1990 to 4.2[1] Gt per year in 2015 (~5% per year). Global cement demand is projected to grow steadily, by a total of 7.5% to 25% by 2050, with significant margins of uncertainty. The latest IEA Cement Roadmap estimates "business as usual" demand will grow by 12-23% by 2050 (International Energy Agency; Cement Sustainability Initiative, 2017[3]). Another IEA report estimates a lower demand growth of 10% by 2060, based on evolving and potential trends in material efficiency (International Energy Agency, 2019[10]). A third source, Chatham House, estimates demand to grow by 25% by 2050 (Lehne and Preston, 2018[2]). Higher growth estimates point to the fast growing demand for materials from less developed countries, especially in Africa, whose economies are "in transition" (UN-Environment et al., 2018[11]). The OECD Global Materials Resource Outlook (OECD, 2019[5]) posits that steel and concrete demand could double by 2060. The Chatham House report warns of potential estimation errors in the opposite direction. The authors argue cement and concrete demand can be reduced, sometimes by more than 50%, using existing technologies through design, by using higher-quality concretes, by substituting concrete for other materials, by improving the efficiency with which it is used on construction sites, and potentially reusing concrete components. These considerations will be re-addressed in later sections.

Global crude steel demand rose 3.3% per year from ~0.65 Gt in 1990 to ~1.5 Gt in 2015, which coincides with the growth in China's economy (Accenture Strategy, 2017[4]; UN-Environment et al., 2018[11]), and is currently 1.8 Gt per year (Worldsteel.org). Steel demand is projected to rise at a slower pace in the future, between 0.4-1.4% per year through 2035, due to slower Chinese demand and broad system efficiencies (although there

[1] There is some disagreement between sources on total global cement production, e.g. estimated production in 2015 is 4.2 billion tonnes in the 2018 IEA Cement Roadmap, 4.6 billion tonnes from UN Environment et al (2018), and 4.0 billion tonnes in the Chatham house report (Lehne and Preston, 2018[2]).

is very recent evidence of demand recovering in China). This is counterbalanced by higher Indian, African and other developing country demand.

How steel and concrete are made

Iron is the main component of steel, occurs naturally in the earth's crust, and is usually found chemically bound to oxygen and sometimes other elements. To make iron ore usable as a metal, the oxygen must be removed, or "reduced". There are currently two standard technologies for reduction. The primary one is commonly referred to as a "BF-BOF", and occurs in two stages. In the first stage, the iron ore is heated with highly purified coal ("coke") in a blast furnace (BF). The carbon in the coke preferentially binds with the oxygen as CO and CO_2, leaving the iron in a melted state. Because iron is soft and will recorrode quickly with oxygen, various other elements (e.g. carbon, chromium, zinc, nickel) are added in a subsequent alloying process in a separate basic oxygen furnace (BOF) to give it stiffness and durability. The most energy efficient BF-BOFs emit about 1.8 tonnes CO_2 per tonne of steel made, but the global average is roughly 2.3 tonnes of CO_2e per tonne of steel (Hasanbeigi et al., 2016[20]). It is also common practice to add recycled scrap (<30% and about 220 Mt globally today) to the basic oxygen furnace to take advantage of the excess heat produced in the process and reduce virgin iron needs, which reduces emissions.

The other main commercial way to make iron and steel from iron ore is the direct reduced iron method (DRI), where the iron is reacted with hydrogen in an H_2 + CO syngas normally made using methane & water.[2] DRI is currently used for about 10% of global steel production. The purified iron is then normally melted in an electric arc furnace (EAF) and alloyed as necessary. The whole process is referred to as DRI-EAF.[3] With best available technology and zero GHG electricity, a natural gas driven DRI-EAF plants can achieve 0.7 tonnes CO_2 per tonne steel produced.

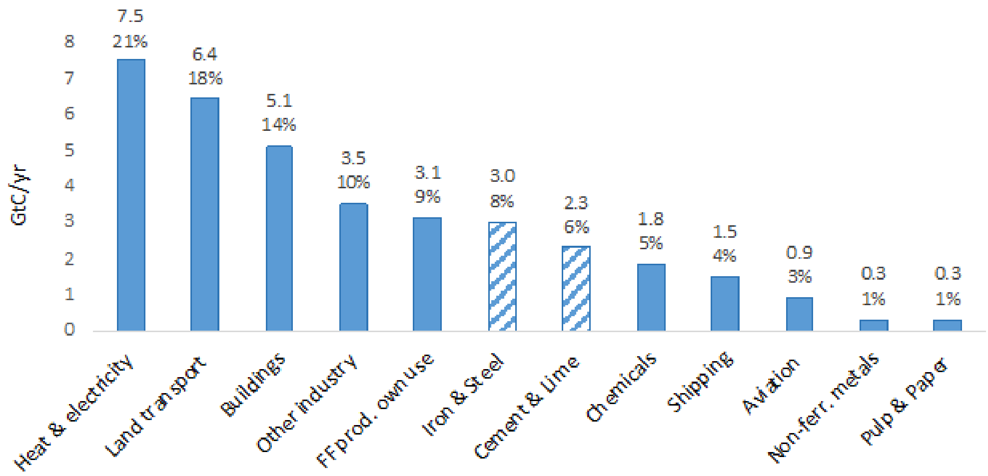
Electric arc furnaces are the standard method for recycling used steel (about 400 Mt globally today), such as end of life vehicles and industrial equipment. EAF operators also typically preheat the scrap using both off-gases from the EAF and fossil fuels for two reasons: to evaporate liquids to prevent formation of dioxins from coated steel scrap, and to save on relatively more expensive electricity. The purity of steel scrap determines what it can be used for. If there is significant contamination, especially of copper which leads to bubbling and delamination in sheet steel, the uses of the steel may be limited. In particular it may not be useable for vehicle sheet steel (Daehn, Cabrera Serrenho, A. and Allwood, J., 2017[21]). Scrap is sold on the market is a number of scrap grades (qualities) with varying composition and is priced accordingly. Depending on the composition and properties of the secondary steel desired from an EAF run, operators will buy various quality mixes of scrap to be processed. As increased volumes of "purer" scrap is requested, more will be produced via more detailed sorting which will raise the prices. This sorting can be eased by making steel products easier to take apart and sort at end of life.

[2] Coal and water are also sometimes used, but far less commonly.

[3] Induction furnaces are another method for heating and melting metals like iron. Electromagnetic induction is used to create eddy currents in the object. Induction allows precise temperature control, and the heats never rises above the prescribed temperature, but all oxides must be absent from the heated object. Induction is the standard method for heating metals in fabrication, and some larger scale alloying facilities have been constructed as well.

The terms "cement" and "concrete" are often mixed in common parlance, but they have specific meanings. Cement is the mineral "glue" that holds concrete together, while concrete is mostly a mixture of varying sized sand, gravel, and stones, also called "aggregates". While there are several different mineral sources of cement that have slightly different characteristics, most cement is made as Ordinary Portland Cement (OPC) from some version of calcium carbonate, typically limestone. The process begins by grinding the limestone into small pieces which are then added to a calciner, where the limestone is heated to ~850°C to liberate a molecule of CO_2 from each molecule of $CaCO_3$, leaving CaO, or "quicklime". Depending on the efficiency and fuel source of the plant, these CO_2 chemical process emissions typically produce about 60% of the CO_2 emitted. This quicklime is then combined with gypsum and iron and aluminium silicates in a clinker kiln, where it is fused into "clinker". A certain amount of blast furnace slag or coal fly ash may be added at this stage to replace the clinker, if available and allowed by local building codes. This reduces the amount of CO_2 process emissions. The clinker is then cooled and ground into powder. In best available technology plants this heat is used to preheat the feedstock limestone in long dry kilns, improving efficiency. Concrete is made when this powder is mixed with sand and various sizes of gravel and stones – when water is added a hydration chemical process activates the clinker and allows it to harden.

Figure 1.2. 2016 Global direct combustion & process CO2 emissions (abs. GtC & %), not including land use



Note: A 1.6 GtC per year difference (i.e. 2.0-3.6 GtC) per year difference was seen in sources for total global iron and steel energy and process CO_2 emissions, up to 4.3% of all combustion and process CO_2 emissions. Worldsteel indicates that 1,202 Mt tonnes of BF-BOF steel was produced in 2016, with 756 700 thousand tonnes in China, where there is little scrap available as precharge. (Hasanbeigi et al., 2016[20]) indicate the GHG intensity of Chinese, German and Mexican BF-BOFs at 2.1 tonnes CO_2/tonne steel and US BF-BOFs at 2.9 tonnes CO_2/tonne steel (with the latter often consuming a 20-30% recycled scrap charge), with Worldsteel indicating a 2.3 t/t average. This indicates at least ~2.7 GtC of CO_2 emissions from just BF-BOFs. Iron and steel emissions in the diagram (3.0 GtC) are based on Worldsteel's estimate of 1.83 tonnes CO_2 per tonne of all crude steel produced (1627 Mt)s.
Source: (International Energy Agency, 2018[1]; Worldsteel.org, 2019[22]; Lehne and Preston, 2018[2]; UN-Environment et al., 2018[11]).

The Paris Agreement commitments require that emissions from iron & steel and cement & concrete, like all other sectors, be net-zero emissions by 2050-2070 or face the marginal cost of negative emissions at that time.[4] Iron & steel and cement & concrete represent 8% and 6% of total CO_2 emissions today. (Figure 2). Given the very long life of steel and cement making facilities, on the order of 20-50 years with renovations and retrofits, it is highly likely that many of the newer facilities operating today could still be operating in 2050, and will need to be retrofitted to be net-zero compliant, pay the prevailing cost for negative emissions, or be retired.

To further complicate the issue, while global supply for primary steel is currently more than 20% in excess of global demand (OECD, 2019[23])over-supply in one national market does not necessarily translate into less new production in other markets. Steel production capacity is often considered a strategic asset, and some countries are not willing to count on others for supply. Several Despite this, several new BF-BOF and many EAF facilities are being built in China, India and across South East Asia. In China at least, it is a reasonable assumption that the new BF-BOFs will take market share from older less efficient facilities, as occurred in coal electricity production. The cement market is not as over-supplied as steel, but the same problem exists that there is already roughly the same amount as production as demand, and therefore not a big market for new entrants.

Barriers to the low-carbon transition in heavy industries: economic, regulatory, technological and political economy challenges

All heavy industries have made significant improvements in energy efficiency, as evidenced by the relatively swift transition to long dry kilns with preheaters in cement. Despite this, the steel and cement industries have made relatively little progress commercialising low GHG intensity options compared to electricity generation, buildings and transport. Why?

- **The steel and cement industries operate with very low profit margins in very competitive markets.** Firms cannot generally pass on costs without losing market share. Steel and cement have also traditionally been operated as relatively undistinguished commodities, but niche markets in both have been emerging. Steel is more traded internationally than cement because of weight to value considerations, but trade in clinker is growing.
- **Capital costs are very focussed and upfront, which increases the investment risk and conservatism**. New steel and cement plants cost hundreds of millions to billions of euros/dollars and are rarely built in the developed world. Most new capacity is being built in in-transition and less developed countries. For these kinds of investments to be made there must be a very robust long-term business case.
- **Facility turnover is slow.** It takes years to plan, get permits for, finance, and build a steel or cement plant, and once built, they can last for 25-50 years with proper maintenance. The current oversupply of steel plants, and supply sufficient to demand for cement , will also naturally serve to slow the development of newer, more innovative facilities.

[4] The marginal cost of land use and technological negatives emissions are highly uncertain but are likely to be in the range of USD 100-300/t CO_2e based on the cost of biomass or direct air capture of CO_2 with CCS **Invalid source specified.**.

- **There has historically been no market for more expensive but less GHG intense materials**. As will be reviewed in later sections, there are many emerging and near commercial options to greatly reduce the GHG intensity of making and using steel and concrete, but there has been little interest or investment into making them commercial because there has been no market for them.

The highly competitive and GHG-intensive nature of these industries and the markets they serve have led carbon trading schemes (e.g. the European Union Emissions Trading System) to allocate heavy industries like steel and cement free tradeable permits. Theoretically, this should have maintained the full price signal and subsequent innovation. There is evidence of increased environmentally orientated innovation in the broader industrial sector, including light manufacturing (Calel and Dechezleprêtre, 2016[24]), but innovation in the heavy industrial sectors has been muted (Neuhoff et al., 2014[25]; Neuhoff et al., 2014[26]). The key innovations that have occurred have been as a result of programs like the EU Ultra Low Carbon Steel program (UCLOS), which has produced pilotable technologies (e.g. the HISARNA and SIDERWIN technologies) and the Swedish HYBRIT hydrogen DRI-EAF project. At the same time, however, carbon leakage has been negligible[5] (Branger, Quirion and Chevallier, 2016[27]), again partly due to free allocations for the EU heavy industry sectors.

The Paris Agreement implies a fundamentally different context, in which emissions from existing plants from all countries must be minimised and eventually reduced to a very low level through operations and retrofitting, or be compensated with negative emissions by 2050-2070. This requires that the best available technology standard become net-zero compliant and fully commercialised by the mid 2030s to allow for long facility lives and slow stock turnover, and that retrofit technologies be commercialised as well. Given the already described global political economy context for these sectors, this implies a fundamentally different approach to policy.

A broad literature review[5] identifies several methods for reducing GHG emissions from steel, concrete and other GHG intense materials which are here divided into two broad categories: 1) "Reducing demand" through purposeful design of vehicles, industrial equipment, buildings and infrastructure. Design considerations include improvements to material efficiency, easier, non-destructive reuse of components, and easier, higher volume and quality of recycling. 2) "Decarbonising production", through intensive research, development and commercialisation of emerging and near-commercial technologies that result in very low or zero emissions.

[5] (Fischedick et al., 2014[12]; Allwood and Cullen, 2015[9]; Åhman, Nilsson and Johansson, 2016[45]; Denis-Ryan, Bataille and Jotzo, 2016[46]; Wesseling et al., 2017[15]; Bataille et al., 2018[8]; UK Energy Transitions Commission, 2018[18]; Material Economics, 2019[17]; Wyns et al., 2019[16])

2. Reducing demand for steel & concrete

The demand for buildings and infrastructure determines concrete and steel demand, while demand for vehicle and machinery also contributes to the latter. Within this relationship, there is significant scope for **material efficiency** and **enhanced recycling** to reduce primary material demand and GHG emissions.

Material efficiency

The basic principle of material efficiency is to use less material to meet the same transport, housing, building or industrial production end-use service. This is done through design to: minimise use of materials from a life cycle GHG intensity perspective; lengthen the life of a vehicle or structure to minimise re-build cycles; lengthen the functional life of a structure by making its use flexible for multiple potential end-uses (e.g. through movable walls and large and easy-to-access conduits); allow for non-destructive reuse of components; and finally, to allow for component recycling (Allwood and Cullen, 2012[28]; Allwood and Cullen, 2015[9]; Material Economics, 2019[17]; International Energy Agency, 2019[10]).

Building construction with steel beams provides a key example of materially efficient design. While structurally beams can get smaller the higher the building (i.e. the stress on a given beam falls with increasing height), to simplify construction they are often one size at all levels. This results in up to 2-3 times too much steel being used in a given building. While optimising beam size for each level would likely be logistically complex and costly, designs that use 2 to 3 different sizes of beam would capture many efficiency benefits with relatively low design and construction difficulties. Beams can also be designed for reuse using common reusable attachment points (e.g. bolt placement, etc.), and for ease of recycling with minimal contamination with other metals.

Another example is the use of concrete. Concrete is cheap by mass, corrosion resistant, and strong in a compressive state, but not in a torsional, shear or pulling state, which is why we add steel reinforcement bars to large cement structures. Because concrete is currently so cheap, however, it is often used for non-load bearing walls and other building components. Steel, on the other hand, is vulnerable to corrosion unless: it has been carefully coated with zinc, chromium and other metals; is embedded in concrete; or is regularly painted. This would suggest concrete be used where we need compression strength and resistance to corrosion, steel where we need high torsional, shear and pulling strength, and other low-cost, low-GHG materials be used for lower-load bearing walls, etc. as needed (e.g. local stone, bricks, wood, Gyproc, etc.)

The IEA's 2019 "Material Efficiency in Clean Economy Transitions" (International Energy Agency, 2019[10]) indicates that material efficiency can significantly contribute to reducing CO_2 emissions. In their "Clean Technology Scenario", which aligns with the objectives of the Paris Agreement but does not prioritise material efficiency, material demand is reduced by 24% from their "Reference Technology Scenario" for steel (equivalent to about six times the production in the United States in 2017) and 15% for cement (two and a half times the production in India in 2017) in 2060. A "Material Efficiency" variant achieves the same degree of energy supply and demand decarbonisation as the Clean Technology Scenario, but it also pursues ambitious material efficiency strategies (e.g. improved buildings design and construction, substantial vehicle lightweighting and material reuse) while considering real-world technical, policy and behavioural constraints. This leads to further material demand reductions compared to in the "Clean Technology Scenario", especially for steel (-16%) and cement (-9%) in 2060.

These results come with caveats. Given the current low cost of steel and especially cement, without any incentive or requirements to pursue material efficiency, or explicit demand from consumers, designers and manufacturing or construction companies may deprioritise material efficiency or simply be unaware of its possible benefits. Material supply chain actors may also choose not to pursue material efficiency due to real and perceived risks, financial costs or lost revenues and time constraints. Overbuilding with cheap but reliable materials like steel and cement is a long-standing practice. Fragmented supply chains may present challenges for achieving material efficiency, such as when users or demolition contractors are not connected to construction companies to facilitate end-of-life materials reuse. The regulatory environment may also restrict pursuit of material efficiency, such as when prescriptive design standards prevent uptake of new materials or design methods (e.g. regulatory limits on the substitution of low GHG cementious materials for clinker in cement).

While the fact that carbon pricing levels are too low in almost every jurisdiction is the single most important hinderance to their effectiveness meeting the Paris targets (Carbon Pricing Leadership Coalition, 2017[29])[6], carbon pricing will also have challenges encouraging material efficiency due to market distortions caused by the sequential nature of decision-making along supply chains, imperfect competition and government intervention to reduce the risk of carbon leakage (Skelton and Allwood, 2017[30]). Compensation mechanisms that reduce the risk of carbon leakage (e.g. free permits for process emissions) can both inhibit investment in low emissions technologies (Flues and van Dender, 2017[31]) and prevent final end-use consumers from seeing and reacting to these prices.

Achieving the benefits of material efficiency will likely require several integrated strategies. First of all, it needs to be included in education, training and regulations for all supply chain actors. This includes architects, designers, transport and civil engineers, construction workers, manufacturing companies, material and parts suppliers, and demolition companies. It will also require cooperative or competitive best practice sharing among companies.[7] Mandatory design standards may also be necessary to ensure widespread acceptance. Finally, eventual full carbon pricing on all parts of the material production and consumption chain will be required; several methods are possible (Section 4).

[6] The commission recommended at least US$40–80 per tCO_2e by 2020 and US$50–100 tCO_2e by 2030, with recognition there was good reason they would likely vary across countries **Invalid source specified.**.

[7] One key example is the UK Offshore Wind Accelerator (https://www.carbontrust.com/offshore-wind/owa/), where companies codeveloped with UK government assistance key technologies they couldn't develop themselves, while remaining competitive in other spheres.

Enhanced recycling & circularity

Circularity is a related concept to material efficiency, but is broader in that the ultimate long term objective is minimal use of primary materials and waste in the economy in via reuse, remanufacturing, repair and refurbishment, followed by recycling and clean disposal when materials are no longer reusable. The laws of thermodynamics indicate that a fully closed system is impossible, that entropic decay must occur, but the global economy is nowhere near these limits. Except for some recycling of steel (85%) and aluminium (~25%) the global economy is currently a once-through system where raw materials are transformed into useful items for a while, and then are discarded as degraded waste.

The use of end-of-life steel (i.e. scrap) should be maximised. From a practical near term standpoint within our technological and organisational capacity, secondary recycled steel (23% of current production[8]) uses about 50% of the energy of primary steel. It can be completely decarbonised if recycled using decarbonised electricity. Scrap is also a significant input to the BOF (<30%). The end-of-life recycling rate of vehicles and structural steel parts and beams is as high as 98% in developed countries, while the recycling rate of rebar is lower - in the range of 70%. The overall steel average is 85%. Developed countries have much higher stocks of steel products to recycle, and there seems to be an evolving pattern where the stock of steel products for vehicles, buildings and infrastructure saturates at 10-12 tonnes per capita.[9] The key outstanding challenge is maintaining the quality of the steel scrap through the separation of copper wiring, other metals, and other materials before the remaining steel scrap is melted. This separation must be imposed *ex-post* (after construction and use) in the developed countries, but all countries have the opportunity to design for lower cost, easier separability if the opportunity is taken.

While little recycling of concrete is done today, this is also possible if structural components (e.g. slabs, blocks) are designed for movement and reuse, i.e. structures are built in sections, with attachment and movement points. Key to higher quality recycling and reuse of both steel and concrete is purposeful design for separable, non-destructive deconstruction. Finally, much of the clinker content in concrete can remain unreacted after hydration, and can be reused if the concrete structures are ground up and the cement separated from the aggregates for reuse (i.e. the principle behind the “Smartcrusher” concept being developed in the Netherlands). In contrast to steel, there is no clear level of saturation for concrete use per capita (UN-Environment et al., 2018[11]).

[8] https://www.worldsteel.org/media-centre/press-releases/2018/world-steel-in-figures-2018.html

[9] Personal communication with J. Cullen.

3. Technologies for very low and zero emissions production of steel & concrete

Prior to the Paris Agreement, there was a limited amount of information scattered in specialist engineering literatures on low- and zero-emissions options for producing steel and concrete, with most of the more well-known literature focussing on carbon capture and utilisation or storage (CCUS) derived from work on carbon capture and storage (CCS) for coal generation plants. One of the outcomes of the Paris Agreement is that there is now a rapidly growing literature[10,11] on emerging and near commercial technologies specifically for steel, cement and other heavy industries, using multiple technological pathways. The following sections will non-exclusively summarise the findings of these studies, which are very consistent with each other on the technological options, if not on their emphasis on which technologies to pursue.

Emerging and near commercial very low and zero emissions steel and cement production technologies

Table 1 and Table 2 list some of the most commonly discussed technologies for reducing GHG emissions to very low or zero levels in the coming generations of steel and cement plants. Technology readiness levels vary widely, with some technologies or process changes being available today but not being used to their full potential (e.g. high quality steel recycling, maximising clinker substitution with other cementious materials), to technologies that work at the lab bench level but have not yet been field piloted (e.g. direct molten oxide electrolysis of iron ore followed by an electric arc furnace, or magnesium oxide cements, which could be GHG negative). The technologies are classified using NASA's commonly used Technology Readiness Level (TRL) scale:

- TRL 1 – Basic principles observed
- TRL 2 – Technology concept formulated
- TRL 3 – Experimental proof of concept
- TRL 4 – Technology validated in lab
- TRL 5 – Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – Technology demonstrated in relevant environment
- TRL 7 – System prototype demonstration in operational environment
- TRL 8 – System complete and qualified

[10] **Invalid source specified.**

[11] **Invalid source specified.**

- TRL 9 – Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies)

These varying levels of technology readiness imply different policy responses; these will be discussed in following sections.

Table 3.1. Very low and zero emissions technologies for making iron & steel

Technology & GHG reduction potential	Notes	TRL, Estimated breakeven cost & Date Available
HYBRIT – Hydrogen DRI-EAF; -99% with very low or zero GHG hydrogen.	SSAB (a steel producer), LKAB (an iron ore pellet manufacturer) and Vattenfall (a power company) formed a joint venture to develop hydrogen based DRI-EAF. http://www.hybritdevelopment.com/	TRL= 5-7; Breakeven with BF-BOF 34-68 €/t CO2e & 40 €/MWh. (Vogl, Åhman and Nilsson, 2018[13]) In pilot phase, commercialisation ~2030 as of October 2019.
SALCOS – Partial hydrogen replacement of NG in a standard DRI-EAF; -30% GHGs.	Collaboration between Salzgitter AG and the Fraunhofer Institute. https://salcos.salzgitter-ag.com/en	TRL=6-7; $=?; 2025.
Siderwin – Aqueous electrolysis / electrowinning; -99% with very low or zero GHG electricity.	Siderwin is a research project initially funded by the EU under the UCLOS project is and now being piloted by ArcelorMittal https://www.siderwin-spire.eu/	TRL=5-6; Breakeven with BF-BOF $20-30/MWh & $20-50/t CO2e; 2030-2035.
Boston Metal - Molten oxide electrolysis / electrowinning; -99% with zero GHG electricity.	Boston Metal is developing the technology to produce a variety of metals https://www.bostonmetal.com/	TRL=5-6; Breakeven with BF-BOF $20-30/MWh & $20-50/t CO2e; 2030-2035.
DRI with post combustion capture CCUS. Capture rate? Potential retrofit.	Al Reyadah, a wholly owned subsidiary of Abu Dhabi National Oil Company, is capturing CO2 from a commercial-scale DRI-EAF plant operated by Emirates Steel and using for enhanced oil recovery.	TRL= 9; Breakeven est. $120/t CO2e; Today
Top gas recirculation with 90%+ CCS. Potential retrofit.	Addition of 90%+ CCS to the current best available technology. No evidence was found for pilots.	TRL = 5; $70-130/t CO2e breakeven; 2025-2030.
Hisarna with 80-90% capture CCS.	Hisarna employs an upgraded smelt reduction process that processes iron ore in a single step, eliminating coke ovens and agglomeration. It is more efficient & produces a concentrated CO2 stream. Small pilot complete in Netherlands, to be commercially piloted in India by Tata. https://www.tatasteeleurope.com/en/innovation/hisarna	Greenfield commercial plants could be available within 10 years of the completion of the current demonstration project. TRL = 7; $40-70/t CO2e; 2025.
Thyssenkrupp project to substitute hydrogen for coke for process heat and reduction. Course 50 project adds CCS (potentially -40%).	https://www.thyssenkrupp-steel.com/en/newsroom/press-releases/press-release-110080.html Course 50 is a Japanese Iron and Steel Federation initiative http://www.jisf.or.jp/course50/outline/index_en.html .	Thyssenkrupp scaled piloting underway. Course 50 full-scale demonstration is planned in the 2030s
Utilisation of waste gases (H2, CO & CO2) for chemicals or fuels.	Thiessen Krupp project to make ethanol, max -50% reduction. https://www.thyssenkrupp.com/en/company/innovation/technologies-for-the-energy-transition/carbon2chem.html	TRL=3-6; Breakeven $50+/t CO2e; 2025-'30.

Table 3.2. Very low and zero emissions technologies for making cement & concrete

Technology	Notes	TRL, Estimated breakeven cost & Potential Date Available
Retrofit all plants to best available technology (up to 7% improvement).	Current BAT is long dry kilns with pre-heaters that recover heat from the clinker heating unit.	TRL=9; Cost of retrofitting equipment; Today.
Substitution of clinker with lower GHG cementious materials (blast furnace slag, coal or waste fly ash; 70-90% improvement).	Substitution of blast furnace slag or fly ash common practise in many markets, and usually absorbs all available slag and fly ash. Requires regulatory permission.	TRL=9; Cost of blast furnace slag, fly ash or pozzolans minus the avoided clinker; Today.
Substitution of clinker with lower GHG cementious materials (calcined clays and limestone; up to 50% improvement).	Up to 50% of clinker in cement can be replaced with local calcined clays (10-15%) and ground limestone (20-30%). This can reduce emissions up to 50% while improving cement strength.	TRL=7; Inconsequential cost difference; 2025? Requires re-training of all supply chain participants & calcined clays.
Use of multi-sized and well dispersed aggregates (The best made concrete can be 400% stronger than the worst concrete that works).	Concrete strength can vary by a factor of 4 or more depending on how well mixed, dispersed and spaced the aggregates are. Professional industrial mixing and dispersants could produce much stronger yet lighter concrete using less cement using existing technology.	TRL=9; There is no breakeven cost, this is best practise. Requires professional industrial cement and concrete mixing and pouring. A first measure is to eliminate bagged cements.
Alternative lower GHG fuels, e.g. wastes (up to 40% improvement) **Invalid source specified.**	Common practise in many markets. Requires special air quality permissions and exhaust cleaning equipment.	TRL=9; Can be cheaper than using coal or NG, depends on waste cost; Today.
Carbon capture and utilisation Possibly partially retrofittable -60% improvement.	One of the most advanced projects is LEILAC in Belgium, which replaces the calciner with a unit that concentrates the process CO2, making it easier and cheaper to dispose of. https://www.project-leilac.eu/	TRL=5-6, 2025 for concentrated sources, e.g. replacing the calciner with a LEILAC-like unit.
Biomethane, hydrogen, ammonia, for process heat.	Any of biomethane, hydrogen or ammonia could produce the necessary heat for limestone calcination or clinker production.	Biomethane; hydrogen, ammonia from electrolysis or steam methane reforming; TRL = 9.
Carbonate looping **Invalid source specified.**	Carbonate looping is a potential method for separating CO2 from flue gases (e.g. from steel plants, coal electricity plants), but requires constant replenishment of the sorbent material, calcium oxide. Portland cement production, as stated above, can use this waste sorbent CaO.	TRL=3-6; Cost=?; 2025-2030, depends on uptake of calcium oxide as a flue gas filtering agent in other industries.
Production carbonation (e.g. Carboncure), up to 30-40% reduction https://www.carboncure.com/	Cement reabsorbs CO2 throughout its lifetime to greater or lesser degrees depending on its exposure to air; production carbonation does at the outset with waste CO2 from other industries.	TRL=8->9; $20-50/t CO2e, cost of CO2 for carbonation; In early commercial use now.
Alternative cement chemistries to OPC, e.g.: Carbonatable calcium silicate clinkers (-43%), Calcium sulfone aluminate (-48%) ; Geopolymer/Alkali activated binders (-80-90%) ; Magnesium silicate or ultramafic cements (<-100%, carbon negative).	See Chatham House report (Lehne and Preston, 2018[2]), (UN-Environment et al., 2018[11]). Magnesium silicates replace limestone, and cure using waste or atmospheric CO_2. All these chemistries have very large potential, some for negative emissions, but require extensive piloting and commercialisation. Architects, designers, civil engineers, and contractors would then need to be familiarised with their properties.	TRLs = 2->4, 7->8 in a few specialty cases. 2035-'40 onwards.

Note: See (UN-Environment et al., 2018[11]) for discussion of almost all options unless other sources noted. Improvement levels are from Figure 8, page 17 of the Chatham House report (Lehne and Preston, 2018[2]).

There are several emerging technologies that are close derivatives of well understood and commercial technologies that could result in significant reductions in emissions in the medium term. For example, the LEILAC process concentrates the CO_2 chemical process gases (which are ~60% of all emissions from cement production) in the calciner portion of cement plants. This allows direct reutilisation or use of already commercialised oil and gas technology for geological disposal of highly concentrated (>=80-85%) CO_2, as opposed to the more technically difficult and not yet commercialised task of separating CO_2 from combustion flue gas streams highly diluted with atmospheric nitrogen. LEILAC is designed to be relatively easy to retrofit to existing calcining units.

The Hisarna process, which produces a waste gas with a higher concentration of CO_2 than BF-BOFs, could also be installed next to existing steel facilities and be used with carbon capture and utilisation or storage (CCUS). BF-BOFs can also accommodate certain levels of natural gas or hydrogen, while continuing to use coke for the main part of the reduction (e.g. the Course 50 and Thyssenkrupp projects). Existing natural gas DRI-EAFs, given reduction is done using a natural gas based syngas of H_2 and CO, can potentially accommodate up to 30% direct hydrogen feed without large modifications (e.g. the SALCOS project).

As a class, these "hybrid emerging/near commercial" technologies could, once commercialised, be retrofitted into existing plants. While expensive, they would not disrupt existing supply chains, business relationships, labour forces, etc., and be an opportunity for some quicker and larger GHG reductions that would also help develop the CO_2 transport and disposal network, and hydrogen infrastructure for other uses.

The IEA's recent "Future of Hydrogen" (2018) report suggests focussing on planning and infrastructure building in industrial port cities that already have refineries. This is because almost all have hydrogen production for hydrogenation of crude portions and for desulphurisation, and there are typically potential users for waste CO_2 (e.g. chemical producers) and geological disposal sites for CO_2 (e.g. the North Sea for Rotterdam's complex of industrial sites, or the Gulf of Mexico for US and Mexican refiners and chemical producers). These potential industrial clusters would require CO_2 transport, hydrogen production and storage facilities, and high voltage electricity transmission. Given geographic proximity, they could also implement district waste heat sharing systems (e.g. like at the Kalundborg complex in Denmark). Waste heat can improve the efficiency of many processes, including hydrogen production by electrolysis or steam methane reforming or auto-thermal reforming. While many potential industrial decarbonisation synergies are possible, all the above requires clear expectations of stringent long term climate policy, planning, clear legal frameworks, finance, and labour force retraining, and above all, markets for very low to zero GHG products.

The limits and barriers to the adoption of low-carbon steel and cement or alternative materials in selected sectors

The barriers to adoption of processes that provide very low and zero emission steel or concrete, or alternatives to them, fall in four main classes: slow stock turnover, higher cost, sector specific needs, and institutional challenges.

Slow stock turnover

The significant amount of existing steel and cement capacity will slow the introduction of low/zero carbon production technologies.

There is currently about 20% more global capacity for primary steel than demand (OECD, 2019[23]). As a result of the 2000s growth in steel demand in China, a large number of steel plants were built to current efficiency standards, resulting in a fleet of relatively modern facilities but which still use coal as their main fuel. Chinese demand for steel has since slowed, with some very recent evidence of a resurgence in demand. New capacity has also been built and is under construction in India, South East Asia, and the Middle East. Given this large existing fleet, and the fact that steel plants can last 25-50 years, new technological options must find market share in a crowded market. Given these dynamics, the short to medium term priorities are minimising emissions from the existing capacity (e.g. using more efficient plants first, optimising operations, methane injection to replace coal for heat, etc.) and technology retrofits of existing plants with strong long-term demand prospects. New very low-emissions plants might be buildable with pre-contracted markets. This will be discussed in the policy section.

The story for cement and concrete is more nuanced. Most developed and in-transition regions tend to have as much capacity as they need. But as we have seen, some of the highest short-term emission reduction strategies are from concrete-limiting design and use of other materials, substitution of clinker, and better mixing and packing of multi-sized aggregates in concrete, all of which can work with existing cement plant capacity. The main challenges to these already commercialised mitigation options are institutional supply chain awareness, education and motivation to change practices, all issues we will deal with in the policy section. Other more comprehensive retrofits involving more advanced technology also need to be planned for in the medium term, e.g. replacing the calciner with one that concentrates the CO_2 for disposal (i.e. the LEILAC project). For this, however, some form of carbon price or regulation would be required.

Higher cost

In terms of cost, the steel and cement industries operate with very low profit margins in very competitive markets. Firms cannot generally pass on costs without losing market share. While some process changes for clinker substitution and concrete mixing do not seem to have substantial financial costs, all the options for decarbonising steel, except for recycling, cost at least 30% more (Fischedick et al., 2014[12]; Vogl, Åhman and Nilsson, 2018[13]). Note that this is for bulk steel; metal parts will be perhaps 10% more, and it will only add $300-400 to a car (0.5-2%) (Lechtenböhmer et al., 2016[32]). For lower emission steel and cement to capture market share, they will likely need niche markets created specifically for them so that consumers willing to pay a premium can identify them.

The mitigation technologies that are discussed in the previous section do not benefit from the iterative innovation experienced with millions of units of electric vehicles, solar panels, and windmill generators. Proving some of these technologies will be an expensive and difficult process, with high failure risk, long time horizons, and very hazy potential benefits if anticipated climate policy is not very clear and stringent. Progress will likely be slow unless government, firms, sector associations, and large consumers work together to share the risk, through such policies as guaranteed markets (perhaps with initially high but falling material feed-in-tariffs, or contracts for difference – these will be elaborated on in the policy section), minimum content shares or priority market access in public infrastructure. Buyers coalitions, like Apple's role in the Elysis green aluminium project, can serve the same purpose.

Capital costs are very focussed and upfront. New steel and cement plants cost hundreds of millions to billions of euros/dollars. Large amounts of long term, risk-tolerant finance will be required, and again, the risk environment around these investments can be greatly reduced if there are guaranteed markets and (declining) prices for very early product, and/or priority access and pricing for public infrastructure projects.

Sector specific needs

There are many different compositions and types of steel and cement specific to end-use, and low-emissions versions will need to be meet the specific needs of these end-uses.

In terms of adoption of green steel or alternatives by specific sectors, notable is the automotive sector's need for high quality, uncontaminated sheet steel with known chemical composition and properties (i.e. how it will bend, weld, perform in crashes, etc.). There is a growing proportion of recycled iron & steel of global annual production and stock (Section 1). If the scrap sorting is inadequate and copper is still present in the steel scrap during melting, levels can build up in the steel and eventually reach amounts that limit the use of the steel produced. This has not been a problem to date because scrap is continually diluted with primary iron, but as stocks of secondary steel rise and the need for primary steel falls, this issue will grow more important. It is important to remember that the recycling of steel scrap in steel production is a well functioning activity that has occurred without policy intervention due to the economic advantages of using scrap in steel production. Scrap is already today sorted in a number of categories according to the composition and physical shape that all have different costs. It is expected that there will be additional scrap grades and/or higher demand for the "purer" grades in the future.

The adoption of lower GHG cements and concretes in the building sector may be hindered by existing regulations. For instance, clinker substitution can change the setting time of concrete, affecting construction schedules, as well as what end-uses it can be used for. In North America and Europe the building code assumes the use of 95% Portland Cement unless for specific uses. The European Union, for example, for safety reasons already maintains five cement classes (i.e. CEM I-V) based on clinker substitution levels with blast furnace slag, fly ash and pozzolanic materials, and clear regulations dictate what the proportion may be and when they may be used. According to our discussion with cement industry associations, this does not pose as much of a barrier as is getting approval for new formulas and uses; anecdotally, over 300 applications have been waiting for up to a decade for approval.

Institutional challenges

The most pressing institutional challenges for low-GHG steel and concrete and alternatives are in institutional supply chain awareness, education, motivation to change practices, and the regulatory environment for buildings, infrastructure and other structures. Architectural, engineering, design and construction practices and their counterpart building codes evolve slowly over time. They prioritise safety and costs in the case of infrastructure, and safety and firms and the public's willingness to pay for a given product in the case of commercial and residential buildings. It is important that many actors (e.g. government, regulatory bodies, sector associations, technical educators) are convinced of the necessity and means for low-carbon steel and concrete design[12], and are (re)trained on how to incorporate it into their work. Finally, once actors understand their roles in decarbonising steel & cement, the entire supply chain must be restructured around these new methods.

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[12] Design for: minimising the use of steel and concrete; use of low GHG concrete, which due to differential setting times can change construction schedules (low GHG steel is identical to high GHG steel); non-destructive reusability of components; and uncontaminated recycling of the steel and concrete once the structure's useful life is over. Reference: (Allwood and Cullen, 2012[28]; Allwood and Cullen, 2015[9])

Moreover, while there is a constant turnover and renewal of buildings and infrastructure in developed countries, most new construction will be in-transition and less-developed countries. Methods must be found to help these countries restructure their construction, steel use and cement and concrete industries around GHG minimising practices in ways that do not significantly increase cost for the builders or end-users. See UN Environment et al (2018) for a detailed discussion of this for cement.

Policy packages to trigger industrial decarbonisation must deal with all the traditional challenges in these sectors, but also directly face the above challenges to bringing new behaviour, technologies and processes to market in the face of slow stock turnover, higher costs, sector specific needs, and institutional inertia.

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4. Policies to reduce steel and concrete emissions to very low levels

At present, despite the overarching net-zero CO_2 emissions goal of the Paris Agreement, iron & steel and cement & concrete firms face a lack of global and national clarity regarding what actual policies they will face. This results in an investment limbo: carbon-intensive choices are incompatible with the Paris Agreement and face risks of more stringent climate policy, while climate-friendly choices lack a clear investment case in the currently uncertain policy regime. To break this impasse clear long term policy signals are needed, followed by comprehensive strategies incorporating all key actors and addressing all key challenges, actualised by policy packages to incentivise all actors to play their parts.

Since the entry into force of the Paris Agreement there is already a global commitment to economy-wide net-zero emissions by later this century, and several regional and national bodies have reaffirmed this commitment. This commitment needs to be reaffirmed, however, at the sectoral, national, and subnational levels where relevant. Arguably, the Paris Agreement has also unravelled the Annex I & II divide between developed and developing countries, which can potentially allow a return to global sectoral approaches that synergistically intersect with national net-zero industrial policies.

Box 4.1. Sectoral approaches to mitigation

Global sectoral innovation, standards, carbon pricing, or other mitigation efforts would aim to put most of the global production of a given emissions intensive traded commodity under one regulatory regime (Bradley et al., 2007[33]; Schmidt et al., 2007[34]; Nachtigall, 2019[35]). With full coverage, this would result in efficient location of production globally, and potentially allow for fuller cost pass through to the consumers. There could, however, be distortions arising from mitigation policy stringency differing between commodities and sectors (e.g. between cement, steel and electricity generation). There could be institutional difficulties in implementing sector-based schemes that would need to involve many producing countries, and issues associated with overlapping national policy approaches. An early attempt at sector-based approaches ran into challenges with the Annex I & II division, with Annex II producers arguing they should be exempted. This may, however, be less of an issue in the post COP 21 environment.

Once the overall objective has been signalled by governments and sector associations, a pathways planning process is required at the sectoral, national, and regional levels (Waisman et al., 2019[36]). It should include all key stakeholders from whom action or acceptance is required. Its purpose would be to assess: strategic and technological options; regional competitive advantages (e.g. based on access to wind, solar, nuclear, biomass or geological storage for CCUS); technological or demand uncertainties; and build a step-by-step transition plan, including investment, infrastructure, labour, and regulatory needs. It should also include appropriate interim targets that reflect the composition of the current producing fleet of facilities, their expected economic[13] and physical[14] lifetimes, and new build and retrofit possibilities. The sectoral transition planning process should include participation, input and buy-in from all key stakeholders, including those on the demand side (e.g. architecture, construction and infrastructure firms and their unions), the supply side (e.g. steel and concrete firms and their unions), and their regulators.

The conversation must also be global from the start. ArcelorMittal, the world's largest steel company, is active in 60 countries, based in Luxembourg and is controlled by the Indian Mittal family. The next nine largest companies are Japanese, Chinese, Korean and Indian companies, all of whom are active globally. Of the five largest cement companies, the 1st, 4th and 5th largest are multinationals (LafargeHolcim, Cemex and Heidelberg) and the 2nd (Anhui Conch) and 3rd (China National Building Materials) are Chinese companies active globally. Italian, Chinese, Taiwanese, Russian, and Brazilian companies round out the rest of the top ten. The implications of this can be shown from the LEILAC project; both Cemex and Heidelberg are active in it, and if and when LEILAC is commercialised, both companies will have the option of using it wherever geological disposal and incentives to use it exist. Given this, the steel and cement firms and associations should engage in a long term technical pathways and policy planning dialogues with engaged regional (e.g. California), national (e.g. the UK, Netherlands, Sweden, France, Germany, China, Canada), hyper-regional (e.g. the EU) and international governmental institutions.

Once a draft transition plan has been mapped out among the appropriate stakeholders, including a variety of pathways depending on uncertain future developments, a policy package needs to be constructed to implement the transition plan, operating at the appropriate jurisdictional level. A policy package for a given region will likely include several elements, which are used to frame the following discussion (Neuhoff et al., 2018[14]; Wesseling et al., 2017[15]; Bataille et al., 2018[8]; Wyns et al., 2019[16]; Material Economics, 2019[17]):

- an asessment of internal and external carbon risk assessment and disclosure;
- enacting policies to reduce demand, induce material efficiency, and increase recycling as appropriate by sector;
- promotion of R&D, strategic demonstration projects to support commercialisation, including niche or lead market demand creation for new very low GHG technologies;
- initially low but rising carbon pricing, combined with assessment of carbon competitiveness impacts;
- identification of potential geographic clusters for investment in infrastructure;
- identification and implementation of retrofit opportunities;
- possible GHG intensity based sunset regulations; and
- formation of supporting institutions.

[13] Years until the investment capital has been completely amortised, i.e. paid off.

[14] How long the facility and its subcomponents may be reasonably expected to last until a major retrofit is necessary.

Policy package components

Internal and external carbon risk assessment and disclosure

Steel and concrete companies are already acutely aware of their carbon risk based on their engagement with national climate policy processes since the 1990s, and the resulting negotiated allocations of free permits or other exemptions in national carbon pricing and cap and trade systems. It is quite possible that formal assessment of exposure to carbon risk will be demanded by investors in varying jurisdictions over the coming decade, and access to capital will be contingent on it. A clear assessment of their exposure mapped to supply chains and core processes will help isolate key actions and how they may be implemented, based on expected policy stringency, the remaining economic life of facilities, and their cost. A clear and well laid out plan that maps out the transition facility by facility, process by process will help inform investors and improve access to capital for all operations.

Policies to reduce demand, improve material efficiency & increase recycling

Co-design of products for material efficiency, durability, repairability, reuse and recycling

Reducing demand for the amount of steel and concrete in products and structures is a first order response to minimising steel and cement emissions. In most developed countries there is already a system of building and white good (e.g. appliance) regulations in place to minimise fire risk, water damage and maximise energy efficiency. Material use and efficiency can in most cases be added under the regulations that govern all of the above. This could include requirements for: minimum life, minimum necessary use of steel and concrete, capacity to be non-destructively disassembled, and high quality recyclability through separation of components. However, much of the above requires that these attributes be included in the initial design of a product or structure.

Actions and policies to induce material efficiency, substitution, reuse and recycling need to be co-designed by architects, civil and industrial engineers, designers, etc. This will require engagement with national architectural, civil engineering, infrastructure bodies and large steel and cement firms. These actions will also need to be translated to developing country environments. This will require reform of: design and construction education; vehicle and building codes to allow or mandate less use of steel and concrete; more clinker substitution, and better concrete mixing using better dispersed and packed aggregates. It will also require co-design for deconstruction procedures to allow for clean separation and recycling of steel and concrete.

The European Union currently enforces an "Eco-design Directive" (2005/32/EC, revised in 2009[15]) as a regulatory framework for energy efficiency for all energy using products. There is also an Eco-Design Working Plan under final stages of review that seeks to incorporate circular economy aspects by taking the complete life-cycle of products and used-materials into account, by:

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[15] Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of eco-design requirements for energy-related products.

- providing consumers with information regarding maintenance and end-of-life of the product, as it is already the case for heaters and freezing equipment;
- enhancing the design for recycling and resource efficiency for domestic products;
- designing vacuum cleaners to support easy disassembly and dismantling;
- assessing the whole life cycle of professional refrigerating and freezing equipment;
- increasing product-specific durability via minimum lifetime of components;
- increasing availability of spare parts to facilitate the sharing, repairing and re-use of products; and
- marking components to facilitate sorting, enhance recyclability, and designing items for easy disassembly.

So far, the directive has been focussed on large consumer appliances, but its scope could be expanded.

Extended Producers Responsibility (EPR) programs will be key to more materially efficient design for mass manufactured products like vehicles and large appliances, which require the producer to plan for end of life for their products. The European automobile sector has already begun to think in these terms. It operates according to the "End of Life Vehicles Directive 2000/53/EC" (ELVD). As such it aims at: preventing the use of certain heavy metals such as cadmium, lead, mercury and hexavalent chromium; collection of vehicles at suitable treatment facilities; de-pollution of fluids and specific components; coding and/or information on parts and components; ensuring information for consumers and treatment organisations; and achieving reuse, recycling and recovery performance targets. With these targets set, the Directive involves four major stakeholders; the producer, the recycling industry, the last holder and the authorities. The ELVD would be the key vehicle in Europe for dialogue and enforcement of material efficiency and steel minimisation and high quality recycling maximisation.

The auto sector is perhaps the ideal environment for an extended producer responsibility programs, given it is characterised by large long-lived firms that mass produce highly designed products using steel, aluminium and plastic, which are all recyclable materials. EPR programs will be harder in industries characterised by smaller companies, more one-off designs, and a more artisanal nature. EPR may only be implementable in these circumstances based on subsystems, subprocesses and products.

More and purer recycling through mandates or Advanced Deposit Fees

Steel recycling is at a high rate in the developed world (~85%) because it costs less to make new steel out of steel scrap. As already mentioned, there is an existing market for various grades of scrap. Increasing recycling will require more intensive sorting, which will significantly increase costs unless products are designed for easier deconstruction and sorting.

A first step would be an assessment of the state of the existing recycling system in each region: what is its overall capture rate, how well if at all does it sort for contaminants? What is the scope to expand the capture rate and for contaminant sorting? It may be necessary for national authorities to mandate separability in vehicle and product design, and post-use separation of copper wiring looms and other material from vehicles and other steel products by recycling and waste disposal companies.

The constituent components of concrete (cement, sand, gravel and other aggerates) are also recyclable with grinding (e.g. using the "Smartcrusher" process[16]). Aggregate recycling would reduce the need for more sand and gravel, which can be limited, and cement is often incompletely reacted and can be reused as filler or reactive cement. However, except for regions in which there is an aggregate shortage and markets have developed, there exist no commercial incentives for concrete recycling, and concrete component recycling would probably need to be mandated at the regional and municipal level.

Increased recycling can also be driven by waste charges for dumping or Advance Disposal Fees (ADFs). ADFs would be levied on sale of products, and are meant to reflect the estimated cost of collection and treatment of products (OECD, 2016[37]). These can be weight based, fixed per unit (e.g. a vehicle), or "eco-modulated", where they vary with the initial design and type of materials (Neuhoff et al., 2018[14]). Transactions and implementation costs will be highest with the latter, but have the highest potential for rewarding better initial design. The largest challenges with ADFs will be their implementation and enforcement.

Promotion of research, development, commercialisation and technology transfer

Research, development and commercialisation support is a key priority given the transformative change that is needed from current practises to very low and zero emissions in the iron and steel and cement and concrete sectors. This includes not just the traditional support for basic research, but mechanisms, policies and business models to successfully help technologies go from the lab bench to the market, i.e. commercialisation. As shown in earlier sections, there are many known technologies and processes for greatly reducing emissions associated with steel and concrete, but there has been no reason to date to do the expensive and risky work of bringing them to market.

Research & development support

Substantial R&D support is needed for net-zero GHG steel and cement production, including finance for R&D and early pilots. There must also be targeted support for key potential gaps in clean supply chains that firms have trouble solving or find too risky to fill themselves. A successful example of this in another sector is the UK Carbon Trust's Offshore Wind Accelerator[17] (OWA). Its purpose is to help wind companies pull apart and examine the full supply and service chain for offshore wind, and to help these firms with challenge points. For example, it was found that the core technologies did not yet exist for services vessels and floats, and the OWA was instrumental in RD&C programs to co-solve these challenges with these companies with support from the UK government. Once the problem was solved and the missing supply chain links were addressed, the firms then returned to their normal competitive mode with each other.

Commercialisation and lead market demand for low GHG technologies

As with solar PV panels, some of the earliest commercial output will be very high cost, and will need "beachhead" niche or lead markets. Complicating this, there is currently no effective demand for low to zero GHG steel and cement. This means that government and/or private sector buyers' coalitions will need to establish a value for low GHG steel

[16] https://www.slimbreker.nl/smartcrusher.html

[17] https://www.carbontrust.com/offshore-wind/owa/

and cement, to help make markets for the output of pilot and early commercial plants. This can be done by several means.

Governments can prioritise purchase of low and zero GHG steel and cement through green procurement and content regulations (e.g. California's AB262 for public infrastructure). This can take several forms, including minimum content regulations or preferential buying for infrastructure (i.e. materials under a certain GHG benchmark are purchased first, potentially at a higher set price for a given volume, e.g. a material "feed-in-tariff").

Another variant of preferential buying is the use of "contracts for difference" or CFDs (Sartor and Bataille, 2019[38]). CFDs are a contract between a producer and government entity for government to pay a carbon based premium over a given carbon price for all material produced to cover ongoing higher operation costs and risks for producing green steel or cements, e.g. €20/t CO_2e for a set period, perhaps 20-25 years. The purpose of the premium is to partly help amortise the higher capital costs, but more importantly, to help counteract higher operating costs and risks, thus lower the overall risk profile of the investment. Another key attribute is that it provides a more stable carbon incentive over the life of the project. The European Emission Trading System has varied between ~€5 & ~€30/tonne CO_2e, making valuation of low carbon investments difficult; the CFD would form a stable carbon pricing component within a varying overall price.

Private firms can also perform the same "market making" function by participating in "early buyers' clubs", e.g. Apple's role as bulk buyer and financier in the Elysis consortium (Rio Tinto, Alcoa, and the governments of Canada and Québec[18]) to commercialise inert electrodes in aluminium production, thereby eliminating graphite depletion process GHG emissions.

"Carbon clubs" (Hermwille, 2019[39]) have also been a suggested as a mechanism for "ring fencing" higher cost green commodity markets. They would be an arrangement whereby a limited number of actors – national and subnational governments as well as producer and possibly consumer companies – agree to form a stable supply and demand market for green commodities. The premise would be that the while governments (and possibly firms) would provide the regulatory framework to justify investment in green steel production, including possibly minimum content regulations, green procurement or contracts for difference, firms would commit the necessary supply and demand investment knowing a friendly market for a given commodity exists. The Elysis green aluminium consortium can be looked at a carbon club. One can also a carbon club where a green steel producer goes into a long term relationship with a car maker, who can pass the cost of green steel down to consumers for whom the additional cost is a small part of purchasing a car, perhaps +0.5-2% (Lechtenböhmer et al., 2016[32]).

Removal of subsidies combined with an initially low but rising carbon pricing

Subsidisation of energy prices is a historic practise to entice industry to a given region and to keep there once established. Energy subsidies, however, and especially those for coal and electricity made with coal, are effectively negative carbon prices. A first step to introducing carbon pricing is to reduce energy subsidies over time (Nachtigall, 2019[35]).

Carbon pricing, whether it is done using a carbon tax or cap and trade system, is the theoretically preferred mechanism for signalling to end-users the marginal climate damages associated with consumption of energy directly or embodied in a given product or service.

[18] https://www.elysis.com/en/what-is-elysis#unprecedented-partnership

While politically and logistically challenging in the short run, a long term efficient response to material GHG efficiency will require eventual exposure of all sectors to full carbon pricing of some form.

For carbon pricing to work, however, the price must be passed by agents through each step of the supply chain from point of policy incidence to point of use. This may not happen if there is imperfect competition of any form (e.g. variable policy incidence (e.g. only on domestic firms), barriers to entry, market power, etc.). Given there is no global carbon price and it is unlikely there will be one for a long time, if ever, mechanisms (such as tax exemptions or reduced tax rates and free tradable permit allocations) to protect competitiveness of energy intense, trade exposed sectors have been a normal feature of carbon pricing systems. At present when carbon pricing via a carbon tax or cap and trade is imposed, these sectors[19] are often fully or partially exempted, usually based on their process emissions. Under these conditions the carbon price is almost never passed down to end use consumers, i.e. there is no GHG material efficiency signal (Skelton and Allwood, 2017[30]).

There are at least two main ways to instigate full material carbon pricing with competitiveness protections. Full upstream GHG intensity pricing with border carbon adjustments[20] for imports (added) and exports (subtracted) can be employed, or upstream intensity pricing over a given benchmark intensity, combined with downstream consumption pricing at the benchmark intensity, which avoids the need for border carbon adjustments or standards (Bataille et al., 2018[8]; Neuhoff et al., 2018[14]). In the latter system, upstream domestic producers would pay a carbon charge on all their emissions, but be refunded an amount equal to the best available technology carbon intensity times their production, while end-users of materials would be charged for the carbon intensity of the material they use, no matter where it comes from, based on best available technology. World Trade Organisation compatibility is maintained in both cases by treating domestic and foreign producers equally in the least trade restrictive manner.

Border carbon adjustments have several practical implementation challenges associated with how the emissions content of imported products is determined, particularly in accounting for intermediate inputs and varying production processes (Dröge, 2011[40]). Border standards based on technology benchmarks have similar challenges but may be easier in that they require proof of a benchmark production process being practised rather than numeric multistep emissions accounting. It has also been suggested to compensate

19 There is a growing literature on the actual level of threatened competitiveness due to environmental regulation; the perceived level cannot be discounted, however, as it directly affects the political calculus. In sum, while the concerns are overstated (i.e. there is no measurable effect) for industry as a whole, which includes both light and heavy industry, there is limited but significant evidence of potential carbon leakage to pollution havens for the most energy intense and trade exposed sectors, e.g. steel, cement, chemicals, paper, aluminium, and bulk glass **Invalid source specified.**. These effects are empirically difficult to measure, however, against background events and due to the granularity of data required to assess the impacts on specific facilities and sub-sectors.

20 Border-carbon adjustments (BCAs) are one way to equalise emissions pricing for imports and domestic production **Invalid source specified.**. They involve adding a charge to imports from countries with lower price regulations to equalise them with domestic production, and potentially refunds to exporters sending goods to countries with lower regulation. This requires accounting for types and variants of production processes and the emissions content of intermediate inputs (including electricity) in the importing and exporting countries.

heavy industry firms for their carbon charges by means independent of embodied carbon (e.g. through lower corporate taxes) (Skelton and Allwood, 2017[30]). Either border carbon adjustments or border GHG standards would be sought by affected industries for establishing “climate policy bubbles” in a world without uniform climate policy stringency.

While carbon pricing can introduce competitiveness concerns about the potential loss of market share from increased costs, the literature indicates that environmental regulations usually induce cost-reducing innovation (Calel and Dechezleprêtre, 2016[24]), and usually enough to offset some but not all compliance costs (Dechezleprêtre and Sato, 2018[41]). This is not including the benefits from reduced pollution, e.g. better air quality, where the benefits far outweigh the costs. These results may apply less for breakthrough technologies in steel and cement production. Some of the technological and process options for steel and cement & concrete production listed earlier indicate fundamental shifts in energy use and input cost structure, e.g. full direct and indirect electrification of primary steel[21], including possible geographic separation of reduction and smelting. Depending on the long run trajectory of these new input structures and how these technologies mature, there will likely be uncertain but significant long run productivity impacts.

Identification of potential geographic clusters for investment in infrastructure

Both the UKCCC *Net-Zero Technical Report* (UK Climate Change Committee, 2019[42]) and the IEA *Future of Hydrogen* report (International Energy Agency, 2019[43]) single out the importance of identifying specific geographic zones for where key infrastructure can be built to support decarbonisation of industry. This includes CO_2 transport and disposal, hydrogen production and storage, and high voltage electricity transmission for industrial electrification and electrolysis. Specifically, both reports singled out seaport cities with strong existing industrial bases and nearby opportunities for enhanced oil recovery or geological storage for CO_2 (e.g. US Gulf coast oil and gas servicing cities, Rotterdam, Teesside, Hamburg). More specifically, they singled out those with oil refineries with existing hydrogen production for oil upgrading and desulphurisation, as well as hydrogen production for petrochemicals. Most hydrogen today is made using steam methane reforming, which produces a concentrated stream of CO_2 emissions. These processes, along with CO_2 from raw formation gas processing, are ideal first candidates for well understood and commercialised geological disposal of concentrated CO_2. The presence of existing hydrogen production also eases initial issues with storage and permitting.

One challenge with choosing geographic clusters for decarbonisation infrastructure is that there needs to be a clear case for long term demand for the products of the sectors, or the risk of propping up senescent industries is quite high. As part of the transition planning process there needs to be a transparent assessment of the pros and cons for investment in given clusters, using several different independent criteria. Possible criteria may include the need for net-zero GHG energy carriers like hydrogen for multiple uses (e.g. chemical feedstocks, process and building heating) and specific regional competitive advantages (e.g. local markets, deep water port, close access to geological storage for CCS, likelihood of regional surplus renewable energy supply, etc.).

More broadly, seaport industrial zones are also ideal first candidates for district heat sharing and cascading, as practiced at Kalundborg complex in Denmark (A wide variety of heat

[21] Hydrogen DRI EAF and molten oxide electrolysis EAF primary steel technologies would use -28% and -48% energy per tonne steel than the most efficient coal driven BF-BOF, but would use electricity instead of coal as the core fuel (Fischedick et al., 2014[12]).

producers and users can help underwrite the building of a heat sharing systems, and residual heat can also be used to reduce the energy load for both electrolysis and methane based hydrogen production.

Industrial clustering for deep decarbonisation need not be confined to seaports. There are several industrial oil, gas & petrochemical regions with a strong petrochemical base, access to geological storage and decarbonised electricity, and sufficiently concentrated proximity to run CO_2 transport and storage, hydrogen and high voltage electrification networks (e.g. around the Persian Gulf; the Canadian provinces of BC, Alberta and Saskatchewan; and the Russian provinces in the Volga-Urals and West Siberia).

Box 4.2. Industrial clustering; case study of Kalundborg

Kalundborg Eco-Industrial Park (http://www.symbiosis.dk/en/) is a private planned and operated industrial symbiosis cluster in Denmark, in which companies in the region collaborate to use each other's by-products and share resources. At the centre of the exchange network is the Asnæs 1500MW coal-fired power plant. Surplus heat from the power plant is used to heat 3500 local homes in addition to a nearby fish farm, whose sludge is then sold as a fertilizer. Steam from the power plant is sold to Novo Nordisk, a pharmaceutical and enzyme manufacturer, in addition to an Equinor refinery. Additionally, a by-product from the power plant's sulphur dioxide scrubber contains gypsum, which is sold to a wallboard manufacturer. Almost all of the manufacturer's gypsum needs are met this way, which reduces the amount of open-pit mining needed. Furthermore, fly ash and clinker from the power plant is used for road building and cement production. These exchanges of waste, water and materials have created other less tangible benefits for these actors, including sharing of personnel, equipment, and information.

Identification of retrofit opportunities

Given the large existing global steel and cement production facility stock, a reduction in global GHG intensity and total emissions compliant with the 2050-2070 net-zero targets will need to include identification and implementation of retrofit opportunities.

Given roughly 60% of cement emissions are from the limestone calcination process, a retrofittable method for capturing and concentrating these emissions could be invaluable. This is the purpose of the EU LEILAC project (www.project-leilac.eu), where the current calciner could be run until the LEILAC unit is built, and the product flow could be rerouted through the LEILAC unit into the kiln. It only captures the calcination process emissions, leaving the process heat emissions, but conceivably these could be reduced using lower carbon alternative fuels, and eventually retrofit with hydrogen or a synthetic hydrocarbon alternatives. LEILAC works based on capture and disposal of concentrated CO_2, which is a well understood and commercialised oil and gas industry technology. To the extent that BF-BOF and DRI steel facilities can have their emissions concentrated (i.e. there are very low amounts of nitrogen), which is part of the premise of the HISARNA technology, retrofitting of CCUS disposal units in the near term could be considered.

One caveat is there must be utilisation pathways or geological storage available for captured concentrated CO_2, confining this option to where utilisation, CO_2 transport or disposal sites are available.

Possible GHG intensity based sunset regulations

It has become a relatively common practise globally to establish sunset regulations for older, high emitting coal generation facilities; Canada, for example, has established a coal phase-out program based on the economic life of facilities. All facilities are to cease operation by 2030, in reverse order of intensity and in consideration of generation needs. As another example, China has an established practise of shutting down older, high emitting coal generation, steel and cement facilities near cities and rebuilding newer, higher efficiency capacity away from urban air sheds.

Working with sector association and firms, given the very large size of the existing fleet and depending on the retirement profile of existing facilities, sunset regulations and phase outs may be required for older high GHG-intensity steel and concrete facilities that cannot be retrofitted. Unless they are replaced with new low-GHG facilities this will present challenges to communities and local supply chains. These considerations will have to be addressed in regional and national industrial transition plans, e.g. through workforce retraining, policies to invigorate other industries, etc.

Clear regulatory backdrop and a "just transition" as key enablers

To support change, we will need to make many modifications to existing institutions, and create new ones. For any form of GHG standards, carbon pricing or border carbon adjustments to work, methods, data and institutions for the assessment of life cycle emissions of given materials and derivative products will be required. There needs to be a clear regulatory backdrop for CCUS, including for transport, access, infrastructure, and liability for leaks. The natural gas and oil regulatory regime could be a model or even an institutional house for CCUS regulation, as it already includes regulations for gas transport, treatment of hydrogen sulphide and brines (which are reinjected underground), flaring and fugitives. Wider use of hydrogen, ammonia, and synthetic hydrocarbons derived from hydrogen and net-zero carbon sources (which would have to be verified) will require expansion of safety and access oversite. There needs to be a very clear legal and insurance backdrop: who is responsible for what in what situations (e.g. leaks, accidents, fires).

A key element that is often overlooked is a transition plan for the management and labouring workforce, whose full support is required. This involves retraining for those already in the workforce, and redefinition of the curriculum in technical schools where electricians, pipefitters, heavy duty machinery specialists, etc. are trained.

Oversight bodies are also required for the national transition plans, which have timetables of expected physical transitions against which they can measure progress and recommend policy adjustments and wholesale changes (Mathy et al., 2016[44]). At present, the UK Climate Change Commission, which recommends five year carbon budgets and parliamentary advice as required, is the best practise example of a national oversite body. It has no statutory authority to change policy, as this is the prerogative of the British Parliament, but it can monitor progress and recommend changes.

5. Main takeaways & research gaps

It is technically possible to transition steel and cement & concrete production to very low or zero emissions. It will require policy actions to reduce the demand for primary steel and cement, and to reduce the production emissions to very low or zero levels.

RESEARCH GAP: A core strategy for demand reduction and improving material efficiency will be the re-evaluation of the professional training and regulatory processes with respect to design and construction for architects, designers, transport and civil engineers, construction companies, trades and contractors. This would allow for: safely minimising the use of steel and concrete, higher rates of clinker substitution in most concrete applications, non-destructive reuse of components, and high-quality recycling when a product or structure's life cycle has ended. The key question is how to carry this out in both developed and developing country environments. Where are the key action points, institutional levers for change? Which ministries must be involved, who must plan it, who must enforce it?

Several existing technologies beyond building design would allow to greatly reduce cement emissions (e.g. up to 75% through better aggregate mixing and packing, up to 50% through clinker substitution)**, but these require consistent professionalisation and industrialisation of cement and concrete production in developing as well as developed countries.**

While much technology development works needs to be done through the 2020s, some of the key challenges are organisational, and a matter of infrastructure sequencing, gathering stakeholder support and participation, market dynamics, policy package formation, finance and progress monitoring and policy adjustment. **Integrated, well-thought-through transition plans and policies will be key to avoiding costly mistakes and conflicts.** These plans will need to be developed in cooperation with all key stakeholders, those whose active participation or acquiescence is required, e.g. national and regional governments, regulators, sector associations, firms, unions, community groups, and NGOs.

Adopting low-carbon technologies requires big, risky upfront capital investments, likely followed by higher operating costs. This needs to be recognised and policies designed and implemented to address it. While private sector will need to lead, **governments would have to play several key roles, including helping address the research gaps that follow**:

- **R&D and commercialisation support for very low and zero emissions technologies for steel and cement sectors, including prioritisation of technologies that can be a retrofit to existing facilities to help keep local supply chains intact** (e.g. CCS for concentrated sources of CO_2, like LEILAC). This includes development and use of combined government & private sector business models to share risk, e.g. the UK Offshore Wind Accelerator. For cement and concrete, the eventual ultimate objective is to eventually commercialise very low emissions or ideally carbon negative chemistries For steel, while higher volume and qualities of steel recycling combined with CCS for existing BF-BOFs will likely be critical for retrofitting the existing stock, in the long run very low or zero emissions technologies should become the commercial standard, e.g. HISARNA with CCS, hydrogen DRI EAF, or molten oxide electrolysis).

- **RESEARCH GAP: Lead market demand creation** through green procurement of steel and cement products, preferential buying for public infrastructure, material "feed-in-tariffs" or contracts for difference. Private firms can perform this role as well through buyers' clubs. There needs to be intensive investigation of the key parts of low carbon supply chains that cannot easily or expeditiously be met by private industry, and how government can facilitate meeting these gaps.
- **RESEARCH GAP: Carbon pricing and efficient and practical competitiveness protection provisions that would be applicable to steel and cement sectors**, e.g. further analysis is needed on the use of carbon pricing and whether border standards or border carbon adjustments would be required to allow innovation and restructuring "bubbles".
- **Identification and planning for key infrastructure for steel and cement industries**: CO_2 transport, hydrogen production and storage, high voltage electricity transmission, and district heat transfer systems.
- **RESEARCH GAP:** The very large existing fleet of steel and cement production facilities and their long economic lifetimes indicate that they must either be retrofitted or decommissioned. **A key area for work will be where, when and how GHG intensity-based retirement "sunset" regulations may be necessary and justified,** that work in time with capital amortisation and the schedule for commercialisation of new technologies. The impact on the facilities' firms, workforces and the communities they are situated in must also be considered.
- **Identification and development of institutions as necessary for the steel and cement industries responsible for developing:** workforce "just transition" strategies; lifecycle GHG assessment to support best available technology standards and potential border carbon adjustments; and a transparent and low transition cost legal backdrop for liability and insurance for infrastructure for hydrogen, district energy and heat sharing, and CCUS. Another key overarching supporting institution is an arm's length agency to oversee physical progress and make recommendations for policy changes if needed, e.g. the role played by the UK Climate Change Commission.
- **RESEARCH GAP: A final question is how to do all the above for the steel and cement industries effectively in developed, in-transition and developing contexts** (Bataille, 2019/2020[19]). What are the roles for developed, in-transition and developing country governments? The roles for multinational steel and cement firms and national and global sector associations? The roles for big steel and cement users like vehicle and construction companies? What are possible sequencings of actions that could build trust and enable transition planning and coordinated action between these players? Are there key trusted convenors, like the OECD, the International Energy Agency, the European Commission, or the Intergovernmental Panel on Climate Change, that can help jumpstart the dialogue?

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