



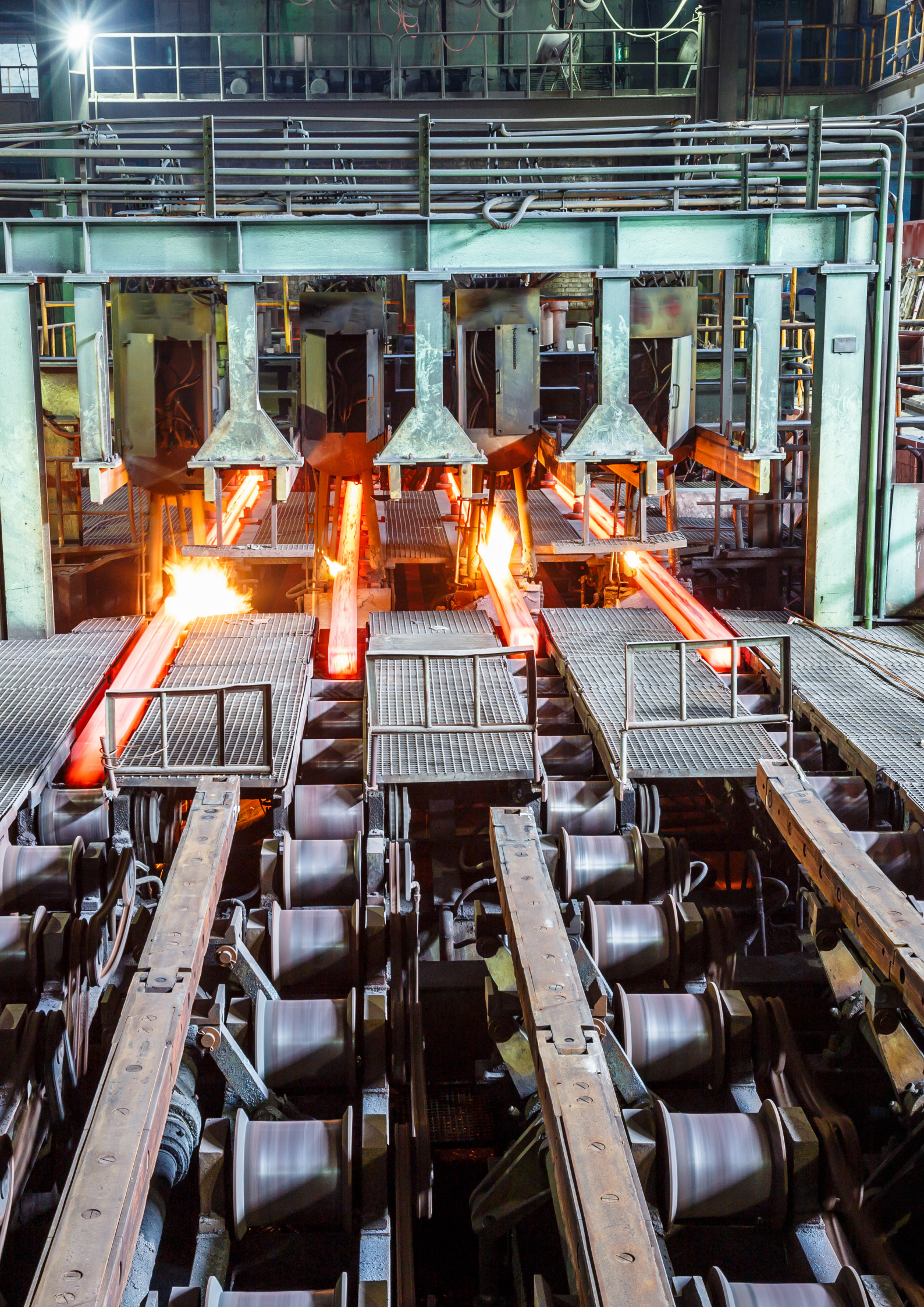
REDUCING CO2 EMISSIONS FROM HEAVY INDUSTRY

August 2019

Energy Industry Report

The Abdullah Bin Hamad Al-Attiyah International Foundation for
Energy & Sustainable Development





INTRODUCTION

REDUCING CO2 EMISSIONS FROM HEAVY INDUSTRY

Heavy industry appears to be one of the hardest parts of the economy to decarbonise. Industry overall contributes 24% of greenhouse gas emissions, with almost half of this from four big sectors cement, chemicals, iron and steel, and non-ferrous metals.

How can these emissions be reduced – by efficiency, electrification, carbon capture and other methods – and at what cost? What practical barriers need to be overcome? And what policy and consumer trends do energy-intensive industries need to look out for, and manage?



Research Series Energy Industry

This research paper is part of a 12-month series published by the Al-Attiyah Foundation every year. Each in-depth research paper focuses on a prevalent energy topic that is of interest to the Foundation's members and partners. The 12 technical papers are distributed in hard copy to members, partners and universities, as well as made available online to all Foundation members.



EXECUTIVE SUMMARY

- Industry is the **third-largest greenhouse gas emitting sector**, with 24% of emissions. Growing global pressure for decarbonisation means public, media and policy attention will increasingly turn to industry.
- **Decarbonising industry is much more complicated than the power or transport sector**, because of the great variety of plant types, processes, products and customers. Industries have to be internationally competitive. They provide well-paid employment and a key technological edge, meaning governments will protect them.
- **About half of industrial emissions come from four large sectors:** cement, chemicals, iron and steel, and non-ferrous metals. These provide the priority sectors for decarbonisation.
- **Decarbonisation can be achieved by five methods:** demand reduction and recycling; energy and material efficiency; low-carbon energy inputs (biomass, renewable/nuclear electricity and hydrogen); new processes; and carbon capture, storage and use (CCUS).
- **Total decarbonisation** requires a mix of low-carbon inputs, new processes and CCUS, depending on the industry. In turn, these need heavy investment in research and deployment.
- **Required policies** for industrial decarbonisation include: carbon pricing; government-led investment in research and commercial-scale demonstration; and international trade policies to maintain a level playing field.
- The chances of industrial demand for gas to pick up depend on its being price-competitive, so that it can gain from coal in industrial power and heat production, and from coke in iron smelting.
- Gas producers can develop markets by working with industrial consortia to develop gas-using processes that replace coal/coke, and/or include carbon capture, storage and use (CCUS). This could include investment in CCUS industrial-power clusters.
- Industries that retain high carbon footprints are likely to be targeted by climate policy and consumer pressure, including the energy-intensive industries developed in major oil and gas producers.
- Exporters of energy-intensive products need to advocate effectively for their interests, and work within industry consortia to achieve effective climate and trade policies.

IMPLICATIONS FOR LEADING OIL AND GAS PRODUCERS

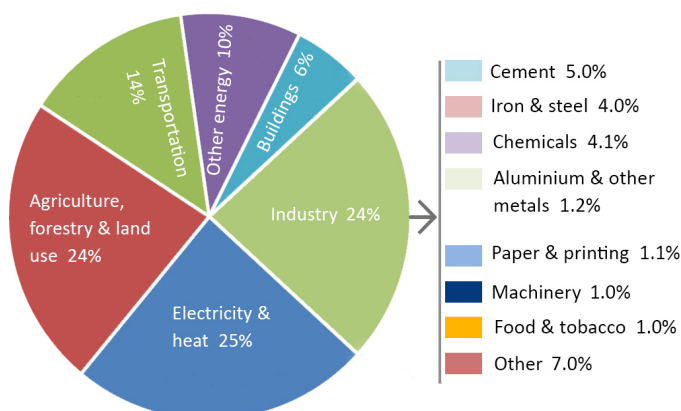
- The use of oil and coal in industry will be flat through the 2020s and reduce sharply afterwards. Gas is likely to pick up demand at least to the 2030s, but may flatten or decline after that. This will contribute to weak oil prices and a possible peak in demand by the 2030s.



INDUSTRY IS THE THIRD-LARGEST SOURCE OF GREENHOUSE GAS EMISSIONS – BUT HAS RECEIVED LESS ATTENTION

Industry is the third-largest greenhouse gas emitting sector worldwide. Note this does not include industry's share of electricity consumption. So far, most emissions reduction attention has focussed on the power sector (renewables, nuclear power, generation efficiency and coal-to-gas switching) and the transportation sector (fuel efficiency, electric vehicles). Agriculture and land-use, which includes a large share of non-carbon dioxide (CO₂), such as methane and nitrous oxide, is made up of a large number of very small sources, and requires action on deforestation and agricultural practices.

Reducing emissions from the industrial sector has garnered less attention from the media and general public, and even from policymakers. But meeting global climate targets will require major reductions from the industrial sector.



Industrial emissions come from process emissions, such as breaking down feedstock (calcium carbonate for cement, which contributes 70% of the emissions from cement-making; coke used for iron ore reduction), which account for about 45% of emissions from heavy industry; the combustion of oil, gas and coal for high-temperature heat (35%); on-site energy (13%); and machine drive (7%).

Almost half of the 15 Gt CO₂-equivalent of yearly industrial emissions come from four big sectors: cement (3 Gt CO₂ annually; iron and steel (2.9 Gt); chemicals (of which ammonia 0.5 Gt and ethylene 0.2

Gt); and non-ferrous metals including aluminium (0.4 Gt), copper (0.07 Gt), nickel (0.041 Gt) and zinc (0.03 Gt).

REDUCING INDUSTRIAL EMISSIONS IS COMPLEX BUT FEASIBLE

Unlike the power sector, industrial emissions come from a wide range of different sources and processes, even within a single facility. The UK pulp and paper sector alone, for instance, contains 350 separate sub-sectors, devices and technologies.

Low-carbon alternatives have not always been practically demonstrated. They have to be introduced at a commercial scale, making them expensive, risky investments, likely requiring government support. Industrial plants have a long lifetime (often 50 years or more, though with regular maintenance and gradual retrofitting). Processes are typically comprehensively designed and interconnected, so a change in part requires alterations all through the production line. In turn, that reduces efficiency, at least initially, and requires worker retraining.

Products are then used by other industries, such as construction, which have strict quality standards and their own procedures.

Industries have to be internationally competitive, which makes it difficult to impose carbon costs or caps on them without cooperation with other countries.

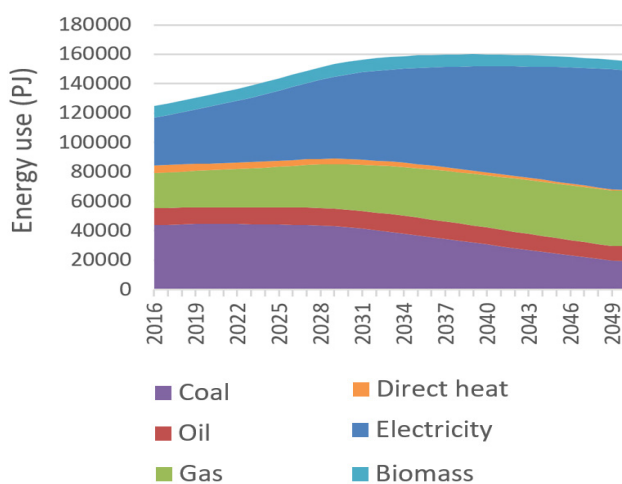
Industry is an important source of employment and technological sophistication. Recent trends in politics and trade make it even more likely that governments will protect their industrial sectors, rather than allowing them to shrink.

On the other hand, as discussed, the bulk of emissions come from a small number of

EMISSIONS REDUCTIONS CAN BE ACHIEVED IN FIVE MAIN WAYS

heavy industries, in turn concentrated into large plants and companies. This makes it much easier to monitor and control emitters than for dispersed sources such as transport, housing and agriculture. Heavy industries have large financial and organisational resources and technological sophistication.

Future energy projections show different views on industrial energy use. DNV's outlook shows efficiency gains leading to a peak in industrial energy use by 2040. Coal is mostly phased out, oil use declines slowly (-0.4% annually), gas use rises strongly (1.3% per year, reaching a peak in 2049), but in particular electricity rises at 2.7% annually, and grows from 28% to 52% of total industrial energy.



A combination of five methods can be used to reduce industrial emissions.

1. Reduce End-Product Demand

The demand for the final product can be reduced by, for example, increasing reuse and recycling; shifting to alternatives with lower embedded carbon (sustainably-harvested wood instead of concrete); or reducing overall material use. Overall, this might lead to a 30-50% reduction in greenhouse gas emissions from the steel and cement sectors.

Components created with additive manufacturing ('3D printing') and nanomaterials such as graphene might replace some traditional materials, and save on waste. On the other hand, alloys and plastics used in 3D printing could see increased demand. Metal printing is typically done with lasers, which could be driven by low-carbon electricity.

Recycling is particularly applicable to metals, but there is growing attention to recycling plastics too, also to prevent their accumulation in the environment. For instance, recycled aluminium makes up more than a third of production each year, but requires just 5% of the energy and emissions of primary aluminium. Producing steel from scrap is widely done in electric arc furnaces, and uses about 25% of the energy required for primary steel.

Various concrete formulations are under development that use less cement. Cement routinely contains 15% fly ash – the fine residue from coal-burning – but new types contain up to 95%, and are also stronger. However, as global coal burning reduces, there will presumably be less fly ash available. Construction methods and standards can be altered safely to use less concrete.

'Green' cements include calcium silicates, which do not release CO₂ in manufacture and in fact harden by reacting with carbon dioxide. However, for various reasons they are unsuitable for many construction applications, although they might take up 10% of the market by 2050. Other companies are working on curing silicate cements with CO₂. The products have some technical advantages, such as faster curing time, which might overcome the disadvantages of unfamiliarity, higher cost and more complicated construction procedures. Other concretes are under development using sulphur, a waste product from the oil and gas industry. However, these still have concerns about durability and flammability, and might not be compatible with steel reinforcement.

It needs to be borne in mind that some materials provide greater energy efficiency in end-use. Lightweight aluminium and carbon composites, for instance, are superior for vehicles and aeroplanes. Low-carbon energy systems such as solar panels, wind turbines, nuclear reactors, hydroelectric dams and transmission cables require large amounts of concrete, steel, aluminium and copper.

Therefore carbon reductions have to be assessed on a life-cycle basis, in the absence of a clear economy-wide carbon price signal.

2. Improve Energy and Process Efficiency

Industries have to be competitive, and therefore they already pay high attention to improving efficiency. In some countries with subsidised energy, inefficient technologies may still be in use. Incremental gains will continue, although some energy-intensive industries are already close to the theoretical optimum.

Overall energy efficiency gains in heavy industry may be in the range 15–20%. This is still only a partial step towards decarbonisation.

DNV's projections imply about a 30–31% improvement in energy efficiency from 2018 to 2050, measured by energy input per tonne of manufactured output, or per \$ of value. But this is partly achieved by a shift to more sophisticated and less energy-intensive outputs, and probably to less material waste and more recycling and 'circular economy' implementation.

Non-CO₂ emissions may result from process upsets. For instance, perfluorocarbons from aluminium production have been reduced 86% from 1990 to 2006, with a further 50% fall targeted by 2020. Electronics and solar panel manufacturing release sulphur hexafluoride and nitrogen trifluoride, two extremely potent greenhouse gases, which can be removed by modern gas abatement systems, or replaced by using pure fluorine.

3. Use Lower-Carbon Energy Inputs

The most straightforward option is to switch from coal to gas or biomass for process heat, and to low-carbon electricity, including renewables and nuclear. Industries may have little influence over the carbon content of their grid electricity, but many (typically less energy-intensive) companies have committed to buy 100% clean/renewable energy. For captive power, they can invest in on-site solar or wind power, or in alternative locations with 'wheeling' through the grid, if local regulations permit this. About half of aluminium is already produced from hydro power.

Widespread electrification of industry will result in sharp rises in demand. This is only environmentally favourable if the increased generation is low-carbon. Therefore industrial switching has to be combined with a near-decarbonised grid.

In gas-importing countries, such as China, India and Australia, gas may be relatively expensive compared to coal. This will deter its use by competitive industries, unless they are encouraged by government policy or consumer pressure.

Process heat could be provided by solar thermal, geothermal, nuclear, electricity or hydrogen. Lower-temperature heat can be supplied by waste heat from nearby power plants or other industries.

All of these options have challenges. Solar thermal or geothermal relies on the proximity of available land or hot rocks. Co-locating nuclear with suitable industries would require extensive coordination by government and industry, and would raise safety concerns, though small modular reactors (SMRs) might be more suitable. Electricity is expensive unless most can be consumed off-peak – bearing in mind that peak demand is likely to shift to winter and early evening as more solar power is introduced. Hydrogen is also expensive and not yet available in quantity.

Finally, these approaches would all require considerable re-engineering of the plant, including

EMISSIONS REDUCTIONS CAN BE ACHIEVED IN FIVE MAIN WAYS

redesign of boilers and furnaces. Electric furnaces are not yet available at sufficient temperatures for cement making.

4. Use alternative processes

Alternative processes aim to eliminate the inherent emissions in industry.

Iron-making requires a reducing agent, traditionally coke (made from coal). Natural gas, already widely used in the Middle East, is one alternative. Others, that would mostly eliminate CO₂ emissions, are shown in the below table.

Process	Pro	Con
Direct Reduced Iron (DRI) with natural gas	Commercial process already in wide use 1-1.1 tonnes CO ₂ /tonne steel versus almost 2 tonnes for coke blast furnace	Still significant CO ₂ emissions Requires relatively low gas prices
Biomass (e.g. waste wood)	Process use similar to coke Carbon-neutral (if biomass is sustainably-harvested)	Delivered biomass relatively expensive Limited supply as biomass needed for other low-carbon uses Quality control & impurities
Hydrogen	No CO ₂ emissions High purity Hydrogen electrolyzers can balance variable renewables	Needs CCUS on steam reforming to make low-CO ₂ hydrogen from natural gas/coal 'Renewable' hydrogen relatively expensive
Molten Oxide Electrolysis ^{xv}	No CO ₂ emissions Can use renewable electricity	Early-stage research Requires higher temperatures & CO ₂ -free electricity Electricity is expensive

For chemicals, bio-feedstocks can be used instead of naphtha, methane, ethane or natural gas liquids

(NGL). Bioplastics are estimated to grow from 2.11 Mt/year in 2018 to 2.62 Mt/year in 2023, compared to the 335 Mt/year petrochemicals market.

Their share is therefore less than 1%, but rising rapidly. Materials derived from algae, seaweed, corn starch, grasses and agricultural waste can replace packaging, fabrics, thermoplastic cutlery, kitchenware, inks, adhesives, tyres, 'bio-concrete' and be used in 3D printing.

Research is ongoing into various processes for producing chemicals directly from captured carbon dioxide, but this is typically complex and expensive. Hydrogen is usually required as a reactant with the stable CO₂ molecule. However, German chemical giant BASF has proposed a methanol production approach based on partial oxidation of natural gas, with recycling of waste carbon dioxide, and close to zero emissions, which it hopes to make commercial within ten years.

For aluminium, inert anodes (rather than carbon anodes, which are gradually consumed), would reduce CO₂ emissions by 40% and eliminate PFC emissions. However, this faces various technical challenges. Inert anodes would also allow the use of multipolar cells which have 40% lower energy consumption.

Developing alternative processes is complex as existing methods have been fine-tuned over decades. New processes will require large research and capital commitments, and will still likely be uncompetitive until several iterations have been built and operated.

5. Employ carbon capture, use and storage (CCUS)

Some process emissions cannot be eliminated by alternative systems. Parts of industries produce concentrated streams of CO₂ that are ideal for capture, for instance methanol, ammonia, ethylene oxide, ethanol, direct reduced iron (DRI), gas-to-liquids, coal-to-liquids, steam reforming of natural

gas, refinery fluid catalytic cracker (FCC), and other syngas-based processes.

Today, five bio-CCS projects are operating worldwide, all ethanol plants, four in the US and one in Canada, totalling 2 million tonnes (Mt)/year of captured CO₂. BECCS can be applied to the paper and pulp industry, but likely with higher costs due to the small scale and complex operations.

The Emirates Steel plant in the UAE is the world's first large industrial CCUS project, capturing 0.8 Mt/year from a DRI plant for enhanced oil recovery. Otherwise, Norway has plans for a cement and a waste-to-energy plant to capture 0.8 Mt/year in total, Shell's Quest project captures 1.2 Mt/year from a heavy oil upgrader, and there are various pilots on refineries, steel and cement plants, and other industries. Some ammonia and methanol plants capture their own CO₂ for use in their process.

CCUS benefits from economies of scale. It may therefore make sense for industries to install carbon capture on both their process and fuel combustion emissions, but this would depend on the specific layout of each plant.

Industrial CCUS clusters have also been proposed, that would be able to aggregate emissions from



multiple sources into a single disposal point. For instance, in the UK, Merseyside (Liverpool area), Teesside (north-east England), Humberside and Grangemouth (Scotland) are candidates for such clusters. All these zones have depleted oil and gas fields nearby offshore.

Rotterdam, which provides 20% of the Netherlands' CO₂ emissions, also has a plan to become a CCUS hub, based on oil refining, petrochemicals and power generation, with storage in the nearby southern North Sea depleted gas-fields.

The balance between electricity, hydrogen or CCUS for process heat depends on electricity prices. McKinsey found that, for electricity prices above 5 US\$/kWh, CCUS would be preferred. For a range of prices from 1.5-5 US\$/kWh, electrical or hydrogen heating would become economic in different industries.

Such low prices are achievable in areas with stranded hydroelectric power. Otherwise, they would likely require integration of large amounts of low-cost solar and wind with some other dispatchable low-carbon generation or energy storage.

Finally, some part of industrial emissions is likely to prove very hard to decarbonise. This will include greenhouse gases from small or remote sites, or fugitive leaks from processes. This can be dealt with by negative-carbon offsets, including direct air capture (DAC) of CO₂, bioenergy with CCS (BECCS), or carbon capture via tree-planting, depleted soil renewal or other biological methods.

BECCS has a wide range of cost estimates, but those for industry are likely in the \$20-76/tonne CO₂ range. For DAC, estimates from Carbon Engineering suggest their process would cost \$94-232/tonne, while Swiss-based Climeworks has a target of \$200/tonne.

Co-fuelling an industrial plant with a high level of CCS with a small amount of biomaterial (biogas, biomass) would make it carbon-negative.

INDUSTRY INTERACTS WITH OTHER SECTORS

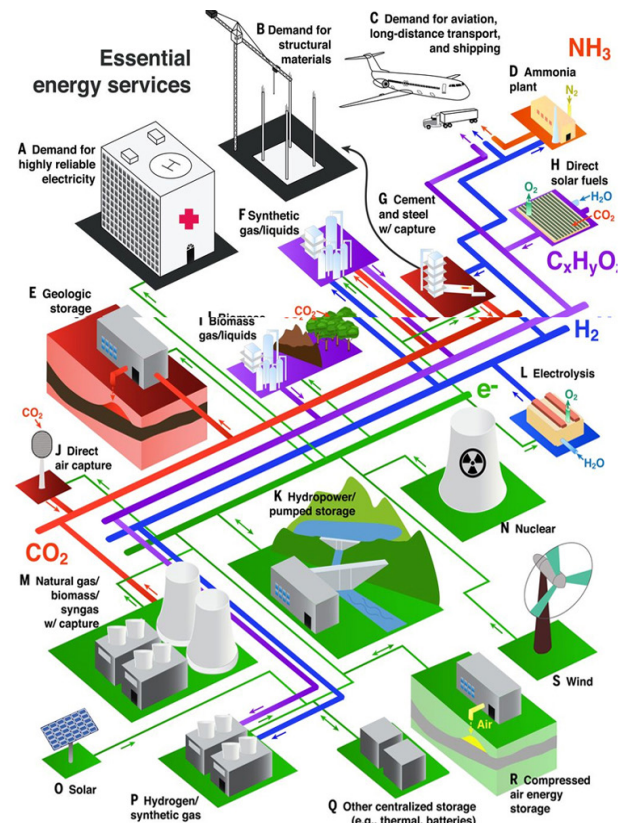
For some industries, CCUS results in only a minor increase in product cost (TABLE 2). This is already close to the range of current US CCUS credits or EU ETS prices. Aluminium, steel and cement would see much greater price increases, likely to the point of being uncompetitive on the world market unless compensated. The higher end of the steel and cement costs suggest that offsets via BECCS or DAC could be more attractive, though CCUS costs will come down with experience. Also, if high carbon prices become a reality, other methods such as improved efficiency and processes will be introduced to lower the per-tonne CO₂ footprint, and hence the final CCUS cost.

Product	CCUS cost, first-of-a-kind, \$/tonne CO ₂	Price increase with CCUS
Ethanol ^{xxx}	21-27	4.4%
Fertiliser	23-33	4%
Aluminium ^{m^{xxxi}}	55	10.5% ^{xxxii}
Steel	67-119	30-41%
Cement	104-194	68%

Industrial decarbonisation is not only confined within the sector itself. The potential for CCUS clusters has already been mentioned, combined with emitters in the power sector. Industrial waste heat can also be used for district heating/cooling and desalination.

Industry typically has a steady baseload electricity demand. With some changes to operations, it can provide an increasing amount of 'demand response', helping to stabilise grids and integrate growing quantities of variable renewable energy.

This leads to proposals such as that in, an integrated system which moves electricity, hydrogen and CO₂ between power plants, industries, energy storage systems and CO₂ use/capture sites.



**INDUSTRIAL EMISSIONS REDUCTIONS
WILL BE DRIVEN BY GOVERNMENT
POLICY AND CONSUMER PREFERENCE**

As the power sector makes progress in decarbonisation, and electric vehicles advance, attention will turn to industry. The EU's Emissions Trading Scheme (ETS) has been running since 2005, and covers large industrial emitters as well as power plants. Emissions prices have generally been too low, though, to encourage large-scale CCUS or other industrial decarbonisation initiatives.

In 2019, EU carbon prices have risen to about €28 per tonne, and could rise to €65 per tonne in 2020. €30 per tonne is thought to be a level at which CCUS in some industries would begin to become viable. Meanwhile, the US's 45Q tax credit provides \$35 per tonne for captured CO₂, and California's low-carbon fuel standard offers credits of \$150-170/tonne for fuels produced with CCUS.

Consumers also will show a preference for low-carbon products. This is indicated by current moves to ban single-use plastics, and by various corporate commitments to move to 100%-recyclable products and 100% clean/renewable energy. In future, this may extend to reducing building carbon footprints, by sourcing lower-carbon steel, concrete and aluminium.

Because of the high cost and risk of new industrial processes, the problems of coordination between different industries, and the risk to competitiveness, governments will generally be required to organise and fund demonstrations of new low-carbon techniques. This is similar to the early-stage funding provided to solar, wind, CCUS and advanced nuclear power. Industry consortia can be organised to deploy such funding. For CCUS in particular, the involvement of power utilities and oil and gas firms (for storage) will also be important.

Countries with strict carbon caps or high carbon prices will seek to protect their domestic industry from competition from high-emitting foreign firms. This could be done by 'border carbon adjustments' (BCAs), which tax imports based on the CO₂ produced in their manufacture, if the supplying country does not adequately do so. Or, products produced with emissions above some baseline could simply be banned, although this would risk dumping them on countries without such policies.

BCAs could be compatible with World Trade Organisation environmental rules, but raise several complex questions about application. However, if a large market such as the EU were to start applying BCAs, exporters such as China would have an incentive to set their own domestic carbon tax at a comparable level, to collect the tax at home.



CONCLUSIONS

MAJOR ENERGY EXPORTERS WILL FACE INDUSTRIAL EMISSIONS PRESSURES

Most major oil and gas exporters, including the Gulf Cooperation Council (GCC) countries, Iran, Russia and the US, have invested heavily in recent years in energy-intensive industries, including oil refining, petrochemicals, cement, steel and aluminium.

These industries could come under increasing pressure from their customers, if their carbon footprints are above best-in-class levels. To avoid this, they need to consider the full suite of emissions reductions options described above.

In particular, sunny countries, including the Middle East, have the option of increasing their use of solar power, and potentially renewably-derived hydrogen, for decarbonising industry. Concentrated solar for process heat is a promising opportunity. Given likely advantages in electricity prices, electrolytic processes, for instance for iron-smelting, may be worth investigating. Aluminium is already a major sector, and some of its use of natural gas could be replaced with solar power.

These energy-intensive industries are often already concentrated in clusters, typically coastal, along with power and desalination plants. These would be ideal centres to develop CCUS, with CO₂ sent to nearby oil fields for enhanced oil recovery or permanent storage.

These industries need to lobby effectively for suitable policies to encourage new technologies, including CCUS, hydrogen, renewable energy supply and others, while enabling them to remain economically viable. To this end, non-OECD industries should consider collaborating with their European, Japanese, American and other peers on suitable government and civil society engagement.

They also need to remain at the technological frontier, to ensure their carbon footprints are not significantly higher than best-in-class operators.

Decarbonisation of industry will put further pressure on oil and coal demand. In the medium term, it should boost gas demand as an easy way to lower emissions. In the longer term, gas too will come under pressure, requiring its price to remain competitive, and CCUS progressively to be implemented. Major gas exporters can benefit by working to develop and implement new, clean and efficient uses of gas for industry, such as DRI.

Reducing and eventually eliminating emissions from heavy industry is a complicated task. Industries have a wide range of plant vintages, locations and processes. They usually operate in internationally competitive markets.

A wide range of approaches will be involved in decarbonisation, from changes in material use and improved efficiency, to the use of low-carbon energy, CCUS and entirely new processes. Some of these will be expensive and technologically-risky and require government support.

Exporters of energy-intensive goods will face a growing challenge from moves to decarbonisation, particularly in the EU. They will need to campaign effectively for appropriate policies, while lowering their own greenhouse gas emissions. This can be done by eliminating energy subsidies; aligning carbon pricing with their main markets; electrifying industry where possible and using more renewable electricity; joining industry consortia developing novel processes; catalysing the appearance of CCUS clusters; developing robust certification for 'low-carbon' products; and developing DAC methods.



APPENDIX

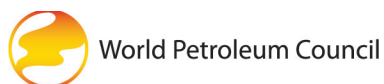
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