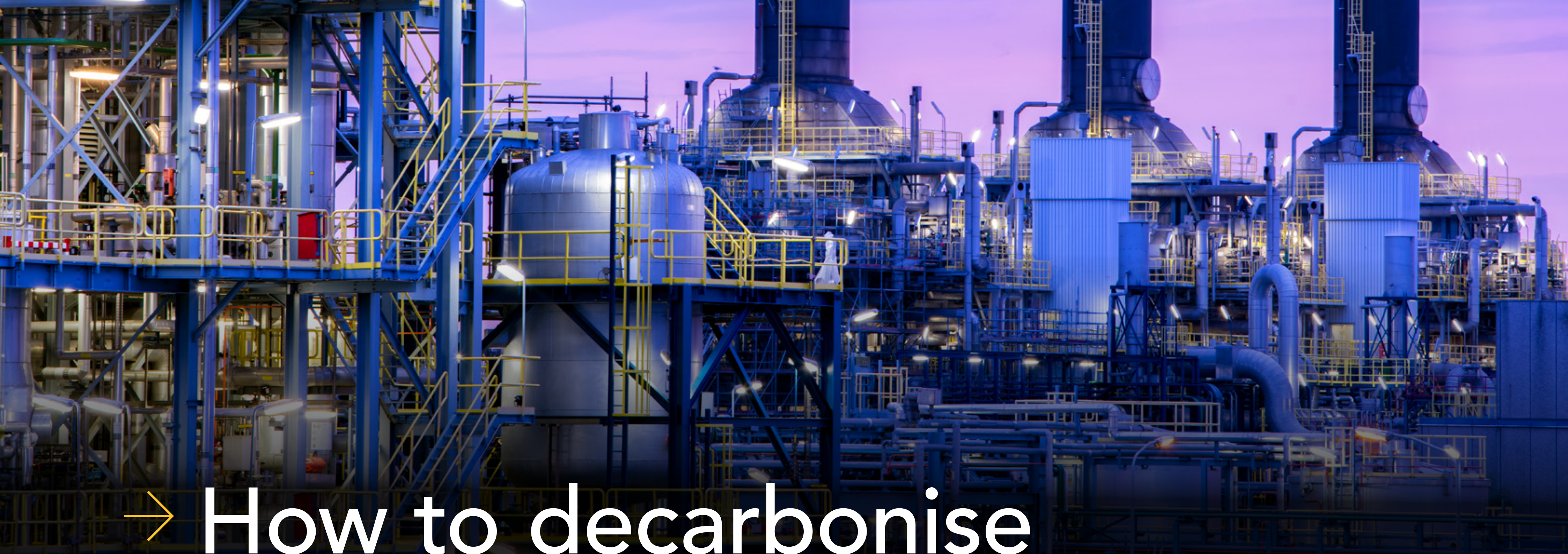


How to decarbonise European industry

Mark Allington, Richard Nayer, Tom Lock,
Renato Roldao, Jonathan Lonsdale, Yeen Chan,
Pawan Tiwari, and Laurent Petithuguenin, ICF

ICF CLIMATE center

Achieving the EU goal of net zero emissions by 2050 will not be possible without decarbonising industry

Executive summary

Decarbonising energy-intensive industries is an enduring challenge requiring complex trade-offs despite low-carbon technologies offering practicable alternatives for companies replacing ageing production assets. Currently, industry produces around 20% of European Union (EU) emissions. This means that achieving the EU goal of net zero emissions by 2050 will not be possible without decarbonising industry, which includes the production of metals and minerals, chemicals, food and drink, paper and pulp, ceramics, glass, oil refineries, and manufacturing.

As a result, industrial decarbonisation is attracting much more attention among decision-makers, as a realisable and necessary route to achieving mid-century net zero emissions goals.

Decarbonisation can occur in many ways including through energy efficiency and heat recovery, switching to less carbon-intensive fuels, and/or technology substitution. The feasible scope, cost, and penetration rate of decarbonisation options varies between and within industries. Those options are at different levels of technical and commercial maturity, as are their supply chains. Developments in adjacent sectors can open new opportunities. For example, the expansion of wind and solar power capacity has made low-carbon electrification of some processes a viable option. Meanwhile, lower-cost, large-scale electrolysers promise to transform surplus offshore wind and hydropower into "green hydrogen." Where carbon emissions cannot be abated, they can be captured, used, or stored.

The policy and market context matters. Many countries are introducing tougher emissions targets. Carbon prices are rising. Consumers want greener products. Some businesses and governments want to reduce reliance on imported fossil fuels, stabilise energy prices, and better manage supply disruptions. EU Emissions Trading System (ETS) auction revenues help, via the EU Innovation Fund, to accelerate some industrial decarbonisation technologies towards commercially viable, large-scale deployment. The EU's ambition to become a green industry leader is indeed possible.

This report explores how to achieve decarbonisation, taking a practical, evidence-based perspective founded in expert analysis of data, covering three areas: *technology, policy, and implementation.*

1. **Technology** is a key enabler for decarbonising industrial heat, with fuel switching (e.g., electrification and hydrogen) energy efficiency, material efficiency/enhanced recycling, feedstock decarbonisation, and carbon capture, utilisation, and storage (CCUS)—all offering *pathways* to decarbonise industrial processes. We analyse the benefits, dependencies and risks involved on each of these pathways, then examine the *main methods* used to decarbonise industrial processes in various sectors, covering what works best in each specific context and why; challenges and how they are overcome; and what future technology enhancements might yield significant contributions to industrial decarbonisation by 2050.

The EU's ambition to become a green industry leader is indeed possible.

2. **Policy** is also essential to providing a supportive environment to attract investment and thereby deploy industrial decarbonisation technologies. European policymakers are seeking to achieve a target by 2050 where industries keep emissions low (through carbon pricing and product standards); continue to operate within Europe (by using trade policies and climate diplomacy to address imbalances with other countries' climate policies); and provide an appropriate enabling environment for decarbonisation (through skills development and supporting innovation).

   We consider two specific **policy areas** that affect progress on investment: *using energy performance thresholds* to encourage procurement of lower carbon intensity industrial equipment and to progressively remove higher carbon intensity equipment from the market; *carbon markets and border taxes*, and how these influence industrial investment.

3. **Practical implementation** of decarbonisation solutions will ultimately result in lower industrial carbon emissions. This requires suitable financing methods that overcome investment barriers and, crucially, the right conditions to enable industrial company boards to make appropriate investment decisions. We analyse the effectiveness of different **financing** methods, building on operational experience. Then we look at how to **leverage** the investments made by industrial company boards, which is central to bringing about practical decarbonisation using available technology and finance options, within the policy context.

   Industrial decarbonisation is full of complex challenges and innovative solutions that are within reach. Those solutions, when deployed at a large scale, will contribute strongly to a net zero emissions future.

1. Technology

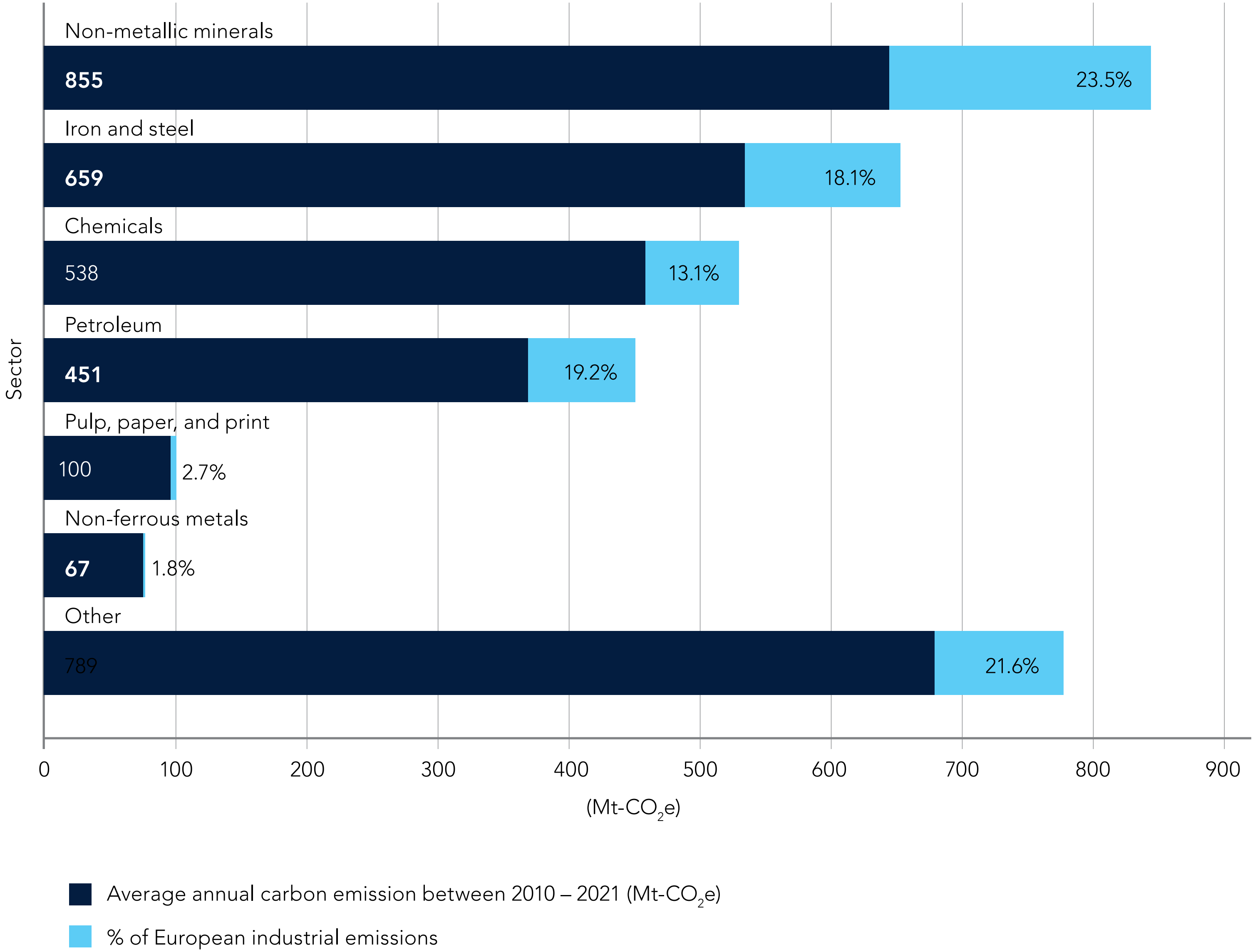
Globally, industrial processes account for approximately 24% of human GHG emissions, or around 14 billion tonnes CO_2e per year (as of 2019, IPCC AR6 Mitigation of Climate Change Summary for Policymakers). This increases to around 34% if emissions from heat and power generators are attributed to their industrial end users. Within the EU and UK, the following six sectors account (on average over 2010 – 2021) for >78% of total industrial greenhouse gas (GHG) annual emissions, and 96% of non-fuel combustion-related GHG annual emissions.

An overview of technology pathways to industrial decarbonisation

Firstly, we will focus on **pathways to industrial decarbonisation** at a macro level, before looking in detail at **technologies for industrial decarbonisation** on a sector-by-sector basis.

Industrial processes account worldwide for approximately **24%** of human greenhouse gas (GHG) emissions, or around **14 billion tonnes CO_2e** per year (as of 2019, IPCC AR6 Mitigation of Climate Change Summary for Policymakers). This increases to around **34%** if emissions from heat and power generators are attributed to their industrial end users.

Figure 1 - Hard-to-abate sectors and their contribution to EU industrial carbon emissions



Source: European Environment Agency

Figure 2 - Grouping of industrial sites by common decarbonisation challenges (BEIS, 2020)

A range of technologies are available for decarbonisation, with their relevance depending on the sector, as well as significant variations in efficacy, cost, technology maturity, and acceptability to site operators. The optimum technology also depends on the location of the industrial site, as this influences the availability of renewable energy sources, carbon sequestration sites, and supply/value chains that support a net zero transition.

The technologies most suited for decarbonisation are strongly influenced by whether production is within an **industrial cluster** or not. For example, in the U.K., industrial emissions are split fairly evenly between **industrial clusters** (such as steel production in South Wales and in Yorkshire) and dispersed sites (such as cement works). These face different **challenges** (see chart on the right). Clusters allow potential for large, integrated investments and nearby CCUS infrastructure, as well as green hydrogen where offshore wind is nearby. Dispersed sites need to transport CO_2 or hydrogen.

Segment	Sector	Profile	Challenges
Clustered sites	Non-iron and steel	Sector breakdown varies across clusters but refineries and chemicals dominate Mostly covered by emissions trading.	These sites present opportunities for early deployment of infrastructure. Challenge is to develop hydrogen & CCUS business models which can support deployment beyond first projects.
Dispersed sites	Dispersed Cement sites	Cement plants located far away from CO_2 storage sites. Covered by emissions trading.	CCUS is the main solution for addressing process emissions. Some sites are located in areas of natural beauty. The location of these cement sites poses cost, distributional and technical challenges.
	Less energy intensive	Sites outside clusters that are less energy intensive e.g. food and drink, equipment and vehicle manufacture. Mostly not covered by emissions trading.	Electricity costs are a barrier given the relative price of electricity vs natural gas. Future decarbonisation options likely to depend on the future of the gas grid.
	Energy intensive (excl. cement)	Sites outside of clusters that are energy intensive such as glass, lime and chemicals. Covered by emissions trading.	Often far away from clusters, so challenging to pipe carbon dioxide emissions to a T&S network or hydrogen in from clusters. Access to hydrogen could be through a dedicated hydrogen supply network or repurposing the gas grid.
	Iron and steel	Two sites make up 95% of emissions from iron and steel Covered by emissions trading.	Decarbonisation options include: (a) hydrogen direct reduced iron coupled with electric arc furnace or (b) CCUS. Scunthorpe would have access to CCUS infrastructure; however, Port Talbot would likely need shipping of carbon dioxide to utilise CCUS or hydrogen.

(Source: U.K. government policy paper: Industrial decarbonisation strategy)

Figure 3 - Overview of technology strategy for the next three decades

Key:

A CCUS operational in two clusters (mid-2020s)

B Four low carbon clusters (2030)

C Industrial emissions reduced by two thirds (2035)

C Share of low carbon fuels increases to around half of total industrial energy consumption (2035)

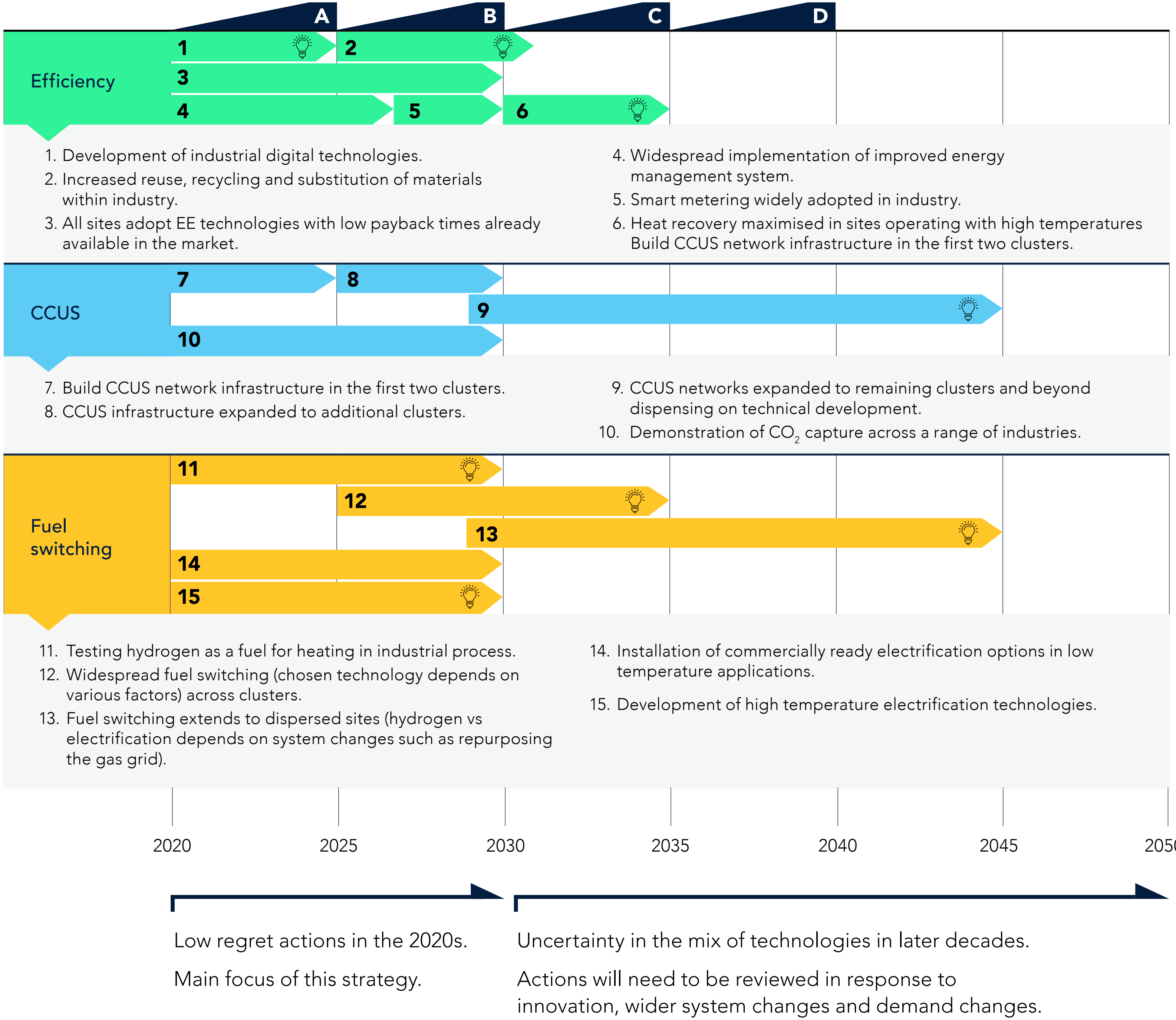
D First net zero cluster (2040)

Icon denotes milestones which require developments in innovation

There are several main approaches offering large potential contributions towards net zero, and industrial decarbonisation (IPCC Mitigation of Climate Change report, figure SPM.7):

1. Fuel switching
2. Energy efficiency
3. Material efficiency and enhanced recycling
4. Feedstock decarbonisation
5. Carbon capture, utilisation, and storage

These pathways are similarly recognised by the EU and by the U.K. in their respective industrial strategies, supported by a range of policy levers that encourage technology development.



We examine each of the technological routes in more detail below:

1. Fuel switching

Fuel switching is a key enabler for reducing emissions from industrial processes, with 7.1 $GtCO_2e$ emitted directly from combustion of fuels, and a further 1.7 $GtCO_2e$ from Scope 2 heat (IPCC Mitigation of Climate Change report, table 1.1). Opportunities exist to substitute current carbon-intensive fuels with low GHG sources for heat, including direct electrification, direct solar, hydrogen, and biomass.

Electrification of a substantial proportion of industrial heat demand can be achieved now using existing commercial technology. Currently, 60% of global electricity generation is from unabated fossil fuels. Electrification only remains an attractive decarbonisation option where the carbon intensity of grid power is low. There is significant public and private investment across Europe, Asia, and the U.S. to reduce grid carbon intensity, taking advantage of the decreasing costs of renewables and energy storage to displace fossil fuel sources.

There are a number of barriers to achieving electrification, however. These include the large gap between natural gas and electrical power prices, the rate at which electrical grids can accommodate increased applications for additional renewable generation, and network load increases.

Across the EU and U.K., action is being taken to reorganise power markets. The aim is to reduce the impact of marginal gas prices and modernise grid modelling and connection request processes. At the same time, renewable generation costs continue to fall. Larger businesses have also de-risked by directly purchasing renewable generation in bulk, such as Google's 100MW PPA for the Firth of Moray wind farm.

With regard to meeting heat demand with renewable power, the issue of intermittency of electrification is also being addressed through large scale Thermal Energy Storage (TES) systems. Several commercial players recently entered the market with innovative materials and phase change systems competing with traditional hot water storage. This has created the opportunity for higher temperature, longer-term heat storage, and the benefits of demand-side response (purchasing electricity when it is cleanest and cheapest).

At least 30% of industrial heat demand falls within the low-temperature range (<150°C) (Insights Series 2017 Renewable Energy for Industry), where electrification technology is mature and available commercially. In this temperature range, heat pumps are likely to dominate in the near future. Leveraging "efficiencies" greater than 200%, large (50MWth) heat pumps are being deployed across Europe already, including combinations of heat pumps with vapour compression to deliver steam at up to 150°C.

It is worth noting that a heat pump capable of 165°C steam output with a coefficient of performance (COP) of 2 was developed and demonstrated as early as 2011 (Experimental performance evaluation of heat pump-based steam supply system).

At the medium (150-400°C) and high-temperature range (>400°C), heat pump technology is not currently mature for use directly replacing combustion boilers. However, it can still be used as a first stage of heating (e.g., pre-heating hot air or boiler feed water) to reduce the overall primary energy use and emissions of a system. In high-pressure hot water and steam applications, direct electric boilers can be used. However, these are not likely cost-competitive with natural gas at present. For very high temperature applications within furnaces and dryers (1,000°C plus) certain technologies are available, which are discussed in detail in the next section. Hydrogen is competitive here.

Hydrogen is widely seen as necessary for high-temperature heating (and for use directly as part of feedstock decarbonisation). The challenges facing hydrogen remain decarbonising the supply itself, with 98% of existing hydrogen being utilised as an intermediate chemical, produced from steam reformation and gasification. The supply of hydrogen from electrolysis using renewables (green) and from CCUS retrofit on existing supplies (blue) has a challenging ramp-up to meet demand. Near-future demand in the U.K. alone is expected to be around 10 tWh in 2030 (in clusters), and as high as 86 tWh by 2050. It is worth noting that CCUS systems for blue hydrogen are likely only to be around 90%-95% efficient, so this pathway has a risk of locking in technology and stranded assets that are not compatible with longer-term net zero goals.

While significant financial incentives exist (e.g., the U.K.'s £240 million Net Zero Hydrogen Fund) to kickstart growth, it remains to be seen if the price of hydrogen can be driven down, especially where electrolysers are competing for renewable power. It is likely the first conversions to hydrogen will be steam boilers and combined heat and power processes on chemicals, refineries, and paper. In the longer term, hydrogen is likely to be used for low-carbon, high-temperature direct firing and as a direct feedstock (e.g., reduction of iron to make steel and in chemicals).

Bioenergy is an option, especially when combined with CCUS to give negative emissions. However, it relies on reliable supplies of sustainable biomass, which are limited in the U.K. There are also air quality issues that need managing, which are directly related to feedstock composition, quality, and moisture content. Dispersed cement sites are likely to see some uptake.

2. Energy efficiency

Historically, industrial energy efficiency has been seen as the "easy win" for decarbonisation, providing incremental improvements to the energy and carbon intensity of processes. Direct GHG emissions intensity reduced from 1970-2000 (IPCC Mitigation of Climate Change report); however, as developing economies drive for growth, this has led to short-term increases. This has primarily been driven by rapid production increases in China in the steel and cement sectors.

While this poses a challenge for rich countries, where further investment poses a carbon leakage risk, it also presents an opportunity for technology providers to pivot towards developing economies where production will continue to ramp up in the coming decades. Within Europe, the opportunity for energy efficiency improvements remains large, and significant funding mechanisms are available to mitigate carbon-flight risks.

It remains to be seen if the price of hydrogen can be driven down

3. Material efficiency and recycling improvements

Primary material extraction and processing have a higher energy and carbon intensity than recycling. Material efficiency and recycling improvements are likely to play a growing role in industry, especially as more countries require mandatory compliance reporting of Scope 3 emissions from feedstocks and product use.

We already see several sector associations and research institutes including resource efficiency as a key pillar within decarbonisation pathways, including for aluminium, cement, and steel. There is a need for new supply chains and value chains to enable circularity, and for industry to forge a path before being pushed by policymakers. We are already seeing the EU including circularity and material efficiency provisions in updates to energy-related products regulations (Ecodesign for sustainable products).

Projects to improve shredding systems and sorting efficiencies have the potential for a significant impact on circularity and energy efficiency. Sites can reduce the amount of primary material required to achieve product quality requirements, while also reducing the transport emissions of material that is often shipped between countries where more efficient sorting equipment is already in place.

4. Feedstock decarbonisation

Several industrial sectors have significant process emissions and Scope 3 emissions, due to their respective feedstocks (this links directly with materials efficiency, where recycled feedstocks generally have a much lower carbon intensity).

Currently, within the chemicals industry, a significant proportion of the feedstock is from fossil sources. Several options are available to reduce this dependency, such as the use of green hydrogen as a building block for ethylene, ammonia, and methanol.

Similarly, feedstock switching can reduce direct process emissions in hard-to-abate sectors such as cement (reducing limestone content, and consequentially carbon emissions, from the limestone decomposition) or steel (switching from coke to green hydrogen as an iron reducing agent).

5. Carbon capture, utilisation, and storage

CCUS currently has the potential to effect significant emissions cuts in several industries. It is likely to play an essential role in decarbonising sectors where process emissions cannot be eliminated by other means, such as cement.

There is significant interest and investment in technology being made by governments and industrial partners across Europe and Asia. Pilot projects are currently being constructed, for example at Norway's Norcem Brevik cement plant. However, technical maturity differs from sector to sector.

The key challenge for CCUS is the proximity of industrial plants to suitable carbon use or sequestration sites. Within some clusters, captured carbon could be utilised as a feedstock, or in remote sites mineralised for sale. However, the value chains for carbon are yet to be established. It remains to be seen if market economics will incentivise long-distance carbon chains, or the relocation of industrial sites to suitable sequestration sites—which poses a competitiveness risk to industrial sites within mainland Europe.

It is likely to play an essential role in decarbonising sectors where process emissions cannot be eliminated by other means, such as cement.

Technologies for industrial decarbonisation

The previous section outlined five pathways, noting that the appropriate path will be highly dependent on the sector, process, and geographical location. Here, we will review some of the technology options available within these pathways for the six sectors mentioned in the previous section.

Non-metallic minerals

Non-metallic minerals, such as cement, lime, ceramics, and glass, represent the most carbon-intensive industry in the EU. They are also critical resources in the global economy, with uses in multiple sectors. Demand is expected to continue increasing as buildings and infrastructure construction accelerate globally and as current low-income economies develop further.

Cement and lime

Most emissions from non-metallic materials are from cement and lime production. These are widely regarded as hard-to-decarbonise sectors, due to emissions being generated directly from the process itself during limestone calcination, and the temperatures required.

Decarbonising process emissions

Materials efficiency will play a key role in reducing primary cement demand and the associated Scope 1, 2 and 3 emissions of cement/concrete manufacture. This is possible through the recycling of concrete from construction waste (e.g., demolition of old buildings) to produce new building materials, such as recycled aggregate concrete (RAC) or recovery back to cement paste. The technologies are already available to enable materials efficiency.

However, value chains need to be created to incentivise investment upstream (crushing, milling, and sorting waste concrete into a valuable feedstock) and downstream (production processes for building materials from recycled products).

Another existing technology, which can be used to decarbonise up to 90% of process emissions (and kiln fuel use emissions for direct fired calciners), is CCUS. This features a high technology readiness level (TRL), with several projects globally either in construction or planning. The challenge related to CCUS is the utilisation and storage aspect, where currently the value chain for captured CO_2 for reuse or storage is immature. The most efficient and cost-effective routes are limited to facilities close to areas with facilities and geology available for sequestration. These are currently focused around coastlines and existing refinery infrastructure. If carbon prices increase, there may be a scenario in which cement production relocates towards industrial clusters and CCUS zones.

There are multiple CCUS technologies available, with post-combustion being the most developed for cement, as oxy-fuel requires changes to the burners and calcination process. Meanwhile, direct separation (where limestone is indirectly heated so the CO_2 liberated is inherently separated from combustion gases) requires the entire calciner to be replaced, and is only demonstrated at pilot scale. However, several larger facilities are under construction.

In the longer term, investigations into feedstock decarbonisation are likely to play a larger role than CCUS. The use of alternative feedstocks to limestone in cement (such as calcined clay and other materials) and, more broadly, alternatives to clinker in concrete production can prevent the carbon releases at source.

Materials efficiency will play a key role in reducing primary cement demand and the associated Scope 1, 2 and 3 emissions of cement/concrete manufacture. This is possible through the recycling of concrete from construction waste (e.g., demolition of old buildings) to produce new building materials.

Originally developed by NASA to measure the maturity of space exploration technology, the Technology Readiness Level (TRL) approach has been adopted by a variety of industries to assess the readiness of technologies for use on site.

Source: Guidance on Technology Readiness Levels - GOV.UK (www.gov.uk)

Decarbonising fuel use

Most fuel use is within the limestone kiln during clinker production (often referred to as calciner), as well as during crushing/grinding of feedstocks, and milling of the clinker. Crushing, grinding, and milling are easily electrified, but the high temperatures within the kiln (~1,000°C) pose a key challenge.

Within the fuel switching pathway, there are options for biomass and waste fuels, hydrogen, and electrification. The use of biomass and waste fuels provides an opportunity to significantly reduce emissions now. However, biomass comes with a risk of societal impacts due to deforestation and biodiversity losses in the provision of biofuels at scale.

Hydrogen provides an opportunity to decarbonise without significant changes to process equipment beyond the burners and gas trains. However, the supply chains for both blue and green hydrogen are currently limited, and near-term opportunities will be limited to facilities located near proposed hydrogen facilities, or those willing to integrate energy supply and invest in renewables and green hydrogen generation on site. Alternatively, they will need to develop working relationships with generators directly.

Electrification of calcining has not yet been demonstrated at scale in the cement industry, and remains at a low TRL, with demonstrations to date only at smaller pilot levels (Electric Arc Calciner, Rotodynamic Heater)

Glass

Emissions from glass manufacturing are dominated by heating, where the temperatures required within furnaces are ~1,500°C, with the remainder a product of the chemical reaction of the raw materials.

Figure 4 - Cement and lime technology options for potential (%) emission reductions from current levels, and market entry timeline along TRLs

Pathway	Technology option	TRL	Max. emissions reductions[1]	Market entry
Fuel Switching	Alternative fuel use (biomass)	9	27% (by 2050)[6]	Present
	Calciner Electrification	5-6	50%	2024+
Material Efficiency and Enhanced Recycling	Recycling of Concrete	8	Up to 98%	Present
Feedstock Decarbonisation	Low-carbon cement 70% (e.g., Clinker replacement with Ground Granulated Blasé Furnace Slag, Recycled Aggregates)	8-9	Up to 70%	Present
	Alternative Supplementary Cementitious Materials (e.g. Limestone Calcined Clay, Alkali Activated Geopolymers)	9	40%	Present
Carbon Capture and Storage/ Utilisation	Indirect Kiln Firing/Direct Separation[2], (e.g., Leilac)	8	20%[2]	Present
	Amine Post Combustion Capture (e.g., Norcem Brevik CCS)	9	50%[3]	2024
	Calcium Looping (e.g., Cleanker)	6-8	90%	2024[3]
	General Carbon Sequestration and Reuse[4]	7-9	90%	Present[5]

> Within the EU, the Close the Glass Loop programme is already committed to achieving a 90% recycling target for glass packaging by 2030.

Process emissions can be significantly reduced through material efficiency and recycling measures, reducing the amount of primary glass produced; the technologies required are already available. However, value chains need to be created to incentivise investment in the upstream to improve efficiency, such as the sorting of glasses into correct types to ensure the quality of the cullet provided to recycling facilities. Within the EU, the Close the Glass Loop programme is already committed to achieving a 90% recycling target for glass packaging by 2030. However, further development is required for other types of higher specification glass (e.g., for windows or technical applications).

Fuel switching of furnaces will play a pivotal role in decarbonisation. Electric glass furnaces are currently available commercially, so can be implemented now. However, the decarbonisation potential depends on the carbon intensity of the grid power supply. Within industry, these types of furnaces have been demonstrated, but are not yet widespread. Development is required to improve electrode performance at higher temperatures, and to prove performance with wider compositions from recycled supplies.

Hydrogen provides an opportunity to decarbonise without significant changes to process equipment beyond the burners and gas trains. However, the supply chains for both blue and green hydrogen are currently limited, and near-term opportunities will be limited to facilities located near proposed hydrogen facilities; or those willing to integrate energy supply and invest in renewables and green hydrogen generation on site, or develop working relationships with generators directly.

Figure 5 - Glass decarbonisation technology options for potential (%) emission reductions from current levels, and market entry timeline along TRLs

Pathway	Technology option	TRL	Max. emissions reductions[1]	Energy savings[2]	Market entry
Fuel Switching	Furnace Electrification	6-7	Up to 75%	56%	2025
	Biomethane	10	Up to 75%	NA	Present
	Biomethane	6-7	Up to 90%	Up to 90%	2030
Energy Efficiency	Batch preheating	8	Up to 33%	7%	Present
Materials Efficiency and Enhanced Recycling	Glass recycling	9	Up to 41%	15%	Present
	Glass re-use	9	Up to 90%	15%	Present
Carbon Capture and Storage/ Utilisation	CCS furnace	6-7	Up to 75%	NA	2030+
	Oxy-fuel combustion	6-8	Up to 46%	20%	2025

CCUS will likely become commercially available and proven in the glass industry around 2030 which will be too late for current 2030 decarbonisation targets.

Ceramics

The emissions within ceramics manufacture (e.g., tiles, bricks) are driven by fuel use to develop high temperatures for drying formed products (~26% of emissions) and then firing to strengthen the product and provide the desired porosity (~57% of emissions).

A key technology for decarbonisation of ceramics is improving energy efficiency. Across several sites, heat is being recovered from kilns via a heat exchanger and/or heat pump to provide heat to dryers, which in combination with heat storage can completely displace current gas consumption within the dryers.

The firing stage remains more of a technical challenge, with kiln temperatures ranging from 800°C to 1,800°C, depending on the product being manufactured. There are several energy efficiency options that can be currently implemented, such as control improvements, waste heat recovery, and insulation improvements.

To meet net zero targets, fuel switching or CCUS are likely to be the key competing technologies. Fuel switching technologies are available now and have been demonstrated within industrial settings. Electrification would allow industry to decarbonise immediately, without waiting for hydrogen markets and supplies to develop, and has been demonstrated at production scale (Wienerberger launches first CO_2-neutral brick production line). An alternative is biomethane; however, on a systems level, it comes with societal impact risks, due to deforestation and biodiversity losses in the provision of biofuels at scale.

There are some cases where CCUS is more applicable, such as where the reduction of kiln materials requires combustion in the kiln. However, these cases are limited, and the cost of implementing the technology on a small scale may not be competitive with alternative brickwork/tile colouring methods. Mineralisation of the produced CO_2 may offer an opportunity to improve the economics of the process. However, the maturity of CO_2 mineralisation technology and the associated value chains is low.

The emissions within ceramics manufacture are driven by fuel use to develop high temperatures for drying formed products and then firing to strengthen the products.

Figure 6 - Ceramics decarbonisation technology options for potential (%) emission reductions from current levels, and market entry timeline along TRLs

Pathway	Technology option	TRL	Max. emissions reductions	Market entry
Fuel Switching	Electrification	6-7	Up to 75	2035[7]
	Biomethane	10	100%	Present
Energy Efficiency	Heat Recovery with Heat Pump	9	20%	Present
Carbon Capture and Storage/Utilisation	CCS (Exhaust Gases)	5-8	Up to 79%	2035[7]

Iron and steel

Like cement, iron and steel is seen as another hard-to-decarbonise sector. This is due to the high temperatures involved, and the release of CO_2 as a by-product of the steel manufacturing process.

Concentrating on steel production, the challenge lies in decarbonising the fuel used to generate high temperatures for furnaces from crude steel through to finished products, as well as process emissions from crude steelmaking.

Decarbonising process emissions

Materials efficiency will play a key role in reducing primary steel demand and the associated Scope 1, 2, and 3 emissions of steelmaking. The recovery of scrap for treatment to crude steel through an electric arc furnace (EAF) can eliminate all process-related emissions from conventional blast furnace (BF) and basic oxygen steelmaking (BOS). The technology to achieve this is available and proven at large scale in industry (TRL 9). The EU and U.K. region is a net exporter of scrap steel, but a significant portion of steel demand could be met through recycling alone, especially with economic incentives.

The efficiency of steel recycling can be further enhanced through the improvement of the scrap quality being fed to EAFs. This could be achieved through improvements upstream within value chains to improve sorting of materials at source, as well as the installation of improved shredders and sorting technology to reduce the feed of impurities into the EAF.

The EAF itself can implement further energy efficiency improvements such as the installation of oxy-fuel burners and pre-heating of scrap prior to introduction into the furnace.

There are technology options to decarbonise steel production from virgin materials, such as the use of hydrogen as a reducing agent to displace coke, or direct electrolysis of iron ore.

Direct reduction of iron ore (DRI). If additional primary steel is needed, because secondary (recycled) steel cannot satisfy demand, DRI is a low-carbon option. With hydrogen from renewable energy and the EAF, it offers a steel production process potentially close to carbon-free, if the hydrogen is produced from renewable energy. Natural gas-based DRI is currently TRL 9 with global production. Hydrogen DRI has been demonstrated at pilot scale, and projects are currently being constructed to scale this up to commercial production scales. One example is the H_2 Green Steel project, due to come online in 2025.

Iron ore can also directly be reduced to iron using the electrolysis process. This concept is being developed under the Siderwin-project funded by the European H2020 programme. Alkaline electrolysis is used to produce direct reduced iron from iron ore using electrical energy. This replaces conventional blast furnaces and fossil fuels in steel production.

Carbon capture and use has the potential to make significant cuts in carbon emissions from blast furnace-basic oxygen furnace (BF-BOF) steelmaking; however, the technologies are unlikely to be available at scale in the near term.

The quantity of CO_2 generated may pose a challenge in attracting sufficient users, while also ensuring that the end uses capture the gas, as opposed to simply transferring responsibility for direct emissions to a secondary party.

This is the case with the production of ethanol from BF gas, which has been demonstrated at scale; if the ethanol is used as a fuel, the GHG emissions continue to occur. The Carbon2Chem project aims to use the gases from steelmaking as a raw material for chemicals production, but the technology is likely to reach industrial scale in the 2030s.

Carbon capture and storage also has the potential to make significant cuts in carbon emissions from BF-BOF steelmaking. However, this is highly dependent on the location of the manufacturer and adjacency to viable sequestration/storage sites.

Energy efficiency improvements can still play a key part in reducing emissions from conventional BF-BOF sites through process improvements that are mature and readily available. However, care must be taken in such investments that these facilities do not become stranded assets, replaced by lower carbon options (e.g., EAF, H_2-DRI) and with increasing production costs as carbon prices increase. These include coke dry quenching, heat recovery, and pulverised coke injection.

Decarbonising fuel-related emissions

The BF and BOF processes do not require a significant amount of fuel, as the reactions are autogenous, releasing the heat required to maintain the reaction. Most of the fuel use is therefore within pre-treatment of metal prior to heating, and the reheat and finishing processes. The higher temperatures required, especially within re-heat furnaces, often lead to use of oxy-fuel burners (where air is replaced by industrial-grade oxygen as the source of oxidiser for combustion). This brings benefits of uniform temperature, very low NOx emissions, and higher efficiency when compared to air fuel combustion.

Within the fuel switching pathway, there are options for biomass and waste fuels, hydrogen, and electrification. The use of biomass and waste fuels provides an opportunity to significantly reduce emissions now. However, biomass comes with societal impact risks, due to deforestation and biodiversity losses in the provision of biofuels at scale.

Electrification of larger reheat and processing furnaces is available now. While widespread adoption in industry has not yet occurred, the technology has been demonstrated at scale, such as in walking beam and roller hearth furnaces up to 1,300ºC (Clean and simple: How electric heating has transformed Ovako's heat treatment furnaces).

Hydrogen provides an opportunity to decarbonise without significant changes to process equipment beyond the burners and gas trains, and has been demonstrated at production scale (First in the world to heat steel using hydrogen). However, the supply chains for both blue and green hydrogen are currently limited, and near-term opportunities will be limited to sites located near proposed hydrogen facilities; or those willing to integrate energy supply and invest in renewables and green hydrogen generation on site, or develop working relationships with generators directly.

Chemicals

For the foreseeable future, the chemicals industry will always employ carbon in some form, given that the organic compounds being manufactured contain it. The challenges for the chemicals sector are reducing the energy consumed during manufacturing and reducing Scope 3 emissions of feedstocks and the end of life for products.

Material efficiency measures are a key part of the decarbonisation of chemicals. Controlling the end-of-life fate of chemical products directly impacts the CO_2 released, especially in the EU where recent drives to reduce landfill waste have increased the quantity

Controlling the end-of-life fate of chemical products directly impacts the CO_2 released.

of incinerated waste, where the CO_2 embedded in products is directly liberated. Recycling these products can significantly close the carbon cycle for chemicals and related GHG emissions.

Fuel switching can play a key part in reducing energy consumption on chemicals sites through the use of electrification or green combustibles to displace fossil fuels used for process heating. There are a range of technologies available, depending on the process temperature. Direct electrifications and heat pumps are the most effective at lower temperatures, and hydrogen or biomass boilers are applicable at elevated temperatures such as high temperature steam.

Energy efficiency also provides scope for rapid progress. Straightforward easy wins are achievable now, such as heat recovery and insulation projects. Process improvements can also be carried out to reduce energy requirements, such as improved catalytic cracking of naphtha or selective membrane filtering systems during ethylene production.

The decarbonisation of feedstocks to avoid further fossil fuel extraction will play a key part in the medium term for the chemicals sector. There are technology options available now to achieve this, such as the provision of green hydrogen from electrolysis powered by renewables, blue hydrogen (from existing steam methane reformation or partial oxidation of hydrogen with CSS), or the conversion of methanol (which can be used as a hydrogen carrier) to ethylene. Developing value chains for green hydrogen is key, especially in ammonia production; in this case, hydrogen is a key feedstock within the Haber-Bosch process and is currently usually produced from steam methane reformation, without CCUS (or so-called grey hydrogen).

For ethylene, against reference technology of naphtha steam cracking:

Figure 7 - Ethylene decarbonisation technology options for potential (%) emission reductions from current levels, and market entry timeline along TRLs

Pathway	Technology option	TRL	Max. emissions reductions[3]	Market entry
Energy Efficiency	Catalytic cracking of naphtha	8	Up to 20%	Present
	Selective membrane for organic filtering systems	6-7	Up to 10%	2025-2030
Material Efficiency and Enhanced Recycling	Low mechanical quality plastics replacements	6 - 9	Up to 11%	Present
	Plastics recycling	9	Up to 11%	Present
Feedstock Decarbonisation	Methanol to ethylene production	8 - 9	Up to 47%	Present
	H_2O and CO_2 conversion to ethylene	3 - 4	Up to 216%4	2030+
Carbon Capture and Storage/Utilisation	Carbon capture and storage furnace	5 - 8	Up to 90%	2030+

For ammonia, against reference technology of methane steam reformation:

Figure 8 - Ammonia decarbonisation technology options for potential (%) emission reductions from current levels, and market entry timeline along TRLs

Pathway	Technology option	TRL	Max. emissions reductions[5]	Market entry
Feedstock Decarbonisation	H_2 production through Solid Electrolyte membrane electrolysis	6 - 7	Up to 75%	2025
	H_2 production through Proton Electrolyte Membrane electrolysis	7 - 8	Up to 75%	Present
	H_2 production through Alkaline electrolysis	7 - 9	Up to 75%	Present
Carbon Capture and Storage/Utilisation	Carbon capture and storage furnace	6 - 7	Up to 97%	2030+

Petroleum

The refinery and petroleum sector will remain key to the global economy in the medium to long term. Though the objective is to transition primarily to clean energy on the road to net zero, the world will remain reliant on refinery and petroleum products for decades during their phaseout.

The primary mechanism for reducing emissions from petroleum is to reduce consumption within the supply chain, such as fuel switching of energy supply (e.g., from fossil fuel to electrification or hydrogen), energy efficiency, material efficiency, and (where hydrogen can be used as a feedstock instead of fossil fuel) feedstock decarbonisation.

Within the boundaries of the refinery, there are several technological pathways to reducing carbon emissions. Energy efficiency and fuel switching can primarily be used, such as waste heat recovery schemes to reduce fuel consumption, and the electrification of heating duties where appropriate. Given the high temperature of the fluids exiting the plant, heat pumps could play a key role in pre-heating pressurised hot water.

There are several existing carbon capture technologies that can be applied within the sector, such as post-combustion and oxy-fuel switching. However, the TRL diminishes in petroleum applications where there are multiple sources of CO_2 at a single refinery, leading to variable CO_2 rates and qualities being fed to the capture technologies.

The world will remain reliant on refinery and petroleum products for decades during their phaseout.

Given refineries' existing infrastructure and transport links to sequestration sites (which are often in geologies formerly containing fossil fuel deposits), CO_2 storage opportunities are generally not the limiting factor.

The production of biocrude—through switching feedstock from fossil deposits to biomass—releases up to 85% less carbon than petroleum. However, this approach has an energy-use penalty of approximately 10% due to the processing requirements of biomass. Biocrude is more appropriate for the production of the remaining crude requirement following fuel/feedstock switching in sectors currently using petroleum. This is because replacing the current refinery output with biocrude would require huge amounts of biomass, likely leading to significant biodiversity and broader sustainability harms.

For petroleum, against reference technology of a gas-heated column:

Figure 9 - Petroleum decarbonisation technology options for potential (%) emission reductions from current levels, and market entry timeline along TRLs

Pathway	Technology option	TRL	Max. emissions reductions[6]	Market entry
Fuel Switching	Electric vehicles	10	Up to 50%	Present
	Biofuels	9 - 10	Up to 50%	Present
Fuel Switching and Feedstock Decarbonisation	Blue fuel synthesis	5 – 7	Up to 100%	2025/2030
Energy Efficiency	Waste heat recovery	7	Up to 10%	Present
Feedstock Decarbonisation	Biocrude	6 - 8	Up to 85%	2025/2030
Carbon Capture and Storage/Utilisation	CCS: post-combustion	6 – 8	Up to 90%	2030+
	CCS: Oxy-fuel	6 – 8	Up to 96%	2025+

Pulp and paper

The production of pulp and the processing into paper web are the most energy- and emissions-intensive parts of the industry's manufacturing process.

In the production of mechanical pulp, wood is ground and refined to a fibrous pulp. A typical by-product is large quantities of waste heat. Chemical pulp is produced using chemicals (sulphite or sulphate) whereby the lignin content is separated from the wood fibres in a cooking process. The lignin (approximately 50% of the initial wood content) is then burned to produce the high steam quantities required for this process. A third process is the production of pulp from recycled paper.

Compared to other energy-intensive industries, the pulp and paper sector has three advantages regarding decarbonisation:

1. Direct access to biomass resources.
2. Solely energy-related, not process-related, emissions (the latter are much harder to reduce).
3. Flexible demand for steam in terms of the energy carrier used for its production (in contrast to furnaces in the high-temperature range, e.g., in the steel industry).

Materials efficiency can play a key part in reducing Scope 3 emissions within pulp and paper, reducing the number of trees used as feedstock; left in place, they play a role in carbon capture, as well as significant biodiversity benefits. Recycled fibres also have significantly lower specific energy needs compared to pulp from virgin fibres. Within the EU, upwards of 70% of paper is currently recycled; in other markets, significant further improvements can be made.

Fuel switching is achievable in the industry, with the temperatures required for pulp and paper manufacture easily within reach of currently available heat pump and vapour compression systems. These are being deployed to existing paper plants. Biomass can also play a role, where it is available as a waste from the upstream process, without introducing further deforestation risk. However, this could risk lock-in should recycled fibres begin to dominate, requiring the sourcing of biomass from outside the existing pulp supply chain.

Additional novel technologies to reduce emissions also exist at a range of TRL levels. These include black liquor gasification, new drying techniques, enzymatic pre-treatment, deep eutectic solvent pulping, and flash condensing. While black liquor gasification and novel drying techniques are available now, other novel technologies are unlikely to enter the market until the late 2020s and are unlikely to contribute to near-term reduction goals.

Compared to other energy-intensive industries, the pulp and paper sector has three advantages regarding decarbonisation.

Figure 10 - Pulp, paper, and print decarbonisation technology options for potential (%) emission reductions from current levels, and market entry timeline along TRLs

Pathway	Technology option	TRL	Max. emissions reductions	Market entry
Fuel Switching	Alternative fuel: natural gas	9	Up to 5%	Present
	Alternative fuel: electric boiler (e.g. AAL SEB project)	7	~5%	2023
Energy Efficiency	Vertical electrode cell[9]	7	100%	2030+
	Alumina Reduction: Carbo-thermic Reduction (Direct)	2-3	~-16.6-38.8%[10]	2050+
	Electrolysis: Wettable Cathodes (e.g., TiB2 composite cathode)	7	Up to 18%[19]	2024
	The Elysis process	7	Up to 55-72%	2024
Carbon Capture and Storage/ Utilisation	CCS	5-7	Up to 90%	Present

Non-ferrous metal

Key sectors within non-ferrous metals are copper and aluminium production, which are dominated by electrolysis of primary production.

Aluminium production is a CO_2 emitter during production, with over 90% of emissions due to fuel use during refining and smelting. With China currently representing more than 55% of aluminium production, this region will be key in carbon reduction in the near term. However, longer-term forecast growth in India and Africa will require low-carbon production technologies to be made highly cost-competitive to prevent the growth of future high-carbon intensity production.

Current emission routes from primary metals production are through the release of CO_2 from carbon anodes during the electrolysis process, emissions from electrical power consumed during electrolysis, and the provision of heat to maintain temperatures within the smelting process and downstream calciners and furnaces.

Within aluminium, there is an opportunity to reduce up to 56% of carbon emissions (Vision 2050 European Aluminium's Contribution to the EU's Mid-Century Low-Carbon Roadmap). Significant reductions can be achieved through material efficiency and recycling, and eliminating emissions due to primary material extraction, refining, and smelting. The rate of uptake and efficiency of this decarbonisation can be driven by investments in the collection, separation, shredding, and sorting of waste. This will maximise the quantity recovered, while reducing the amount of contamination in furnaces and the amount of primary material added to maintain the composition of the product.

Within primary metals production, electrical demand is a key driver of emissions, where the generation mix on the grid is outside the control of the user. Opportunities exist for primary aluminium producers to integrate their power supply chain, through PPAs and direct investments, and to increase use of virtual batteries to manage variability in renewable supply; a technology now entering commercial deployment within the industry.

Electricity demand can also be reduced in the near term through energy efficiency measures and process changes. This could be through utilising different anode types or installing magnetic compensation on supplies. Longer term, there are promising alternative electrolysis techniques, such as multipolar cells and ionic liquids. However, the TRL of these technologies is low at present.

Efficiency measures can be used to reduce carbon emissions from heating during production (both primary and secondary) today, using commercially available technology such as heat recovery and insulation. Recuperative burners can significantly reduce fuel demand in current installations using mature technology.

Fuel switching will play a key part in decarbonising heating duties. Technology is currently available to electrify both upstream calciners and product furnaces, as well as steam production through direct steam-producing electric boilers. However, uptake remains limited, primarily due to the costs of electrification vs. the business-as-usual option of natural gas fuel (or in some cases fuel oil, which in the short term can be switched to natural gas to provide a modest improvement in emissions). Heat pumps used at lower temperatures to pre-heat air and water supplies can reduce energy demand from electrification.

The key challenge in electrification will be ensuring renewable electricity or heat can be stored, especially given the damage that can occur following an uncontrolled loss of heating to a smelter or furnace containing molten metal. Technologies available for this include large-scale battery storage, thermal storage, and virtual batteries.

The alternative to electrification is hydrogen, which provides an opportunity to decarbonise without significant changes to process equipment beyond the burners and gas trains. As well, it can be used in a combined heat and power (CHP) function to deliver power as well as heat for steam on site. The economic balance compared to electrification needs to be achieved, as the costs of green and blue hydrogen are equally uncompetitive with natural gas at present. From an overall energy balance point of view, they also require more primary energy than direct electrification. Compensating for this is the ability to store and transmit hydrogen directly to reduce the impact of variable renewables availability, and to provide a low carbon fuel to regions with limited renewables potential.

Using biomass and waste fuels could provide an opportunity to significantly reduce emissions now. However, biomass comes with societal impact risks, due to deforestation and biodiversity losses in the provision of biofuels at scale.

Figure 11 - Aluminium decarbonisation technology options for potential (%) emission reductions from current levels, and market entry timeline along TRLs

Pathway	Technology option	TRL	Max. emissions reductions	Market entry
Fuel Switching	Alternative fuel: natural gas	9	Up to 5%	Present
	Alternative fuel: electric boiler (e.g., AAL SEB project)	7	~5%	2023
Energy Efficiency	Slotted anodes	8	0	Present
	Vertical electrode cell	7	100%	Present
	Alumina reduction: carbo-thermic reduction (direct)	2-3	~16.6-38.8%	2050+
	Electrolysis: wettable cathodes (e.g., TiB2 composite cathode)	7	Up to 18%	2024
	The Elysis process	7	Up to 55-72%	2024
Carbon Capture and Storage/ Utilisation	CCS	5-7	Up to 90%	Present

2. Policy

Policy initiatives, undertaken at the European, national, and local government level can facilitate a supportive environment to attract investment and thereby help to deploy industrial decarbonisation technologies. In this section, we consider two specific **policy areas** that affect progress on investment: using energy performance thresholds to encourage procurement of lower carbon intensity industrial equipment and to progressively remove higher carbon intensity equipment from the market; and carbon markets and border taxes, which can influence the location and scale of industrial investment.

Improving procurement using energy performance thresholds

Minimum environmental performance standards (MEPS) as a tool for removing inefficient industrial products from the market

The U.K./EU Ecodesign Directive and equivalent U.K. legislation removes the worst performing products from the market and establishes performance benchmarks by creating minimum environmental performance standards (MEPS). These MEPS require products to meet mandatory energy efficiency and environmental performance levels. The European Commission (EC) estimates that in 2021, Ecodesign, together with mandatory A-G Energy Labelling, delivered energy user savings exceeding €120 billion, with half of the EU's total final energy use consumed in products that are subject to this legislation.

Ecodesign considers a product's environmental impacts throughout its life cycle—from design, extraction of raw materials, manufacturing, distribution, and packaging, to use and end-of-life. Its integrated framework for assessing products sets standards so that adverse environmental impacts are removed at the design stage. Until recently, these environmental impacts have focused on the energy in-use phase of a product's life cycle. Recently however, the EC has introduced circular economy and material efficiency requirements to address end-of-life impacts.

As a framework directive, requirements on products are set through the introduction of implementing measures, covering specific product groups. Out of the 27 groups covered by Ecodesign to date, in the industrial setting, these measures have been focused on space heaters, refrigeration, process chillers, power transformers, pumps, lighting, electric motors, welding equipment, and industrial fans.

The EC plans to repeal the Ecodesign directive and replace it with an Ecodesign for Sustainable Products Regulation (ESPR). The focus is likely to target product groups such as textiles, paints, detergents, and furniture. It might also include products like iron, steel, and aluminium—but that would influence industries only involved in their production, as opposed to meaningfully reducing the environmental impacts from wider industry consumption.

The earliest the ESPR proposals could be adopted is mid-2023. However, with preparatory studies taking 18-24 months, the first measures arising from the ESPR will not come into force until 2026 at the earliest. Following preparatory studies, the EC prepares draft working documents, delivers a consultation forum, conducts an impact assessment and inter-service consultation, notifies the World Trade Organisation, holds a regulatory committee vote, facilitates European Parliament and Council scrutiny, then finally moves to adoption and publication.

As a result, product measures from Ecodesign are unlikely to resolve the complex challenges to come on industrial decarbonisation. The comparatively lower sales volumes, the long timescales for developing MEPS, and the challenges involved in categorising and standardising industrial products, mean other measures are likely to deliver more effective decarbonisation results.

MEPS require products to meet mandatory energy efficiency and environmental performance levels.

Endorsement labels and higher environmental performance standards (HEPS) as progressive benchmarks of highly efficient industrial products

At the opposite end of the performance spectrum, endorsement labels and higher environmental performance standards (HEPS) identify products that are among the most energy-efficient in their respective class. The U.K.'s energy technology list (ETL) aims to define product energy performance criteria that represent the top 25% in class. Products specifically targeted at industrial audiences include:

- Waste heat to electricity conversion equipment, such as organic Rankine cycle (ORC) heat recovery equipment and screw expanders
- Electric motors
- Boiler and boiler retrofit equipment, including steam boilers, burners, and retrofit burner control systems

Endorsement labels and HEPS schemes (e.g., EU Eco-label, Blue Angel, and Nordic Swan) can also target the reduction of environmental impacts across a product's life cycle, not just the in-use phase. This can include considering the extraction of critical raw materials and the addition of resource efficiency measures to achieve a circular economy (such as durability, repairability, and recyclability).

To be effective, endorsement labels and HEPS need to be widely communicated, raising sufficient awareness to attract both manufacturers and purchasers. Mutual recognition and use creates a self-enhancing value proposition for audiences and, ultimately, more sustainable product purchase decisions. Linking labels and HEPS to financial incentives (e.g., tax breaks, grants) and/or government buying standards (i.e., green public procurement) helps further enhance their value. For example, the U.K. government is leveraging its considerable buying power and seeking even closer ties between its government buying standards and the ETL requirements. Binding label or HEPS conformity with access to other third-party, private sector schemes and initiatives further enhances the adoption of progressive benchmarks. For example, certain product categories on the ETL align with the BREEAM environmental assessment method for sustainable buildings, meaning ETL accreditation acts as a gateway to achieving a higher BREEAM rating.

Endorsement labels and HEPS schemes can also target the reduction of environmental impacts across a product's life cycle, not just the in-use phase.

Figure 12 - MEPS vs HEPS

	MEPS	HEPS and endorsement labels
Focus	MEPS are designed to remove the poorest performing products from the market.	HEPS can set best practice benchmarks, leading the market, and be linked to green public procurement and financial incentives.
Adaptability	Innovative industrial products tend to be more bespoke, not easily fitted to standardised categories and definition for regulation.	HEPS can be flexible, nimble, and solution-focused, targeting specific niche areas where certain industries would benefit.
Speed	The regulatory development process can take five years from study, industry consultation, development, impact assessment, institutional consultation, and scrutiny to adoption.	HEPS can be delivered within a year and are considerably quicker to implement. Priorities can be set more easily and are cheaper to prepare.
Future challenges	Some industrial products already have MEPS, set at challenging levels e.g., electric motors. MEPS are poor tools for targeting, accessing, and delivering "system-level" savings.	HEPS are an important testbed for innovation. Combining their adaptability and focus with advice provision can deliver new solutions.

How procurers can benefit from using HEPS to improve process and building efficiency

Procurers can save time and resources and build confidence in their sustainable product purchase decisions, by using the pre-performed verification and market benchmarking inherent in endorsement labels and HEPS. These certifications can add credibility to new/emerging energy-saving technologies, providing impartial advice and independent verification of technology performance. This is often coupled with government-backed authority in the case of the ETL. By using endorsement labels and HEPS, procurers can future-proof their operations by purchasing high-performing and innovative technologies, rather than at the minimum levels associated with MEPS.

Procurers can leverage significant financial benefits from making sustainable product purchase decisions. Data from the U.K.'s industrial heat recovery scheme demonstrates that private sector companies can make significant purchases in energy-efficient equipment, such as heat recovery from exhaust gas at a cost of £650,000, which deliver a return on investment in a three-year window.

Procurers should consider how the performance of products will affect the performance of the system as a whole, particularly in industrial applications. By adopting a product-systems approach, procurers consider the interaction of numerous products and how they have been designed, installed, operated, and maintained to deliver further energy savings and reduce environmental impacts. System-wide savings are more appropriate and feasible for industrial customers; HEPS schemes are quicker and more flexible to this end. Procurers should consider system thinking especially for pumps, fans, and lighting, and the role of building energy-management systems (BEMS)—endorsement criteria for which are on the ETL—in optimising the energy efficiency of HVAC plants.

Within the EU, the EC has tried to address systems thinking within the Ecodesign framework. Notably, this has included studies on BEMS, lighting systems, and an extended product approach (EPA) proposal within a revised pumps regulation. However, the EPA concept was first proposed in 2018 and is yet to be realised—evidence of the slower implementation of solutions via MEPS. The role of equipment installers and commissioners is important to deliver system-level savings via product optimisation.

Embracing efficiency savings from smart technology and the circular economy

Endorsement label and HEPS schemes offer the chance to connect and integrate through smart meters, giving procurers solutions for performance benchmarking and purchasing more efficient equipment. Benefitting from integration with third-party software providers, and utilising application programme interfaces (API), smart meter operators can receive personalised product recommendations directly based off their own product's consumption, such as those offered by the ETL.

Smart technologies are those that have external communication capability and can:

- **Respond automatically to demand-side response signals by shifting or modulating their electricity consumption.**
- **Adapt and control operation to optimise energy consumption according to user needs or local conditions.**
- **Provide users operational information related to the product in a timely and useful manner, representing a significant opportunity for procurers.**

These functionalities and capabilities can be built in or enabled through a separate controller. Heat pumps, HVAC equipment, and refrigeration products now provide procurers with the greatest opportunity to implement these capabilities.

To fully decarbonise industry, procurers will need to rapidly move beyond consideration of the in-use phase of a product's full life cycle—to design and extraction of raw materials, through to end-of-life.

The EU is rapidly realigning the Ecodesign MEPS policy to be much more targeted at resource efficiency and the circular economy; it sees MEPS as a key delivery vehicle for change via the Circular Economy Action Plan. But these changes will take significant time and benefits from the ESPR might not be realised for at least five years. Endorsement labels and HEPS can use their strengths of focus, adaptability, and speed to fill the void and leverage near-term carbon savings and prepare industry for this more complex decision-making. Consideration should also be given to product environmental footprints, if available.

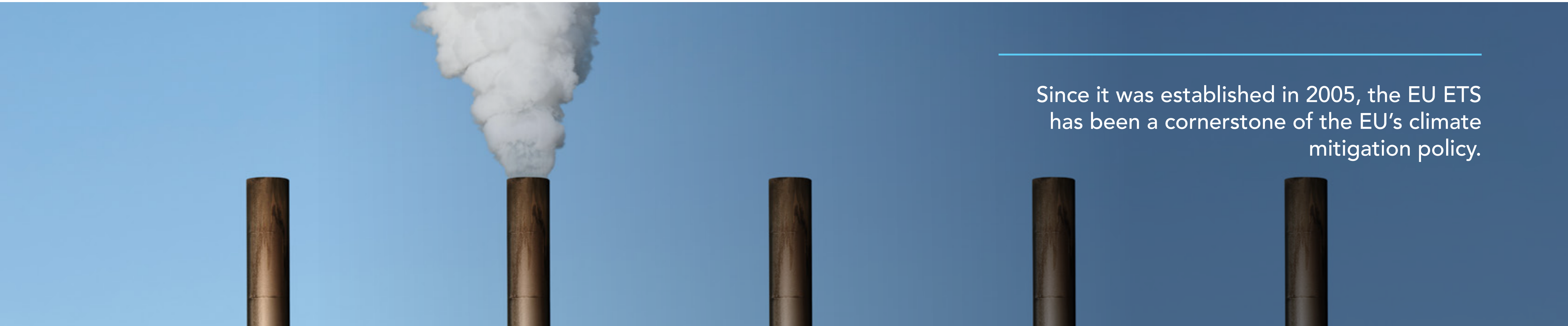
The use of digital twins can also accelerate the realisation of wider carbon savings for industrial users, saving carbon from the maintenance, repair, and disposal phases of a product's life cycle. Improved maintenance can leverage in-use savings and extend lifetimes.

Carbon markets and border taxes in compliance and regulated markets

Carbon pricing, emissions trading policies, and border taxes are powerful tools to mitigate GHG emissions. As such, they can help to accelerate the decarbonisation cycle of industry. One of the largest and most significant emissions trading schemes is the EU Emissions Trading System (EU ETS).

Since it was established in 2005, the EU ETS has been a cornerstone of the EU's climate mitigation policy. It has driven GHG emissions reductions in the power sector and most of the energy-intensive industries within the EU in a cost-effective way. Emissions trading is now helping to decouple GHG emissions from the EU's economic growth in the post-COVID-19 recovery cycle.

The EU's ETS policies are also being continually designed and improved. As a result, we are now seeing how the practical lessons learned so far are being incorporated into new systems being designed in the rest of the world. There is now a growing body of experience that can be applied to how and where ETSs can play a role in reducing the emissions of heavy industry and other energy-intensive industries.



Since it was established in 2005, the EU ETS has been a cornerstone of the EU's climate mitigation policy.

The success of the EU ETS in driving carbon prices up also sends an important message to the industrial sectors and participating companies. They understand that they should take decisive action to avoid or reduce the additional costs derived from their carbon footprint or as a result of the carbon content of their industrial processes and products. Being proactive in the market will then allow compliance entities to benefit from the upside of the market. This in turn enables them to either accelerate their clean energy transition and/or meet their own climate plans.

Carbon pricing and emissions trading also play an important role in enabling access to green finance in order to accelerate industrial decarbonization.

Carbon allowances are allocated free of charge in markets such as China. However, in the EU, they are allocated by auction. As a result, the auction revenues generated by the EU ETS are now financing innovative technologies and bring large- and small-scale projects to the market that would otherwise take much longer to emerge. In addition, with emissions allowances trading at a price several times higher than originally estimated, the auction revenue is now also considerably higher. This means that the capitalisation of funds such as the EU Innovation Fund (which ICF is supporting) is also much higher, which, in turn, increases the fund's ability to support the introduction of high-end technology into the market. Funds such as this allow companies to extend their technological frontiers, innovate, and increase their competitiveness in the international marketplace.

In the context of ongoing geopolitical and economic crises such as the Russia-Ukraine war, the EU ETS, and the Market Stability Reserve (MSR), which provides stability to the EU ETS by adjusting the supply of allowances to be auctioned, are playing a role in financing initiatives such as REPowerEU. This initiative aims to reduce energy dependency on Russia and, in turn, increase EU energy security; in December 2022, the European Parliament agreed that the Innovation Fund should provide up to 60% of the €20 billion in grants that will help to deliver the REPowerEU plan. In this way, the EU ETS itself is a part of the short-term financial solution to financing the longer-term energy transition away from gas.

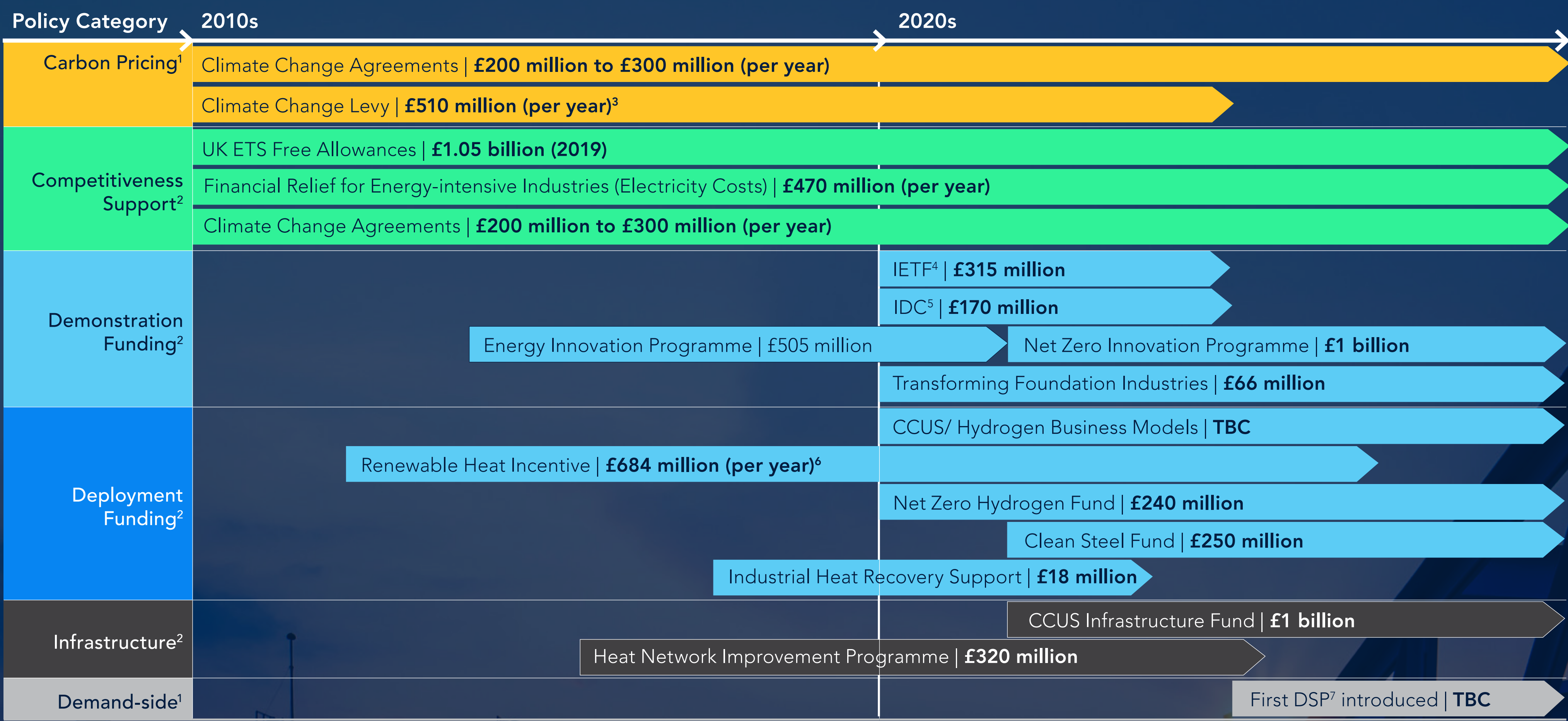
We cover the financial aspects of industrial decarbonisation in more detail in the **finance section of this report**.

Alongside EU ETS, the U.K. government is also making use of emissions trading. The U.K. used to be an integral part of the EU ETS, pre-Brexit, but it is now aiming to use this market-based mechanism to support the reduction of industrial emissions by **two-thirds** from the 1990 baseline **by 2035**. The U.K. government is also making interventions to address market failures that obstruct decarbonisation and to fairly share the cost between industry, consumers, and taxpayers.

The aim is to avoid carbon leakage (where industries relocate overseas to avoid carbon limits) and to support large-scale infrastructure development for CCUS and hydrogen, where there is a shared benefit. The U.K. is using carbon pricing, climate change agreements, demonstration funding (for near commercial technologies, such as hydrogen switching), deployment funding (for commercial technologies, such as heat recovery), infrastructure support funds, and skills development.

There is now a growing body of experience that can be applied to how and where ETSs can play a role in reducing the emissions.

Figure 13 - Industrial decarbonisation policy in the 2020s, with costs



Cost figures taken from most recent government publication or announcement unless stated otherwise.

1. Cost to industry
2. Cost to government
3. Estimated cost based on energy consumption. Total CCL cost is £2 billion per year across all sectors, including industry, agriculture, commercial and public services
4. IETF = Industrial Energy Transformation Fund
5. IDC = Industrial Decarbonisation Challenge
6. Annual costs were £684 million in 2019-2020, including commercial, industrial and public premises. £1.01 billion total budget for domestic/non-domestic schemes in 2019/2020.
7. DSP = Demand-side policy

(Source: U.K. government policy paper: Industrial decarbonisation strategy)

European policymakers are seeking a situation by 2050 where industries keep emissions low (through carbon pricing and product standards); stay within Europe (by using trade policies such as the forthcoming carbon border adjustment mechanism (CBAM) and climate diplomacy to address imbalances with other countries' climate policies); and provide an appropriate enabling environment (through skills development and supporting innovation).

A key part of achieving these policy goals will be through attracting investment into industrial decarbonisation. This can be done by:

a) A carbon pricing mechanism to motivate investors to seek low-carbon solutions

Carbon pricing sends a signal that motivates investors. This is true in jurisdictions both where carbon pricing already exists, and where there is none. International and national regulations now make installing carbon pricing schemes and seeking out low-carbon solutions a cost-effective way of creating a win-win situation—one where industries stay competitive while progressing on their own climate goals and benefitting the environment.

b) Funding mechanisms that overcome barriers to secure private sector investment

The EU is a regulated market, so the decision to set up the EU ETS, design it, and regulate it are primarily driven by the public sector. However, once up and running, it attracts large amounts of private sector investment, not the least in terms of the carbon market itself. In markets, such as China, the market is only open to compliance entities, but, in the EU, the market is also available to non-compliance entities, so banks, insurance companies, fund managers, etc., are also able to operate and bring in increased funding. This creates far greater liquidity in the market and reduces the mitigation costs.

c) Policy measures that mitigate the risk of 'carbon leakage'

If the EU's proposed carbon border adjustment mechanism (CBAM) (or similar) goes ahead, we may also soon see broader impacts on the decarbonisation of industries in regions beyond Europe's borders. CBAM creates a level playing field that is WTO-compatible by adding a carbon tariff at the border to products coming from countries outside the EU who do not have an ETS in place. This equalises the cost of carbon on the product, which otherwise would put European industries at a disadvantage.

Crucially, if something like CBAM is established, it then creates an incentive for other jurisdictions, that do not have a carbon price, to start delivering one internally, in order to avoid the EU border charge. This is just another way of avoiding carbon leakage and offers an alternative to the free allocation of allowances.

Carbon pricing sends a signal that motivates investors. This is true in jurisdictions both where carbon pricing already exists, and where there is none.

3. Practical implementation

Financing industrial decarbonisation

The scale of the challenge: Understanding financing requirements, investment horizons, and returns on investment

As noted in Section 1, there are numerous areas where companies can invest across their operations to achieve decarbonisation, as well as relying on emissions trading to achieve regulatory emissions reduction targets. To be able to identify the most cost-effective, "low hanging" opportunities, companies must understand their processes very well and ideally have established monitoring and verification of emissions.

Undertaking a site (or even group or sectoral) benchmarking exercise can also help to identify decarbonisation opportunities. This includes more strategic and costlier investments that may have been deployed successfully elsewhere.

Key challenges for companies include:

- Translating decarbonisation opportunities into an investment roadmap—and understanding how different financing mechanisms can be deployed to best effect, i.e., to achieve the maximum impact on the company bottom line.
- Ensuring ESG commitments are fulfilled and wider stakeholder endorsement is achieved.

Typically, the progressive technologies and processes that can achieve far greater decarbonisation outcomes (i.e., absolute tonnes of CO_2 equivalent abated or avoided over a given period compared to a standard existing process) will invariably require significant payback times for companies. Nowhere is this challenge more evident than for small and medium enterprises (SMEs), where investment periods of two years or less continue to be the norm.

The current economic climate also makes it even harder to justify more radical and expensive process changes, especially where there is internal competition for investment. Prioritising decarbonisation in this context is difficult.

Furthermore, a company must also consider how its actions will sit within the wider sector in which it operates. Questions that decision-makers could think about include:

- Are they a sectoral leader?
- Does their ESG strategy commit them to a more progressive set of actions that will help to differentiate them, their products, and their overall brand?
- Will they be able to add a green premium (a "greenium") to their product to help pay for their decarbonisation investments?

There is no "one size fits all" finance route for decarbonisation. Every situation requires careful consideration, depending on the scale of the investment needs and inherent risks.

Numerous financing options exist that companies need to consider, often in combination, to arrive at the ideal financing structure that meets their needs. Some of the examples on offer include:

- **Internal company finance.** The simplest option, using the balance sheet to finance investments.
- **Commercial bank debt /guarantees.** Financing could range from a working capital loan, longer term loans to finance capital projects, or guarantees to support the investment.
- **Corporate green bonds.** Where the company goes out to the market to attract private investors to commit to their future investment plans, based on a published and independently verified green bond framework that identifies key investment themes.
- **Special purpose vehicle (SPV).** An off-balance sheet option that involves establishing a standalone entity that can then attract project finance from different sources.
- **Equity funds.** For example, private equity funds (including those that have been established specifically to mobilise private finance into either near commercial or early commercial, yet sparsely adopted, low-carbon technologies across hard-to-abate sectors, such as cement, chemicals, refineries, or steel).
- **Government support.** A mixture of instruments but predominantly grants, with some specialist schemes that may offer loans, quasi-equity, or guarantees for specific types of investment. State aid considerations are an important aspect of this type of financing, since there will be limits to how much government support any company can benefit from, depending on their particular situation.

At a fundamental level, companies face two potential routes forward in terms of financing their decarbonisation actions:

a) Innovate to become game-changing (i.e., to radically cut or avoid emissions) and therefore seek grant support to overcome investment gaps created by technology/operational risks, etc.

b) Buy off-the-shelf, proven technologies/processes to incrementally improve.

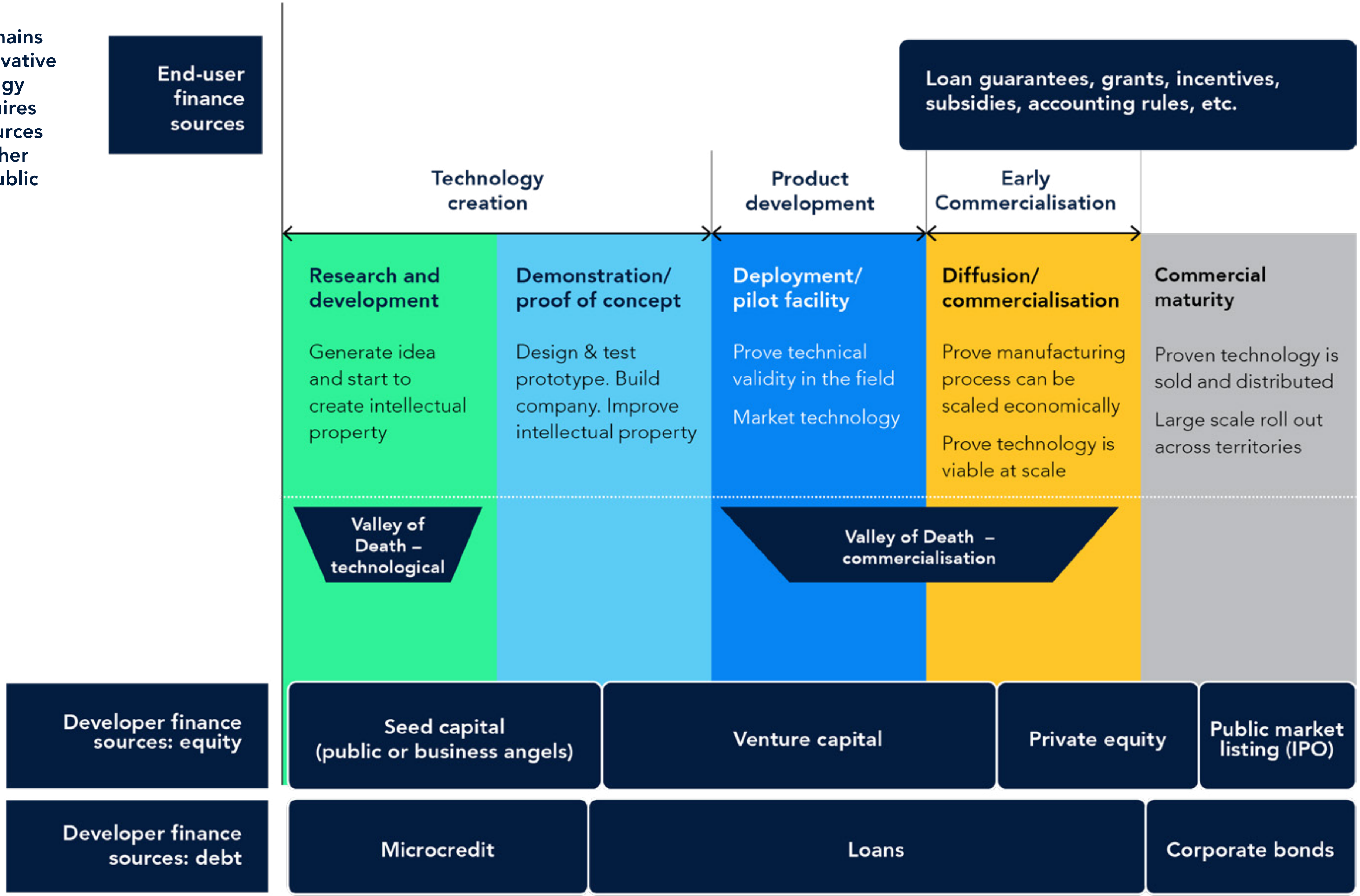
For innovative activities, the use of different financing mechanisms is key to achieving successful project outcomes at different stages in the innovation cycle.

For proven technologies, companies could draw on either the company balance sheet finance or external debt/loans, which can be sourced from commercial banks (who may or not be supported via government support schemes or national promotional banks) to reduce the cost of borrowing.

The chart next page illustrates the different potential sources of finance that are available for both the industrial end user, as well as the technology developer (or within a SPV) that is seeking to bring an innovative process to market.

There is no "one size fits all" finance route for decarbonisation. Every situation requires careful consideration.

Figure 14 - The commercialisation 'Valley of Death' remains problematic for innovative low-carbon technology developers and requires private financing sources to be brought together alongsie available public support



(Source: ICF, 2015, based on diagram by Bloomberg New Energy Finance)

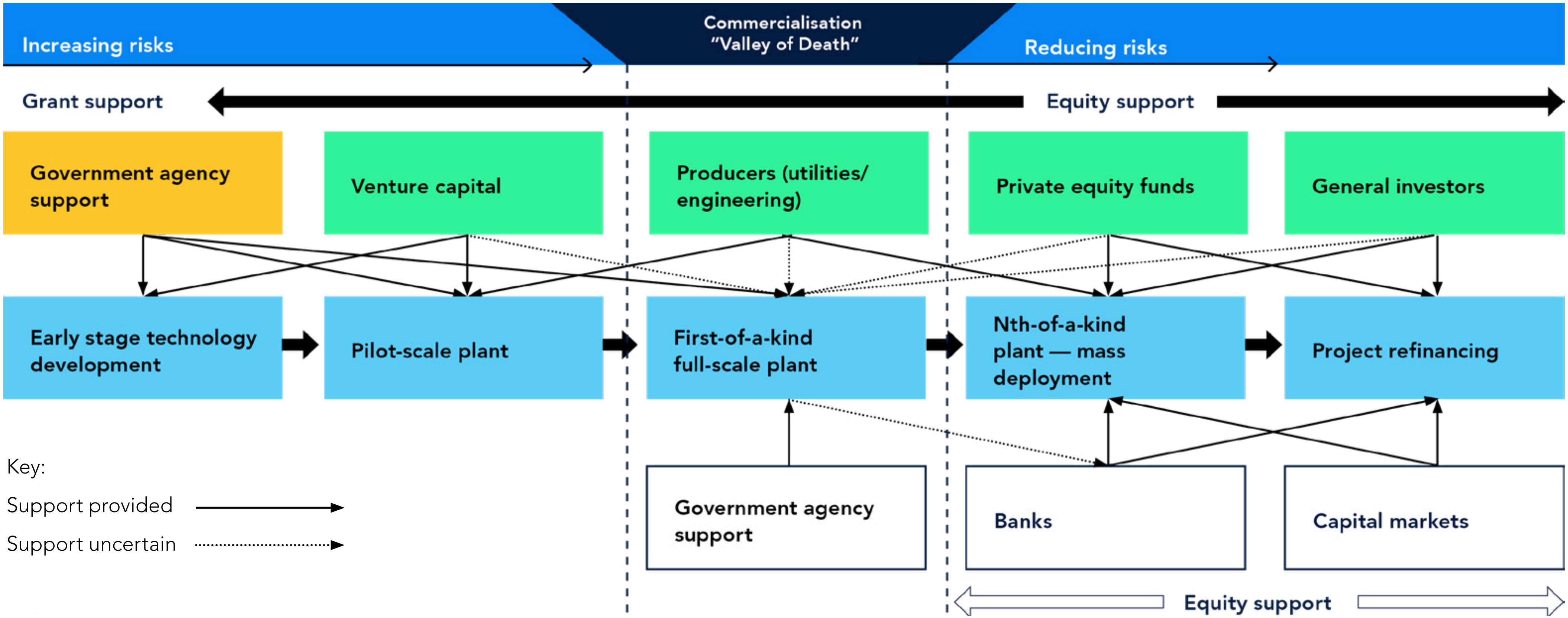
Market participants (i.e., those providing funding) have different strategies and propensities for high-risk ventures. This depends on their investment objectives and required return on investment.

With reference to the diagram below, looking at the particularly high-risk area of first-of-a-kind (FOAK), large-scale, early commercial demonstration of low-carbon technologies, it is challenging to align investors with the inherent risks that such projects carry.

This so-called "valley of death" creates a strong rationale for the public sector to close the funding gap with targeted interventions. For any particular decarbonisation innovation, the need for such public and private collaboration (using various forms of finance, such as grants, equity, or debt) remains common, albeit to differing degrees. This can also depend on the level of existing project demonstrations that may have created market precedents, thereby potentially reducing risk perceptions.

This so-called "valley of death" creates a strong rationale for the public sector to close the funding gap with targeted interventions.

Figure 15 - Financial market participants have different strategies and propensities for high risk ventures leading to a 'Valley of Death' for first-of-a-kind project



(Source: ICF, 2016, for European Commission)

Innovative technological solutions deployed by companies can help to cut emissions to well below industry sector benchmarks (for example, the respective EU and U.K. ETS). These can then generate excess carbon allowances that can be monetised by selling them on the market.

Facilitating finance for commercial and near commercial industrial decarbonisation technologies

Since 2019, ICF has supported the development and deployment of the EU's **Innovation Fund (IF)**. With a total volume of €38 billion to invest up to 2030, financed completely from the EU ETS, this is one of the world's largest low-carbon demonstration funding programmes.

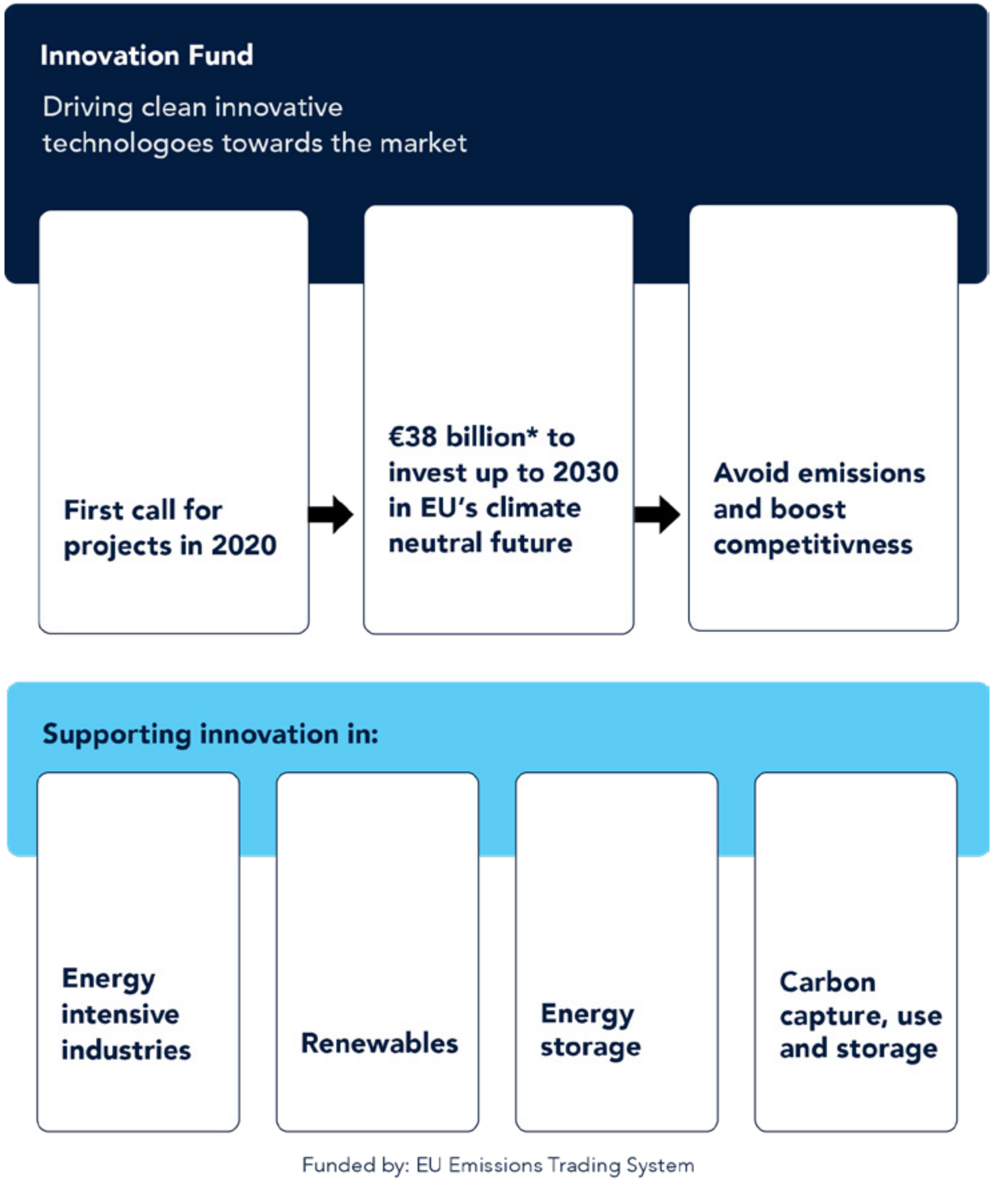
With two large-scale calls (for projects with capital expenditure over €7.5 million and in total worth €2.8 billion) and one small-scale call (projects with capital expenditure of less than €7.5 million and worth €100 million) now concluded, the IF has, to date, made 54 awards (24 large projects; 30 small projects), worth €2.9 billion, of which a large majority were to industrial decarbonisation projects across Europe. Seven projects, awarded in the first large-scale call, are estimated to reduce 77.4 megatonnes CO_2eq over their first 10 years of operation.

Key sectors being supported include chemicals, steel, and hydrogen production via electrolysis.

What lessons can be learned from this?

1. Applicants often overestimate how advanced they are before they apply. Projects require significant time to develop and refine their project concept, achieve a feasible financial strategy to make them bankable to private investors and the public sector, as well as form the right project delivery team. In this regard, for smaller projects, the IF provides a useful **self-check questionnaire**, developed by ICF, to give applicants an initial steer on whether to apply. The IF also provides project development assistance (PDA), delivered by the European Investment Bank, which can help the most promising applicants to improve the maturity of both their project and financial model once they have been evaluated positively, yet have failed to reach the award threshold.
2. Applicants can benefit from blending together national funding support with the IF, in order to maximise the level of public sector financing, while remaining within state aid boundaries.

Figure 16 - The Innovation Fund is one of the world's largest funding programmes for the demonstration of innovative low-carbon technologies



*depending on the carbon price.

Source: **Innovation Fund Progress Report, August 2022**

The enormous size of the funding gap for large-scale, low-carbon demonstration projects requires careful packaging together of available support to reach financial close.

3. Opportunities to explore innovative configurations of technologies into novel, hybrid solutions provide an important differentiator against more "standard," sectoral-focused projects.

ICF was the delivery partner for the industrial heat recovery support (IHRS) programme, an £18 million grant fund provided by the Department for Business, Energy, and Industrial Strategy (BEIS). This was designed to encourage and support investment in heat recovery technologies and to help businesses identify and invest in opportunities for recovering and reusing heat that would otherwise be wasted. Funded studies and projects brought about a total potential of decarbonising applicants' industrial processes by over three million tonnes of CO_2 annually. Key technologies supported included organic Rankine cycle generators, thermal storage, electrification of heat, absorption cooling, and waste heat boilers/ economisers.

What lessons can be learned from this?

1. The availability of specific funding for industrial processes enabled, and, in some cases revived, many potential decarbonisation projects that would otherwise be shelved or overlooked due to competing agenda and other business priorities.
2. A well-designed grant programme can provide multiple added benefits to applicants and wider sectors. The IHRS's structured application process provided additional due diligence to strengthen the business case and de-risking of decarbonisation projects.
3. Grant funding is a fundamental element in enabling decarbonisation projects. However, the success of the project depends on multiple other factors affecting the successful delivery of the project.

The extent to which policymakers are responsive to market needs and can develop appropriate funding interventions is amply demonstrated by the rapid growth in support schemes across Europe to promote hydrogen generation. Below, we illustrate a selection of the different schemes that are either already in place or are planned across several European countries. Much of this activity has been a direct result of both the REPowerEU initiative, discussed earlier, as well as the Recovery and Resilience Facility that was put in place in EU member states to help Europe recover from the impact of the COVID-19 pandemic. They are now also helping Europe to move to a more energy secure footing in light of the war in Ukraine.

Grant funding to support industrial decarbonisation can be greatly beneficial to companies, but it may not be ideal for every company.

Benefits can include:

- Capital is freed up on the balance sheet
- Greater scale of investment is possible
- Leverage to attract other investors
- Visibility and free marketing, if project is advertised by the public body
- Linked consultancy support (often free or heavily subsidised), to enhance the investment readiness of the company
- Follow-on funding opportunities from the same or different public agencies, following positive outcomes

Drawbacks can include:

- Bureaucracy, which may be excessive
- Uncertainty of the funding, if tendering required
- Monitoring requirements once awarded
- Knowledge-sharing/ disclosure to the wider market, which may create intellectual property rights (IPR) challenges
- Potential requirement to involve partners, including from other countries, which may create an organisational challenge

Figure 17 - Level of ambition and support schemes for hydrogen across a selection of European countries

Key countries	H_2 strategy	Scale of H_2 ambition	Scale of funding (M EUR)	Schemes identified/form of support
Belgium	Yes	At least 150 MW of electrolysis capacity in operation by 2026	€125 M (Flemish region); €160 M (Walloon region)	Energy Transition Fund
Denmark	Yes	6GW of electrolysis capacity by 2024 and 40GW by 2030	€190 M	Power-to-X Strategy
France	Yes	6.5GW electrolysis capacity by 2030	€1,900 M until 2030	Hydrogen technology bricks and demonstrators Hydrogen Important Projects of Common European Interest (IPCEI) projects
Germany	Yes	5 GW electrolysis capacity by 2030, to be increased to 10 GW by 2030 soon (according to the coalition's agreement)	€3,200M for the realisation of the national hydrogen strategy (National Recovery and Resilience Fund)	Hydrogen IPCEI projects Carbon contracts for difference becoming available in 2023
Italy	Planned for 2022	5GW electrolyser capacity by 2030; 2% penetration by 2030 & 20% hydrogen penetration into final energy demand by 2050	€500 M of which: €110 M is allocated towards Programme Agreement with ENAE until 2025; €20 M on R&D	National Recovery & Resilience Fund
Norway	Roadmap and white paper	GHG emission reduction by 50-55% by 2030; 90-95% by 1990 baseline	€20 M allocated from national budget in 2021; an additional €1.5 M spent on R&D (increased to €3M in 2022) until 2030	PILOT-E (R&D/demonstration)
Poland	Yes	2GW of electrolysis capacity by 2030	€5,000 M for RES inc. Hydrogen (National Resilience & Recovery Fund)	Hydrogenation of the economy programme for 2023, to support technical infrastructure for production, storage, transport, use of hydrogen
Spain	H_2 roadmap	300-600 MW of electrolysis capacity by 2024; 4 GW by 2030	€150 M H_2 Pioneers Programme €250 M Incentive Programme	H_2 Pioneers Programme; Incentive Programme
The Netherlands	Yes	50-100 MW; 75% carbon emission reduction by 2030; 90% by 2050	€16,000 M (via SDE++)	SDE++ (subsidies on OPEX and CAPEX)
United Kingdom	Yes	2GW by 2025; 10GW by 2030	€270 M to support low-cost hydrogen technology; €112 M for project operation before 2025	Industrial Decarbonisation and Hydrogen Revenue Support (IDHRS) funding 1GW of green H_2 and 1GW of blue H_2

Source: ICF

The support schemes for hydrogen across Europe fall into four broad categories:

4. Applied research and development (supporting academic research, for example in IT)
5. Pilot plant / large-scale, commercialisation-focused support (Denmark, Spain, France, Norway, Poland)
6. Project development support (FEED studies and development capital, for example in the U.K.)
7. Operational support, principally via contracts for difference, such as the SDE++ scheme in Netherlands, and planned schemes in France and the U.K.)

How far can a company's innovation be supported by grants?

Companies need to consider the allowable intervention rates for grant support. Generally, the closer to market, the less generous the support that is available. These illustrative examples show how an innovation being developed by a company could be publicly supported as it journeys towards commercialisation:

- **Up to 75% grant funding for early stage, proof of concept research and development**
- **Up to 50% grant funding for alpha/beta prototype or small pilot plant projects**
- **Up to 25% grant funding for (large-scale) pre commercial, demonstration projects**

Within the EU's IF (see above), up to 60% of the "relevant costs" of the project can be applied for. Relevant costs cover the additional costs (capital expenditure and operational expenditure) to demonstrate the new innovation, when compared to a reference plant producing a similar product.

The level of allowable funding is also important to policymakers since it dictates how far public finances can stretch. The table below is taken from a recent study for the Czech Ministry of Environment, in which ICF helped to evaluate the various sectors that could be supported by the **EU's Modernisation Fund**. The table shows different intervention rates and their impact on the leverage of private finance. Make the grant too generous, and private investment is crowded out and public sector cost-efficiency reduced. Make support too small, and actors are not incentivised to invest in new innovations. Modality 2A, for example, aimed to support industrial decarbonisation for EU ETS installations across the Czech Republic.

The role of taxonomies

Both the EU taxonomy for sustainable activities and the U.K.'s planned green taxonomy should drive positive investment behaviours for both companies and, most importantly, investors/financiers.

Planned climate mitigation investment activities that fall into the activities considered as making a "substantial contribution" to decarbonisation of the economy under the EU taxonomy (and are deemed to "do no significant harm" across five other environmental objectives, including biodiversity) will attract investors more easily, as the criteria provide some guarantees against claims of "greenwashing."

Green taxonomies will play a central role in shifting and scaling up investments in projects that are necessary to meet global and national decarbonisation ambitions set in policy goals such as the Paris Agreement or the European Green Deal. They will benefit companies by helping them plan and finance their green transition. Taxonomies will also help mitigate market fragmentation and information asymmetry, by harmonising what is recognised by investors as green.

Figure 18 - The MF could leverage between €4.8B and €11.2B of additional capital in the Czech Republic between 2021 and 2030

	Share	Total MF support	Intervention rate (%)			Financial leverage (M Euro)			Total funding mobilised (M Euro)		
Modality	**%**	**(M Euro)**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Mod 1A (10c)	30	1,500	30	40	50	3,500	2,250	1,500	5,000	3,750	3,000
Mod 1B (new RES)	40	2,000	30	40	50	4,667	3,000	2,000	6,667	5,000	4,000
Mod 2A (EU ETS)	10	500	30	40	50	1,167	750	500	1,667	1,250	1,000
Mod 2B (non-ETS, Prague)	5	250	30	40	50	583	375	250	833	625	500
Mod 3A (Public buildings)	5	250	40	50	60	375	250	167	625	500	417
Mod 3B (Govt buildings)	2	100	50	70	90	100	43	11	200	143	111
Mod 4 (CES)	4	200	40	50	60	300	200	133	500	400	333
Mod 5 (Transport)	4	200	30	40	50	467	300	200	667	500	400
Total		**5,000**				**11,158**	**7,168**	**4,761**	**16,158**	**12,168**	**9,761**
MF Leverage Multiplier						**2.23**	**1.43**	**0.95**			

Source: ICF, 2020. Notes: 1) CES = Community Energy Systems; 2) model assumes 100% disbursement across modalities and over the lifetime of the MF, as well as an intervention rate covering all capital investment; 3) MF allocations per modality are estimates solely used as the basis for determining environmental and economic impacts in the D4 and are not definitive levels of support.

Finally, finance isn't everything.

Wider framework conditions are fundamental in either supporting investment decisions or acting as major constraints.

Key factors to consider include:

- The extent to which company ESG policies must be adhered to.
- How procurement rules and practices may need to be factored into investment plans.
- Supply chain needs and constraints (for example, the availability of the right components and systems may be challenging—recent examples include the shortage of semiconductors, which has led to reduced car production for several manufacturers).
- Skills and training requirements (there may be a limited or non-existent labour market which might inhibit the deployment of new technologies).
- Public acceptance, which may be the most crucial and underestimated condition of them all.

Significant strategic planning is required for major decarbonisation projects to ensure such factors are fully considered and mitigated against.

The extent to which state aid is granted must also be carefully considered and approved within prevailing legal frameworks. Clearly, every country must consider how it can effectively support its industry to decarbonise, particularly those that are very energy intensive. To avoid over-compensating individual companies, and creating potential market distortions, the optimal level of state aid must be assessed and approved within current state aid regulations. In the EU, updates to the **Climate and Energy State Aid Guidelines**, which come into effect in 2023, have helped to address some of the challenges faced by companies in the recent past.

Decarbonisation decision-making

As mentioned at the start of this report, industrial decarbonisation solutions often require complex trade-offs from a technical and commercial perspective. The parties involved in the overall solution will likely increase with complexity. As such, it is unsurprising that decision-making for decarbonisation projects takes considerable effort and resources. Some challenges are surmountable, while many are disproportionately extensive, resulting in halts to projects.

Critical risk factors within the decision-making chain

To understand the complexities of decarbonisation, it is important to examine key critical risks and challenges affecting industrial enterprise decision-making processes and overall confidence embarking on longer term emission-reduction solutions:

Market risk. Commodity price remains the central market driver to the economics of decarbonisation solutions stretching across the supply chain. While short-term pricing fluctuation significantly affects business operations, decarbonisation solutions will require longer-term macroeconomic and mega-trend considerations, adding to the risk the decarbonisation asset will fail to deliver its intended benefit. Prevailing commodity price distortion (i.e., cheaper, fossil-driven commodities that do not account for the full environmental cost and impact of climate change) continues to deter faster rollout of decarbonisation solutions.

Politics and regulation. Geopolitical tension can alter the relative priority for decarbonisation. In the case of REPowerEU, its emphasis on accelerating clean energy is positive. On the contrary, the previous US withdrawal from and subsequent re-joining of the Paris Agreement unsettled business decisions concerning decarbonisation pathways. Ongoing east-west trade tensions will continue to unsettle enterprise decarbonisation pathway decisions, particularly for international conglomerates

Prevailing commodity price distortion continues to deter faster rollout of decarbonisation solutions.

with a wider supply chain impact planning on a longer-term regional scale.

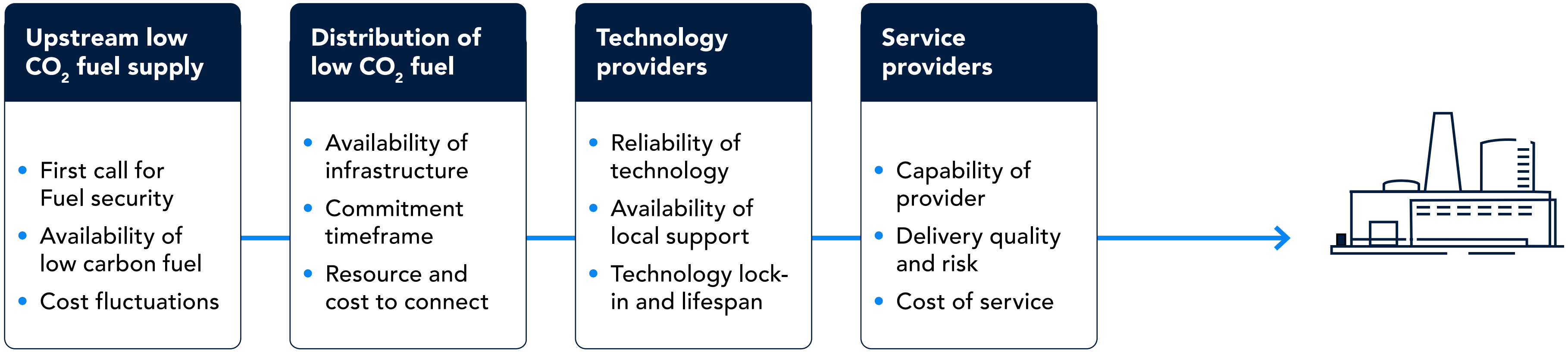
Technology and service supply chain. Establishing a strong supply chain of low carbon technology and service providers hinges on the demand for such solutions. While demand is increasing, the current market share is disproportionate in comparison with established technologies. It is crucial for industrial enterprises to have confidence in the reliability of their technology and service providers in contributing to the success of long-term decarbonisation asset operation. The technical supply chain extends from the upstream low-carbon fuel producer through to the industrial end user. The core risk within each part of the supply chain is highlighted here, each leading to a multitude of other risk factors that need to be considered.

Further to the factors external to the industrial enterprise discussed above, it is worthwhile examining internal factors affecting decision-making:

Inertia and bounded rationalities. This relates to the individual tendency to rely on established or familiar assumptions, with consequent reluctance to revise those assumptions, even if they are irrelevant or obsolete. Decision-makers steering an enterprise's strategic goals often rely disproportionately on such assumptions. This resistance to change can affect evaluation of decarbonisation solutions; whereby the more radical the proposed solution, the higher the resistance to accept or change the set of prior assumptions. This results in favouring easy, low-investment opportunities with lower expected returns, via familiar status quo solutions that may be less intrusive on existing operations.

The more radical the proposed solution, the higher the resistance to accept or change the set of prior assumptions.

Figure 19 - Risk factors along the supply chain



On the other hand, inertia or bounded rationalities can work in the opposite manner, whereby an investment will proceed irrespective of its financial attractiveness provided the decision originates from top decision-makers. When an idea is generated from the top (attributable to strategic priorities, biases, appeal to shareholder/customers, or other bounded rationalities), momentum is established and, more often than not, the decision is made prior to completing a proper decision-making process. There are four key stages (prior to implementation) in an investment decision-making process: Initial idea → diagnosis → build up solutions → evaluation and choice, bounded by internal organisational and individual factors. It has been observed, from prior empirical studies, that financial evaluation techniques are often not as important, often playing a secondary role and carried out at very late stages of the decision-making process. In smaller organisations, decisions are often made by a single or very few individuals, which further aggravates the rationality issue as decisions are potentially influenced by bounded rationalities (or biases) of very few individuals[1].

Imperfect evaluation criteria. The decision to implement a decarbonisation solution is often based on imperfect evaluation criteria, i.e., the potential benefits and risks of the solution are assessed through differing facts, perceptions, or biases. This is mainly attributed to asymmetric information, whereby the presenter of the solution has more or superior information compared to the decision-maker, or vice versa. Enterprises tend not to reveal operational issues (often viewed as trade secrets) to external parties due to competitive reasons. As a result, the true potential of a decarbonisation solution may be obscured if the supplier or service provider is unaware of an application for it, leading to suboptimal decision-making.

Internal competencies and awareness. Business enterprises often lack the internal skills and competencies to interpret technical information or evaluate decarbonisation solutions.

These are often highly complex and involve multiple system components across multiple technical disciplinaries (electrical, thermal, mechanical, civil, etc.). Solutions with benefits that rely on multiple system and plant processes require a strong integrated understanding of the site's manifold operations to realise the benefits. This integrated understanding is often difficult to achieve in practice due to resource and time constraints.

Aligning stakeholder interest in decarbonisation assets

The figure on the right explores, for a typical decarbonisation project, the perspective of eight stakeholder types, along with the key factors influencing their decision-making.

[1] Cooremans, C. (2012); Investment in energy efficiency: do the characteristics of investments matter? Energy Efficiency

Figure 20 - Managing stakeholder perspective and interest

Decarbonisation project

Shareholders

Shareholder interest will steer and drive the primary interest on the decarbonisation project, and ultimately provide the mandate. Considerations will differ significantly depending on how the board is made up: numbers, stake, local and international shareholders. Although decarbonisation is critical, there are many other operational issues competing for board interest, time and commitment.

Surrounding asset owners

Apart from the project site, it is important to consider the land ownership structure of surrounding area which the project infrastructure may depend on (shared energy resources, utility interconnections, land leases, land co-ownerships).

Low carbon fuel utility

Large scale transition to net zero will depend on the availability of secure, affordable and low carbon sustainable fuel. Negotiations and commercialisation of long-term low carbon fuel purchase agreements is a key factor in determining the success of a decarbonisation project.

Customer

Most industrial plants have stringent long-term delivery commitments to their customers, restricting any flexibility of the plant to alter its industrial processes. Conversely, customers are increasingly pressured to decarbonise their supply chain.

Financial partners

Large scale projects typically supported by various financial partners (financial institutions, private equity, ESCos, multilateral agencies or grant providers), each with their own due diligence process, interest, risk appetite, and investment conditions. Commercial agreements and negotiations are often complex.

Government authorities

While support from central government is expected to be strong, regional government authorities may not have the right capacity to support potentially complex requirements of decarbonisation projects within their jurisdiction.

Supply chain partners

Decarbonisation solution often involve a range of established and emerging technologies. Contractual arrangements require detailed consideration of the supplier's ability to fulfill its technical obligations. Suppliers may need to invest in its capacity to support client commitments over the project lifespan

External public stakeholders

Decarbonisation projects will often have a direct impact on external stakeholders with differing or conflicting interest to the decarbonisation objective. Attention required to Engagement, management and communication with external stakeholders

The following factors are also frequently a call to action for decision-makers on industrial decarbonisation investments:

Disclosure of ESG initiatives and climate-related information.

There is increasing pressure on businesses to disclose their approach in managing environmental, social and governance (ESG) initiatives. More specifically, enterprises also need to reveal the impact their business operations have on the climate and how they intend to manage the impact of climate change. The process of disclosure enables businesses to reflect, prepare, and manage ongoing ESG issues that may be otherwise overlooked—and in doing so integrate them into the core of their business objectives.

Standards, targets, and benchmarks.

There is an array of established standards to support the disclosure process, ranging from the Global Reporting Initiative (GRI), Sustainability Accounting Standards Board (SASB), United Nations Sustainable Development Goals (UN SDG), and Task Force on Climate-Related Financial Disclosure (TCFD), among others. The Science Based Targets Initiative (SBTi) provides guidance on how enterprises can reduce their emissions in line with the Paris Agreement. While benchmarking of enterprise ESG performance is provided by ratings agencies, standards are in development to support businesses in measuring their progress and deter greenwashing. The role of taxonomies has also been expanded in a previous section.

Continual optimisation of regulatory framework.

Some countries are adopting legally binding net zero targets. Such net zero regulations are highly effective at imposing critical actions. However, the pressure on businesses should be carefully managed to avoid adverse economic impact.

With the overarching, long-term nature of climate issues, harmonising current and upcoming regulations will be needed to support businesses in their decarbonisation efforts and to makes sure that progress is made at a realistic pace over a sustained timeline.

Customer obligation and social media platforms.

Regarding decarbonisation of non-industrial enterprises (e.g., commercial retailers), the bulk of their emissions often lie beyond the boundaries of their own business, within the upstream or downstream supply chain, i.e., Scope 3 emissions. Industrial enterprises serving these customers have an obligation to disclose the carbon intensity of their operations. The power of customer demand can increase the pressure on both these types of organisations to decarbonise their supply chains. Interaction with customers and stakeholders—for example, through social media—is important in upholding suppliers' reputations, particularly on climate.

Better infrastructure planning.

Economic and industrial clusters (or industrial symbiosis) can centralise decarbonisation efforts through sharing resources effectively between clustered companies, alongside other strategic competitive benefits.

Fiscal incentives

In the form of tax credits, exemption, abatement, and grants can mobilise critical actions on decarbonisation, especially for hard-to-decarbonise industrial sectors. ICF has successfully supported the U.K. government across two industrial grant programmes in unlocking and mobilising deep decarbonisation solutions offered to all industrial sectors in the country.

The process of disclosure enables businesses to reflect, prepare, and manage ongoing ESG issues.

4: Conclusions

Industrial decarbonisation technologies vary significantly from sector to sector in efficacy, cost, technical maturity, and acceptability to site operators. Their relevance to a particular site often depends upon proximity to other net zero enablers, such as renewable energy sources, carbon sequestration sites, and supportive supply chains. Sites located in industrial clusters may need to adopt different decarbonisation solutions than those located at dispersed sites.

The industrial decarbonisation pathways likely to contribute most towards net zero are fuel switching, energy efficiency, material efficiency, enhanced recycling, feedstock decarbonisation, and CCUS.

Electrification offers a ready route to decarbonise low temperature processes where low-carbon electricity is available. Storage systems can be used to tackle supply intermittency.

Hydrogen can be used for high temperature heating and for feedstock decarbonisation in certain circumstances. However, its value is constrained by the way it is produced. It looks likely that demand will outstrip supply of green hydrogen for many years, while blue hydrogen risks locking in technology that is not compatible with net zero goals.

Bioenergy is a viable decarbonisation option in certain circumstances but faces challenges around obtaining reliable supplies of suitable quality feedstock and managing air pollution impacts.

Materials efficiency and recycling initiatives—to reduce the need for primary material extraction and processing—are becoming more prevalent, enforced by circular economy legislation.

Finally, CCUS can fill gaps if other decarbonisation options are impractical.

This report has detailed the applicability of these pathways and technology options, along with their likely contributions to reducing emissions, for several energy-intensive sectors: non-metallic minerals, iron and steel, chemicals, petroleum, pulp and paper, and non-ferrous metals, in order of their relative emissions-saving potential. Very considerable savings are possible, and the technology to achieve them, is often available today.

Concerning policy, higher environmental performance standards and related green procurement processes are important mechanisms to help buyers to purchase net zero-compatible equipment, reflecting energy efficiency, materials efficiency, and circular economy priorities.

Carbon-pricing mechanisms are helping to motivate investors to implement solutions that drive emissions reductions in energy-intensive industries, and thereby help decouple emissions from economic growth.

Financing mechanisms available to investors include their own equity, commercial debt, corporate green bonds, off-balance sheet options, private equity, and government support. The options they select, and use, are influenced by factors including the purpose of the investment, attitude to risk, and adjacent financing demands. This report has presented the advantages and drawbacks of these options in different circumstances, with practical examples from our experience of advising decarbonisation funds.

The decision to invest in an industrial decarbonisation solution is often complex, addressing multiple risks and operational factors, and requiring alignment of the interests of multiple stakeholders. Business objectives, compliance requirements, reputation, and customer needs are all influencing factors, and there are often significant barriers. Yet these must be overcome to achieve net-zero emissions in Europe.

Very considerable savings are possible, and the technology to achieve them, is often available today.

Glossary

TOC

Scope 1, 2 and 3 emissions

Scope 1 emissions: These are direct GHG emissions that occur from sources that are owned or controlled by an organization. Examples include emissions from combustion of fossil fuels in company-owned boilers or vehicles, emissions from on-site chemical production, and emissions from refrigerant leaks.

Scope 2 emissions: These are indirect GHG emissions that result from the consumption of purchased electricity, heat, or steam. These emissions occur at the facility where the electricity, heat, or steam is generated, rather than at the facility where it is consumed. Scope 2 emissions are often used as a proxy for the emissions associated with an organization's energy consumption.

Scope 3 emissions: These are indirect GHG emissions that occur in the value chain of an organization, including both upstream and downstream emissions. Examples of upstream emissions include emissions from the production of purchased materials, while examples of downstream emissions include emissions from the use of the organization's products or services. Scope 3 emissions can be more difficult to quantify than scope 1 and 2 emissions, as they often involve multiple parties and complex supply chains.

Source: GHG Protocol

Technology readiness level (TRL):

The technology readiness level (TRL) is a measure used to assess the maturity of a technology. It is based on a scale from 1-9, with one being the lowest level of maturity and nine being the highest level of maturity. The TRL scale is used to assess the readiness of a technology for implementation, and is based on the following criteria:

- TRL 1: Basic principles observed and reported.
- TRL 2: Technology concept and/ or application formulated.
- TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept.
- TRL 4: Component and/or breadboard validation in a laboratory environment.
- TRL 5: Component and/or breadboard validation in a relevant environment.
- TRL 6: System/subsystem model or prototype demonstration in a relevant environment (ground or space).
- TRL 7: System prototype demonstration in a space environment.
- TRL 8: Actual system completed and "flight qualified" through test and demonstration (ground or space).
- TRL 9: Actual system proven through successful mission operations.

Source: NASA

Carbon capture

- **Post-combustion capture:** This involves capturing CO_2 after it has been generated through the combustion of fossil fuels.
- **Pre-combustion capture:** This involves capturing CO_2 before the fuel is burned, typically through gasification of the fuel.

- **Oxy-fuel combustion:** This involves burning the fuel in an atmosphere of pure oxygen, which results in a more concentrated CO_2 stream that is easier to capture.

Source: IPCC

Calciner

A calciner is a high-temperature furnace used in cement production to heat raw materials to a high temperature (up to 1400°C) in order to initiate a chemical reaction that results in the formation of clinker.

Indirect/direct kiln firing

Indirect kiln firing is a method of heating materials in a rotary kiln without directly exposing them to a flame or combustion gases. In an indirect fired kiln, the heat source is located outside of the kiln chamber and heat is transferred to the material through the kiln shell. The combustion gases from the fuel source are directed through a heat exchanger, where they transfer their heat to a fluid or gas, such as air or nitrogen. The heated fluid or gas is then circulated around the outside of the kiln, where it transfers its heat to the kiln shell. The kiln shell then transfers the heat to the material being processed inside the kiln.

Direct kiln firing is a method of heating materials in a rotary kiln by directly exposing them to a flame or combustion gases. In a direct fired kiln, the fuel and combustion gases are introduced directly into the kiln chamber, where they come into direct contact with the material being processed.

Calcium looping

Calcium looping is a type of carbon capture, utilization, and storage (CCUS) technology, used in cement production that involves capturing carbon dioxide (CO_2) emissions from the combustion of fossil fuels, such as coal or natural gas, and then reusing the captured CO_2 in the cement production process.

Batch preheating

Batch pre-heating is a process used in glass production to pre-heat the raw materials (or batch) before they are fed into the melting furnace. The purpose of batch pre-heating is to reduce the energy required to melt the raw materials and to ensure uniform melting of the batch.

Biomethane

Biomethane is a pipeline-quality gas that is chemically identical to natural gas but is produced from biodegradable materials such as food waste, agricultural residues, and sewage.

Source: National Grid

Heat Pump

A heat pump is a device that transfers heat from a source to a sink, using mechanical energy. Heat pumps can be used for space heating, water heating, and cooling in residential, commercial, and industrial settings.

Source: European Commission

Catalytic cracking

The process of breaking down large molecules of hydrocarbon liquids, primarily heavy petroleum fractions, into smaller molecules of lower boiling range by use of a catalyst. Catalytic cracking is considered more efficient than conventional methods of refining crude oil, such as thermal cracking, because it produces a higher yield of desirable products, such as gasoline and diesel fuel, and it consumes less energy.

Source: Adapted from ASTM

Selective membrane

A selective membrane in oil and gas production is a type of membrane that is designed to selectively allow certain molecules or ions to pass through while blocking others. Typically used to separate and purify gases, selective membranes are also used to remove impurities from liquids and for wastewater treatment. Selective membranes can provide higher separation efficiency in comparison with conventional methods.

Methanol-to-ethylene

Methanol to ethylene production is used as an alternative to traditional ethylene production methods, such as steam cracking of hydrocarbons (typically natural gas). The process involves using methanol produced from renewable carbon sources such as biomass and waste gases.

H_2O and CO_2 conversion to ethylene

The alternative low-carbon pathway to ethylene production uses methanol based on hydrogen, produced by water electrolysis with low-carbon electricity, followed by hydrogenation of CO_2 as carbon source. This option offers a negative CO_2 footprint through the use of CO_2 as carbon feedstock.

Alternative electrolyte membrane electrolysis

Alternative electrolyte membrane electrolysis is a process that produces hydrogen by splitting water into hydrogen gas (H_2) and oxygen (O_2). This low carbon alternative involves powering the electrolysis process with renewable or low carbon energy sources. In this process, alternative electrolytes can be used, e.g. a solid electrolyte membrane, proton exchange membrane or alkaline.

Vertical electrode cell

As the name suggests, the electrodes in these cells are arranged vertically, with the anode and cathode separated by a permeable membrane or diaphragm. Vertical electrode cells have several advantages over other types of electrolysis cells, including high efficiency, low energy consumption, and ease of maintenance. They also have a high production capacity and can be operated continuously, making them suitable for large-scale industrial applications.

Direct carbothermic reduction

This process involves the direct reduction of alumina with carbon at high temperatures, without the need for an intermediate step of producing aluminium metal. Direct carbothermic reduction has several advantages over traditional methods of aluminium production, such as the Hall-Héroult process, including lower energy consumption and fewer greenhouse gas emissions.

Wettable cathodes

'Wetting' refers to improved electrical contact between molten aluminium and the carbon cathode, resulting in lower energy consumption during the aluminium production process.

Elysis process

The ELYSIS process is a revolutionary technology for producing aluminium that replaces carbon with advanced conductive ceramics as the electrolysis material. The ELYSIS process was developed by a joint venture between Rio Tinto and Alcoa, in partnership with the Canadian government and Apple Inc. The process uses a proprietary ceramic material as the anode, which is completely inert and does not react with the alumina, thereby eliminating greenhouse gas emissions and eliminating the production of carbon dioxide during aluminium production.

Source: Rio Tinto

SOURCES

Linköping University: Review of measures for improved energy efficiency in production-related processes in the aluminium industry—From electrolysis to recycling

International Journal of Thermofluids: The aluminium industry: A review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery

Energy Efficiency: Effects on primary energy use, greenhouse gas emissions and related costs from improving energy end-use efficiency in the electrolysis in primary aluminium production

ECEEE: Electrification of industrial process heat: long-term applications, potentials and impacts

International Aluminium: Primary aluminium smelting energy intensity

Hatch: Alumina tube digestion

Global Cement: Holcim opens its first calcined clay unit in Saint-Pierre-la-Cour cement plant in France

Istructe: Beyond Portland cement: Low-carbon alternatives

Cembureau: The role of cement in the 2050 low carbon economy

Norcem: Carbon capture and storage (CCS)

Leilac: Roadmap 2050

Construction and Building Materials: Recycled concrete made with different natural coarse aggregates exposed to high temperature

European Commission: Reaching new heights with CO_2 capture at cement plants

BCC: Net zero and the decarbonisation of ceramics

Elysis: Start of construction of commercial-scale inert anode cells

Elysis: Carbon free aluminium smelting a step closer: ELYSIS advances commercial demonstration and operates at industrial scale

Contact us

ICF CLIMATE center

twitter.com/ICF

linkedin.com/company/icf-international

facebook.com/ThisIsICF

#thisisicf

icf.com/climate

The ICF Climate Center offers compelling research and unique insights that help organizations establish clear, practical pathways forward through the combination of climate science and predictive analytics.

The Center builds upon the work of 2,000+ climate, energy, and environment experts worldwide—making us one of the world's largest science-based climate consultancies. ICF works with business, government, and nonprofit organizations to design and implement programs and policies that drive low-carbon transitions and build resilience against the effects of climate change.