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# Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070

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## HIGHLIGHTS

- Technology and policies enable net zero industrial greenhouse gas emissions by 2070.
- Electrification, use of hydrogen, energy efficiency, and carbon capture.
- Material efficiency, longevity, re-use, material substitution, and recycling.

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- Specific technologies for iron & steel, cement, and chemicals & plastics.
- Carbon pricing, research support, standards, government purchases, data disclosure.

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A B S T R A C T

Fully decarbonizing global industry is essential to achieving climate stabilization, and reaching net zero greenhouse gas emissions by 2050–2070 is necessary to limit global warming to 2 °C. This paper assembles and evaluates technical and policy interventions, both on the supply side and on the demand side. It identifies measures that, employed together, can achieve net zero industrial emissions in the required timeframe. Key supply-side technologies include energy efficiency (especially at the system level), carbon capture, electrification, and zero-carbon hydrogen as a heat source and chemical feedstock. There are also promising technologies specific to each of the three top-emitting industries: cement, iron & steel, and chemicals & plastics. These include cement admixtures and alternative chemistries, several technological routes for zero-carbon steelmaking, and novel chemical catalysts and separation technologies. Crucial demand-side approaches include material-efficient design, reductions in material waste, substituting low-carbon for high-carbon materials, and circular economy interventions (such as improving product longevity, reusability, ease of refurbishment, and recyclability). Strategic, well-designed policy can accelerate innovation and provide incentives for technology deployment. High-value policies include carbon pricing with border adjustments or other price signals; robust government support for research, development, and deployment; and energy efficiency or emissions standards. These core policies should be supported by labeling and government procurement of low-carbon products, data collection and disclosure requirements, and recycling incentives. In implementing these policies, care must be taken to ensure a just transition for displaced workers and affected communities. Similarly, decarbonization must complement the human and economic development of low- and middle-income countries.

## 1. Introduction

To avert dangerous climate change, it is necessary to reduce greenhouse gas (GHG) emissions from every sector of the global economy. Modeled emissions trajectories that limit likely warming to 2 °C generally require reaching net zero emissions in the latter half of the 21st century and net negative emissions thereafter [1]. To limit warming to 1.5 °C, emissions must reach net zero around 2050 [2].

The industry sector was responsible for 33% of global anthropogenic GHG emissions in 2014. This figure includes emissions from on-site fuel combustion, emissions from manufacturing processes, and indirect emissions associated with purchased electricity and heat; without indirect emissions, the industry sector was still responsible for 19% of global anthropogenic GHG emissions (Fig. 1).

Industry is at the core of developing low-carbon solutions: it is responsible for producing technologies such as renewable electricity generation facilities, clean vehicles, and energy-efficient buildings. Therefore, it is imperative to reduce emissions from industrial operations while industry continues to supply transformational technologies and infrastructure. These approaches should be compatible with a pathway to zero industrial emissions.

A variety of technologies, product design choices, and operational approaches can rapidly and cost-effectively reduce energy consumption and GHG emissions across a broad range of industries. Breakthroughs in areas such as 3D printing, improved chemical catalysts, and facility automation are transforming how we make everything from

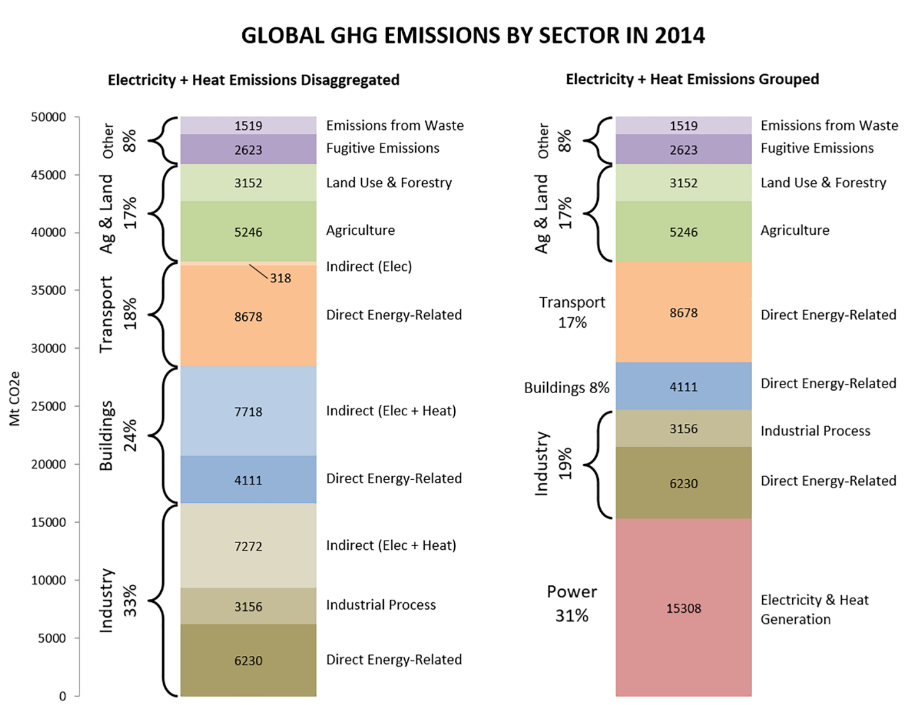


**Fig. 1.** Emissions by sector in 2014, displayed with indirect emissions (from the generation of purchased electricity and heat) assigned to the sectors that purchased that energy, or grouped into a single “power” sector. For more detail on which industries are included in the “industry” sector, see Fig. 2. Emissions from agriculture, from waste (e.g. landfills, wastewater treatment), and fugitive emissions (e.g. methane leakage from coal mines and natural gas systems) are not considered part of the industry sector in this paper [3,4].

smartphones to aircraft. Meanwhile, techniques such as lightweighting and design for longevity/reuse offer ways to reduce material consumption while providing equivalent or better services. All of these technologies and practices can be enhanced by integrated systems design. Over 90% of GHG emissions are from about a dozen industries (Fig. 2), so very large reductions in industrial GHG emissions are possible by focusing on a limited set of product and process improvements.

Technologies are only part of the picture. Enacting the right policies can make investment in cleaner industrial processes more profitable and dramatically accelerate emissions reductions. The right policies can even spread innovations through international supply chains, improving companies in countries that lack strong policies of their own. Companies that invest in improved technology will be positioned to be leaders throughout this century, when concern over climate change is likely to make inefficiency and high emissions increasingly serious business liabilities.

To help guide policymakers and businesses, this work develops a blueprint for action that addresses the inter-connected concerns of innovation, technical feasibility, cost-effectiveness, an enabling policy environment, and the need for social equity in delivering human wellbeing globally.

## 2. Two-degree-compatible industrial decarbonization pathways

Holding global average temperature increase to well below 2 °C (the goal of the 2015 Paris Agreement) requires decarbonizing global industry in tandem with all other sectors. Direct industrial emissions, including energy and non-energy process emissions, rose 65% from 1990 to 2014 [21]. This was driven in part by industrialization in the developing world, and further industrialization is expected to raise the standards of living in developing countries [22].

Industrial decarbonization will be motivated by the declining costs of cleaner technologies, environmental regulation, and voluntary climate action. Numerical assessments of decarbonization potential can highlight critical knowledge gaps and research and development (R&D) opportunities.

The Shell Sky Scenario [23], the 2-Degree Scenario (2DS) and Beyond 2-Degree Scenario (B2DS) from the International Energy Agency's (IEA) Energy Technology Perspectives [7], and the pathway described in the "Mission Possible" report by the Energy Transitions Commission (ETC) [24] are four scenarios that limit warming to below 2 °C. These scenarios present break-outs for global industry sector $CO_2$ emissions, hydrogen use, and CCS use. The Sky Scenario shows projections to the year 2100 from a World Energy Model (WEM) framework. The IEA shows projections to the year 2060 from a technology-rich, bottom-up analytical "backcasting" framework. The ETC projections are based on modeling by the firm SYSTEMIQ, which ETC indicates will be described in forthcoming technical appendices. Though complete time-series data are not yet available from ETC, data are reported for the net-zero emissions system, which is achieved in 2050 by developed countries and in 2060 by developing countries [24]. The graphs below show ETC results in 2060, as the results are global (and most of the world's industrial activity occurs in developing countries). All four scenarios consider only combustion and process $CO_2$, not other GHGs.

### 2.1. Modeled global industry emissions

The Sky Scenario projects a continued rise in heavy industry $CO_2$ emissions through the early 2030s, followed by a decline as $CO_2$ capture and hydrogen technologies are deployed. Emissions in light industry begin falling from the late 2030s, driven primarily by electrification. The IEA 2DS shows modestly rising industrial $CO_2$ emissions through 2025, followed by a linear decline, driven by efficiency and CCS technologies. The IEA B2DS includes steep cuts to Industry emissions beginning in 2014. ETC finds that global industry emissions can be reduced to net zero, except for "residual" emissions of 2 Gt $CO_2$/yr, consisting of "end-of-life emissions from chemicals (plastics and fertilizers) and the last 10–20% of industrial emissions" [24] (Fig. 3).

### 2.2. Modeled global hydrogen adoption

As the cost of renewable electricity continues to decline [25,26], there is growing interest in the role of renewable electricity-sourced hydrogen (i.e., via electrolysis) as a contributor to industrial decarbonization, both as a direct fuel and as a chemical feedstock [27].

Global industrial decarbonization scenarios that have explicitly

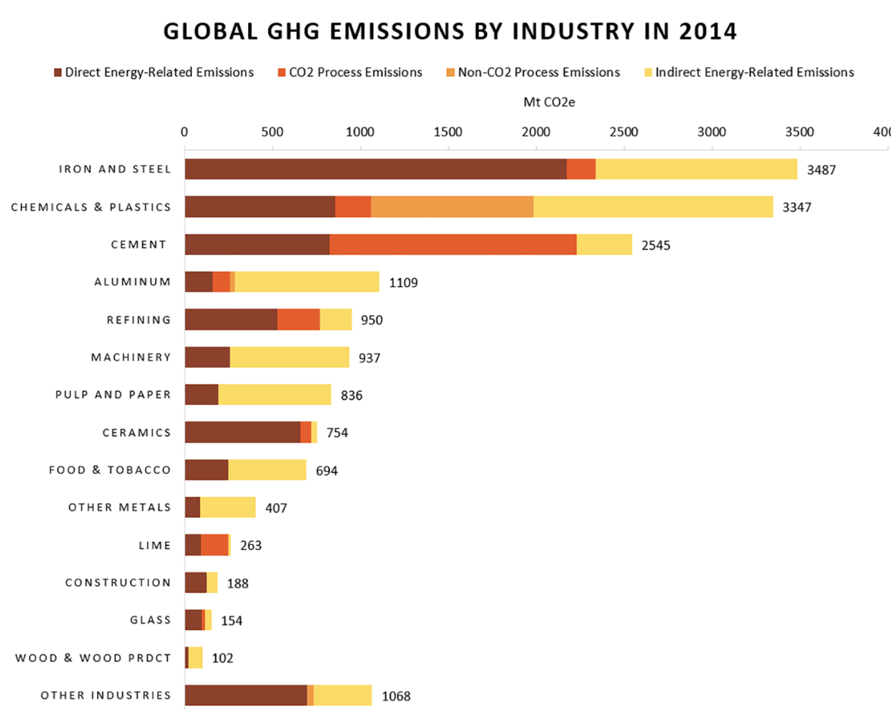


**Fig. 2.** Industry sector GHG emissions disaggregated by industry and by emissions type. Energy-related emissions are from fuel combustion, while process emissions are from other industrial activities. Direct emissions are from industrial facilities, while indirect emissions are associated with the production of electricity or district heat purchased by industry (not generated on-site). Emissions associated with transporting input materials and output products are considered part of the transportation sector and are not included in this figure. "Chemicals and plastics" includes all fluorinated gas emissions, even though most of those gases (e.g. refrigerants, propellants, electrical insulators) are emitted due to the use or scrappage of products. Chemicals production by refineries is included in the "refining" category, not the "chemicals and plastics" category. "Ceramics" includes brick, tile, stoneware, and porcelain. "Food and tobacco" includes the processing, cooking, and packaging of food, beverage, and tobacco products, not agricultural operations. "Other metals" includes copper, chromium, manganese, nickel, zinc, tin, lead, and silver. "Lime" only includes lime production not accounted for in another listed industry (e.g. cement). Total industry sector emissions do not match those in Fig. 1 due to differences in data sources [4–20].

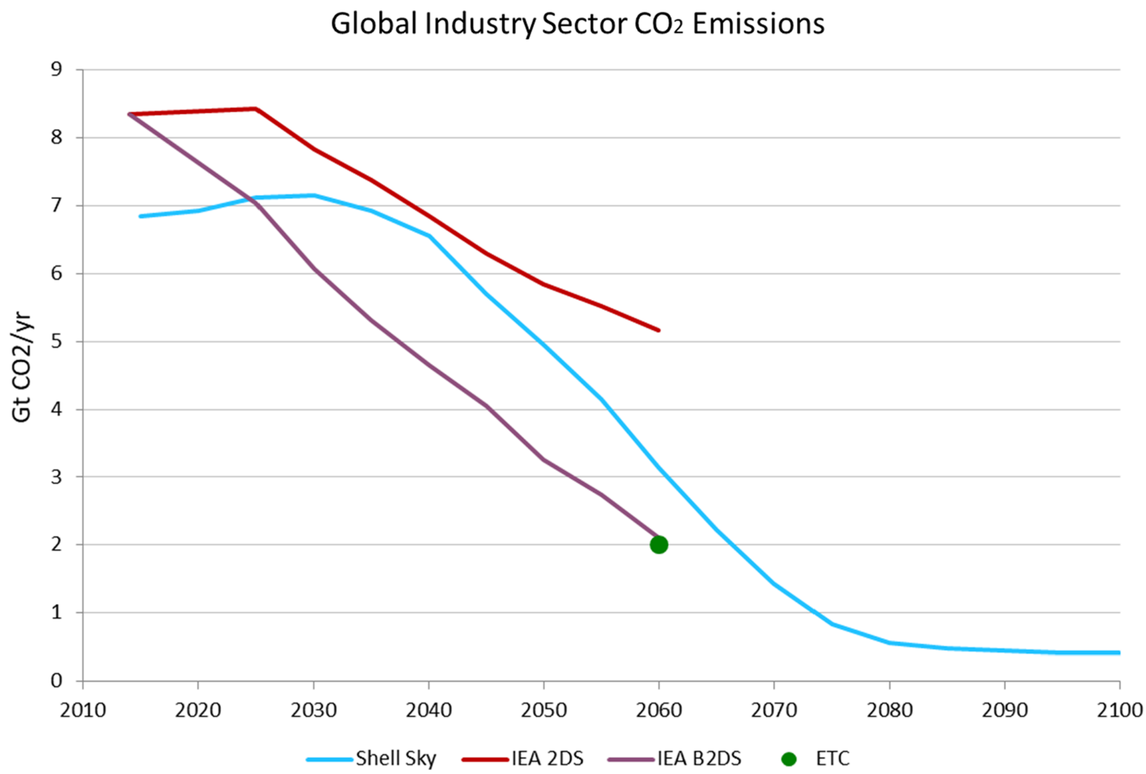


**Fig. 3.** $CO_2$ Emissions from Industry in the Shell Sky, IEA 2DS, IEA B2DS, and ETC scenarios. These scenarios include only direct emissions, not emissions from the production of purchased electricity or heat. This graph includes only $CO_2$ that reaches the atmosphere, not $CO_2$ that is captured and stored. The Sky scenario excludes fuels used as raw materials (such as petrochemical feedstocks) from the Industry sector, while IEA considers these fuel uses to be part of Industry. This might help to explain IEA's higher 2014 Industry sector emissions.

considered zero-carbon hydrogen—e.g. [7,23,24,28–30]—while differing in their technological and subsector scopes, have generally similar conclusions. Namely, renewable hydrogen can play a significant role in industrial $CO_2$ mitigation in both light and heavy industries, but the high current costs of electrolyzers and hydrogen transport, competition with cheap natural gas, need for new process heating equipment (e.g., avoidance of hydrogen embrittlement of metals), and moderate technology readiness levels of some emerging solutions (e.g., hydrogen-reduced steel) pose challenges for large-scale market penetration in the absence of good policy. Smart policy can accelerate the uptake of renewable hydrogen in industry by making the required R&D and infrastructure investments more cost-effective, and/or by requiring emissions reductions from industries whose best emissions abatement option is hydrogen. (For more details, see Sections 4.1 and 6.2 below.)

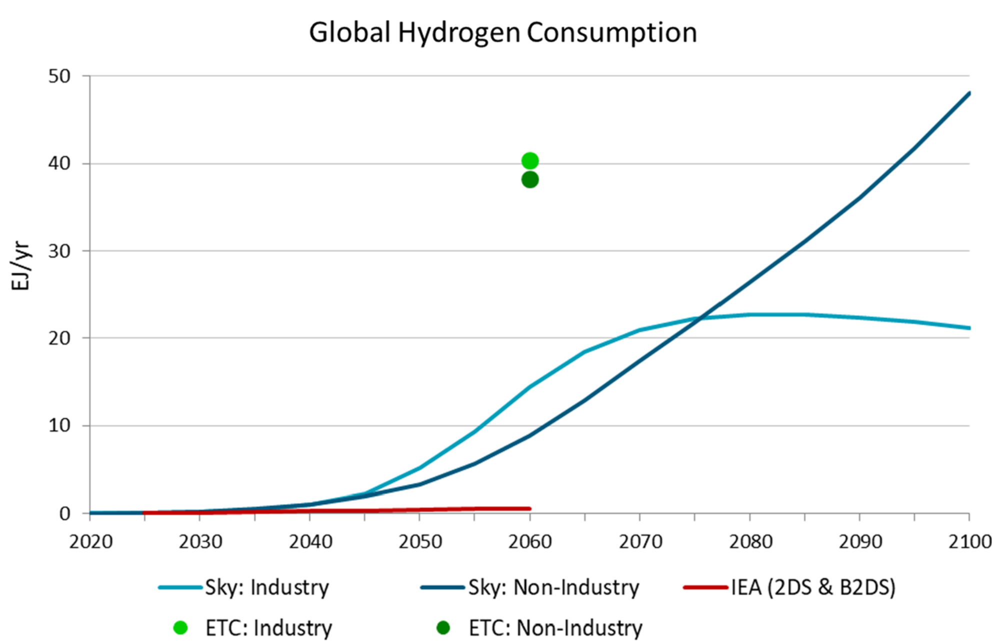


**Fig. 4.** Global hydrogen consumption in the Shell Sky Scenario, the ETC scenario (both disaggregated by end user), and in the IEA 2DS and B2DS (total). The IEA 2DS and B2DS are not identical, but their values are so close (0.59 vs. 0.85 EJ/yr in 2060) that their lines cannot be separately distinguished on this graph.

The IEA, Shell, and ETC scenarios have different predictions regarding hydrogen usage. The IEA scenarios do not show any hydrogen use by industry and very little by the transportation sector, reaching just 0.59 EJ/yr (2DS) or 0.85 EJ/yr (B2DS) in 2060. (Note these IEA hydrogen projections are out-of-line with IEA's more recent work in *The Future of Hydrogen* [30] and may no longer reflect the IEA's expectations regarding the importance of hydrogen in a decarbonized economy.) The Shell Sky Scenario includes steady growth of hydrogen use, from zero in 2020 to 69 EJ/yr in 2100. Hydrogen use by industry peaks in the early 2080s, as efficiency technologies reduce industrial energy consumption. The ETC scenario has the most aggressive numbers: 40 EJ/yr of hydrogen consumption by Industry and 38 EJ/yr by the rest of the economy (converted from mass of $H_2$ using hydrogen's lower heating value, as recovery of the latent heat of vaporization of water vapor in the exhaust stream is unlikely in most high-temperature industrial contexts) (Fig. 4).

Rapid adoption of hydrogen by industry implies similarly rapid scaling of hydrogen production, distribution, and storage infrastructure. Large industrial facilities with access to cheap electricity may produce their own hydrogen on-site, while other industrial facilities may buy hydrogen, particularly if a robust hydrogen distribution system develops to accommodate transportation sector demand. The infrastructure required to produce and deliver 15 EJ of hydrogen (the Sky scenario's projected 2060 hydrogen use by industry) could be compared with the historical development of the liquid natural gas (LNG) industry. The first large-scale LNG facilities were built in the 1960s, and by 1990, the LNG industry had scaled to 2.5 EJ, or 1% of global energy supply. Today, global trade in LNG is some 15.5 EJ of final energy, accounting for roughly 2.5% of global energy supply [31]. This "rapid" scale-up of the LNG industry nonetheless took 50 years. For global industry to decarbonize in line with these Paris-compliant scenarios, even faster hydrogen scale-up will be needed, illustrating the need for robust investments in hydrogen R&D and infrastructure to accelerate adoption.

### 2.3. Modeled global carbon capture and storage

Carbon capture and storage (CCS) is also expected to play an important role in helping to decarbonize industry [32,33]. The Shell Sky Scenario and IEA 2DS are largely in agreement about the magnitude of industry sector CCS, though the IEA projects scaling-up to begin roughly 5–10 years earlier. The ETC scenario closely agrees with the Sky scenario in total magnitude of $CO_2$ captured annually, but ETC projects most carbon capture to occur in industry rather than in non-industry sectors. The IEA B2DS projects an industry $CO_2$ capture rate falling between the Sky and ETC scenarios (Fig. 5).

### 2.4. Three phases of technology deployment

Independent of the Paris Agreement, national and sub-national policies, economic forces, technology development, and voluntary corporate action will cause the industrial sector to substantially reduce its emissions over the coming century. But an outcome consistent with Paris requires net zero emissions within 30–50 years.

The European Commission has modeled a number of ambitious emission reduction scenarios for the EU that are compatible with 2-degree and 1.5-degree global trajectories. Projected energy intensity of EU industry (Fig. 6) may reflect technology and policy pathways also available to other developed economies and, with sufficient financial support and technical assistance, to developing economies. These intensity trajectories require a broad range of supply-side measures (electrification, energy efficiency, circular economy, hydrogen, etc.) and should be accompanied by demand-side measures (material efficiency, longevity, re-use, etc.).

In considering a rapid transition for industrial facilities worldwide, the following framework for change is proposed (Table 1). Note the timing of proposed phases refers to a global average. In reality, developed countries likely would need to decarbonize more rapidly, to compensate for any developing countries that deploy technology more slowly. Also note that the "timeframe" specifies when each measure becomes widely used and begins delivering significant emissions reductions; R&D to improve technologies used in later phases must begin

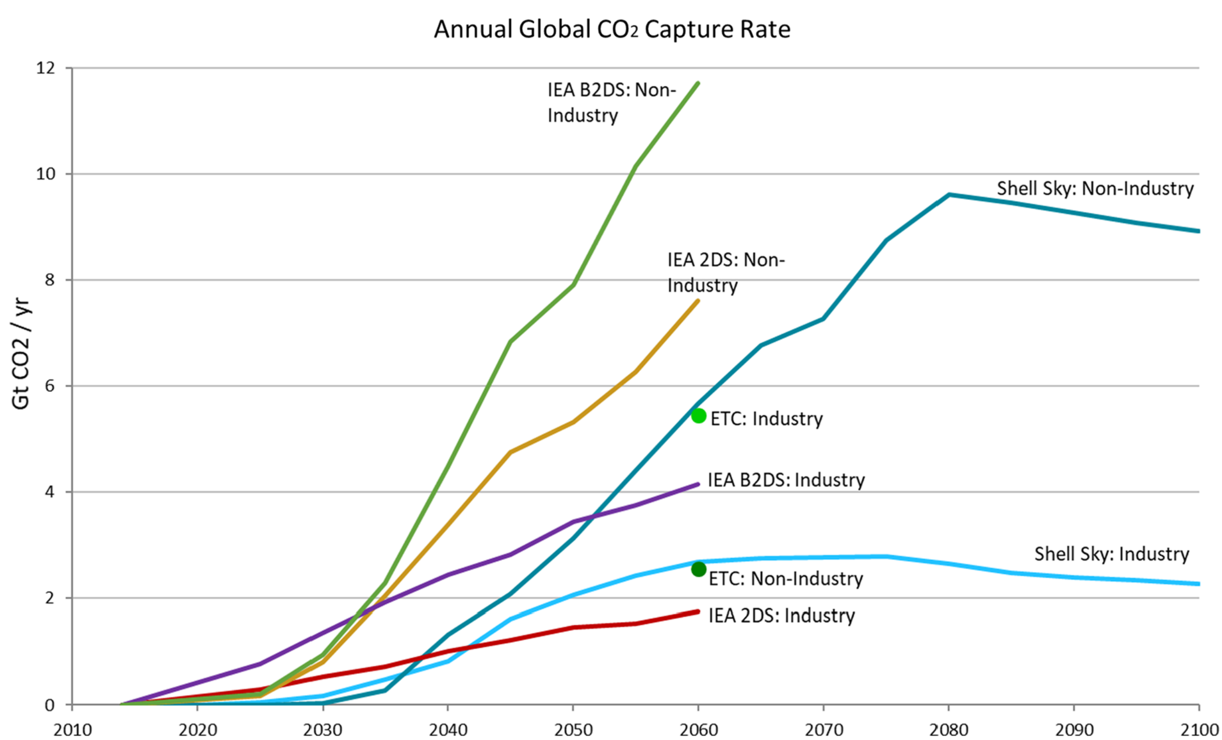


**Fig. 5.** $CO_2$ emissions from industry and non-industry sources captured in the Shell Sky, IEA 2DS, IEA B2DS, and ETC scenarios.

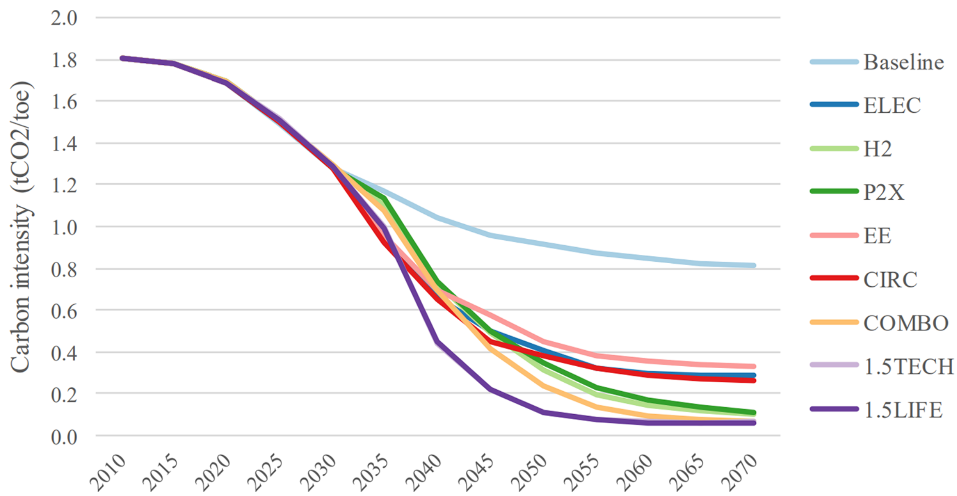


**Fig. 6.** Carbon intensity of EU industry under nine scenarios appearing in the European Commission's long-term plan [34]. Image CC BY 4.0 (permission).

now, and measures started in earlier phases must persist in later phases.

This framework is informed by the phases of technology development and deployment commonly seen in large-scale energy systems [35]. New technologies go through a few decades of high-percentage growth but from a very small base. Once the technology becomes 'material'—typically just a few percent of the system—growth becomes linear, then tapers off as the technology approaches its final market share. These deployment curves are remarkably similar across different technologies. As a result, there is often a lag of up to 30 years between initial testing of a technology and large-scale deployment. Two notes:

- Demand-side interventions, such as material efficiency, longevity, and re-use (discussed in Section 5.1), may have less need for new physical technologies. However, they may involve more changes to social practices, business models, production location, etc. Like new energy technologies, demand-side interventions may need policy support and a multi-decade timeframe to achieve materiality.
- If political pressure to rapidly reduce emissions becomes acute (perhaps in response to accelerating climate damages), the investment cycle can be sped up through mandatory early retirement of the highest-GHG-intensity industrial facilities. This practice is already being used to phase out coal electricity generation in certain regions. For instance, Ontario completed a coal phase-out in 2014 [36], and U.S. air quality regulations have accelerated the retirement of older coal units that would be too expensive to retrofit with pollution controls [37]. The Chinese government has shut down highly polluting industrial facilities for air quality reasons [38].

## 3. Supply-side interventions: Materials and carbon capture

### 3.1. Cement production

Hydraulic cement, a powder that reacts with water to act as a binder in concrete, is one of the most-used materials in the world. Annually, cement production exceeds 4 billion metric tons [39]. Currently, global demand is largely driven by China and other Asian countries, which were responsible for 80% of cement production in 2014 (Fig. 7). In regions such as these, recent growth in heavy industries and a relatively high dependence on coal as an energy source has led to high $CO_2$ emissions from manufacturing [40].

Cement manufacturing releases $CO_2$ through two main activities: energy use and calcination reactions. Energy-related emissions (30–40% of direct $CO_2$ emissions) occur when thermal fuels, most commonly coal, are used to heat a precalciner and rotary kiln. The other primary source of direct $CO_2$ emissions ("process emissions") come from a chemical reaction that takes place in the precalciner, where limestone (largely calcite and aragonite, with chemical formula $CaCO_3$) is broken down into lime (CaO) and carbon dioxide ($CO_2$). The $CO_2$ is released to the atmosphere, while the lime is used to make clinker, one of the main components of cement [42].

Cement production has substantial environmental impacts. Globally, cement and concrete are responsible for 8–9% of GHG emissions, 2–3% of energy demand, and 9% of industrial water withdrawals [43–45]. Further, the selection of fuels for cement kilns, and in part the kiln materials used, currently lead to notable air pollutant emissions [46]. It is critical to select mitigation strategies that can contribute to reduced $CO_2$ emissions while lowering other environmental burdens. This is especially true considering the high near-term projected future demand for cement [47]. These factors must be taken into consideration when evaluating strategies to decarbonize cement production, one of the most difficult industries to decarbonize [48], due to the need for high temperatures, the generation of $CO_2$ process emissions, and the large quantity of cement demanded globally. However, there exist a number of approaches that show promise, each with varied effects on other environmental impacts:

#### 3.1.1. Techniques that reduce process emissions from cement

Mineral and chemical admixtures are a critical mechanism for reducing $CO_2$ emissions [49]. Mineral admixtures can range in properties. Supplementary cementitious materials can be pozzolanic (i.e., a material that is not cementitious on its own, but reacts with cement hydration products to contribute desirable properties to concrete) or cementitious (i.e., possess cementitious properties). Supplementary cementitious materials contribute to the formation of crystalline structures that can improve concrete properties [50]. Mineral admixtures also include inert fillers that can improve packing and reduce demand for cement. Quantities of mineral admixtures can vary greatly between concrete mixtures depending on properties desired and local specifications, but common cement replacement levels range between 5 and 15% for inert fillers [51] and are higher for supplementary cementitious materials, in some cases exceeding 50% replacement [52].

Chemical admixtures can contribute to reductions in cement demand. Chemical admixtures are typically used in relatively low quantities compared to cement. These admixtures allow desired setting times, workability, air entrainment, and other properties to be achieved. Because of the additional control that can be gained over concrete properties through use of chemical admixtures, changes that would have otherwise required altering water or cement content can be obtained. As a result, lower levels of cement use are possible. The use of chemical admixtures also facilitates greater use of mineral admixtures

**Table 1**
A framework for decarbonization of global industry from 2020 to 2070. This table is a projection of what would be necessary to achieve rapid global industry decarbonization, not a prediction of what will happen. Achievable emissions reductions are relative to present-day emissions levels. Technologies that achieve materiality in one phase continue to be used and refined in subsequent phases. Even after a technology achieves materiality, further R&D is necessary to continue to drive down costs and improve performance, but this R&D will increasingly be conducted by private firms.

| Timeframe | Actions | Technologies achieving materiality | Key R&D areas to enable future technologies | Achievable emissions reductions |
|---|---|---|---|---|
| 2020–2035 | Efficiency improves continuously, with most industrial processes undergoing incremental improvements. After 2030, efficiency delivers diminishing returns. A growing number of processes shift towards electricity, particularly for light industry, where electricity use doubles from 2020 to 2040. Material efficiency, longevity, and re-use are recognized as key strategies and begin to be codified into policy. Heavy R&D investments are directed into technologies that will be important in subsequent phases, such as building CCS demonstration plants and reducing the cost of zero-carbon hydrogen. | ● Electrification<br>● Material efficiency<br>● Energy efficiency<br>● Increased re-use and recycling (circular economy) | ● CCS<br>● Zero-carbon hydrogen production<br>● Hydrogen use<br>● Novel chemical catalysts and separations<br>● New cement chemistries | 20% |
| 2035–2050 | Structural shifts emerge based on technologies that are available and nearing maturity for commercial deployment in the 2020–2035 timeframe. CCS falls into this category and deploys rapidly through this period, assuming a market pull or price push to incentivize it. Alternate materials (new cement chemistries, tall wood buildings) gain market acceptance and are widely adopted. | ● CCS<br>● New cement chemistries<br>● Alternative materials<br>● New chemical production methods | ● Zero-carbon hydrogen production<br>● Hydrogen use | 50% |
| 2050–2070 | Widespread deployment begins for process and energy technologies that are nascent today but are refined through large-scale pilots in 2020–2050. Hydrogen in heavy industry scales rapidly during this period. With sufficient policy push, this period could deliver net-zero emissions for industry. | ● Zero-carbon hydrogen production<br>● Hydrogen use | ● Ongoing refinement of existing, promising technological pathways | 80–100% |

in concrete mixtures and, in conjunction with smart concrete management, the effectiveness of chemical and mineral admixtures can be improved as a $CO_2$ mitigation tool [53]. While the application of admixtures has been common practice in the manufacture of concrete to achieve desired properties, such as reduced heat of hydration, their use to reduce GHG emissions is a focus of current research [54].

Beyond admixtures, the use of alternative inorganic cements to replace conventional Portland cements may play a critical role in achieving tailored properties from concrete with lower carbon dioxide emissions [55,56]. These alternative cements are typically classified into two categories: clinkered alternative cements, which are produced using similar technologies to conventional Portland cements, and non-clinkered alternative cements, which are produced without pyroprocessing [55]. $CO_2$ reductions from clinkered alternative cements derive from differences in raw materials or a lower energy requirement for kilning [57]. Different clinker phases have different enthalpies of formation; as such, there is the potential to lower energy demand in kilns if changes are made to the cement phase composition [58]. Depending on fuel resources used, there could be improvements in other environmental impacts through a reduction in energy demand [58]. However, some of these alternative clinkered cement systems require the availability of raw material resources that may not be as prevalent as those used in conventional cements. Considering the high global demand for cement, resource availability or competition with other sectors for resources can be a constraining factor for some alternatives in certain regions.

A range of non-clinkered alternative cements can be produced; the most commonly discussed cements in this category are alkali-activated materials. Depending on the solid precursor selected, the alkali-activator selected, and any energy requirements for curing, alkali-activated materials are expected to yield lower GHG emissions than conventional Portland cement [56]. As alternative cement systems can lead to changes in performance, such factors should be taken into consideration in their use.

Unlike Portland cement binders, which react with water to solidify, there are binders that can instead harden by reacting with $CO_2$ [57]. Among these, the most frequently discussed are MgO-based binders and carbonatable calcium silicate-based binders. Often, to drive the reaction with $CO_2$ at a reasonable rate, high concentrations of $CO_2$ are required. Currently, MgO-based binders are predominantly explored in an academic setting, but carbonatable calcium silicate-based binders have started to be used in early-stage commercialization [57]. As with other alternative cements, availability of raw materials to form these cements could be a constraining factor in their use, and some raw material resources for these cements could lead to a net increase in lifecycle $CO_2$ emissions relative to Portland cement, even considering the carbon uptake during curing [58]. Further, due to the low pH of these cement systems, they would not be suitable for applications in which the concrete requires conventional steel reinforcement.

#### 3.1.2. Techniques that reduce thermal fuel-related emissions from cement

To reduce energy-related emissions from cement (e.g. from the fuel used to heat the precalciner and kiln), the main options are improving the thermal efficiency of cement-making equipment, fuel switching, electrification of cement kilns, and carbon capture and sequestration (CCS).

Reducing the moisture content of input materials improves energy efficiency, as less energy is needed to evaporate water. This can be achieved by using a dry-process kiln and ensuring the kiln has a precalciner and multi-stage preheater. Recovered heat can be used to predry input materials. A grate clinker cooler is better at recovering excess heat than planetary or rotary-style coolers [47]. The extent to which these upgrades can reduce energy use depends on the age and efficiency of the technology already in use. Most modern kilns incorporate this processing stage, which is reflected in the high-producing regions that recently expanded cement production capacity [59].

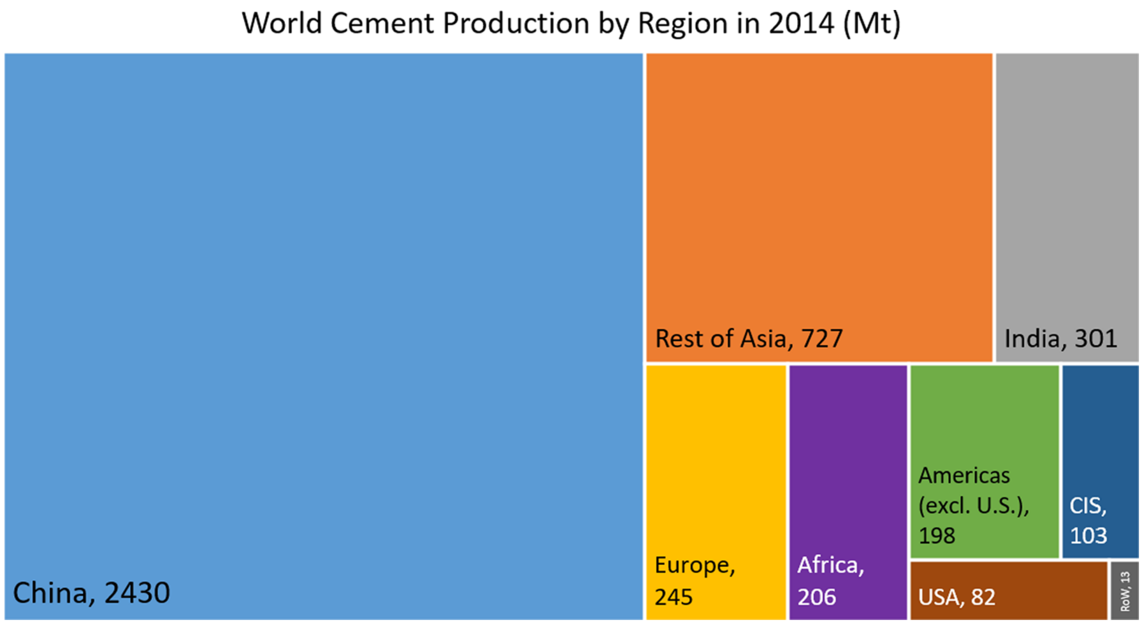


**Fig. 7.** Cement production by world region in 2014. CIS = Commonwealth of Independent States. RoW = Rest of World [41].

Certain mineral compositions can lower the temperature at which input materials are chemically transformed into clinker, and less fuel is needed to reach a lower temperature [47]. However, some of these alternatives can alter cement performance, so testing and certification of alternative cement chemistries will be important. Another approach is to react fuel with oxygen-enriched air, so less heat is lost in the exhaust gases [60]. Oxy-combustion also has the benefit of reducing the concentration of non-$CO_2$ gases in the exhaust stream, making carbon capture easier.

Today, 70% of global thermal fuel demand in the cement industry is met with coal, and another 24% is met with oil and natural gas. Biomass and waste fuels account for the last 6% [47]. Biomass and waste fuels typically have lower $CO_2$-intensity than coal, though they may have other drawbacks, such as a higher concentration of particulates in the exhaust [61].

To completely decarbonize heat production for cement, electrification of cement kilns or CCS may be necessary. The best route may vary by cement plant, as it will be influenced by the price and availability of zero-carbon electricity, as well as the feasibility of carbon capture and storage at the plant site [24]. Due to the ability for hydrated cement to carbonate, and in doing so uptake $CO_2$, some work has started to quantify potential carbon capture and storage through using crushed concrete and fines at the end-of-life [62,63].

#### *3.1.3. Techniques that reduce both process and energy-related emissions from cement*

There are design and engineering techniques that can reduce the amount of concrete required to achieve a given strength, such using curved fabric molds instead of standard geometries with sharp angles and corners [64] and pre-stressing concrete using tensioned steel cables [65]. The use of concrete mixture optimization [66,67], improved design of members or structures through use of high-performance concrete or through better tailoring mixture selection with steel reinforcement [68,69], and increasing time to functional obsolescence have all been proposed as means to reduce GHG emissions [70,71]. Most of these methods would reduce total material demand, and in doing so, cut production-related emissions. More options to reduce concrete demand are discussed in Section 5.1. Additionally, there may be human settlement patterns that require less construction materials. For example, not building in areas threatened by sea level rise may

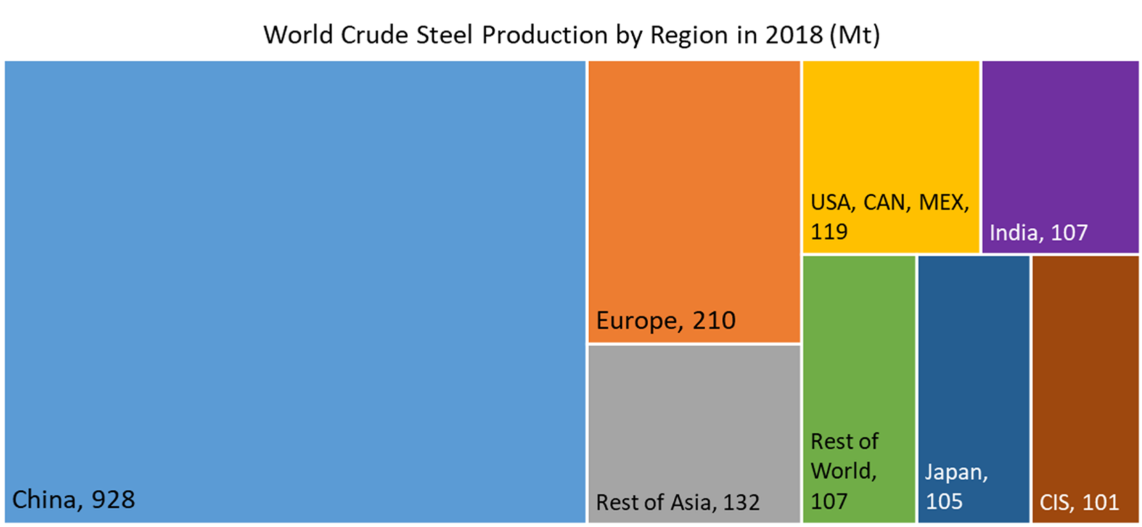


**Fig. 8.** Crude steel production by region in 2018 (Mt) [73].

reduce demand for concrete to construct seawalls and to repair buildings [2].

Finally, the cement industry may use carbon capture technology, discussed in Section 3.4.

### 3.2. Iron and steel production

Steel is an essential material for vehicles, buildings and infrastructure worldwide. It is a product of a large and technologically complex industry characterized by high capital intensity, dependence on bulk raw materials, cyclical growth and profitability trends, and periodic over-capacity. These factors hinder the adoption of emissions reduction technologies that would add costs to an industry with relatively low profit margins.

Global steel production during 2018 was 1808 million metric tons (Mt), with more than half contributed by China (Fig. 8), though China's steel demand is projected to gradually decline by around 40% through 2043 [72].

There are several pathways for primary (from iron ore) and secondary (recycled) steel production [74].

**Primary production using a blast furnace/basic oxygen furnace (BF/BOF)** is used for 71% of all steel production [73]. In the BF/BOF process, iron ore and coke (purified coal) are placed in the blast furnace, where a chemical reaction removing (reducing) oxygen from iron ore occurs. The reduced iron and remnant carbon are then transferred to the basic oxygen furnace, where the desired carbon level is established by adding powdered carbon, and the mixture is alloyed with other metals (such as manganese, nickel, or chromium) to create steel with desired properties. Sometimes, up to 30% recycled scrap is added to the BOF to reduce the need for raw iron and to dilute any impurities in the scrap. Coal is combusted for process heat, is used as the chemical agent for reducing the iron ore, and is a source of carbon. The BF/BOF process produces combustible byproduct gases (e.g. coke oven gas, blast furnace gas, and converter gas), which can be used as supplementary fuel within the steel plant or transformed into salable chemicals, such as methanol [75].

BF/BOF producers typically have large, integrated steel-making facilities with coal-coking operations. BF/BOFs can produce any type and quality of steel. The average emissions intensity from the BF/BOF route is 2.8 metric tons of $CO_2$ per metric ton of steel, but the most efficient ones produce only 1.8 t $CO_2$/t steel [76].

**Primary production using direct reduced iron method followed by an electric arc furnace (DRI-EAF)** is used for about 6% of all steel production [73]. In a typical DRI, methane is transformed into a syngas of hydrogen ($H_2$) and carbon monoxide (CO), with hydrogen playing the primary role of scavenging the oxygen (reducing the iron) and CO contributing carbon to the steel. The hot briquetted iron that emerges is then melted and alloyed in an electric arc furnace. DRI-EAFs were originally used only for long steel products (such as wire, rails, rods, and bars), but the latest plants can make any type and quality of steel. The GHG intensity of DRI-EAFs can be as low at 0.7 t $CO_2$/t steel if decarbonized electricity is used.

**Secondary production in an electric arc furnace (EAF)** accounts for 20–25% of all steel production [73]**.** In an EAF, scrap metal is melted by running an electric current through it. This is the most widely used method for recycling scrap. EAFs require already-reduced input materials, such as scrap steel, pig iron, direct-reduced iron (DRI), and ferro-alloys. Like DRI-EAFs, modern EAFs can potentially make any type of steel, depending on the scrap quality. However, if the scrap is too contaminated, it can only be used for some long products and reinforcing bar. The GHG intensity of the EAF route depends on the electricity source and can be GHG-free if supplied with decarbonized electricity. EAFs can operate cost-effectively at smaller scales than BF/BOFs, so EAFs are often found in mini-mills.

**Induction furnaces are used to melt already-processed metal in secondary manufacturing** using surface contact to create electromagnetic eddies that provide highly controllable heat. They are potentially highly efficient but cannot handle oxidized metals. They are also used for secondary steel production—for example, induction furnaces accounted for 30% of India's 2018 steel production [77]—but this route doesn't allow for effective control of steel composition or quality [78]. China banned induction furnace-based steel in 2017, causing many of these furnaces to be sold to companies in Southeast Asian nations [79]. As with EAFs, the GHG intensity of induction furnaces depends on the electricity source.

In recent decades, the steel industry has achieved significant reductions in energy input and $CO_2$ emissions intensity. Increasing use of EAFs, as well as utilization of waste heat recovery technologies, have contributed to a 61% reduction in energy consumption per ton of steel produced since 1960 [80]. However, these intensity improvements have not been sufficient to reduce total absolute GHG emissions from steel production. Globally, the average final energy intensity of steel production is approximately 21 GJ/t crude steel [81], and there remains an estimated 15–20% improvement potential using existing efficiency and waste heat recovery technologies [80], but this varies by country [82].

Modern steel plants operate near the limits of practical thermodynamic efficiency using existing technologies. Therefore, in order to drastically reduce the overall $CO_2$ emissions from the production of steel, the development of breakthrough technologies is crucial. There are fundamentally two pathways to reduce carbon emissions from steel production: one is to continue to use current carbon-based methods and capture the carbon; the other is to replace carbon with another reductant such as hydrogen, or direct electrolysis. Technological options include [83–85]:

- EAF with decarbonized electricity. When possible, e.g., given sufficient supply of scrap steel, powering EAF with decarbonized electricity would reduce the carbon intensity of steel to just 2–5 kg $CO_2$/ton steel (residual emissions from the electrodes), a reduction of over 99% relative to a traditional BF/BOF process [86]. Studies have considered a much higher penetration rate of EAF in total steel production, reaching 47–56% of the EU's or 100% of Germany's steel production by 2050 [87].
- **HIsarna** combines the BF/BOF steps to create a more efficient process that also produces a concentrated $CO_2$ waste stream, easing carbon capture. The process directly injects fine iron ores and crushed coal into the smelt reduction vessel, thus eliminating sinter, pelletizing, or coking [88]. Since 2010, HIsarna has been piloted at small scale, supported by the EU's Ultra-Low Carbon Dioxide Steelmaking (ULCOS) and Horizon 2020 programs. A Hlsarna pilot plant was built in Ijmuiden, the Netherlands and has been testing its processes since 2011 [89]. Tata Steel is considering a full-scale pilot in India. According to the Technology Roadmap conducted by UNIDO and IEA, Hlsarna equipped with CCS could capture about 80% of $CO_2$ emissions [90].
- Hydrogen DRI-EAF, also known as **HYBRIT**. HDRI-EAFs use low-GHG hydrogen (via electrolysis or steam methane reforming with CCS) directly (instead of a methane-derived syngas) as the iron ore reducing agent, avoiding $CO_2$ creation [91]. This direct reduction of iron (DRI) process produces a solid porous sponge iron. After direct reduction, sponge iron is then fed into EAF, where iron is melted by electric current. After the EAF process, liquid steel is produced for final chemical composition adjustment before casting. HYBRIT has completed feasibilities studies, and the first demonstration plant by SSAB, LKAB, and Vattenfall is under construction in Sweden. The company plans to complete pilot plant trials in 2024 and start offering fossil-free steel products commercially in 2026. SSAB aims to convert all of its plants for fossil-free steel production by 2040–2045 [92]. ArcelorMittal is planning another pilot in Germany [93].
- Prior to the HYBRIT effort, the only commercial application of hydrogen DRI was in Trinidad, where DRI was produced in fluidized

bed reactors with hydrogen from steam reforming [94]. Authors such as the Fifth Assessment of the Intergovernmental Panel on Climate Change (IPCC) and Weigel et al. (2016) identified hydrogen-DRI as the most promising zero-carbon steel production route through a multicriteria analysis (including economy, safety, ecology, society, and politics), comparing it with electrowinning and blast furnace steelmaking with and without CCS [64,95]. Vogl et al. estimated that hydrogen-based DRI-EAF would require 3.48 MWh per ton of liquid steel (or 12.53 GJ/ton) to produce, including electricity demand for hydrogen production (51 kg of hydrogen per ton of steel) [96]. Otto et al. similarly estimated this steel production route would consume 12.5 GJ/tonne of liquid steel, where 62% of energy is used for producing hydrogen [97].

- Electrolysis of iron ore, either through an aqueous process [98] or molten oxide electrolysis. Aqueous electrolysis (or "electrowinning") is being piloted by Arcelor Mittal as **SIDERWIN**, another product of the EU ULCOS technology program [99]. The molten oxide electrolysis method involves directly reducing and melting iron ore with electricity [100,101]. The technology is being piloted by Boston Metals. Similar to hydrogen DRI-EAF, an electrolysis-based approach could entail significant electricity demand [86].
- BF/BOFs using biocharcoal as the fuel and reducing agent. There are facilities in Brazil that utilize some biocharcoal. However, for every ton of steel produced, about 0.6 tons of charcoal is needed, which requires 0.1–0.3 ha of Brazilian eucalyptus plantation [48,102,103]. This poses a land-competition challenge between growing fuels and food. This also limits the adoption of this type of steel-making technology in countries with limited arable land [102].
- BF/BOFs utilizing top gas recirculation and CCS. Blast furnaces are the largest source of direct $CO_2$ emissions in the steel-making process. By utilizing exhaust gas ("top gas recycling") on BFs, the $CO_2$ concentration in the exhaust could be increased up to 50% [48]. By adopting CCS on BF/BOF routes, it is estimated that $CO_2$ emissions could be reduced at about 80% [86]. Retrofitting existing facilities to fit CCS units could increase cost and complexity. Retrofits can be challenging because steel plants may have unique designs and multiple emission sources with different gas compositions and flow rates [104].

These technologies range from lab bench through pilot phases and will cost more than BF/BOF steel in early commercial versions. They will need R&D support, as well as dedicated starter markets, to achieve market share and scale.

Additionally, substantial reductions of GHG emissions are possible through increased recycling and by reducing total steel demand, discussed in Section 5.

### 3.3. Chemicals production

Chemicals production is a major global industry, producing chemicals worth €3475 billion in 2017 (Fig. 9). In the chemicals industry, considerable emissions intensity reduction has been achieved by switching to lower-carbon fuels, improving energy efficiency, and using catalysts to reduce emissions of nitrous oxide ($N_2O$), an important GHG. For example, the energy intensity of the European chemicals industry has declined by 55% since 1991 [19]. However, these measures have been refinements of existing technologies. To enable significant, absolute GHG reductions required for climate stabilization, new chemical production technologies are needed [105,106].

#### 3.3.1. Avoiding fossil fuel emissions

Fossil fuel combustion is the largest source of $CO_2$ in the chemicals industry, so developing processes that reduce these emissions is the top priority. There exist promising approaches that may be refined for commercial use.

For example, steam crackers (machines that break large hydrocarbons into smaller molecules) must reach a temperature of 850 °C to break down naphtha for further processing. If this energy could come from zero-emissions electricity, $CO_2$ emissions could be reduced up to 90%. Six major chemical manufacturers (BASF, Borealis, BP, LyondellBasell, Sabic, and Total) have established a consortium to jointly investigate the creation of the world's first electrical naphtha or steam crackers [107].

New catalysts can reduce input energy requirements for various chemical transformations. For example, recent catalyst systems allow methane ($CH_4$) to be dry-reformed into dimethyl ether ($CH_3OCH_3$), which can in turn be transformed into various olefins [108] such as ethylene ($C_2H_4$), the most-produced organic compound in the world [109]. More broadly, there exist a range of energy efficiency options for chemicals production, including options with negative lifetime costs [110].

Significant volumes of $CO_2$ are released for hydrogen production, which is used in large quantities by the chemicals industry as a reactant, e.g. for ammonia production. Techniques to decarbonize hydrogen production are discussed in Section 4.1.

#### 3.3.2. Biomass feedstocks and recycled chemicals

Today, petrochemical raw materials are important inputs to the process of making many chemicals. Biomass may be used instead of fossil fuel feedstocks for specific target molecules.

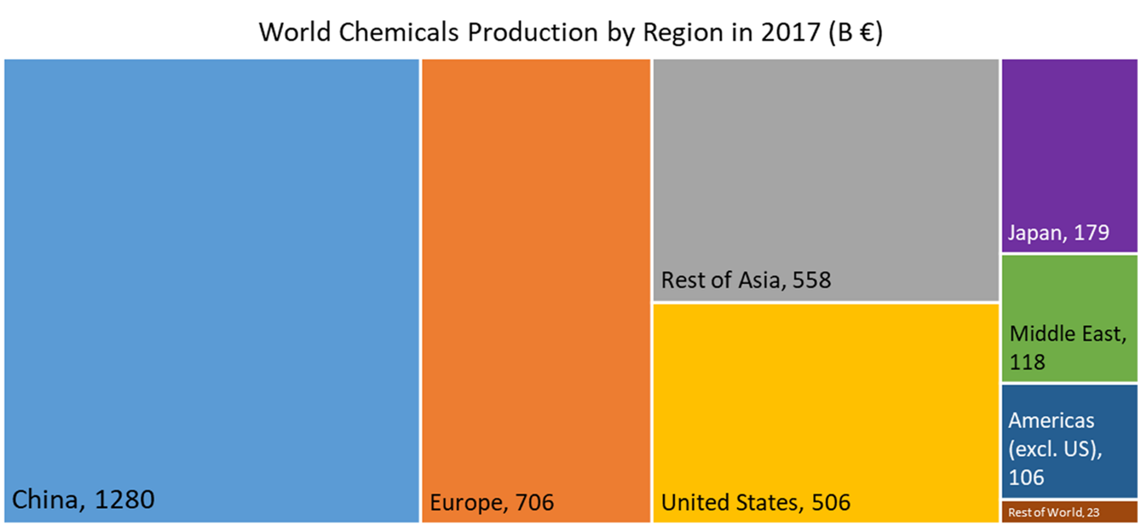


**Fig. 9.** World chemicals production by region in 2017 (billion €). Calculated from sales, import, and export data in [19].

Lignocellulose—essentially dried, inedible plant material, including wood, grasses, agricultural byproducts, and industrial byproducts from saw and paper mills—is the most abundant organic substance on Earth [111] and a promising option to produce chemical feedstocks. Lignocellulose has three main components: cellulose, hemicellulose, and lignin. Biomass can be fractionated into these components, which have an estimated value of $500 per metric ton of dry biomass when used as inputs to the chemicals industry [112]. However, it is typically less costly to use petroleum feedstocks, in part because today's commercialized technology does not recover and allow for the use of all of the cellulose, hemicellulose, and lignin in biomass [112]. Therefore, proper financial incentives (such as sellable credits under a carbon trading scheme) will be key to the deployment of biomass-derived chemical feedstocks, along with a methodology to allocate the greenhouse gas emission savings to final products, to allow for the development of a market [113]. Additionally, there are limits to the quantity of biomass that may be sustainably produced, given competition with food agriculture and biodiversity needs [2].

Today, recycling companies refuse certain plastics, including mixed and polluted plastic material. Mechanical separation of recycled plastics encounters limits due to sorting requirements and decreasing material quality with each cycle. One solution is to break plastics down into monomers, which can then be used as building blocks for chemical production [114] For example, poly(ethylene terephthalate) (PET), one of the most commonly used plastics in the packaging and textile industries, can be broken down using alkaline hydrolysis with a 92% yield at relatively low (200 °C) temperatures with short reaction time (25 min) [115]. Pyrolysis (thermal decomposition of plastics in an oxygen-free environment) can also be used to create recycled chemical feedstocks [116], but depending on the plastic source, contamination with phthalates [117] or other chemicals [118] can be a concern. Currently, traditional feedstocks are cheaper than recycled feedstocks, but the right policy environment (e.g. a cap-and-trade system, regulatory requirements, tradeable credits, etc.) could make recycling these chemicals economically viable.

#### 3.3.3. *Reuse of $CO_2$ for chemicals production*

$CO_2$ has long been used as a feedstock to produce certain chemicals whose molecular structure is close to that of $CO_2$, such as urea, $CO(NH_2)_2$ [119]. Urea used in fertilizer soon releases that $CO_2$ back to the atmosphere, but urea is also used for the production of longer-lived goods, such as melamine resins used in flooring, cabinetry, and furniture.

Researchers have investigated the capture and re-use of $CO_2$ as a feedstock for the production of other chemicals, including synthetic fuels production (by reacting $CO_2$ with hydrogen). In theory, if very large amounts of zero-carbon electricity or hydrogen were available, the chemicals industry could sequester more carbon than it emits. One study found the European chemicals industry could reduce its $CO_2$ emissions by 210 Mt in 2050, a reduction 76% greater than the industry's business-as-usual 2050 $CO_2$ emissions [120].

However, in most cases, use of feedstock $CO_2$ is accompanied by high energy demands (Fig. 10). This limits the number of potential applications. For carbon capture and use in the chemicals industry to have a material impact on global $CO_2$ emissions, the industry would need substantial technological innovation, and the availability of affordable, zero-carbon hydrogen would need to scale greatly [121]. Therefore, fuels and chemical products manufactured from $CO_2$ are unlikely to be significant contributors to global abatement in the next one to two decades. Often, the energy required to convert $CO_2$ to higher-energy molecules could be used more efficiently to provide demanded services directly (for instance, using electricity to power electric vehicles) or to drive other chemical pathways, at least until abundant renewable electricity and zero-carbon hydrogen are available.

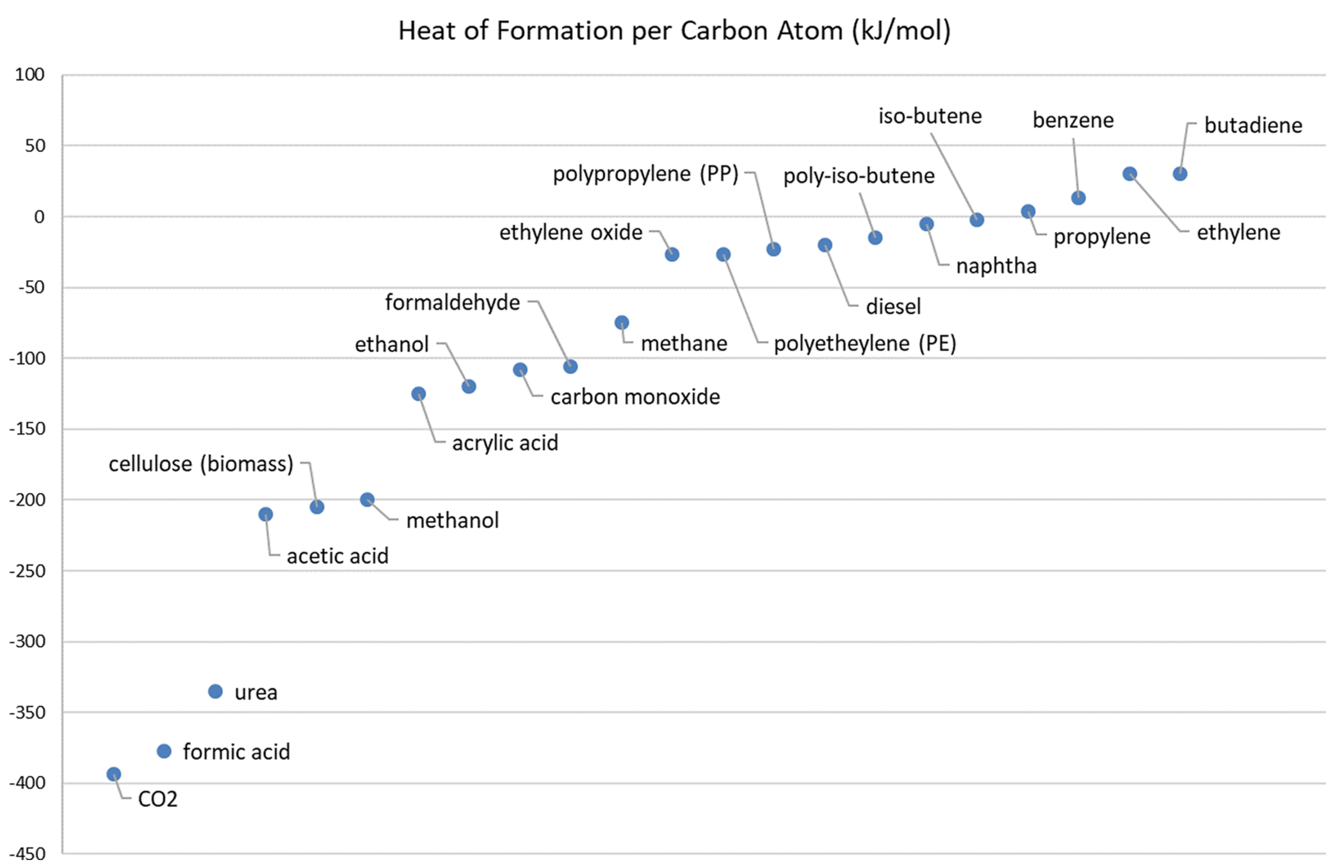


**Fig. 10.** Heat of formation $\Delta_f H_{(g)}$ of $CO_2$ and various chemicals per carbon atom (kJ/mol). Chemicals are in the gas phase, except urea, which is in the solid phase. Condensation energy (such as energy associated with water formation in the urea production process) is not considered [121].

#### 3.3.4. Chemical separations

Separating chemical and material mixtures into their components is a common process requirement across the manufacturing sector. Oak Ridge National Laboratory and BCS [122] found that separations in the U.S. chemical, refining, forestry, and mining industries account for 5–7% of U.S. total energy use. (The range depends on the use of direct energy use vs. purchased electricity.) Chemical separations are most commonly accomplished through the thermal processes of distillation, drying, and evaporation, which together account for 80% of chemical separations' energy use. Less energy-intensive processes such as membrane separation, sorbent separations, solvent extraction, and crystallization have been less-frequently used because of issues of cost, performance, and familiarity. As of 2005, Oak Ridge estimated that accessible improvements could reduce direct energy use for separations by about 5%, which would reduce U.S. emissions by about 20 million tons of $CO_2$e/year. A more recent report [123] suggests that improved approaches could increase the U.S. emissions reduction potential to 100 million tons of $CO_2$e/year.

Improved separation technology may also increase the efficiency of the desalination industry, which operates almost 16,000 plants producing 95 million cubic meters of desalinated water per day worldwide [124]. Desalination capacity is growing rapidly—capacity has more than tripled since 2005 [124]—and more desalination may be needed in the future, particularly in regions that will suffer increased water scarcity due to climate change.

Many new opportunities for improving the energy efficiency of separations stem from tailoring the molecular properties of membrane pores or sorbents to interact with the target molecules with great specificity. For instance, computational design of metal-oxide frameworks has yielded improved products for capture of $CO_2$ from flue gas and other sources [125,126]. Similarly, tailored metal-oxide frameworks can be used for separation of gold from seawater [127]. The chemical industry has recognized the value of pursuing more efficient separations, and several initiatives to drive innovation in this space are underway [128].

### 3.4. Carbon capture and storage or use (CCS or CCU)

Transforming industrial processes via electrification, alternative chemistries, hydrogen combustion, and other non-fossil fuel technologies can lead to an eventual outcome of zero $CO_2$ emissions, but these technologies are likely to leave a level of "residual" $CO_2$ emissions unaddressed until after 2060 [24]. This introduces the need for carbon dioxide capture and permanent removal, either via geological storage or embedding carbon within industrial products.

Capture of carbon dioxide from industrial processes is a well-established technology and has been used in the oil refining and natural gas processing sectors for decades. There are many methods available for capture, which can be classified as follows, with numerous variants of each class existing:

- **Pre-combustion:** partially combusting a fuel to produce carbon monoxide, which is then reacted with steam via the water-gas shift reaction to produce a mixture of hydrogen and carbon dioxide, which are then separated for subsequent use;
- **Post-combustion:** a chemical absorbent or adsorbent is used to pull carbon dioxide from combustion exhaust, before being regenerated by, for example, heating;

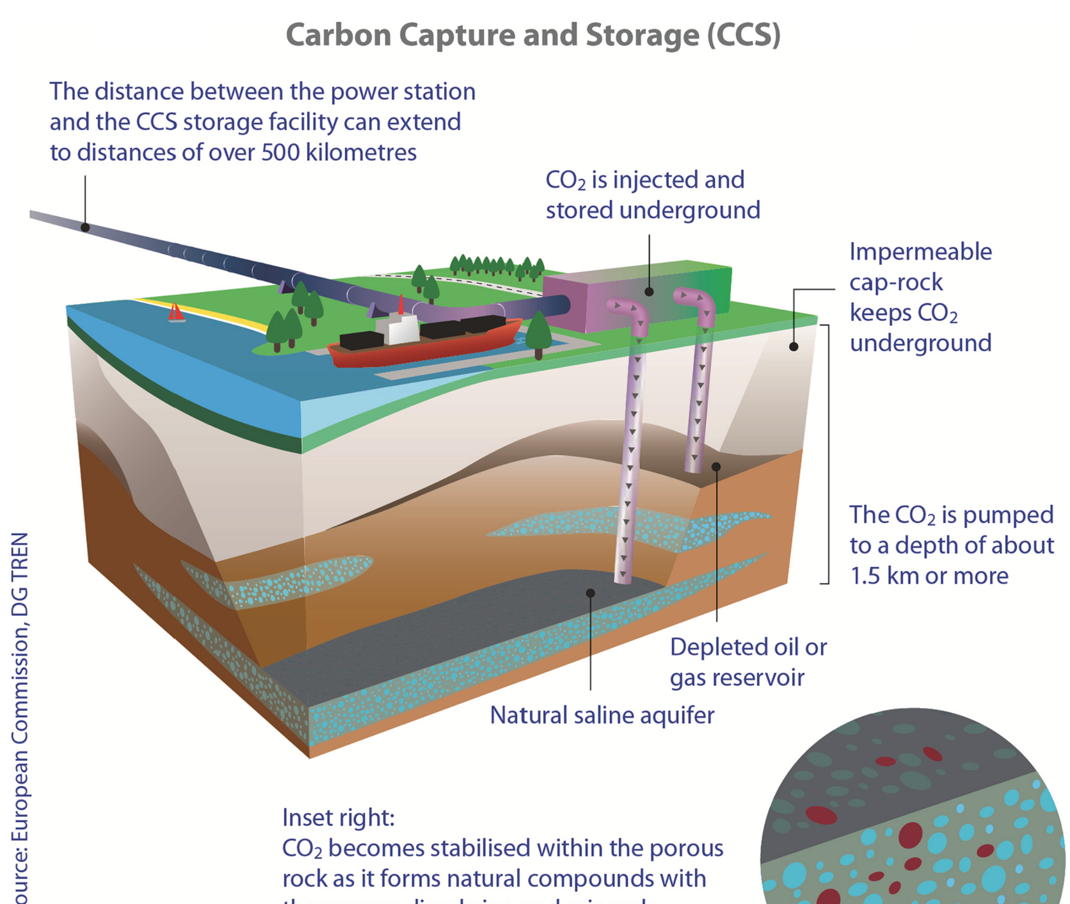


**Fig. 11.** An overview of underground carbon storage. Though this diagram indicates compressed $CO_2$ comes from a "power station," it may also be produced by an industrial facility or a cluster of facilities. Image CC BY 4.0 European Commission (permission).

- **Oxyfuel combustion:** oxygen is separated from air and reacted with fuel in combustion reactions, producing a stream of pure $CO_2$ (some of which is recycled to act as a temperature moderator in the combustion reaction).

Similarly, geological storage of carbon dioxide has roots within the oil and gas industry and can be commercially delivered at scale today [33,129,130]. In appropriate reservoirs (e.g. deep saline layers that encourage fixation of the $CO_2$ by reaction with surrounding geology), scientists believe storage of $CO_2$ to be a safe option for long-term carbon management [130,131]. However, there is strong public opposition to underground $CO_2$ storage in some parts of the world [130], so increased education and outreach may be necessary to improve public acceptance.

A key challenge to CCS uptake is increased energy requirements and associated costs. Capturing and compressing $CO_2$ is energy-intensive, so some of the energy produced must be devoted to powering the CCS process. A 2015 study of U.S. coal power plants found an efficiency penalty of 11.3–22.9%, which was sufficient to increase the levelized cost of electricity produced by these plants by 5.3–7.7 cents/kWh, on top of a cost of 8.4 cents/kWh for plants without CCS [132]. The European Environment Agency reports a similar finding: energy demands are increased by 15–25%, depending on the CCS technology used [133]. Since more fuel must be combusted to meet these increased energy demands, but only $CO_2$ is captured (not other air pollutants), CCS can increase conventional air pollution. Fine particulate matter ($PM_{2.5}$) and nitrogen oxide ($NO_X$) emissions increase roughly in proportion to fuel consumption, while ammonia ($NH_3$) emissions may more than triple, if amine-based sorbents are used to capture the $CO_2$ [133]. Ambient air pollution causes roughly 8.8 million deaths per year worldwide [134], so capturing a significant share of global $CO_2$ emissions could be accompanied by a large increase in pollution-driven mortality, or else large investments in equipment to remove $NO_X$ and particulates from the exhaust streams (which, along with increased energy costs, would challenge the cost-competitiveness of CCS) (see Fig. 11).

Carbon capture and use (CCU) operates differently from permanent geological storage (CCS). Carbon dioxide is converted into a finished product (such as synthetic fuels, plastics, building materials, etc.). The effectiveness of CCU as a form of long-term $CO_2$ storage depends on the fate of these manufactured products.

If the manufactured product is a synthetic hydrocarbon fuel, it may be burned, releasing the captured carbon back to the atmosphere. Abatement depends on the energy used to make the synthetic fuel and the extent to which the synthetic fuel displaces fossil fuels. This option is discussed in more detail in Section 3.3.

If the manufactured product is not a fuel, the carbon must remain trapped in the industrial product. The key determinant of the effectiveness of this storage option is not the useful life of a single product (which may be just a few years or decades) but the total stock of $CO_2$-derived products in society. To continue sequestering $CO_2$ year after year, that stock of products must continually grow (just as, if using CCS, the amount of $CO_2$ stored underground must continually grow). This may require $CO_2$-derived products to be securely stored (protected from decay) at the end of their useful lives, or it may require an increasing rate of $CO_2$-derived material production, to offset the decay of an ever-larger existing stock of material.

Carbon capture also offers the prospect of stand-alone $CO_2$ removal facilities. Carbon dioxide can be removed directly from the air via emerging separation technologies ("direct air capture") [135] or by growing biomass. In the latter case, the biomass is converted to an energy product and the carbon dioxide from this reaction is captured. Combining these forms of air capture with geological storage or $CO_2$ use offers a sink, which could be used to counterbalance the emissions of an industrial facility.

Direct air capture operates on a very small scale today, and scalability has yet to be demonstrated [136]. Capture from bioenergy facilities is scalable now and is being demonstrated at a commercial ethanol plant in Illinois [137]. A related option is to use biomass as a carbon sink. For example, Section 5.3 discusses increased use of wood in buildings.

CCS is a commercially ready technology, as demonstrated by a number of large industrial facilities. As of late 2019, the Global CCS Institute lists 21 currently operating CCS projects with a combined $CO_2$ capture capacity of 35–37 million metric tons per year [138] (though not all of these plants are operating at maximum capacity). Examples include the QUEST hydrogen production facility in Canada (1 Mt $CO_2$/yr), Archer Daniels Midland's corn-to-ethanol plant in Illinois (1 Mt $CO_2$/yr), and the first CCS project in the iron and steel industry, located in Abu Dhabi (0.8 Mt $CO_2$/yr).

Key to large-scale CCS deployment is a policy environment that delivers $CO_2$ transport and storage infrastructure (such as a regulated asset base model [139]) and provides revenue to support the additional operating costs (such as carbon pricing and/or financial incentives for CCS). A clean energy or emissions intensity standard may also drive CCS adoption.

## 4. Supply-side interventions: Energy

### 4.1. Hydrogen

While electricity is a highly flexible energy carrier for a net-zero energy system, it is presently difficult and expensive to store, and today's batteries have lower energy density than thermal fuels. This makes electricity difficult to use for long haul aviation, heavy freight, and high process heat needs [48,84]. There are also several chemical feedstock needs that cannot be met with electricity, or only at very high cost [140]. To maximize the potential of electricity, one or more companion zero-carbon energy carriers are required.

The most-discussed candidates for such an energy carrier are hydrogen ($H_2$) and chemicals that can be derived from hydrogen, particularly ammonia ($NH_3$) and methane ($CH_4$) or methanol ($CH_3OH$). Relative to hydrogen, ammonia is easier to transport and store [141], and existing natural gas infrastructure and equipment is built to handle methane. Fortunately, ammonia and methane can be made from hydrogen with an energy penalty—efficiencies of 70% for ammonia [141] and 64% for methane [142] have been demonstrated—so the ability to produce low-cost, carbon-free hydrogen is of great value even if ammonia or methane is the energy carrier of choice.

Currently, about 70 Mt of pure hydrogen are produced worldwide annually. Of this total, 76% is produced by steam reforming of methane, 22% by coal gasification, and 2% by electrolysis (using electricity to split water molecules) [30]. In addition, hydrogen is also produced as a by-product of industrial processes, e.g., direct reduction of iron for steel-making and the chlor-alkali process to produce chlorine and sodium hydroxide. Globally, about 30 Mt of hydrogen is produced each year as a byproduct [30]. Most of the produced pure hydrogen is used in ammonia production (43%), oil refining (34%), methanol production (17%), and other sectors (6%). About 0.01% of the produced pure hydrogen is used by fuel-cell electric vehicles [30]. Global hydrogen production from fossil fuels emits 830 Mt of $CO_2$ per year [30], equivalent to the annual emissions from the energy used by 100 million U.S. homes.

Steam reforming of methane requires input heat and produces chemical process $CO_2$ emissions. These process emissions are ideally suited for carbon capture because there is no need to filter out atmospheric nitrogen [143]. The IEA estimates that "blue" hydrogen, where hydrogen is made with steam methane reforming (SMR), with CCS to capture the process emissions, could be made for $1.5/kg in the Middle East and the U.S. (compared to $1.0/kg for unabated SMR hydrogen), $1.6/kg in Russia, and $2.4/kg in Europe and China [30]. There are also emerging technologies to make hydrogen directly from fossil methane via pyrolysis, with elemental carbon as a co-product [144,145]. The sale of potentially high-value carbon co-products such as carbon black, graphite, carbon fiber, carbon nanotubes, and needle coke could help reduce the net cost of $CO_2$-free hydrogen production via methane pyrolysis to \$2/kg $H_2$ or less [146].

Coal-based hydrogen production also exists, mostly in China. About 60% of China's hydrogen production is from coal [147], and China accounted for 35% of the world's pure hydrogen production as well as 28% of by-product hydrogen production [148]. Hydrogen production based on coal gasification is more carbon-intensive than natural-gas based steam methane reforming, emitting 19 $tCO_2$/t $H_2$ produced [30]. It also has lower $CO_2$ concentration in the syngas with higher impurities (e.g., sulphur, nitrogen, minerals) making carbon capture difficult and costly [30].

There are several ways to split water into hydrogen and oxygen using variants of electrolysis [120]. The current standard process is alkaline electrolysis. Solid oxide fuels cells (SOFCs) have the potential to dramatically improve electrolysis efficiency compared to alkaline electrolysis, while proton exchange membrane fuel cells (PEMFCs), originally developed for vehicle use, promise the capability to provide small, modular, and mobile electrolysis units. Both SOFCs and PEMFCs offer the possibility of improving the efficiency and cost of electrolysis by at least 50%. There are also several research projects to directly use sunlight to generate hydrogen from water [149,150]. Other approaches, such as the use of bubble column reactors filled with liquid metal, have been explored [151].

The current economics of hydrogen production through electrolysis depends on capital cost, the cost of electricity, and efficiency of the system. Using renewable electricity, per unit cost of hydrogen is in the range of \$2.5–6/kg $H_2$ [30], or in some cases as high as \$10/kg $H_2$ [152,153]. Studies estimate the future cost of electrolysis-based hydrogen production may be reduced to \$2–4/kg $H_2$ [30]. Producing hydrogen from electricity also raises challenges for electricity demand and water needs. At the current technology level, it needs 51 kWh/kg $H_2$ and 9 L of fresh water per kg $H_2$. If sea water or brackish water is used, reverse osmosis for desalination is required, which would add another 3–4 kWh/$m^3$ for water treatment. This would increase the cost of hydrogen slightly, about \$0.01–0.02/kg $H_2$.

Hydrogen has a very low density (0.09 kg/$m^3$ at ambient temperature and atmospheric pressure). Thus, hydrogen storage is one of the key barriers for scale-up. Currently, most hydrogen is stored in compressed gas or liquid form for small-scale mobile and stationary applications [153]. Both compressing and liquefication of hydrogen require high energy input, at about 2.21 kWh/kg $H_2$ for compressing to 40 kg $H_2$/$m^3$ and 15.2 kWh/kg $H_2$ to achieve liquefication and 70.8 kg/$m^3$ [153,154]. In addition, stored hydrogen is released through boiling-off losses to the atmosphere. The losses are estimated to be larger for smaller tanks (0.4% for a storage volume of 50 $m^3$) and smaller for larger tanks (0.06% for a 20,000 $m^3$ tank) [155]. In addition, solid-state storage of hydrogen is also another potential alternative. For example, salt caverns have been used by the chemical industry for decades. The low cost and high efficiency of this form of storage made it economically attractive, but its accessibility and capacity pose challenges for wider use [30].

Today, 15% of the global hydrogen production is transported via trucks or pipelines, while the remaining 85% is produced and consumed onsite [30]. To enable large-scale and long-distance transportation and distribution, new infrastructure is needed. In addition, hydrogen is prone to leaks because of its small molecular size, and it can embrittle and diffuse through ordinary metals. Therefore, "existing high-pressure natural gas pipelines are not suitable for hydrogen transport" [156]. Some low-pressure distribution and service pipes (such as those installed in the UK since 1970) are made of polyethylene and can safely transport hydrogen [156]. Alternatively, it is possible to blend 5–15% hydrogen with natural gas in existing natural gas systems [157], or hydrogen could be transformed into another chemical energy carrier [158], as discussed above. In addition, liquefied hydrogen could be transported via trucks, railway tank cars and containers or pipelines [153]. Hydrogen transportation losses also need to be improved, as studies pointed to a loss of 20% of using natural gas pipelines [159]. As with all fuels, hydrogen needs care in fire safety, with risks different than but roughly on par with those of natural gas or LPG [160]. Transporting hydrogen not only poses challenges financially for building new pipelines, but also requires policies and regulations to be in place to regulate "blending" and harmonize regulations across regions [161].

In addition to its potential application in fuel cells electric vehicles and buildings (to provide heat and electricity), bulk net-zero-GHG hydrogen can be combusted for high temperature ($>$ 1000 °C) heat for a wide variety of industries, including steel and cement production. As discussed in Section 3.2 hydrogen could be used as a reagent (instead of methane) in the direct reduction of iron to produce sponge iron, which could be used directly in an electric arc furnace. Without considering hydrogen losses, a hydrogen-DRI process would require 51 kg $H_2$/ton of steel, in addition to about 3.5 MWh of energy per ton of steel produced [96]. Steelmaking using hydrogen as a chemical reducing agent would be competitive in a region with a carbon price of \$40–75/t $CO_2$e, assuming electricity costs of \$0.05/kWh [83,96]. As steel producers may locate where electricity is inexpensive, and LCOE for utility-scale solar and wind is already \$0.03–0.05/kWh [162] and is likely to drop further, lower costs for hydrogen-based steel may be achieved.

As noted in Section 3.3, hydrogen is a widely-used chemical feedstock. Accordingly, another promising "starter market" could be ammonia production for urea-based fertilizers, amines, fibers, and plastics. Hydrogen could outcompete natural gas over historic price ranges as a feedstock with no carbon pricing at renewable electricity costs achievable today (\$0.03–0.06/kWh) if the electrolysis load factor exceeds 40%, or else, with a halving of electrolysis capital costs [27,158,163].

Low-cost renewable electricity also increases the attractiveness of hydrogen energy storage. Wind and solar electricity can be moved to clusters of industrial facilities using high voltage transmission lines, transformed to hydrogen, and stored for eventual use, as is being explored in North Rhine Westphalia, Germany [164]. Alternatively, hydrogen may be produced where large amounts of renewable electricity are available, optionally converted to ammonia or methane, and then transported to industrial facilities. Industrial carbon capture technologies like calcium- and iron-based chemical looping [165,166] could eventually be combined with renewable hydrogen and oxygen production to allow for economic bulk production of net-zero emitting synthetic hydrocarbons or for energy storage [84]. Hydrogen could also provide support for variable electricity generation through fuel cells or combustion turbines, while excess zero-carbon power (for example, wind power generation on a windy night) can be used to make and store hydrogen.

Thanks to its versatility (as an energy source and chemical feedstock), as well as the difficulty of directly electrifying *all* industrial processes, hydrogen or chemical energy carriers derived from hydrogen will likely be a key part of a net-zero emissions industry sector.

### 4.2. Electrification

In 2016, direct fuel combustion accounted for 73% of global industry energy use, while electricity accounted for only 27% [167]. Fuels combusted in industrial facilities are primarily used for process heating (46%) and for fueling boilers (41%), with the remainder powering motor-driven systems and other end uses (Fig. 12). Therefore, electrifying process and boiler heating with decarbonized electricity should be an early focus of industrial electrification efforts.

Electromagnetic (EM) energy interacts with different materials in unique ways. In some cases, there may exist a transformation pathway that produces the desired output product with less total heat input than

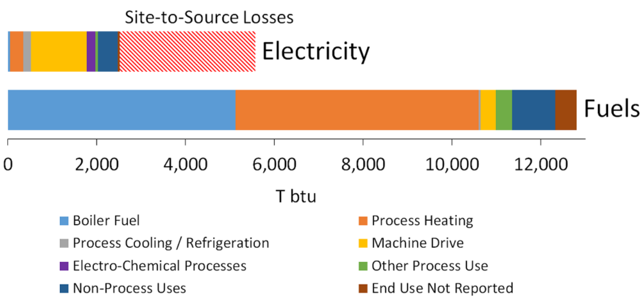


**Fig. 12.** Distribution of energy end-uses in the U.S. manufacturing sector in 2014. The top bar shows end uses of electricity (including site-to-source losses) and the bottom bar shows direct combustible fuel use [168].

traditional, fuel-using process heating operations. Electricity-based technologies that can lead to process improvements and enable new pathways with reduced thermal requirements and high efficiencies include:

- **General-purpose heating** may be provided by heat pumps, induction heating, or infrared, microwave, and radio frequency excitation of molecules [169,170].
- **Specific applications** where thermal heat can be replaced with electricity include laser sintering, resistive heating, and electric arc furnaces.
- **Non-thermal alternatives to heating** may be provided by ultraviolet light and electron beams in some applications.

One of the challenges to widespread industrial electrification is cost [171]. Using a U.S. industry-weighted average thermal fuel price of \$6.86/MMBtu and an electricity price of \$20.54/MMBtu, electricity loads would need to be 1/3 of those for thermal fuels in order to equalize energy costs. Process heating offers instances where heating with fuel has an efficiency less than a third that of electrical heating, making electricity costs lower than fuel costs in these cases. On the other hand, thermal fuel-fired boilers often have much higher efficiencies (80% or higher), making steam derived from fuel-fired boilers less expensive than steam produced by electric boilers. However, the correct approach is not to look at boiler efficiency in isolation, but to also consider the efficiency of the service provided by the steam. There are instances where steam use itself has low efficiency (e.g. heating products by steam injection), and these cases should be identified as candidates for replacement of steam with electric heating.

In addition to energy cost issues, there are a number of challenges arising from the interrelated nature of the technologies and processes. For example [172]:

- **Specificity of application:** EM wave interactions vary by material in complex ways, requiring a greater command of relevant physics, slowing industry uptake.
- **Specificity of equipment:** In a traditional system, the same type of equipment (e.g. a boiler) is sufficient for many processes. In a highly efficient, electrified process, the material to be processed may become an integral part of the system, and equipment may need to be designed specifically to handle this material and its transformation.
- **Challenges of scale-up:** Technology barriers, such as limitations of power supplies, may make it difficult to implement electrified processes at very large scale.
- **Challenges of scale-down:** Very complex, expensive equipment may be difficult to scale down to a size and cost that is accessible to small manufacturers.

An integrated R&D approach can aim to overcome these limitations. High-performance computer simulation of EM interactions with materials in proposed industrial systems can help to clarify the relevant physics and assist in system design. Additionally, R&D into EM sources for manufacturing, the use of EM energy in industrial systems, and new designs for industrial equipment must be pursued.

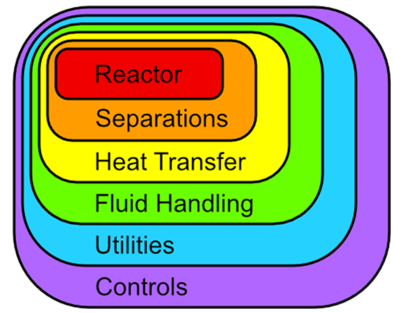


**Fig. 13.** Traditional process design in the petroleum refining industry starts at the reactor and moves outward, layer by layer, rather than designing the system as an integrated whole [174].

### 4.3. Energy efficiency

#### 4.3.1. The importance of integrated design

Industrial energy efficiency is often over-simplified to procuring efficient equipment. Realizing the full efficiency potential requires reviewing not only equipment efficiency but, more importantly, the systems of which it is a part [173]. For example, in the petroleum refining industry, traditional process design starts at the reactor and then moves outward layer by layer, rather than designing the system as an integrated whole (Fig. 13).

To maximize the yield of desirable products, thermodynamics and chemical kinetics are used to establish desired pressures and temperatures in the reactor and for separation operations. Next, based on stream flow rates and other physical properties, a heat exchanger network is designed around the reactor and separation operations to provide required heating or cooling [174]. Processes are often integrated through flows of material, energy, and information, so each process often affects interrelated processes. For example, improved material efficiency will improve energy efficiency, and the collection and transmission of data enables process optimization and controls that improve both.

Efficiency measures can be categorized by the level at which they are implemented and by whether they directly affect the flow of mass, energy, or information. Each presents opportunities for technological improvement; however, system-wide optimization requires complex, multi-physics solutions, and the performance of various process heating and motor-driven components is heavily affected by enabling technologies like sensors and process controls, advanced materials, and design tools/systems integration.

In some cases, the system to consider may not be limited to a single production line or even a single facility. Clusters of industrial facilities may benefit from heat integration and may use each other's co-products. A recent study investigating the integration of a steel mill, cement plant, fertilizer plant and recycled paper facility in an eco-industrial park found that a 21% energy savings could be achieved by co-location and intra-site transfer of heat, with payback time of only 43 days for the heat exchanger network [175].

Many industries face similar challenges and can benefit from system-oriented design. For example, some characteristics of common industrial process heating operations are shown in Table 2.

Designing systems as an integrated whole can result in favorable financial returns. In roughly \$40 billion of diverse industrial projects, whole-system redesign was found to yield 30–60% energy savings in retrofits (with a payback period of a few years) and 40–90% energy savings in newly built facilities (at equivalent or lower capital cost) [177]. Most industrial practice is not yet at this level.

**Table 2**
Characteristics of common industrial process heating operations, including typical applications and required temperature ranges [176].

| Process heating operation | Description/example applications | Typical temperature range (°C) |
|---|---|---|
| Fluid heating, boiling, and distillation | Distillation, reforming, cracking, hydrotreating; chemicals production, food preparation | 70–540 |
| Drying | Water and organic compound removal | 100–370 |
| Metal smelting and melting | Ore smelting, steelmaking, and other metals production | 430–1650 |
| Calcining | Lime calcining, cement-making | 800–1100 |
| Metal heat treating and reheating | Hardening, annealing, tempering | 100–800 |
| Non-metal melting | Glass, ceramics, and inorganics manufacturing | 800–1650 |
| Curing and forming | Polymer production, molding, extrusion | 150–1400 |
| Coking | Cokemaking for iron and steel production | 370–1100 |
| Other | Preheating; catalysis, thermal oxidation, incineration, softening, and warming | 100–1650 |

#### 4.3.2. Efficient steam systems and heat recovery

Steam systems (including the boilers used for generating steam and the condensate return, steam trap, and heat exchanger networks used in the distribution and application of steam) constitute one of the largest end uses of energy in the global manufacturing sector [5]. As such, technology opportunities for improving the efficiency of steam systems have long been a focus of industrial energy efficiency programs [178], yet facility audit data routinely reveal untapped energy savings potential in the steam systems found in many plants [179]. Common causes of inefficiency include aging boilers; improper system control, insulation, and maintenance; and fouling of heat transfer surfaces. Limited capital funds and low fuel prices were found to be persistent barriers to efficiency upgrades.

The current efficiency gap is largely one of deployment as opposed to technology availability: the efficiency of modern boiler packages with integrated heat recovery can exceed 85%, while advanced system monitoring and controls, coupled with best-available process heating equipment, can reduce overall steam demand to its practical minimum value [180]. For example, Japanese boiler manufacturer Miura found that replacing a single, large boiler with multiple, small boilers whose operation is controlled to match fluctuations in steam demand can achieve energy savings of 10–30% [181]. As water becomes a scarcer resource in many locations, avoiding water costs by raising steam system efficiency can improve the economic value proposition and accelerate equipment upgrades [182].

One option to further reduce the carbon footprint of industrial steam systems is to fire boilers using solid, liquefied, or gasified biomass, though the quality and moisture content of the biomass must be controlled to avoid inefficiencies. Another option is to use electric boilers coupled with renewable power sources, though as noted in Section 4.2, boilers that burn thermal fuel are highly efficient, so energy costs of electric boilers are likely to be higher (absent policy such as a carbon price, and excepting systems where steam itself is used inefficiently).

Despite the relatively high efficiency of modern steam systems, investments in boiler technology R&D may yield further improvements. A public-private partnership to develop an innovative, space-saving, maximally-efficient boiler (dubbed the “Super Boiler”) achieved demonstrated fuel-to-steam efficiencies of 93–94% over a decade ago [183]. However, further investments are needed to deliver such innovations to market and to drive down costs. Cost reductions are particularly useful to increase uptake in developing countries, where relatively inefficient equipment remains in widespread use.

For some processes where high temperatures are not required, such as food processing [184], an industrial heat pump can deliver heat at efficiencies far greater than is possible using either fuel combustion or resistive electric heating. For example, Kraft Foods replaced a natural gas-fired water heater with a heat pump at a plant in Iowa, resulting in energy savings of $250,000 per year, while also saving 53 million L of water per year from reduced load on their refrigeration systems’ evaporative condensers [185]. Today’s commercially-available heat pumps deliver temperatures up to 100 °C, and with R&D, heat pumps that deliver higher temperatures could be developed [186]. Considerations in heat pump selection include the technology to be used (double-effect absorption, compression-absorption, solar assisted, chemical, etc.), capacity, cost, and payback period [187].

#### 4.3.3. Best practices for energy-efficient industrial system design

The best practice in designing efficient industrial operations is to analyze the entire process by working “backwards” from the desired application to the energy-consuming equipment. Design should be an integrative process that accounts for how each part of the system affects other parts. The opportunity may be divided into the following design layers [176]:

1. Optimize the core process system for energy efficiency
   - Apply utilities (electricity, heating, cooling, physical force) at appropriate quality
   - Leverage energy recovery opportunities
   - Switch to fundamentally more efficient processes that achieve the same end—for example, replace compressed air systems with fans, blowers, vacuum pumps, brushes, etc. [188]
2. Design an efficient distribution system
   - Minimize losses in distribution systems through appropriate sizing, reducing distances, insulating pipes, avoiding 90° bends of pipes and ducts, etc.
   - Manage leaks and uncontrolled use of steam, hot and chilled water, and compressed air
3. Select correctly-sized equipment that provides the desired utility, e.g.,
   - Right-size equipment to allow for operation around optimal load
   - Balance refrigeration system and chiller capacities to needs
4. Install efficient equipment
   - Select pumps and fans that provide sufficient flow while minimizing energy use
   - Install best available boiler technologies
   - Utilize highly efficient, controllable motors (such as variable-speed drives)
5. Control the system for efficient operation
   - Avoid idling of equipment
   - Manage/reduce variability in the process and product flow
6. Plan for efficient equipment upgrades
   - Time equipment upgrades to correspond with system redesign
   - Budget for decommissioning of obsolete facilities

Many interventions are best implemented when existing equipment fails or during a major plant modernization or retrofit [189]. For example, core process redesign may require many ancillary components to be replaced, while distribution system upgrades (e.g. pipes, etc.) can be complicated by physical constraints and the need to relocate equipment. Even upgrading a single piece of equipment can have unintended challenges or result in a need for cascading upgrades, making it risky to attempt such upgrades during routine maintenance periods [189,190]. In contrast, some operational or control system improvements can be made through re-training of workers or software updates outside of a plant retrofit.

The challenge of achieving significant improvement in energy efficiency is not primarily about new technology but improving design, equipment selection, and control practices. Large potential savings are found in applying known technologies in more efficient ways rather than deploying break-through solutions. Some organization-level (training, goal-setting, procurement) interventions include:

1. Training programs and curriculum for engineers and operators should shift to a systems focus.
2. Energy management should be integrated into existing performance management structures and tool boxes (ERP, lean, six sigma, ISO, etc.). This provides visibility into energy performance and is a critical first step to identifying opportunities [191].
3. Equipment should be designed or purchased as an optimized system, rather than as a collection of individual components [192].

Although large emissions reductions can be realized today via in improved system design, equipment selection, and controls, these measures will not be sufficient to achieve a *zero*-carbon industrial sector. Completely eliminating GHG emissions from industry will require R&D to develop new technologies, adapt these technologies into commercial components, and to progressively integrate those components into highly energy-efficient and cost-effective systems [170]. Some opportunities for future R&D effort in industrial process heating operations include non-thermal water removal technologies (e.g. membranes), hybrid distillation, precisely targeted high-temperature materials processing (e.g. microwave heating), and net-shape manufacturing (creating components that do not require finish machining) [193].

## 5. Demand-side interventions

Reaching Paris Agreement targets will require not only the innovative processes and efficiency improvements described in previous sections, but also demand-side interventions. Demand-side interventions include improved product longevity, more intensive product use, material efficiency, material substitution, and demand changes driven by circular economy interventions [194,195].

### *5.1. Reduced material use: longevity, intensity, and material efficiency*

**Extending the life** of cars, trains, and buildings will reduce demand for steel, concrete, and other materials, as well as their associated GHG emissions. Concrete and structural steel can last for 200 years if well maintained [64]. However, typical building and infrastructure lifetimes are 60–80 years in developed countries and half that long in China [196,197].

In many cases, the limit to building longevity is not the failure of the building's structural materials, such as wood frame, steel, and concrete. A study of demolished North American buildings found that over 87% of demolitions were driven by changing land values (the building was no longer a cost-effective use of the land), the building's lack of suitability for current needs, or a lack of maintenance of non-structural components [198]. Similarly, in China, many new buildings are demolished long before the failure of their structural materials. Key reasons include hasty construction with poor workmanship, low-quality finishes, a lack of maintenance, Chinese consumer preferences for new products, and government condemnation [199]. (In China, all property taxes are paid upon purchase of a building, so local governments have a financial incentive to order buildings be demolished to make way for new ones [199].) Therefore, increasing the longevity of buildings is not simply a matter of improved materials. Addressing this challenge requires solutions specific to the needs of each community, such as designing buildings for flexible re-use, expandability, ease of maintenance, use of quality interior and exterior finishes, and reform of financial incentives for builders and governments.

Though increased longevity lowers material-related emissions, in the case of products that consume energy (such as vehicles and machinery), longevity may increase energy-related emissions by keeping less-efficient products in service when they otherwise would have been replaced with more efficient products. Therefore, longevity is best-suited to products that have a large percentage of their total lifecycle GHG emissions embodied in their materials (such as buildings and infrastructure).

**More intensive product use** can be achieved by increasing product utilization rates (so fewer products are needed to provide the same benefits). For example, the average light-duty vehicle in the United States is used for about 6 h per week to carry 1.4 people at a time [200]. Using smaller vehicles, better matching the vehicle to the specific need, and sharing vehicles could all significantly reduce demand for vehicles and, thus, the emissions associated with material production. (Using public transit is even more material-efficient.) One study found that dense urban areas have per-capita emissions 20% lower than rural areas, despite urban areas' smaller household sizes, due to shorter travel distances and increased ability to share carbon-intensive goods [201]. Short-term rentals of rooms or entire homes can decrease the demand for new hotel construction, and programs for sharing tools and clothes show emissions benefits, even after accounting for trips to pick up and return the shared items [202].

**Material efficiency** is a general term for producing the same set of products with less material. In some products, far more material is used than is required. Commercial buildings in developed countries are frequently built with up to twice the amount of steel required for safety [64]. Based on a set of engineering case studies of common product classes like cars, structural beams, rebar, and pipelines, Allwood and Cullen [65] estimated that "we could use 30% less metal than we do at present, with no change in the level of material service provided, simply by optimizing product design and controlling the loads that they experience before and during use." Similarly, engineers have been able to reduce concrete mass in buildings by up to 40% by using high strength concrete only where needed (e.g. using curved molds), instead of using the simplest mold shapes [64]. Because commodity materials typically represent a very small portion of the final cost of a product, manufacturing and construction firms frequently choose to use more material to save labor, reduce legal or financial risk risks, simplify supply chains, or simply to conform with customary practices. Appropriate technology, markets, and legal structures would facilitate higher material efficiency in buildings, infrastructure, and other products.

Material efficiency is closely associated with **lightweighting**, reducing a product's mass to reduce its in-use energy consumption. It is most often considered for vehicles, where steel can be replaced with aluminum, carbon fiber, or other strong, lightweight materials, thereby increasing the fuel efficiency of the vehicles [203]. These materials often have higher embodied emissions per vehicle than the heavier materials they are replacing [194,204]. Fortunately, the energy and GHG emissions saved by a lightweight vehicle during its lifetime are generally greater than the extra energy and emissions associated with making its special materials [205]. Life cycle assessments (including production, use, and disposal/recyclability) can be used to understand the trade-offs and show where material substitution makes sense [206].

At first glance, calling for reductions in demand for industrial goods can seem politically, economically, or socially unpalatable. However, through increased longevity, intensiveness, and material efficiency, industrial demand reductions can be achieved while maintaining or even improving the quality of the services delivered. Providing better services with less material will be a cornerstone of a clean development pathway for developing countries, helping to make widespread prosperity compatible with global climate goals.

**Fig. 14.** Brock Commons, an 18-story student residence building at the University of British Columbia, was the world's tallest wooden skyscraper when completed in May 2017. Image CC BY-NC 2.0 University of British Columbia.

### 5.2. Additive manufacturing (3D Printing)

Digital manufacturing—a key component of the "Industry 4.0" concept [207]—links designers, supply chains, production facilities, and customers to reduce product lead times, optimize inventories, reduce costs, and increase product customization [208].

Within the digital manufacturing movement, additive manufacturing (AM) is one of the most visible and potentially transformative process technologies [209]. Under the right circumstances, AM offers several advantages compared to conventional manufacturing methods. Such advantages—while highly application-specific—can include reductions in lead time, materials scrap, and inventory costs while delivering novel geometries that were previously extremely costly, or impossible, to manufacture using conventional methods [210].

Driven by these advantages, the market for AM technology has grown rapidly in recent years. In 2017, the global AM industry grew by 21% to over $7.3 billion [211] and may exceed $21 billion by 2020 [212]. However, AM currently faces barriers that may limit the pace of adoption in the near term, including high production costs, low throughput rates, and part fatigue life limitations [210,213]. For these reasons, early adoption of AM has been primarily driven by applications with high material costs, low production volumes, and novel/complex geometries, such as those in the aerospace, medical, and tooling industries [214]. As AM machine manufacturers innovate to reduce costs and improve process performance—e.g., new binder jetting technologies may increase production speeds by an order of magnitude [215]—new high-volume applications such as automotive parts may become feasible, while improved powder metallurgy and process controls may open markets in demanding applications such as turbine blades [216].

From energy and resource perspectives, the benefits of AM may be significant. When replacing subtractive conventional manufacturing methods, such as milling, drilling, and grinding, AM can reduce materials scrap, leading to avoided raw materials production and shipping. The "on demand" nature of AM can reduce inventories of tools, dies, and finished parts, further reducing materials demand. As an electricity-driven process, AM may promote industrial electrification by replacing thermal forming processes such as metal casting and forging. Finally, novel AM geometries may lead to energy savings beyond the industrial sector though improved engineering functionality in end-use applications; for example, AM enables the creation of optimized heat sinks that reduce energy waste [217]. AM has also been used by Airbus to produce lightweight aircraft components that reduce fuel consumption [218], an industry for which the life-cycle energy and resource savings of AM parts can be substantial [219].

### 5.3. Material substitution

Substituting lower embodied-carbon materials for higher embodied-carbon materials in products can be an important mechanism for reducing industrial GHG emissions. The product category that represents the largest amount of GHG emissions is building materials, especially concrete and steel. Collectively, these represent nearly 10% of total global emissions [3,7]. Because of their enormous scale—4 Gt/year of cement production and 1.8 Gt/year of steel production [39,73]—very few other materials are available in quantities sufficient to noticeably reduce consumption. Within building materials, two commonly-discussed opportunities for substitution at scale are timber-based products and partial replacement of cement with supplementary cementitious materials.

Wood products can be substituted for steel and concrete in much of the superstructure of low- and medium-rise buildings. Glued-and-laminated timber ("glulam") is increasingly used for bearing weight in high-rise buildings, and cross-laminated timber (CLT) has strength and performance superior to traditional plywood [220]. Recent projects demonstrate the feasibility of large wood buildings. Towers over 84 m tall were recently built in Austria [221] and Norway [222], surpassing the 2017 record set by an 18-story, 53-meter building in British Columbia [223] (Fig. 14). In addition, wood fibers and straw can be used for insulation material [224], timber frame constructions can replace brick and reinforced concrete, fiberboards can replace gypsum boards, etc. [225,226].

In addition to emitting far less GHGs in their production, wood products also store carbon for the life of the structure and can be sustainably produced if forestland is properly managed. From a lifecycle perspective, wooden buildings typically outperform an equivalent building made from concrete [227]. Oliver et al. [228] found that substituting wood for structural steel is the most efficient way to use forests to mitigate GHG emissions. However, more research is needed to:

- quantify how much steel and cement could realistically be replaced based on structure type, climate, and construction demand;
- quantify the emissions from making the wood products under realistic forest management and manufacturing assumptions; and
- understand the safeguards that would be needed to prevent an expansion of wood-based construction from turning into a driver of deforestation or forest degradation.

Supplementary cementitious materials (SCMs) are a wide range of materials that can substitute for some or much of the limestone-based clinker in ordinary Portland cement. They include fly ash, a by-product of coal combustion; granulated blast-furnace slag, a by-product of the iron industry; calcined clay; and naturally occurring pozzolanic minerals. (For more detail, see Section 3.1.) Today, SCMs replace nearly 20% of the clinker in cement worldwide. The UN Environment Program estimates that an appropriate combination of SCMs could substitute for 40% of clinker [229]. Among the lowest-emissions and most widely-available options for reducing clinker content in cement are calcined clays and inert fillers, which will not compromise performance if used appropriately and could reduce annual emissions from the cement sector by over 600 $MtCO_2$ per year if widely adopted [49].

In cases where a material is crucial to a building's energy performance (e.g., insulation), a lifecycle assessment must be considered before substituting a lower-carbon material, to ensure the emissions savings from using the substitute material are not outweighed by poorer energy performance during the building's lifetime. Certain advanced insulation materials have higher embodied carbon than traditional insulation, but they may more than make up for this through heating and cooling energy savings.

### 5.4. Circular economy

The term Circular Economy (CE) contrasts with the idea of a "linear economy," the predominant value chain structure today, in which goods are produced, consumed, and discarded. In a CE, every end-of-life product is considered a resource that can be put to valuable use. Rather than being a single type of activity (such as "recycling"), CE is a cascade of options that put each product, component, or material to its highest or best use, minimizing value loss [230]. The first option is for a product's original user to keep it for longer, share it with others, and prolong its service life through proper maintenance and repair. When this is not possible, the next-best option is to transfer the product to a new user. The third-best option is to refurbish or remanufacture the product. (Remanufacturing is dis-assembling and re-using the components of the product.) The fourth-best option is to recycle the raw materials that make up the product (Fig. 15).

Assessments of the techno-economical potential of increased circularity vary widely and can be difficult to compare, due to different units and assumptions. For example, Cooper et al. find CE has the potential to save 6–11% of worldwide energy used for "economic activity" [231], while Material Economics finds that CE could reduce 2050 $CO_2$ emissions from steel, plastics, aluminum, and cement in the EU by 56% relative to a 2050 baseline scenario (a 59% reduction relative to 2015 emissions levels) [232]. There is, however, broad consensus that CE potential is held back by limited ability to achieve comparable performance with virgin material, driven by the challenges of separating blended or assembled materials. For example, the copper content of recycled steel is generally higher than is allowable for the most common steel end uses [24], unless the recycled steel is diluted with primary steel. New separation technologies may help to improve the quality of recycled metals [233].

One key barrier to high-quality secondary materials is that information about the material is lost over the course of its service life. For example, structural steel is usually in fine condition for reuse when a building is demolished, but its alloy content and specifications are no longer known. This means that expensive testing is required to determine its composition before it could be reused, and it is often more cost-effective to put it in poorly-differentiated waste streams for recycling at a lower grade. The standard categories for steel scrap do not specify the copper content [234], even though copper will prevent the recycled steel from being used in many high-value applications [235], like sheet metal for vehicles. Policies that ensure sufficient information follows the materials and components throughout their life, whether through low-technology interventions like indelible marking or higher-technology options like blockchain [236], facilitate first reuse then higher-value recycling of product components and materials.

Design for reuse and recycling takes this one step further, not just providing information but modifying the products to encourage reuse and recycling. Approaches include modular design, reversible attachments, and material standardization. Again using the example of structural steel, reversible joints like ConX joints [237] standardize the mounting and disconnecting of beams, making it easier to reuse them. The primary policy mechanism that has been used to encourage these types of design changes is Extended Producer Responsibility (EPR), where the manufacturer or retailer is required to take physical or financial responsibility for discarded products [238]. However, EPR has not yet been widely applied in the contexts that would have the greatest impact on industrial emissions, namely building materials and commodity metals.

Increasing the circularity of our economy may require the creation of business models around secondary materials, which can be facilitated by supporting policies. Leasing models can require products be returned at the end of the lease period for refurbishment and subsequent lease or

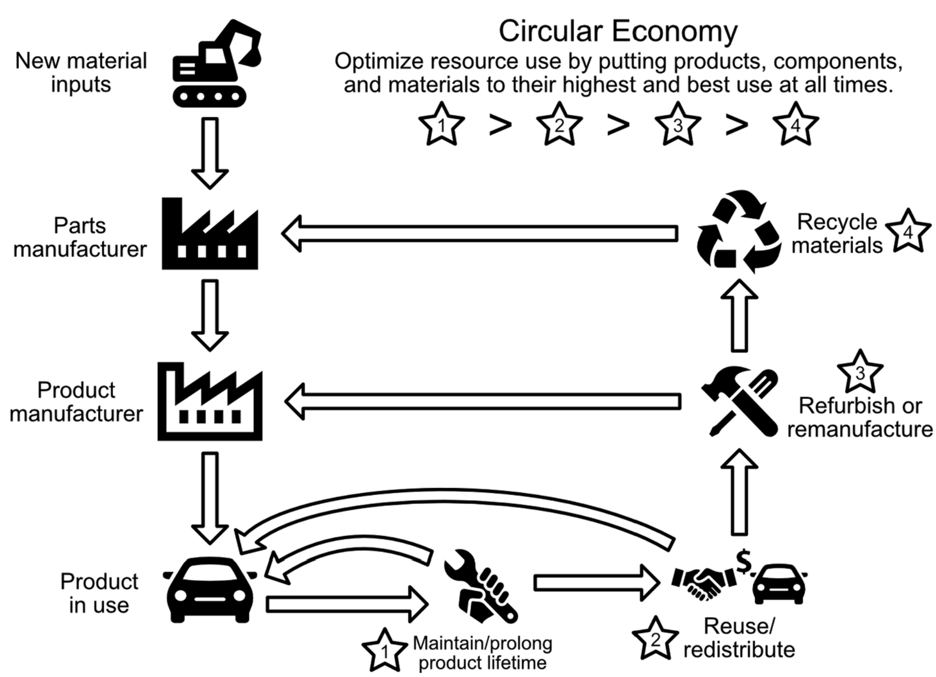


Fig. 15. A schematic overview of material flows within a circular economy. Products, components, and materials are put to the best possible use, minimizing value loss [230].

sale to another consumer. While such business models exist for certain products (e.g. cars) and are easy to imagine for durable consumer goods (e.g. large appliances), they are less intuitive for short-lived consumer goods, public infrastructure, or the built environment. Some nations and regions are beginning to implement supporting policy, such as China's Circular Economy Promotion Law of 2009 [239] and a CE package implemented by the European Commission [240].

Ultimately, to limit global warming to acceptable levels, significant decreases in carbon-intensive material consumption will be required. CE can help to achieve this decrease without lowering countries' standard of living or hampering their development. The opportunity of CE leads to an imperative for policy action (and may result in significant business opportunities). Key areas for policy intervention are:

- Ratchet up performance requirements in building codes at defined intervals to drive innovation.
- Include the implications of shared mobility solutions in zoning and urban planning.
- Build out reverse supply chains for collection of used products for repurposing or recycling.
- Regulate requirements for disassembly of products (e.g. batteries in electronics must be removable).
- Establish tools and information infrastructure to track and monitor material flows to enable new business models and improve material recapture.

## 6. Policies

Policy interventions can cause emissions reductions via a number of economic channels [241]. These include input substitution (use of low-carbon energy or input materials), process changes (energy efficiency, novel process development, use of recycled materials, carbon capture), and demand reduction (material efficiency, material substitution, circular economy, etc.).

Economically-efficient policies often provide incentives for decarbonization via all channels, facilitating the proper allocation of resources in investment decisions [242]. For example, well-designed carbon pricing can invoke efficient responses in all channels (see Section 6.1). Well-written, technology-neutral emissions standards can also be economically efficient. A standard applied to a specific industry would be met via input substitution and/or process changes. A flexible emissions intensity standard that enables trading of credits across facilities within a sector, and ideally trading of credits across sectors, could deliver cost effectiveness similar to that of carbon pricing. Emissions intensity standards may also drive demand reduction. For example, if steel producers switch to hydrogen-based direct reduced iron (e.g. HYBRIT) to comply with emissions intensity requirements of a technology-neutral standard, costs may be 30–40% higher than steel made in existing state-of-the-art electric arc furnaces [96,163,243]. Higher-cost steel could trigger demand reduction through material efficiency, longevity, or output substitution to use of other materials.

Even if a policy does not provoke all of these responses, it can still be a worthwhile policy to help decarbonize the industry sector, if used as part of a package of policies. For example, policies to support R&D efforts can accelerate progress on new technologies in the laboratory and can help these new technologies successfully reach the market (discussed in Section 6.2). R&D support policies might not, on their own, achieve emissions reductions via all channels, but the technologies they produce make compliance with other policies (such as carbon pricing or emissions standards) possible at lower cost. There is a similar, enabling role for policies such as government procurement of low-carbon goods (helping to build a market for low-carbon technologies, so they achieve economies of scale), labeling and disclosure requirements (giving policymakers and purchasers the information they need to make decisions), and more. No single policy is a "silver bullet." Decarbonizing the industry sector requires a comprehensive package of policies, the best of which are discussed in the following sections.

### 6.1. Carbon pricing

One of the most prominent emissions-reduction policies is carbon pricing, which requires emitters to pay a fee per ton of $CO_2$ (or, better, per ton of GHGs, measured in $CO_2$-equivalent) they emit. Some benefits of carbon pricing include [244]:

- Carbon pricing is technology-neutral, allowing emitters to find the lowest-cost way to reduce emissions, or to pay the carbon price in cases where emissions reductions would be more expensive.
- Carbon pricing helps regulators to cost-effectively limit GHG emissions from the industry sector without the need to develop expertise in manufacturing processes, as might be required to intelligently set emissions standards for certain types of equipment or per unit of a commodity produced.
- Carbon pricing generates government revenue, which can be used to support socially beneficial objectives and programs (such as funding R&D in new technologies) or to reduce taxes on income or labor.

A carbon price may be implemented as a carbon tax (a fee per unit of emissions), which results in certainty about carbon prices but uncertainty regarding emissions from covered industries. Another approach is a cap-and-trade system (where industries must purchase credits on a market or at auction in order to emit). This provides certainty about emissions from covered industries, but there is uncertainty over how much permits will cost, as permit prices are determined in the marketplace on the basis of how expensive it is to reduce GHG emissions. Carbon pricing may be implemented as a hybrid of these two systems: most commonly, a cap-and-trade system with a price ceiling and a price floor, which effectively turns the carbon cap into a carbon tax if the permits would become too cheap or too expensive. The hybrid approach limits price uncertainty and quantity uncertainty to known bounds, effectively balancing the economic and environmental objectives of a carbon pricing policy [244].

One frequent concern with carbon pricing is "leakage," or the relocation of emitting industrial activities to jurisdictions with less stringent or absent carbon pricing. Estimating leakage risk accurately is challenging [245], and estimates of the importance of leakage vary widely from study to study. For example:

- An ex-post analysis of the steel and cement industries under the European Union ETS found no evidence of leakage during the first two phases of the program, covering 2005–2012 [246].
- Carbon Trust and Climate Strategies find that the European Union ETS Phase III targets to 2020, without any free allocation of allowances or other pricing protections, "would drive less than 2% of emissions abroad," though leakage would be higher for energy-intensive industries: "5–10% of cement or steel emissions" [247].
- A study of the U.S. Portland cement industry found that a carbon price of \$60/ton $CO_2$ with all permits auctioned (effectively, a carbon tax) would reduce domestic emissions by almost 1000 Mt $CO_2$ and would increase foreign emissions by about 200 Mt, a leakage rate of slightly over 20% [248].
- A study by Ho, Morgenstern, and Shih found an economy-wide \$10/ton carbon tax in the U.S. without border adjustments would result in a 25% overall leakage rate and a leakage rate of over 40% in the three most energy-intensive industries [249].

There exist several approaches to limit leakage. One remedy is output-based, free allocation of emissions allowances to energy-intensive, trade-exposed industries (e.g. the Western Climate Initiative and European Union systems) or tax rebates based on a firm's output (e.g. Canada's system). This approach will help to preserve the market share of regulated industries, but it will limit decarbonization, as final consumers do not receive the full price signal to drive product substitution or conservation. Alternatively, border tax adjustments can apply an import tariff calibrated to reflect embodied emissions in imported goods and to rebate taxes on goods for export, or a fee can be placed on the consumption of goods based on embedded carbon [243,250]. These approaches have the advantage that all economic channels are priced with respect to domestic consumption, but they require reliable information about GHG emissions from production activities inside and outside the jurisdiction.

A tradable emissions intensity performance standard also provides an incentive for input substitution and process changes. This approach is analytically equivalent to output-based allocation under cap and trade, except there is no cap. Output can grow or contract if the performance standard is achieved, and tradability ensures a cost-effective allocation of emissions reduction efforts within the silo of regulated entities, just as in direct carbon pricing. Examples of tradable intensity performance standards include vehicle fleet efficiency standards and low carbon fuel standards in the transportation sector, as well as renewable portfolio standards in the electricity sector. Together, these policies in the U.S. and Europe have contributed the major portion of GHG abatement achieved to date from climate-related policies [164,251–253]. Carbon pricing and tradable emissions standards can provide incentives to develop technologies that enable further emissions reductions [254].

### *6.2. RD&D support*

#### *6.2.1. RD&D policies in context*

Research, development and demonstration (RD&D) is important both for developing new technologies and processes, as well as addressing hurdles in scaling existing processes. New technical challenges emerge at every stage of market development (Fig. 16). While company research can address some of these hurdles, policies and programs to support RD&D can speed technological development. Successful innovation in this space also depends on coordination across manufacturing scales, as much of the learning takes place as companies move their ideas beyond prototypes and demonstration through commercialization [255].

#### *6.2.2. Policies to promote industrial RD&D*

A wide range of policies and programs have been successful in supporting industrial research at various stages of technology maturity and deployment, with governments at the local and federal often playing an important role. For example, the U.S. Department of Energy (DOE) has many case studies illustrating approaches to encourage innovation [176].

Government policies to promote industrial RD&D generally fall into five broad categories:

- Supporting government laboratories (Japan's METI, DOE National Labs)
- Governmental funding of academic, public, or private research institutes (Germany's Fraunhofer-Gesellschaft, Manufacturing USA Institutes, the U.S. National Science Foundation)
- Establishing research partnerships between government, industry, and sometimes philanthropy (Industries of the Future, Elysis partnership)
- Supporting entrepreneurial development of innovative technologies (Sustainable Development Technology Canada (SDTC), DOE's Advanced Research Project Agency-Energy)
- Financial incentives for corporate R&D (R&D tax credits, contract research, grants)

Government laboratories can be an important source of expertise and physical facilities that may be too costly for individual companies to develop. Examples of national laboratories include the U.S. Department of Energy (DOE) Laboratories and the French CNRS Institutes. These institutions conduct research on their own and in cooperation with academic institutions and private companies. DOE laboratories have initiatives to aid in the commercialization of technologies, such as the Lab-Embedded Entrepreneurship Programs, which aim to help entrepreneurial scientists and engineers complete the RD&D necessary to launch new energy or manufacturing businesses [257].

Some countries have supported the creation of independent research institutions to fill a similar role to government-run national laboratories, with Germany's Fraunhofer-Gesellschaft being perhaps the best known. The U.S. has emulated this approach over the past decades with the establishment of the Manufacturing USA institutes. These institutes partner with academic institutions and private companies to

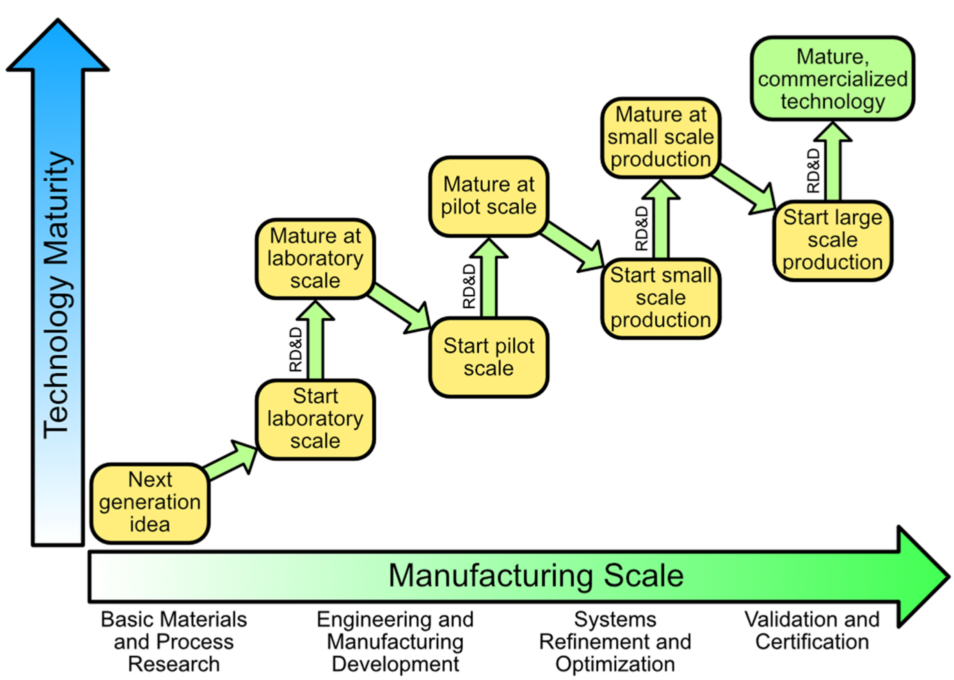


**Fig. 16.** This figure is a notional depiction of technology progression, highlighting that significant technology challenges occur at every stage of market development. RD&D has a role at all levels of manufacturing scale, and RD&D programs and policies will be most successful when designed to stimulate innovation across the entire opportunity space [256].

address technical challenges. Regional and local initiatives are also important to drive innovation and stimulate economic development needed for a vibrant industrial ecosystem. For instance, the Ben Franklin Technology Partners in Pennsylvania provides manufacturers with funding, business, and technical expertise, and access to expert resources. It has thus far achieved a four-to-one return on investment for the state [258].

The U.S. has in the past successfully co-funded industry-specific research at academic institutions in partnership with industrial trade associations. For example, the *Industries of the Future Program* aimed to identify and address energy efficiency challenges specific to energy-intensive industries. The U.S. DOE's Bandwidth Studies series assesses the technical potential for state-of-the-art and next generation technologies to improve the energy footprint of the most energy-intensive industrial subsectors [259].

Direct government support for entrepreneurial development of innovative technologies is a relatively new approach to deriving greater benefits from government support. The Sustainable Development Technology Canada program an early example, founded in 2001. It is accountable to the Canadian government, yet operates as an independent foundation tasked to help Canadian entrepreneurs accelerate their innovative clean energy technologies. Their impact is well documented and includes 91 projects that have created products in the market, delivering over 10 Mt of $CO_2$ emissions reductions [260]. Another example is the U.S. Advanced Research Projects Agency-Energy (ARPA-E), first funded in 2009 [261]. It focuses on a slightly earlier stage of technology development than SDTC, emphasizing high-impact clean energy technologies that are too early and too high-risk for private sector investment. The most successful ARPA-E projects are ready to receive private sector investment after ARPA-E support. As of 2018, 145 ARPA-E-supported projects have in combination raised \$2.9 B in private investment to commercialize their technologies [262].

Recently, unique partnerships have emerged to address critical technology challenges and reduce GHG emissions through supply chains. For example, the Elysis partnership has brought together Alcoa, Rio Tinto, the Government of Canada, the Government of Quebec, and Apple to provide a combined \$188 million (CAD) to commercialize inert anode technology for aluminum smelting [263], which effectively eliminates GHG emissions associated with aluminum production when zero-GHG electricity is used. Additionally, philanthropic investments are finding creative approaches to address emissions reductions, such as adopting a venture-based investment model with the longer time horizons required for successful RD&D and commercialization of industrial technologies. Examples include the PRIME Coalition [264] and Breakthrough Energy Ventures [265].

Governments can also encourage corporate research by providing direct funding or favorable tax treatment of company funds invested in RD&D. This tax treatment has been important for many decades in the U.S. [266]. Other, more aggressive policies have been proposed in the past, such as accelerated depreciation of capital investments to stimulate new investment [267].

### 6.2.3. Elements of successful RD&D programs and policies

Successful RD&D initiatives must address barriers that hinder investments by companies or investors, including:

- Prior investments may have "locked in" old technologies, given high capital costs for new equipment, especially for the large energy-intensive industries.
- Long development times for RD&D of next generation industrial technologies are common.
- There are technical and market risks associated with attempts to improve or replace a technology (i.e. a risk the technology does not work as well as expected, or that changes in the market unrelated to the technology may nonetheless reduce its economic competitiveness).
- There is regulatory uncertainty (i.e. the risk that a policy environment relied upon by industry today in making decisions may be altered in the future).
- Relatively low energy costs for fossil fuels can cause clean energy or efficiency technologies to require long periods to earn a return.
- Next generation industrial technologies may concurrently require new energy infrastructure.
- Older technologies benefit from the failure to monetize social and environmental externalities.
- Whole-system design improvements may be overlooked, despite their large energy-saving potential, as they are not a single technology and may be facility- or site-specific.

Key elements of success include partnering with companies through all stages of market development and targeting RD&D to key technical challenges faced by industry. These public-private partnerships can

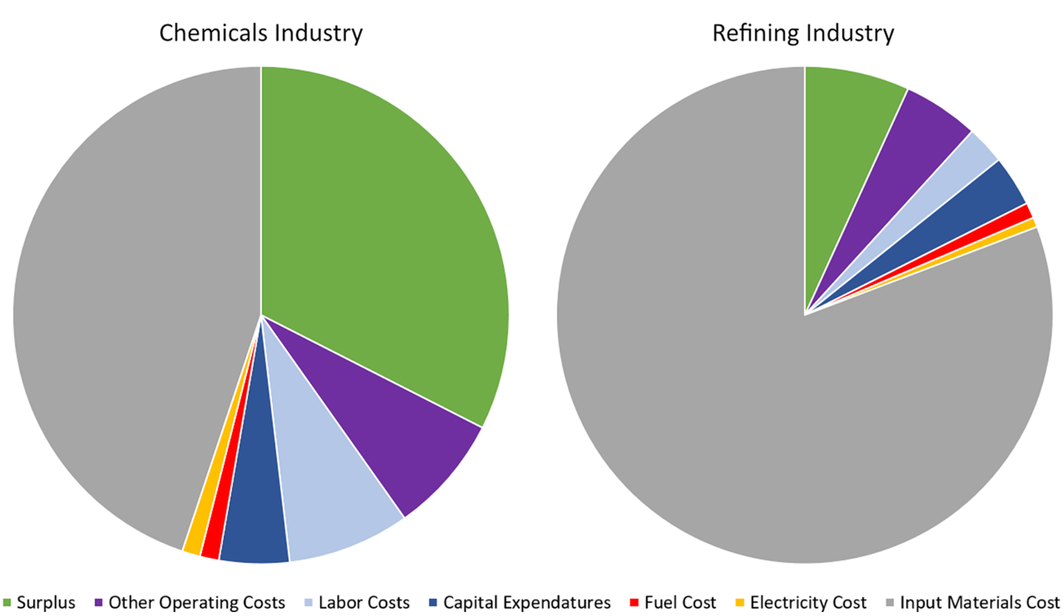


**Fig. 17.** Revenue breakdown for the U.S. chemical manufacturing industry (NAICS #324) and the petroleum and coal products manufacturing industries (i.e. predominantly refining) (NAICS #325) in 2016 [272].

drive innovation and lead to more rapid adoption of new developments. Further, the involvement of trade associations and government in the RD&D process can address government's antitrust concerns by ensuring new technology is available to multiple companies.

### 6.3. Energy efficiency or emissions standards

Appliance, equipment, and vehicle standards have proven among the most effective policy strategies for energy use reductions [268], both in developed and developing countries. In industry, electric motor standards have played a major role reducing electricity consumption, since motors account for two-thirds of industrial electricity consumption [269].

Despite steady improvement in energy efficiency for decades, there is still considerable room for energy efficiency improvement in the industrial sector [7], with many efficiency upgrades coming at low cost with quick (i.e., less than 2-year) financial paybacks [270,271]. However, years of industrial energy audit data suggest that manufacturers routinely forgo proven, low-cost efficiency improvement opportunities. For example, an assessment of 15 years of audit data from the Industrial Assessment Centers (the U.S. Department of Energy's audit program for small and medium enterprises) indicates that small plants seized only 1/3 of recommended low-cost energy savings, citing unattractive economics and lack of budget as two of the most common reasons [270]. The Save Energy Now program, which audited over 600 of the largest industrial plants in the United States, had similar findings: annual monetary and energy savings of all recommendations totaled $858 and 114 T btu respectively, but less than half of the identified cost and energy savings were ultimately pursued [271].

One reason for the difficulty in interesting businesses in energy efficiency upgrades is illustrated in Fig. 17, which provides revenue breakdowns for the U.S. chemicals and refining industries. Chemical companies have higher profit margins (greater surplus, in green), and so are in a better financial position to invest in energy efficiency upgrades. However, electricity costs (in yellow) and non-feedstock thermal fuel costs (in red) are a small share of total costs for both industries, so it may be difficult to convince company management to devote the time and resources to plan and execute energy efficiency upgrades, even if such upgrades offer a short payback period. A business may choose to focus on reducing the largest costs—particularly input materials, labor, and capital equipment spending—to maximize *absolute* financial savings, even when energy efficiency upgrades offer a better *percentage* return on investment.

A more holistic accounting of the productivity, environmental, safety, and other improvements associated with energy efficiency might yield a different investment decision. In a pioneering study, Worrell et al. showed that energy efficiency improvements in the iron and steel industry would also result in productivity improvements. Accounting for these co-benefits, by adding them to energy cost savings, would double the amount of energy efficiency improvements that would be deemed financially attractive [273]. Other non-energy benefits associated with energy efficiency improvements can include [274]:

- revenues from emission reduction credits or demand response program participation fees
- improved ability to market products to environmentally-conscious buyers
- qualify to sell products to governments or businesses with green procurement policies
- reduced energy capacity charges
- reduced requirements for cooling water or other input materials
- reduced maintenance costs
- reduced waste generation and disposal costs
- reduced capital costs and associated insurance premiums
- improved workplace health and safety
- reduced exposure to energy price volatility

Comprehensively considering all of the benefits of energy efficiency improvements offers a superior means of evaluating the economic value of these measures and could accelerate their uptake.

As businesses will not always adopt efficiency upgrades solely on the basis of financial return, efficiency standards are a crucial tool to drive uptake and accelerate the decarbonization of global industry. In the past, efficiency standards have been very technology-specific, but standards have evolved to become more performance- or objective-oriented, e.g. the transition from energy-based to GHG intensity-based standards in the auto sector. Standards have tended to work better with mass-produced products that are used widely with administratively feasible points of policy application, usually the point of purchase or installation. Standards have proven challenging to implement in retrofit applications because there is typically not a well-identified entity responsible for compliance. Generally, standards work best at the national level, with harmonization internationally through treaties and international organizations such as the International Standards Organization (ISO).

As component-level standards become increasingly mature, the focus is shifting to system-level standards [275]. While a component-level standard might specify allowable energy use by pumps, fans, or compressors, a system-level standard might specify allowable energy use by a system that delivers a certain amount of fluid or air to the point of use. System-wide efficiency standards are best-suited to applications with certain criteria: 1) a well-defined system that delivers a service; 2) widespread use of the system in replicable applications; 3) the ability to devise a representative and stable performance indicator that works in the marketplace; and 4) a willing collaboration by key industry stakeholders. Support from manufacturers and installers is key, because they have the expertise and data necessary to develop the indicator and associated market structures [276].

Possible industrial process end-use services to be targeted for GHG intensity might include steam and hot-water systems, driers, water treatment systems, chilled water systems, and cooling towers. Highly integrated process equipment has not proven a good target for standards because the output is site-specific products, not a defined service. This approach might be extended to limit energy use or emissions per unit of product produced for certain commodity materials (e.g. grades of steel, types of cement) [276].

Emissions intensity standards can identify goals and drive technological change. Standards may be based on the most efficient products on the market, which ensures the standards are able to be achieved by commercialized products. Standards should be routinely updated based on the newest, most efficient products, so they do not stagnate and continue to drive innovation. Japan's "Top Runner" policies are an example of this approach [277]. Standards can also be used to induce innovation down a GHG-mitigating path when the technology roadmap is relatively well-known. For example, the California Air Resources Board's use of zero emissions vehicle standards in the 1990s drove the design and adoption of hybrid nickel-hydride-based electric vehicles such as the Toyota Prius, which eventually led to the lithium-ion-based full battery electric vehicle.

Performance standards do not internalize a carbon price commensurate with the abatement they cause (as the added cost of buying standard-compliant equipment is often far lower than the social cost of the avoided emissions). Also, standards impose no price on the residual emissions from standard-compliant equipment. These traits increase the political acceptability of performance standards, but this comes with the disadvantage of eroding the incentive to reduce product use or switch to lower-carbon alternative products that would come from carbon pricing. Standards and carbon pricing work best in tandem.

### 6.4. Building codes

Buildings are a necessary component of human wellbeing [278], and their construction is responsible for a significant share of economic activity (e.g. 8% of GDP in the U.S.) [279]. However, construction has notable environmental impacts: over 20% of the world's energy and process-related GHG emissions are from the production of materials, primarily structural materials [280], such as steel and concrete. Routes to reduce emissions from these materials include optimizing their use in construction, increasing their performance life (thus reducing maintenance and replacement impacts), and improved material composition [43,47].

Policies and design guidelines outline methods to improve buildings' energy efficiency, as well as encourage the use of materials that have lower environmental impacts (including reuse of recovered materials). However, environmentally-friendly design guidelines may sometimes conflict with one another, due to the complexity associated with initial design choices and the ability to implement different retrofits at different times. Today's guidelines focus on individual components at single points in time, overlooking implications of decisions on subsequent components or on other phases of the building lifecycle. For example, energy-efficient buildings may incorporate large masses to provide thermal inertia and reduce heating or cooling needs, but the GHG emissions from producing the required quantity of material can outweigh GHG abatement from the thermal energy savings, especially as buildings become increasingly energy efficient [281,282]. In multi-material buildings or structural components, there may be trade-offs between the different materials. For example, while in most cases steel reinforcement in concrete can be reduced while staying within the confines of acceptable design, it could lead to a greater member size and thus more concrete usage [68]. Further, seemingly inconsequential alterations within the confines of acceptable design, such as scheduling one phase of construction before or after another phase, can yield large changes in the quantity of material required and, thus, the overall environmental impacts [283,284]. Smart building codes must account for these complexities.

While buildings can last many decades and serve different functions over their lifespans, the materials used within buildings—such as carpeting, wall panels, and roofing materials—can have significantly shorter lifespans [285]. As a result, the selection of long-lived interior finishes and roofing materials can decrease environmental impacts.

Prefabrication of building systems is another technique to improve building energy performance while reducing construction waste. Prefabrication involves producing finished components in a manufacturing facility, then transporting those components to the building site for final assembly. This dramatically reduces material waste and on-site construction time. Incorporating prefabricated components into a building design can improve quality and durability, which increases building lifespan. In addition, stricter quality assurance is achievable in a factory than on a construction site, which helps ensure greater thermal integrity and energy performance.

Prefabricated buildings have great waste reduction potential, particularly in developing economies. For example, in 2013, China's building materials waste exceeded 1 billion tons [286]. Only 5% of this waste is recycled [287]. Cases of prefabrication in China and elsewhere have shown to increase lifetime by 10–15 years while reducing construction material loss by 60% and overall building waste by 80% [288].

Modernization of guidelines and codes is needed for acceptance of emerging technologies and materials in the built environment [289]. For example, with concrete, there is some room within current codes to improve sustainability by reducing cement content, often through inclusion of supplementary cementitious materials [290]. In contrast, current codes may hamper the use of alternative materials whose long-term behavior is less certain than that of conventional materials [55,56]. Updated codes, combined with targets, labelling, and economic incentives for alternative materials, could facilitate the incorporation of these materials into buildings.

### 6.5. Data disclosure and ESG

Data is central to industrial decarbonization. Digital technology is transforming industrial production processes and, simultaneously, generating a profusion of data that allow plant managers to better understand facilities' energy use, emissions, and opportunities for abatement. Meanwhile, investor pressure, corporate and government procurement requirements, and stakeholder expectations of transparency are increasingly driving public disclosure of company data.

In its earliest form, transparency over environmental performance took the form of Corporate Social Responsibility (CSR) reporting. These reports of environmental and social information were typically company-authored and non-verifiable. Over time, a demand for third-party verification of CSR data arose, along with calls for standardized approaches to measure and report specific information, including decarbonization. As investors started to use this information to rate the long-term viability of a firm, independent organizations emerged to provide an assessment of companies' environmental performance. For GHG emissions, the main such organization is CDP (formerly the Carbon Disclosure Project), founded in 2000. Over 8400 companies now disclose their emissions impacts through CDP, which represents over 525 investors with \$96 trillion in assets [291]. Another aligned effort, the Task Force for Climate-Related Financial Disclosures (TFCD), was established in 2015 and released final recommendations on voluntary disclosure guidelines in 2017 [292]. A third program, the Science-Based Targets initiative [293], has enabled 294 global companies to commit to Paris-aligned (and increasingly 1.5 °C-aligned) GHG reduction targets. By focusing on disclosure and target-setting, these platforms are helping to support industrial company GHG mitigation best practices [294].

Companies and governments are increasingly extending expectations of carbon accounting, goal-setting, and decarbonization into their supply chains. Emissions from a firm's supply chain are, on average, 5.5 times larger than a company's own carbon footprint [295]. Through CDP's Supply Chain program, 115 organizations with \$3.3 trillion in annual spending (including Walmart, Microsoft, and the U.S. Federal Government) collectively engage over 11,500 suppliers in 90 countries [296]. In 2018, 5500 suppliers reported implementing projects totaling 633 million metric tons of $CO_2e$ emissions reductions, equivalent to the footprint of South Korea, at a collective savings of \$19.3 billion [297].

While these platforms are voluntary, governments are also supporting industrial decarbonization data through policy mechanisms such as mandatory disclosure, minimum performance standards, procurement, and labeling schemes. France's Energy Transition Law Article 173 and China's requirement that all listed companies report emissions data by 2020 are two recent examples of growing policymaker interest in mandating industrial decarbonization data collection and disclosure. Since supply chains span national boundaries, governments can influence foreign suppliers by requiring large corporate purchasers to report emissions from their supply chains (i.e. "scope 3" emissions reporting requirements). Government policymakers can further support industrial decarbonization data by providing resources for companies to compile and publish GHG emissions inventories, set science-based targets, and quantify best practices.

### 6.6. Labeling of low-carbon products and materials

Decarbonizing the economy involves increasing the market size for low-carbon products and materials. Carbon labeling schemes are one instrument that can add value to and grow the market for low-carbon products by informing interested purchasers of the reduced carbon impacts, increasing their willingness to pay.

For some completed products, labels may be aimed at consumers, similar to existing labeling schemes for energy-efficient appliances, lighting, windows, etc. (but disclosing manufacturing-related GHG emissions rather than the energy efficiency of the product). However, many of the best GHG abatement opportunities are in low-carbon materials such as cement and steel, which are seldom purchased by consumers directly. In these cases, labels would be aimed at companies or governments that purchase these materials in large quantities. Such labels can be useful for public procurement programs that favor green products and for companies seeking to attain environmental, social, and governance (ESG) goals. An example is Apple's voluntary commitment to zero-carbon aluminum [298]. Low-carbon labeling also can serve as advertising and provides an incentive to industry for greater innovation, to earn the label for more products at lower cost.

A prominent example of low-carbon labeling is a green building rating (GBR). A GBR scheme provides a comprehensive assessment of various environmental impacts of buildings, and these schemes increasingly include assessment of embodied carbon in building materials. Akbarnezhad and Xiao [299] reported that the share of a building's carbon impacts represented by embodied carbon spans a large range—varying from as low as 20% to as high as 80%, depending on building type, climate zone, operational energy efficiency, and other parameters.

Two of the greatest challenges of carbon labeling are the variability of the accounting methodology and the scarcity of data necessary to asses a product's holistic GHG impacts [300]. Calculating carbon embodied in materials needs to be based on a transparent and proven methodology. Life Cycle Assessment (LCA) is generally the method of choice, and it has been standardized by the International Organization for Standardization. Several carbon labeling schemes, including the environmental product declaration (EPD), follow ISO standards [301]. Incomplete adoption of labels and the difficulty of calculating LCA values has led to the failure of labeling schemes in the past [302]. Adopting labels at the manufacturer level (rather than the retailer or reseller level) can help with these issues.

### 6.7. Government procurement policies

Numerous technological approaches and process innovations have the potential to reduce industrial emissions. Initially, new technologies tend to be more expensive than incumbent technologies, since incumbents benefit from many years of refinement and returns-to-scale. Additionally, incumbents usually are not required to pay the costs of negative human health and environmental externalities associated with their emissions. Therefore, it can be difficult for novel, low-carbon products to compete with traditional products on price.

Government has an important role to play in helping to develop and commercialize new technologies, particularly those that offer benefits to society, such as emissions reduction. To leave the laboratory and become successful products, low-carbon alternatives to traditional products need a market. If there is insufficient demand, producers will have no incentive to invest in low-carbon technologies, and the new technologies will not benefit from returns-to-scale.

Governments are a major purchaser of industrial goods: government procurement accounts for an average of 12 percent of GDP in OECD countries and up to 30 percent in many developing countries [303]. Therefore, a government policy to preferentially purchase low-carbon products can lead to the creation of a substantial market for these products. This policy can help overcome a key barrier in refining and bringing down the costs of new technologies.

Examples of government procurement programs for low-carbon products include the Buy Clean California Act [304], Japan's Act on Promoting Green Purchasing [305], and India's Ujala program for efficient lighting [306]. Japan's program went into effect in 2001, and by 2013, 95% of government-purchased products in covered categories met green purchasing criteria, resulting in an annual savings of 210,000 tons of $CO_2e$ [305]. As of 2019, India's Ujala program achieves annual savings of 46 TWh of electricity per year, reduces peak demand by 9 GW, and avoids the emissions of 3.7 billion tons of $CO_2$ per year [306].

### 6.8. Recycling incentives or requirements

When products containing recyclable materials reach end-of-life, the choice of whether to recycle or to send the product to a landfill depends on the relative costs of landfill disposal versus recycling. For some materials, such as steel and aluminum, the intrinsic value of the discarded materials can be high enough to justify the costs and effort of recycling. However, even these materials are often not recycled. For example, in the U.S., only 33% of steel and 19% of aluminum in municipal solid waste (MSW) is recycled [307].

There are a number of barriers to higher recycling rates. The materials composing some products are difficult to separate, making them costlier to recycle. Contamination of recyclable materials with inappropriate materials can force an entire load to be sent to a landfill. "Approximately 25 percent of all recycling picked up by Waste Management," the largest waste handling company in the U.S., "is contaminated to the point that it is sent to landfills" [308].

Other issues are economic. The price of scrap metal tends to fluctuate greatly based on demand; for example, since homebuilders are large consumers of copper, the rates offered for scrap copper rise when many homes are being built and fall when housing demand is weak [309]. Developed countries often export recyclable products to developing countries, where workers sort through the discarded metal by hand. This can also result in financial unpredictability, as when China imposed rules in 2018 limiting the types of materials it would accept and imposing stringent limits on allowable contamination [308]. These factors can make it difficult for cities and waste management companies to agree on terms for multi-year contracts and can lead to disputes when economic conditions change [310].

Although MSW is more visible, construction and demolition (C&D) debris is the largest source of solid waste. In the U.S., C&D generated 548 Mt of debris in 2015, twice as much as MSW [307]. Therefore, policies targeting C&D waste can have an outsized impact on the quantity of material recycled. For example, jurisdictions can require contractors or property owners to ensure C&D debris will be diverted for reuse or recycling. The city of San Francisco has a Construction and Demolition Debris Ordinance that requires all C&D debris materials to be recycled or reused [311].

Municipalities can incentivize recycling practices by reducing recycling costs and increasing landfilling costs. For example, the city of Adelaide in Australia has increased its landfill tax every few years to encourage recycling [312]. In Europe, many countries are increasing private sector participation by implementing an extended producer responsibility (EPR) system. In an EPR system, the cost of recycling of materials is borne by the producer. Either producers pay the municipality directly for the cost of recycling, or they develop a system where citizens return the product at end-of-life. EPR systems reduce government costs, divert waste from landfills, and encourage manufacturers to design more recyclable products. In addition to covering the costs of recycling, EPR fees may be used to support R&D programs and waste prevention outreach activities [313].

Some cities and countries have set ambitious targets to reduce their waste significantly. This is the case in Wales, which aims to achieve zero waste by 2050, and in Scotland, which has set a target to recycle 70 percent of its waste by 2025 [314]. Similarly, the European Commission has set reuse/recycling targets of 50% by 2020, rising to 65% by 2035 [315]. Targets are generally accompanied by a waste management plan that includes specific regulations, measures, and incentives. For example, in 2014, Scotland implemented a ban on any metal, plastic, glass, paper, cardboard, and food collected separately for recycling from going to incineration or landfill, and provided a wide range of support packages to help businesses, local authorities, and the waste management sector make the necessary transition.

At the city level, in 2003, San Francisco became one of the first major cities to set a zero-waste goal. A 2009 law made separating recyclables, compost, and landfilled trash mandatory. By 2012, the city reached a recycling rate of 80% (including compost), the highest rate of any U.S. city, and a much higher rate than the U.S. average of 34% [316]. However, the remaining 20 percent has proven challenging to address, as it can be difficult to achieve 100% compliance with recycling requirements, and some products are too difficult to recycle.

For hard-to-recycle products, a litter fee can be charged, and that fee can be invested in a recycling education and investment fund. Where alternative products exist, hard-to-recycle products can be banned. For example, San Francisco has prohibited the use of polystyrene foam in food service since 2006, banned plastic bags in drugstores and supermarkets in 2007, and banned single-use plastic straws in 2019.

Community outreach and financial incentives also encourage waste reduction and recycling. In San Francisco, households receive a detailed bill for waste management fees, so they can better understand their waste disposal practices and their financial impact. Households pay less if they shift their waste from mixed waste bins to individual bins designated for recycling or composting, and if a household switches to a smaller trash bin, they receive a lower monthly bill. The city also has implemented a compliance plan to inspect waste bins regularly, and households that fail these inspections first receive warnings, which are later followed by financial penalties.

## 7. Sociological considerations

### 7.1. Equity for labor and disadvantaged communities

Globalization, technological innovation, and climate change are accelerating socioeconomic disruption in communities all over the world. Concern about the accessibility of economic opportunity is fueling the rise of populist movements, nationalism, and partisanship [317,318]. The availability of high-quality jobs is often a focal point in discussions about how society is being restructured. Technological and policy approaches to decarbonize industry must account for human needs in order to lessen, rather than exacerbate, the political and cultural forces that are dividing society.

Worldwide, fossil fuels remain a large and growing source of emissions, but jobs in fossil fuel production are disappearing. For example, in the U.S., total employment in natural resources and mining (which includes coal, oil and gas) is 700,000, about 0.5% of the total nonfarm employment. This is down from 2.9% in 1940 (Fig. 18).

The workers in declining fossil energy sectors, such as coal plant operators, are on the front lines of a broader economic transformation. Fortunately, changes in industries do not necessitate a loss of economic activity, nor a reduction in the number of jobs. Studies have found that economic transformation toward climate stabilization at 1.5 °C or 2 °C pathways will result in more jobs than 5 °C pathways [320,321]. For example, renewable energy technology development and deployment offer more job opportunities than legacy fossil systems. However, the gains and costs from economic transformation are not evenly distributed. To achieve an equitable transformation toward low-carbon industry, policymakers, companies, and other stakeholders should consider the following three guiding principles:

- Keep people at the center: focus on human impacts and communities.
- Avoid capture by vested interests.
- Where possible, opt for policies that promote win-win green growth solutions. Where this is not possible (e.g., coal mining), establish support programs for detrimentally-affected communities.
- Utilize a mix of supply-side interventions (new energy technologies, etc.) and demand-side interventions (material efficiency, etc.). In the short term, supply-side interventions may increase capital spending and (hence) employment, while reducing demand for industrial products and materials may cause job disruptions. Balancing the two types of policy may help to maintain a stable and growing job market, avoiding a boom-and-bust cycle.

These principles will require policymakers to shape decarbonization policies to provide adequate timeframes for industrial transition and include workers and community representatives at all stages of the policy development and implementation process. A just transition will also require a better understanding of how social safety nets, such as unemployment insurance and government-supported training programs, should be utilized, where they fall short, and how they can be improved. The transition to green industry will be an iterative process, but it must be accelerated to address our growing list of social, economic, and environmental challenges.

### 7.2. A low-carbon development pathway for developing nations

The 2015 Paris Agreement recognizes that the challenge of cutting emissions is particularly acute for developing nations, which must identify creative ways to lower their carbon emissions, even as they grow their economies and their people demand more services.

The highest-emitting developing countries are China and India, responsible for 24% and 7% of 2014 global GHG emissions respectively [21], and India's emissions are forecast to nearly quadruple by 2050, largely due to growth in the industrial sector [322]. China's Paris Agreement pledges are focused on committing to a year of peak $CO_2$ emissions and a minimum share of non-fossil energy within China's energy mix. India's pledges emphasize the emissions intensity of India's economy, efficiency enhancement, and fuel switching, rather than absolute emission reductions.

Both technology deployment and policy implementation have crucial roles to play in a low-carbon development pathway. In recent years, India and China have implemented innovative policies that reduce the energy intensity of industry, helping their manufacturing sectors to begin catching up with the best commercially-available technologies [323–325]. India's history of energy conservation efforts dates back to the Energy Conservation Act of 2001 [326]. In 2008, India announced the Perform, Achieve, and Trade (PAT) policy, a system of mandated fossil energy intensity targets based on tradable certificates [327], which has brought about substantial declines in industrial energy use [325]. Interviews with Indian cement, paper, and steel plants revealed that managers are interested in ways to improve climate and environmental performance beyond energy efficiency if those measures enhance their economic competitiveness [323].

Two notable Chinese policies that have reduced energy consumption while promoting sustainable development are the Top-1000 and Top-10,000 Energy-Intensive Enterprises Programs. The Top-1000 Program was initiated in 2006. This program required the largest 1000

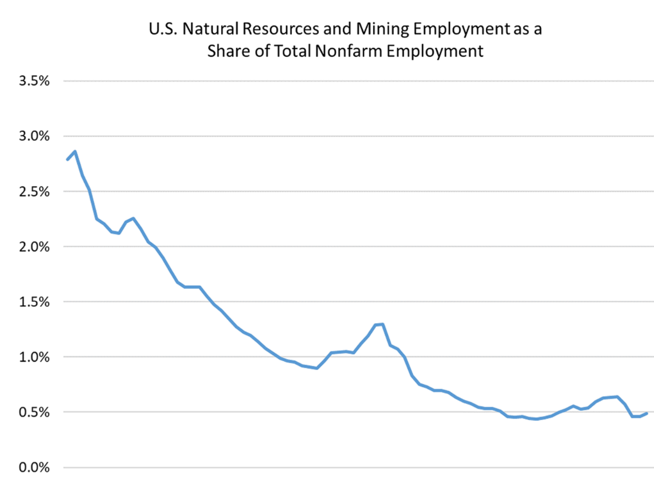


**Fig. 18.** U.S. employment in natural resources and mining as a share of total nonfarm employment has dropped from a high of 2.9% in 1940 to 0.5% today [319].

energy-consuming industrial enterprises to implement energy-saving measures, with a target of saving 100 million tons of coal equivalent (Mtce) over five years. The program also implemented measures such as carrying out energy audits, conducting energy efficiency benchmarking, improving energy management, and promoting energy-saving technical retrofits. As a result, the program saved a total of 150 Mtce during 2006–2010 [328] and reduced carbon dioxide emissions by 400 million tons [329]. The Economist called the Top-1000 Program “arguably the most important climate policy in the world” [330].

China built on the Top-1000 program by launching the “Top-10,000 Energy Efficiency and Low Carbon Action Program” in 2011. The Program targeted over 10,000 enterprises in the industry and transportation sectors that consume more than 10,000 tons of coal equivalent (tce) of primary energy annually, as well as businesses, hotels, and schools that consume more than 5000 tce. The Top-10,000 Program continued the measures implemented in the Top-1000 Program and emphasized establishing energy management systems based on a national standard, conducting energy-efficiency retrofits (especially focusing on waste heat and waste pressure utilization, motor energy efficiency, coal-fired boiler retrofits, and high-efficiency heat exchangers), and promoting energy service companies. By 2014, the program had saved 309 Mtce, exceeding its original target of 250 Mtce [331].

China and India are not alone: many countries are developing rapidly. Collectively, Sub-Saharan Africa had a GDP in 2018 (adjusted for purchasing power parity, PPP) roughly equal to that of China in 1998. Two other large countries, Brazil and Indonesia, are as productive as China was in 1995–1996 (Fig. 19). It is urgent that technical and policy innovations be rolled out as broadly as possible to ensure no country is left behind in the global transition to clean industry.

China and India illustrate that effective policy to encourage emissions reduction from industry is compatible with development goals. However, deep decarbonization of industry in developing countries has many inter-dependencies. Success hinges on decarbonizing the power sector, ensuring policies have sector-wide coverage and full participation, and providing for new fuels (such as hydrogen) or carbon capture and sequestration for difficult-to-decarbonize industries such as cement and steel. In many cases, international collaboration on R&D will be necessary. Great potential for cost-saving efficiency improvement remains, particularly at the system level. Additionally, reducing demand for industrial materials without compromising development goals or standards of living will play an important role in limiting emissions, using approaches, such as material efficiency and product longevity, described in Section 5.

## 8. Conclusion

Fully decarbonizing the global industry sector is a central part of achieving climate stabilization, and reaching net zero emissions by 2050–2070 is necessary to remain on-track with the Paris Agreement’s goal of limiting warming to well below 2 °C. Technologies will likely be deployed in waves, with demand-side interventions and already-commercialized efficiency technologies dominating through 2035, structural shifts becoming more pronounced in 2031–2050, and nascent technologies such as hydrogen becoming important thereafter. The groundwork for each of these phases must be laid in prior phases through investments in research and development, pilot projects, and infrastructure.

Achieving net zero industrial emissions will require an ensemble of different interventions, both on the supply side and on the demand side. Key supply-side technologies will be various energy efficiency measures, carbon capture, electrification in certain industries, and the use of zero-carbon hydrogen as a heat source and chemical feedstock. There are also promising technologies specific to each of the three top-emitting industries: cement, iron & steel, and chemicals & plastics. These include cement admixtures and alternative chemistries, several technological routes for zero-carbon steelmaking, and novel catalysts and chemical separation technologies. Crucial demand-side approaches include measures to deliver equivalent services with less material use, reductions in material waste (e.g. from additive manufacturing and automation), substituting low-carbon for high-carbon materials, and circular economy interventions (such as improving product longevity, reusability, ease of refurbishment, and recyclability). Even with cutting-edge, low-carbon technologies, it will not be possible to meet the needs of developing and urbanizing countries without employing measures to reduce material demand while delivering equivalent or better services.

Though the costs of low-carbon technologies will come down with additional research and scale, these cost reductions alone will not be sufficient to decarbonize the global industry sector. Strategic, well-designed policy is required. High-value policies include carbon pricing

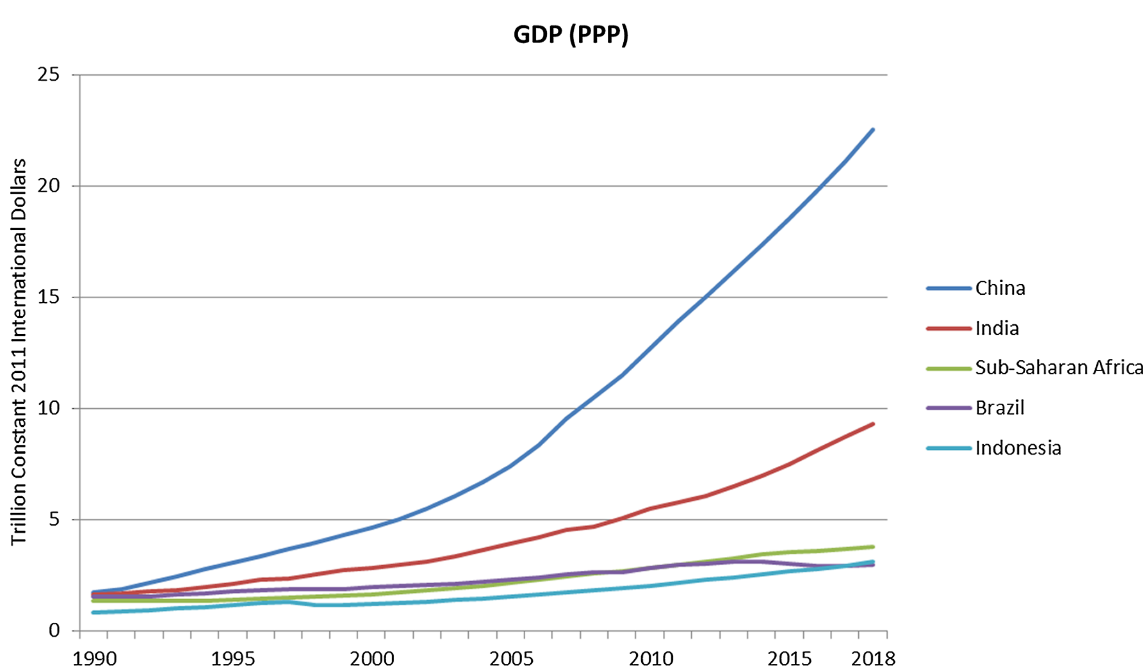


**Fig. 19.** GDP (adjusted for purchasing power parity, PPP) for China, India, Sub-Saharan Africa, Brazil, and Indonesia from 1990 to 2018 [14].

with border adjustments; providing robust government support for research, development, and deployment (RD&D); and energy efficiency or emissions standards on various products or processes (including tradeable emissions intensity standards and building codes that regulate the materials, longevity, and energy performance of buildings). These core policies should be supported by labeling and government procurement of low-carbon products, data collection and disclosure requirements, and recycling incentives. Certain policies, particularly disclosure requirements and emissions targets, can apply to industries' supply chains, thereby helping to decarbonize supplier industries in countries that may not have yet implemented meaningful industrial decarbonization policies of their own.

In implementing these policies, care must be taken to ensure a just transition for displaced workers and affected communities, seeking win-win solutions that help these communities play a valued role in the emerging, decarbonized economy. Similarly, decarbonization actions must not hamper the development of low- and middle-income countries. Instead, these efforts must be spearheaded by the developing countries themselves, with declining technology costs and smart policy allowing them to leapfrog dirty technologies and follow a low-carbon pathway to prosperity.

Though the industry sector is large and heterogeneous, the goal of decarbonizing global industrial production this century is achievable. A set of known technology and policy options offers a roadmap out to 2070, and more opportunities will present themselves as low-emissions industrial technologies become cheaper and more widespread. Policymakers and corporate decision-makers each have a part to play in embracing the transition to clean industry and hastening a sustainable, prosperous future.

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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## *Appendix A. Workshop background*

Identifying the most promising technologies and politically-implementable, effective policies to decarbonize the industry sector requires cross-disciplinary expertise. To map a way forward, the Aspen Global Change Institute (AGCI) and three co-chairs assembled a group of 28 experts in various industries, policy design, and sociological considerations of equity and global development. A week-long workshop was held in Aspen, Colorado in November 2018. The workshop included presentations by every expert, discussions, break-out groups, and an end-of-workshop survey.

**Workshop proposal and funding:** Since 1989, AGCI has convened workshops on understanding global environmental change, including key consequences and solutions. In 2017, Jeffrey Rissman (Industry Program Director at Energy Innovation LLC) proposed to AGCI a workshop on decarbonizing the industry sector. The workshop proposal was accepted by AGCI's board in December 2017. Rissman and AGCI secured funding for the workshop from the Hewlett Foundation in early 2018.

**Co-chairs and invitees:** Two other industry sector experts accepted offers to serve as co-chairs: Nan Zhou (Head of the International Energy Analysis Department at Lawrence Berkeley National Laboratory) and Jens Dinkel (VP of Corporate Strategy – Sustainability Management at Siemens). Together, the co-chairs used research and their networks to build a list of 120 experts from around the world, covering all major areas of expertise needed to plan a route to global industrial decarbonization. 82 of these experts received invitations to the workshop. 25 invitees and the three co-chairs attended the workshop in November 2018, for a total of 28 experts. The countries represented were Australia, Canada, China, Germany, India, Norway, the United Kingdom, and the United States.

**Workshop content:** Each expert prepared a 20-minute presentation on his/her area of expertise. Presentation topics were carefully distributed to achieve broad coverage of the major industries, technological approaches, policies, research, and sociological/development considerations. A group discussion was held after every block of 2–4 related presentations. Once all presentations were complete, an afternoon was spent on break-out group discussions focusing on major topics and challenges identified during the workshop. The last day included group planning of an outline for this paper.

**Survey:** In order to gather quantitative data to complement the insights shared by the experts during the workshop, a survey was conducted on the last day. 27 of the 28 experts completed the survey. The survey asked respondents to supply up to five answers to each of three questions regarding the most important technologies, policies, and future research directions to bring about the decarbonization of the industry sector. Surveys were tabulated to identify the most frequently-occurring responses. Survey results, along with group discussion, helped inform the topical coverage of this paper. The full survey results appear below.

**Co-Authorship:** This paper was jointly written and reviewed by all workshop participants.

### *Survey results*

In order to gather quantitative data to complement the insights shared by the experts during the workshop, a survey was conducted on the last day. 27 of the 28 experts completed the survey. The survey asked respondents to supply up to five answers to each of the following three questions. Tabulated results appear below. There are fewer than 135 (27 * 5) responses for each question because not every expert provided 5 answers for each question.

**What are the most important technologies or manufacturing processes that should be pursued in the next 5 years in order to efficiently reduce GHG emissions from the industry sector?**

| Technology or process | Responses |
|---|---|
| CCS, BECCS, CO2 transport (from exhaust streams, not direct air capture) | 17 |
| Hydrogen production, transport, storage, use | 16 |
| Change cement chemistry, clinker substitution, CO2-curing | 11 |
| Electrification | 10 |

| | |
|---|---|
| Energy efficiency for equipment (motors, etc.) or system-wide | 9 |
| Low-carbon, high-quality steel production | 8 |
| Reduced material use, lightweighting | 5 |
| Substituting low-carbon materials for high-carbon materials | 5 |
| Recycling, re-use, circular economy | 4 |
| Improved chemical processes, catalysts, bio-plastics | 4 |
| Waste heat recovery, heat pumps, heat exchangers | 4 |
| Use of renewable energy | 3 |
| Substitute natural gas or biomass for coal | 3 |
| Additive manufacturing, 3D printing, prefab construction | 3 |
| Reduce methane leakage | 2 |
| IT improvements, data, connectivity, tracking embedded carbon | 2 |
| Low-carbon pulp, paper | 1 |
| Replace compressed air with other technologies | 1 |
| Low-carbon glass production | 1 |
| Fuel cells | 1 |
| Ammonia production | 1 |
| Metal alloys for use in high-temperature processes | 1 |
| TOTAL | 112 |

**What are the most important policies that should be enacted by lawmakers or regulators in the next 5 years in order to bring about the decarbonization of the industry sector?**

| Policy | Responses |
|---|---|
| Carbon pricing, cap and trade, border adjustments | 19 |
| R&D financing, R&D tax credits, research partnerships | 13 |
| Energy efficiency standards per unit product, or on components/processes | 10 |
| Government procurement of low-carbon materials and products | 9 |
| Financial incentives for use or production of low-carbon materials | 6 |
| Building codes for longevity, low-carbon materials, material efficiency | 5 |
| Subsidy for use of alternative fuels, renewable energy, net metering | 5 |
| Data collection and disclosure requirements, including supply chain | 4 |
| Labeling of low-carbon products, materials, buildings | 4 |
| Financial incentives to upgrade inefficient equipment, financing | 4 |
| Emissions standards for building materials, products | 3 |
| Require or incent companies to have emissions targets, net-zero transition plans | 3 |
| CCS mandates or incentives | 3 |
| Financial incentives for recyling, use of recycled materials | 3 |
| Education, awareness of low-carbon strategies for companies or workforces | 3 |
| Worker retraining, just transition policies, helping impacted communities | 3 |
| Decarbonize the electric grid, incentives for renewables or nuclear | 3 |
| Methane leakage standards, monitoring requirements | 2 |
| Policies to prevent offshoring and emissions leakage | 2 |
| Clean development aid to developing countries | 2 |
| Public education campaigns, raising consumer awareness | 2 |
| Build out CO2 transport infrastructure | 1 |
| An award, publicity for low-carbon product design | 1 |
| Time-of-use electricity price signals | 1 |
| Subsidy for low-GHG ammonia production | 1 |
| Requirement for land use GHG sinks | 1 |
| TOTAL | 113 |

**What are the most important research topics that should be pursued to ensure the technologies we will need are available (6 or more years from now)?**

| Research Topic | Responses |
|---|---|
| Low-carbon cement and steel, or suitable replacement materials | 18 |
| Hydrogen production, transport, storage, use | 15 |
| Best policy implementation approaches, market barriers, demonstration projects | 12 |
| Public reaction, social acceptance, just transition, identifying suitable countries | 8 |
| CCS | 6 |
| Electrification | 6 |
| Zero-carbon chemical production, reduction in chemical feedstocks, low-C feedstocks | 6 |
| Recycling, recycled material use, circular economy | 5 |
| Biomass availability and use | 4 |
| Market impact of industry decarbonization, addressing stranded assets | 4 |
| Improvements to computer models, more use of modeling | 4 |
| Additive manufacturing, 3D printing | 3 |
| Full LCA of various technical options, quantifying embedded carbon | 3 |
| Renewable electricity generation | 2 |
| Material use reduction, lightweighting | 2 |
| Locating industrial facilities to maximize synergies, reduce greenfield development | 2 |
| Petroleum-free plastics | 1 |
| Electricity storage | 1 |
| Impacts of mining, availability of rare earth minerals | 1 |
| Low-carbon food production, reduction of food waste | 1 |
| Blockchain to track commodities | 1 |
| How urban design can change demand for building materials | 1 |

| | |
|---|---|
| Ammonia production | 1 |
| Improved electrodes | 1 |
| Photonic materials for catalysis, heat management, computation, etc. | 1 |
| Industrial purification or separation technologies | 1 |
| Artificial intelligence, automation | 1 |
| TOTAL | 111 |

## Appendix B. Supplementary material

An infographic accompanying this article can be found online at https://doi.org/10.1016/j.apenergy.2020.114848.

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