ARTICLE

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Decarbonizing industry: Policy approaches to eliminate hard-to-abate emissions

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HIGHLIGHTS

- Industrial activities account for over a fifth of greenhouse gas emissions, but are notoriously difficult to decarbonize.
- Decarbonizing the production of just five commodities —cement, steel, ammonia, methanol, and ethylene—would reduce global annual CO_2 emissions by 11%.
- In the near-term, decarbonization can be achieved by carbon capture, electrified heat, or using alternative feedstocks, while revamping conventional processes could lead to long-term decarbonization.
- Existing policies are primarily economics-based, with a variety of financial incentives for developing and deploying novel technologies.

Heavy industry remains among the hardest sectors to decarbonize while accounting for more than a fifth of all greenhouse gas emissions in the U.S. Industrial emissions remain so challenging to mitigate largely due to the enormous scale and the diversity of production processes involved. However, just steel, cement, and major petrochemicals (ammonia, methanol, and ethylene) account for half of industrial emissions, and share similar potential decarbonization pathways. This article reviews two major classes of decarbonization: short-term drop-in technologies such as clean heating, and long-term material-specific technologies such as electrochemistry. Implementing both classes of emissions reduction approaches will require significant policy intervention at all stages of the commercialization of these new technologies. Due to recent legislation, there is a notable amount of funding for scaling these technologies, but there remains opportunity for further support via regulation and demand-side interventions.

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The international scientific community has reached a consensus that societal emissions of greenhouse gases such as carbon dioxide (CO_2) are warming our atmosphere and impacting the global climate [1]. To mitigate the worst effects of climate change, international agreements have been made to decarbonize our society, with the goal of reaching net-zero or net-negative emissions [2, 3]. Greenhouse gas emissions from major activities like transportation and the heating and cooling of buildings can be readily eliminated through electrification if the grid is decarbonized with nuclear and renewables [2]. However, 21% of emissions originate from industrial activities such as the production of cement, metals (primarily steel), and chemicals, as shown in Figure 1 [4]. These basic materials are critical for daily life but are deemed "hard-to-abate" because they would require major changes to their production process to decarbonize [2], making rapid scaling difficult. This is further challenging because producers of raw materials face intense global competition, highly mature technologies, and thin profit margins, so they are reluctant to deploy new technologies.

This review first surveys the conventional production of these materials to develop an understanding of their embodied emissions, finding that the production of five commodities,

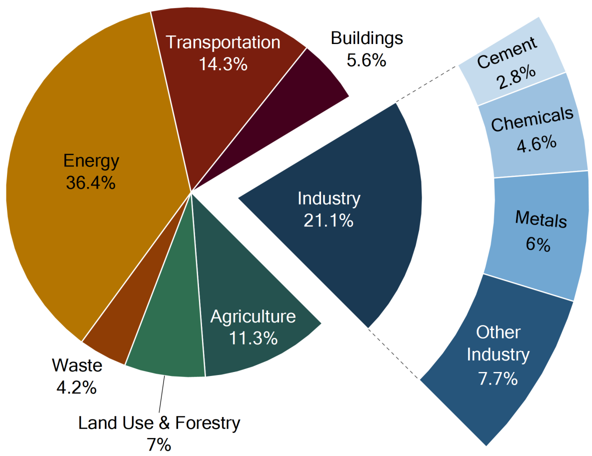

Figure 1: 2021 Breakdown of global emissions by sector and further breakdown of industrial sector emissions, totalling 56.8 Gigatons of CO_2 equivalent [5]. Differing classifications of overlapping activities can yield different sector breakdowns by cited source.

cement, steel, ammonia, methanol, and ethylene, contribute to 11% of global annual CO_2 emissions. We then provide a summary of promising technologies to reduce or eliminate their carbon footprints, either through retrofits of existing infrastructure, use of alternative feedstocks, or development of new processes with low-emissions reaction pathways. Next, we discuss current policy incentives to progress technology through stages of innovation, from R&D to mass deployment. Finally, we identify gaps in existing policy and opportunities for future policy development.

Conventional production processes

Cement: Cement is critical for infrastructure as it is one of the key components of concrete. Annual production exceeding 4 billion tonnes of cement [6] contributes 2.4 gigatonnes of CO_2 emissions. The primary components of cement are calcium oxide (or calcia, CaO) and silicon oxide (or silica, SiO_2), with smaller amounts of aluminum oxide (or alumina, Al_2O_3) and iron oxide (Fe_2O_3) [7]. While the latter three materials are naturally available in abundance, calcia must be produced from calcium carbonate ($CaCO_3$) from the following reaction (called calcination):

$$CaCO_3 + (heat) \rightarrow CaO + CO_2 \tag{1}$$

This reaction only occurs at high temperatures exceeding 800°C (1500°F) [8]. The calcia produced can then be heated in the presence of silica, alumina, and iron oxide, bonding them (through sintering) to produce cement.

Therefore, the emissions associated with cement production are twofold; fuel must be burned to provide high temperature heat to the reactions, and carbon dioxide is released from the calcination reaction as outlined in Figure 2.

Steel: Steel, like cement, is critical for infrastructure, as well as many other everyday products, with around 1.9 billion tonnes produced annually [9], contributing to 2.7 gigatonnes of CO_2 emissions. Steel is composed primarily of iron and carbon. Iron is found naturally in the form of iron oxides (Fe_2O_3 or Fe_3O_4). The most common method of removing oxygen from iron oxide is by melting in a blast furnace in the presence of coal (exceeding 1500°C, or 2700°F). Coal first burns to form carbon monoxide, which then strips the oxygen off the iron oxide and turns into CO_2:

$$Fe_2O_3 + 2C + O_2 + (heat) \rightarrow Fe_2O_3 + 2CO \tag{2}$$
$$\rightarrow 2Fe + 2CO_2 \tag{3}$$

This reaction is called reduction [10] and produces pig iron. Some excess carbon usually remains in the pig iron, but can be burned off with additional oxygen to reduce the carbon content and create steel. Similar to cement, the emissions associated with blast furnace steel production are twofold; fuel combustion for heat, and CO_2 production during the reduction reaction as outlined in Figure 3.

In 2019, blast furnaces accounted for nearly 73% of steel production worldwide [11]. Most of the remaining 27% of steel was instead produced using electric arc furnaces or in some cases oxygen furnaces, melting metal to enable the removal of impurities and the addition of desired alloying elements. The feedstocks for these processes are either recycled scrap iron/steel (78% of feedstock) or direct reduced iron ("DRI," 22%), which is made from ore by reducing hot (800–1200°C), but still solid, iron oxide with syngas (see "Petrochemicals" for syngas discussion). In the case of recycled steel, no reduction reactions are required, lowering associated carbon emissions per unit by an order of magnitude compared to blast furnace processes and DRI feeds [11].

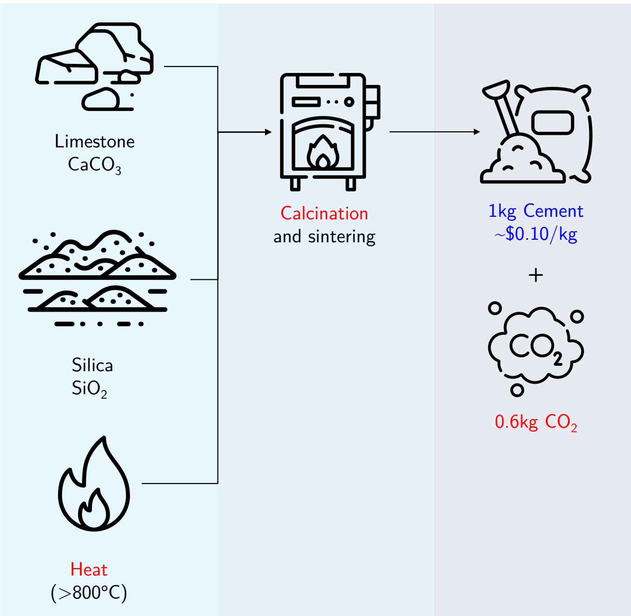

Figure 2: Overview of conventional industrial processes to produce cement. Major contributors to CO_2 emissions highlighted in red.

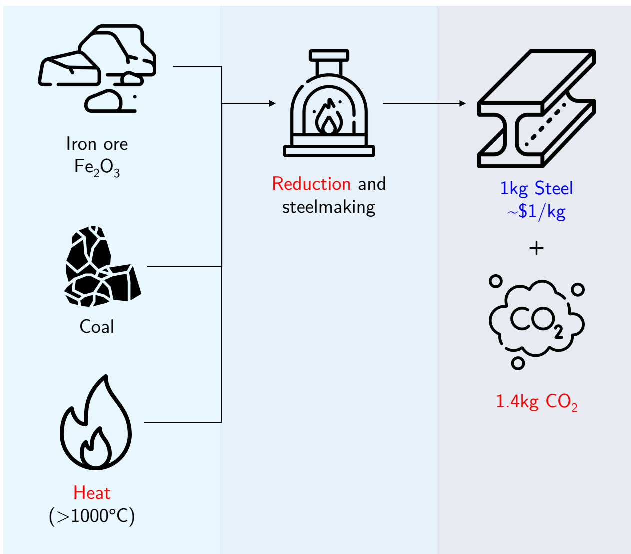

Figure 3: Overview of conventional industrial processes to produce steel. Major contributors to CO_2 emissions highlighted in red.

Petrochemicals: Petrochemicals are critical for a wide array of products, ranging from consumer goods such as cleaners and plastics to industrial chemicals like solvents and fertilizers, with around 2.4 billion tonnes produced annually [12], contributing 1.7 gigatonnes of CO_2 emissions. Broadly speaking, petrochemical production typically involves reforming mixed fossil fuels into simpler molecules, which are then purified and used as building blocks to make useful products. The production of three of these simple precursors, methanol, ammonia, and ethylene, contribute to nearly half of all chemical sector emissions [13].

Methanol and ammonia: Ammonia is mainly used to make fertilizers and methanol is mainly used as an intermediate to make fuels, chemicals like formaldehyde, or as a solvent itself. They both use syngas (hydrogen + carbon monoxide) as a precursor. Syngas is produced using steam methane reforming, reacting methane (natural gas) with water over a catalyst at high temperatures ($\sim$900°C):

$$CH_4 + H_2O + (heat) \rightarrow 3H_2 + CO \tag{4}$$

Methanol (CH_3OH) can be produced from this syngas:

$$CO + 2H_2 \rightarrow CH_3OH + (heat) \tag{5}$$

Ammonia can be produced after converting the syngas to hydrogen (water-gas shift) and then reacting hydrogen with nitrogen (Haber-Bosch):

$$CO + H_2O \rightarrow H_2 + CO_2 + (heat) \tag{6}$$

$$3H_2 + N_2 \rightarrow 2NH_3 + (heat) \tag{7}$$

Therefore, the emissions associated with methanol and ammonia production are fuel combustion for heat for syngas production through steam methane reforming (Eq. 4), and CO_2 production in the water gas shift reaction (Eq. 6) to produce hydrogen. The other reactions are all carbon neutral and exothermic, but this heat output does not fully compensate for the energy required to operate the process, so additional fuel combustion is often required.

Ethylene: Ethylene (C_2H_4) is used primarily as a precursor to produce chemicals like ethanol and plastics such as polyethylene. It is primarily produced by cracking naphtha (petroleum) or ethane (C_2H_6, found in natural gas). During cracking, the naphtha or ethane is mixed with steam and then heated to 850°C (1600°F). In naphtha cracking, multiple reactions occur, yielding numerous products (including ethylene); the ethane cracking process is more straightforward:

$$C_2H_6 + (heat) \rightarrow C_2H_4 + H_2 \tag{8}$$

The embodied emissions of ethylene production are mostly from burning fuels for the energy-intensive cracking process, since the cracking reaction itself does not produce CO_2.

While not discussed in-depth here, thermally-driven separations (e.g., drying or distillation) make up $\sim$50% of all industrial energy consumption, much of which falls under chemical production [14]. For the processes discussed here, these are particularly relevant in removing CO_2 from hydrogen (Eqs. 6 and 7) and in purifying ethylene and other hydrocarbons after fossil fuel cracking (Eq. 8).

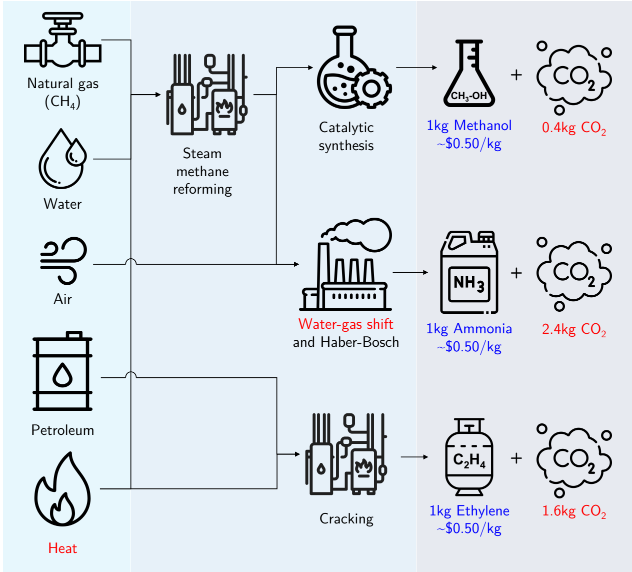

Figure 4: Overview of conventional industrial processes to produce petrochemicals (methanol, ammonia, ethylene). Major contributors to CO_2 emissions highlighted in red.

Strategies for decarbonization

To this point, we have focused on understanding how the vast majority of cement, steel, and petrochemicals are currently made, and how their associated emissions arise. With this context, we now aim to provide an overview of technologies and processes being developed to mitigate these industrial emissions. We also discuss the current status of each technology in terms of commercialization, noting that many technologies are still in the early stages. Policy approaches to accelerate development are outlined in the following section.

We first note that all the processes above require heat and emit CO_2. Therefore, we will start with two cross-cutting decarbonization technologies: clean heating and carbon capture. We will then move to decarbonization techniques that are material specific: decarbonizing the feedstocks and electrochemical alternatives.

Decarbonizing heating: We can decarbonize heating in several ways. Instead of using conventional fuels such as natural gas, we could use fuels with no carbon content such as hydrogen, so that when they burn they do not release CO_2. However, it is important that no CO_2 is released during the hydrogen production process either; this is discussed further in the Decarbonizing Feedstocks section. Biofuels could also be used to reduce emissions, as any CO_2 released upon combustion had been previously absorbed from the atmosphere. It should be noted that the embodied emissions of biofuels are nonzero due to the land use, transportation, and processing required [15]. Combustion of metals is another alternative for heat generation, but regeneration of reduced metal fuels from the oxidized products must be done cleanly to achieve net-zero emissions [16]. The combustion characteristics (flame speed, flame temperature, etc.) of alternative fuels can differ greatly from those of conventional fuels, making direct replacement nontrivial. Retrofits can require additional customization based on the application, and may end up only partially decarbonizing the process. As a result, alternative fuel solutions have not yet been widely adopted by industry on a large scale. However, future projects such as ExxonMobil's proposed Baytown facility, which aims to use hydrogen burners for onsite heating, could potentially alter this landscape [17, 18].

Alternatively, industrial heating could be decarbonized through electrification. Direct electrification could be done through resistance (Joule) heating of a heating element, but since most electricity in the current grid is produced from natural gas, this option does not reduce carbon emissions. Also, this relies on constant power from the grid, which subjects industrial plants to price spikes during peak demand hours and potential shutoff during power outages. Using heat pumps could alleviate some of these issues. Heat pumps are able to transfer more heat than resistance heating, reducing the carbon intensity and cost of the generated heat [19]. Companies like Skyven Technologies and AtmosZero are starting to deploy this technology to provide low-temperature heat ($\sim$200°C) [20, 21]. However, for higher temperatures ($\sim$1200°C), heat pumps' maximum theoretical performance is only $\sim$30% higher than resistance heating [22] and likely require significantly higher capital cost.

A promising alternative is to use renewable electricity sources coupled with thermal energy storage. Electricity generated from renewable sources (solar, wind) is too intermittent to be directly used in industrial plants. Instead, the electricity can be converted to heat and stored; common approaches are to heat inexpensive solid materials such as bricks (Rondo, ETS) [23, 24] or graphite (Antora, Fourth Power) [25, 26] to high temperatures [27]. Then, the storage material can supply heat to the industrial process on demand, improving reliability. Using cheap electricity and cheap storage materials, thermal energy storage has the potential to be cost-competitive with fuels [28]. While these technologies have been shown to work in the lab and at intermediate scales, full coupling to industrial processes has yet to be demonstrated.

Carbon capture, utilization, and storage (CCUS): CCUS approaches retrofit existing combustion-driven infrastructure with an additional separation unit to prevent release of the evolved CO_2 to the atmosphere. This separation is typically achieved thermally or electrochemically with sorbents [29], or driven by pressure with selective membranes or adsorption columns [30]. No matter the driving force, the carbon capture unit incurs an overall energy penalty, increasing the fuel or electricity requirements of the industrial process. Due to this inherent loss in efficiency, carbon capture is only implemented if mandated or incentivized by policy. Once a pure CO_2 stream is produced, it then can be either sequestered underground or repurposed for utilization or conversion. CCUS processes have been demonstrated in large scale projects such as Petra Nova, but further cost reductions are necessary to achieve economical operation [31].

Decarbonizing feedstocks: Many of the major industrial processes use feedstocks as inputs that have carbon embedded in their chemistry that get emitted during the production process. Using alternative feedstocks can reduce or eliminate these emissions.

For cement, $CaCO_3$ contains embedded carbon, so alternative materials without carbon content would be beneficial. Supplementary cementitious materials (SCM) could be used to dilute the amount of conventional cement going into concrete production, but it is difficult to fully offset emissions this way [32]. Instead, alternative calcium containing materials such as calcium silicate rocks could be used as the material input [33]. Brimstone has a pilot project in progress using this technique [34]. One interesting property of cement/concrete is its naturally affinity for carbon dioxide; over time, concrete will absorb CO_2 and act as a carbon sink [35]. It could be possible to accelerate this carbonation process with additives to the concrete materials such as sodium bicarbonite or magnesium [36]. While not discussed in detail here, alternative cements such as those based on magnesium oxide could have lower carbon intensity, but their differing mechanical properties from ordinary Portland cement make their adoption difficult [37].

For blast furnace steel, coal is the main carbon-containing input. Recall that the purpose of coal is two-fold: to provide heat for the chemical reactions, and provide the CO for reduction. Providing alternative heating satisfies the former need. For the latter need, one could use an alternative CO source such as reduced CO_2 for a carbon neutral process, or use hydrogen as an alternative reducing agent, either by exposing the ore to hot hydrogen or creating a hydrogen plasma, both of which strip oxygen off of iron oxide (reduction) [38, 39]. However, if using hydrogen, the direct reduced iron product has no carbon content; elemental carbon would then need to be added, for example from biomass, coal, graphite, or recycled steel [40]. This added carbon would then be reacted at high temperatures, and this heat addition decarbonized by taking advantage of the electrical conductivity of the iron, in a technology known as the electric arc furnace. In this process, electricity is intentionally made to generate high-temperature arcing plasma, which melts the iron and enables adding carbon content through graphite or recycled steel [40]. SSAB, LKAB and Vattenfall have demonstrated a hydrogen steelmaking process at the pilot scale through their Hybrit initiative [41].

For the production of methanol and ammonia, the primary carbon-intensive feedstocks are hydrogen and carbon monoxide. Low-carbon hydrogen can be achieved with existing infrastructure by retrofitting steam reforming plants with carbon capture and sequestration systems ("blue hydrogen") [42], which is currently being pursued by a range of companies including Shell [43]. Other alternatives include electrolysis, which splits water into hydrogen and oxygen with heat or electricity input ("green hydrogen") and methane pyrolysis, which thermally decomposes natural gas into hydrogen and elemental carbon ("turquoise hydrogen") [44, 45]. Green hydrogen companies have proliferated in recent years, but even the largest scale companies have plants producing ∼5 tons per day [46, 47], although electrolyzer producers like Electric Hydrogen are scaling up production [48]. Turquoise hydrogen companies are even smaller scale and many have focused largely on the carbon-based output product over the hydrogen produced due to the higher value [49, 50]. It should be noted that while ambitious Department of Energy (DOE) targets aim for electrochemical hydrogen to compete with Steam Methane Reforming (SMR) (2018: $1/kg in the U.S.) by 2031 [51, 52], demonstrated electrochemical costs still exceed $3/kg. Depending on legislation driving decarbonization and future costs of natural gas, hydrogen from SMR and CCUS or methane pyrolysis could also potentially reach $1/kg targets, but further R&D is needed in scalability to maximize the economic value of pyrolyzed carbon byproducts [53].

For carbon monoxide, CO_2 can be used as a carbon source instead of fossil fuels, achieving carbon neutrality so long as the CO_2 comes from direct air capture. Among the most promising routes is catalytic hydrogenation of CO_2 to produce methanol [54]. As of 2022, this pathway has been demonstrated at the 100 kton methanol/year scale [55]. Another indirect pathway is to produce syngas from CO_2 and H_2 through the reverse water gas shift reaction (the inverse of Eq. 6) [56]. Lastly, as another source of carbon, biomass feedstocks can also be used in place of petroleum or natural gas as a net-neutral carbon supply for producing ethylene [57] or syngas for methanol [58].

Electrochemical processes: In electrochemical processes, electricity can be used rather than heat as the primary energy input to drive the relevant chemical reactions, enabling integration with renewable energy and potential energy savings. Existing processes for production of materials such as aluminum and copper already involve electoextraction steps [59, 60], so there is significant precedent for deploying electrochemical processes at scale.

For cement, an example is Sublime Systems' process that extracts calcium from non-carbonate materials and converts it to calcium hydroxide, which is then reacted with silicates to make an alternative to traditional cement that still meets industry standards [61, 62]. Sublime's technology has reached pilot scale with a production capacity of ∼250 tonnes per year [63]. Similar innovative electrochemical techniques could be used as a replacement for traditional cement production.

For steel, electrochemical processes can decarbonize the production of iron, which can be converted to the desired alloy in existing electric arc furnaces. Molten oxide electrolysis is one option that uses electrons to split the oxygen from the iron oxide to produce molten metal and pure oxygen [64]. Another option is to dissolve iron ore in aqueous solutions and selectively electrodeposit metallic iron. These processes have been demonstrated at the pilot scale by Boston Metal and Electra, respectively [65, 66].

For petrochemicals, electrochemical CO_2 reduction could be used to convert carbon dioxide and water into small hydrocarbons. Depending on the catalysts selected and the reaction conditions, different products can be favored; this enables direct synthesis of methanol and ethylene. Nonaqueous media or solid state fuel cells can also be used for CO_2 electro-reduction, typically to produce carbon monoxide for syngas [67]; energy savings are possible by integrating carbon capture-and-conversion processes [68]. Electroreduction of CO_2 has been demonstrated for this purpose at the pilot scale by startup companies like CERT Systems [69, 70], but has not yet proven to be profitable. For ammonia, alternate electrochemical pathways exist such as electrolysis of N_2, nitrate reduction, and hybrid electro-thermochemical looping [71], but challenges with selectivity and efficiency remain. Plasma-enabled synthesis has been demonstrated at the pilot scale by Nitricity [72].

Summary of decarbonization strategies: As previously mentioned, there are a variety of decarbonization options for each material's production process. However, some decarbonization technologies may perform better than others. Approaches that simply alter the inputs or outputs but keep the processes the same may be easier to immediately implement and scale up, but may still be cost adders at scale. As seen in Figure 5, some examples of cross-cutting retrofitting technological solutions are thermal energy storage, clean fuels, and carbon capture, utilization, and storage (CCUS).

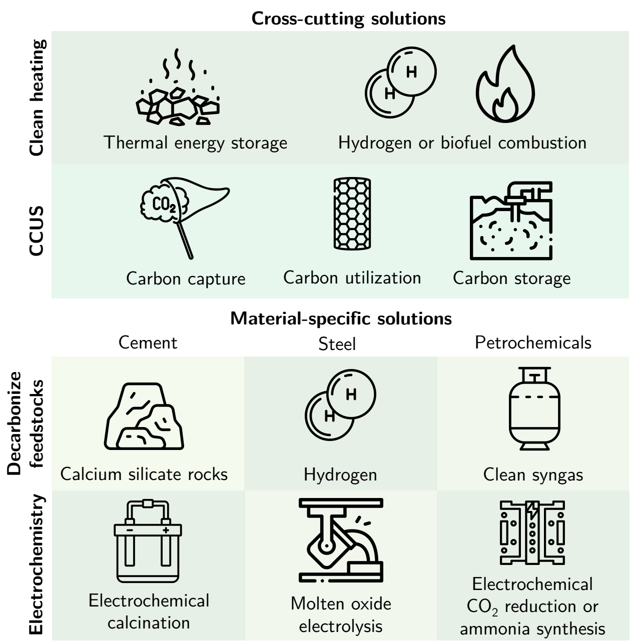

Figure 5: Overview of decarbonization solutions to produce cement, steel, and petrochemicals.

Approaches that revamp the processes themselves may be harder to implement as they may require extensive innovation (research, development, and deployment) and therefore may be more difficult to scale. However, they may perform better at scale in terms of costs and thus end up cheaper than retrofitting. Examples of cross-cutting revamping technological solutions are alternative reaction pathways using decarbonized feedstocks, and using electrochemistry, as seen in Figure 5.

The decarbonization technologies outlined above can be considered breakthroughs, but are still in the R&D or small-scale pilot stages and must be scaled up to have real impact. Scaling up may also bring to light limitations previously unknown that would require new advances to be overcome. Policy approaches could be instrumental in accelerating scale-up while incentivizing new technological development to avoid lock-in, as discussed in the following section.

Policy approaches

To support the development and deployment of the industrial decarbonization technological solutions discussed in the previous section, the U.S. federal government has enacted policies which can generally be broken down by the stage or technological readiness level (TRL) of the technology supported:

(1) Research & Development (TRL 1–5)
(2) Pilot & Demonstration (TRL 6–8)
(3) Early Market (TRL 9)
(4) Mass Deployment (Beyond TRL 9)

This review uses the TRL scale developed by the U.S. Department of Energy as a reference [73].

(1) Research & development: For nascent technologies, the first step toward commercialization is research and development. This can occur in research universities, national labs, other publicly funded research labs, or within the private sector. Across these venues, the federal government has offered a varying level of funding and subsidies, from direct grants for projects to fellowships and career awards.

For technologies relevant to industrial decarbonization, these grants generally come from the DOE, although outside agencies such as the National Science Foundation (NSF) also participate. The Advanced Research Projects Agency in Energy (ARPA-E) is an agency within the DOE that funds revolutionary ideas in energy, and recently has funded industrial decarbonization projects on transforming the steelmaking process (ROSIE) and advancing CCUS (FLECCS), among others [74]. Also within the DOE is the Office of Fossil Energy and Carbon Management (FECM), whose focus includes carbon dioxide capture, transport, and storage [75]. FECM is the predominant funder of CCUS R&D and early demonstration projects, having already obligated roughly US$1 billion to this area [76]. The federal government also financially supports a substantial amount of basic scientific research that can eventually be (and has been) applicable to industrial decarbonization, even without an obvious connection at the onset of the research. One such example is the Department of Defense (DOD), which has funded R&D grants related to clean energy and energy efficiency from an energy security and lean operations perspective [77].

However, funding for research grants specifically related to industrial decarbonization was relatively limited until the recently passed Bipartisan Infrastructure Law (BIL, 2021 (1)) and the Inflation Reduction Act (IRA, 2022 (2)). As a result of this legislation, there has been a significant increase in funding available for research alongside the creation and expansion of specific offices within the DOE to disburse these funds effectively. One key office is the Industrial Efficiency and Decarbonization Office (IEDO), which provides grants to accelerate innovation and the adoption of clean materials production technologies [21].

The private sector also receives R&D funding support in the form of tax policy. Not only can businesses deduct R&D expenses from their taxable income, but they can also claim a tax credit for a percentage (generally 5–10% [78]) of these expenses.

While all decarbonization technologies discussed previously benefit from R&D funding, they do not necessarily do so evenly. Funding for more basic research will tend to support more infant technologies, while private R&D tends to be focused on more developed and near-term technical solutions.

(2) Pilot & demonstration: Once a technology has been proven at a laboratory scale, there is a need to progress towards operating in a commercial-scale plant. The first step in this process is a pilot plant, which is orders of magnitude larger than the laboratory-scale demonstration and capable of producing meaningful quantities of product [79]. This stage, however, is generally not profitable and mainly aims to de-risk the technology to allow for the subsequent step: a demonstration plant. Demonstration plants are first-of-a-kind commercial-scale projects meant not only to prove out the technology, but also achieve cost reductions through economies of scale and learning-by-doing [79].

Each of these steps requires progressively larger capital investments while stil serving as the the least profit-producing plants to be built in a technology's lifetime. Thus, there is often difficulty finding the funding for this stage of technological development. This period, known as the "valley of death," is the point in technological development beyond the stage of most government grants but before there is easy access to debt and project financing. This can be a greater challenge for low-margin, capital-intensive industries like steel, cement, and petrochemicals. This is a particularly high-leverage point for policy intervention because successful pilot- and demonstration-scale projects allow companies to attract future investment through venture capital (generally equity) or private companies (generally debt). Fortunately, policy solutions currently exist to support these endeavours and help technologies through this stage by providing financial support and creating partnerships.

The primary role of government in this stage has been as a financial supporter. Pilot projects can take advantage of grants created and funded by the BIL. One such example relevant to CCUS are the Carbon Capture Large-Scale Pilot Programs, which will provide nearly US$1 billion in total for carbon capture pilot projects [31]. For demonstration plants, there have been several new funding sources, such as the BIL and IRA. Specifically, the BIL created and funded a new Office of Clean Energy Demonstrations (OCED), which is spending US$6.3 billion on its Industrial Demonstrations Program alone in addition to the nearly US$1 billion pilot program previously mentioned [75]. There is also the contribution of the FECM for pilot and demonstration projects, as discussed in the (1) R&D funding subsection [75]. Another relevant program is the ARPA-E SCALEUP program, which has provided over US$200 million in grants to aid ARPA-E-funded technologies to reach commercial scale [80]. These programs build on the work of the DOE Loans Program Office (LPO), which provides low-cost debt to first-of-a-kind energy-related infrastructure projects [81]. Specifically, the loans provided to firms are lower interest than otherwise available, specifically structured for clean energy technologies, and catalyze future private-sector investments through vetting and de-risking [82]. This is generally applicable across the industrial decarbonization technological landscape, but will be especially helpful to the most CAPEX-sensitive technologies like thermal energy and carbon storage. The LPO receives nearly US$412 billion in funding for this purpose from the Title 17 Clean Energy Financing Program, which provides funding for clean energy deployment (with the "innovative supply chain" project category relevant for industrial decarbonization [83]).

Second, governments can also serve as connectors between new technology start-up companies and industrial partners. In this role, governments use soft power (informal influence) to pull together these groups in a space where partnerships can be formed, requiring limited funding while creating important connections that can lead to off-take agreements (purchasing agreements for goods yet-to-be made) or joint projects. This is not restricted to the federal government; state governments have also shown interest and ability in creating hubs of industry by connecting start-ups with established local manufacturers. For example, the Regional Clean Hydrogen Hubs program brings together a variety of stakeholders to create an initial network of hydrogen production, distribution, and consumption, connecting producers to off-takers and lowering infrastructure costs [84]. This program is supported by US$8 billion in federal funds and a proposed US$157 billion in private-sector funds [84]. This can be a high-leverage demand-side intervention that generally aids all technology approaches equally.

While these are the main policies specifically targeting pilots and demonstrations, downstream or tangential policies can also improve the prospects of these projects by lowering technology risk and cost projections. For example, if a company knows that an early market is available and eager to purchase clean products, it is less risky to invest in a demonstration plant and they are more likely to find funding to do so (either more favorable venture capital funding or better financing terms on debt). Alternatively, support for mass deployment of renewable electricity generation such as solar and wind is crucial for technologies like thermal electrification and electrochemical production. Such support lowers the input price of zero-carbon electricity for these industrial decarbonization technologies, improving the economic outlook of these projects and likewise encouraging more investment.

(3) Early market: While the above policies incentivize technology development and initial demonstration, it is important for cleanly manufactured materials to be able to be sold in a market. Policy can therefore be helpful in creating initial markets for these materials.

There are a variety of regulatory policies that remove barriers to market entry; however, these are generally not legally binding. One such approach involves adjusting government procurement requirements. For example, the Federal Buy Clean Initiative is a cross-cutting initiative started by the White House in 2021 to ensure federal agencies procure low carbon intensity materials for federal projects [85]. There are similarly a variety of Federal-State Buy Clean Partnerships, with commitments from 12 states [86]. Some states including California [87], New York (3), and Colorado [88] have their own emissions regulations for the procurement or production of concrete, as an example.

Purchasing of green materials can often be more expensive, so the government has also enacted financial policies to incentivize buyers to choose cleaner alternatives. For example, the IRA provides US$4.5 billion in funding for using low-carbon materials in federal construction projects [89]. Similarly, the First Movers Coalition, a public-private partnership has assembled a group of companies committed to purchasing US$16 billion worth of clean materials. The coalition has set a goal that by 2030, 5-10% of various carbon-intensive materials such as concrete, steel, and aluminum should be low- or zero-carbon [90]. Financial policy also includes direct subsidies, either for capital investment required for these technologies or for production of final materials, and more favorable financing terms. These will be discussed in more detail in the following Mass Deployment section, where they are most relevant.

These early market policies are important to demonstrate a clear demand for clean materials, which incentivizes innovation downstream (technology R&D and demonstration). The policies also help buyers manage the higher initial costs of green materials (the "green premium") by encouraging larger-scale production, which can lower prices through economies of scale [91, 92].

(4) Mass deployment: After a technology has been shown to work at a moderate scale in its early market where it is most ideal and valuable (either through policy incentives or willingness to pay a premium), it must expand to the remaining applicable markets to reach full scale. In the context of industrial decarbonization, this could be pushing technologies further down the cost curve or bringing a technology to global competitive markets. Policy can have a highly impactful role in accelerating this process. We can group relevant policies into three main categories: financial, market expansion, and regulatory.

Starting with financial policies, these directly reduce the costs of industrial decarbonization projects. The main type of relevant financial policies are tax credits. Specifically, the tax credits available for industrial decarbonization are:

- 45Q: Carbon Capture and Storage (2), [93]
  - $12 to $180/ton depending on method of capture, final utilization, and other labor-related factors
- 45V: Clean Hydrogen Production (2), [65]
  - Up to $/kg depending on the amount of CO_2 emitted during production
- 45X: Advanced Manufacturing (2), [94]
  - For domestically-produced components for clean energy systems including solar, wind, inverters, and batteries, which enable electrification of heating and electrochemical processes
  - Also applies to thermal storage components ($45/kWh)
- 48C: Advanced Energy (2), [95]
  - For investments in clean energy projects (from 6% to 30%, depending on labor factors)
  - Specifically includes industrial decarbonization projects

Moving to market-expansion, while the policies discussed above (Buy Clean and First Movers) establish an early market, mass deployment requires larger-scale markets. There are relatively few policies here, however, one example currently under negotiation is a trade agreement between the U.S. and European Union for tariff-free trade of green materials, including steel and aluminum (GASSA and TIST) [96, 97]. This agreement could make a significant impact because, if green materials are traded tariff-free, their cost (assuming a green premium) would be similar to tariffed traditional products. Global policies are one way of expanding the market of green materials beyond the initial markets discussed above.

Lastly, regulation can help ensure large-scale market penetration. So far, these policies have been softer and not legally binding. For example, the General Services Administration (GSA) which oversees nearly 370 million square feet of rentable federal real estate, has implemented standards for carbon intensity of building materials [98]. These are longer-term standards than the aforementioned Buy Clean Initiative which is intended for initial procurement. More generally, larger climate goals such as the Biden administration's 50% GHG reduction by 2030 and a net zero economy by 2050 [99], or international agreements such as the Paris Agreement [3], can help expand the market of green materials through a soft power approach.

Future policy opportunities

As outlined above, there are many policies helping industrial decarbonization technologies progress across different technology readiness levels. However, this policy landscape contains gaps that, if left unfilled, may hinder the pace of decarbonization in these key industries.

One manner in which existing policies could be improved is by expansion. Particularly for grant programs, the number or value of grants could be expanded to achieve greater impact. Similarly, for subsidies such as tax credits, the benefit provided per unit could be increased. Further, existing regulation and or commitments could be made more stringent. For example, the Buy Clean Initiative or First Movers Coalition could increase the fraction of their purchased material that must be green, or have stricter requirements for what constitutes green materials.

While this approach is relevant in the policy discussion, the focus of the remainder of this section will be on identifying gaps in U.S. policy, instead of expanding existing policies.

To frame the discussion, we will step through each of the previously mentioned technological readiness stages and provide policy options that fill existing policy gaps. It is important to note, however, that policy within one stage interacts with technological development in other stages. This can be seen in additional private research funding in response to full-scale production subsidies or increased funding for demonstration projects given a defined early market with guaranteed purchasers.

(1) Research & development: It is important to consider relevant timelines when considering R&D policy, particularly for industrial decarbonization, where facilities are generally expected to operate for decades. There is a tradeoff between investing in near-term solutions that can be retrofitted onto existing processes (electrified heating, carbon capture) and more radical changes to manufacturing processes that may result in cheaper decarbonization on a longer timescale but are not yet fully proven (alternative reactions, electrochemistry). There will be a similar tradeoff between supporting many different technologies to diversify technology risk versus investing in the most promising technologies in an attempt to encourage learning by doing and economies of scale.

If the desire is to focus on more near-term, applied research, then one international model of R&D the U.S. could learn from and expand upon is the German Fraunhofer Institute network. These are research facilities with narrow areas of expertise that partner with industry on application-focused R&D and receive a majority of their funding through competitive grants or direct contracts with industry [100]. These close connections between independent research labs and industry help bridge the gap between academia and manufacturing and encourage the development of technologies that industry is interested in implementing [100]. The U.S. could pivot towards this model by building on its current National Laboratories network, as well as the

Technology stage

Policy approaches	R&D	Demonstration	Early Market	Mass Deployment
Current	• IEDO/ARPA-E/FECM grants	• Pilot project grants • Demonstration funding/LPO financing • Gov't procurement • Public-private partnerships	• IRA Funding for federal procurement • Buy clean commitments • Innovation hubs (e.g. Clean Hydrogen)	• Production and investment tax credits (e.g. 45X, 48C) • Global trade agreements • Infrastructure standards
Future Opportunities	• Connected R&D with focus on manufacturing	• Off-take agreements • Fast-track permitting	• Regulation of clean material procurement • Low-cost financing	• More stringent infrastructure standards • Tariffs on high-carbon materials • Int'l agreements

Figure 6: Overview of current and future policy approaches categorized by technology stage.

National Institute for Standards and Technology, to encourage more connection to industry [101].

Also, it is worth noting that policy focusing on later stages can impact the R&D phase indirectly. If policy creates a more favorable landscape for decarbonization technologies, companies have a greater incentive to invest in R&D due to the greater foreseen future benefit of successful technological development.

(2) Demonstration: For technologies approaching full-scale production for the first time, there is serious financial risk in addition to technological risk. This could be alleviated with policy via the creation of off-take agreements or feed-in tariffs.

Off-take agreements are commitments for the future purchase of goods from a specific supplier. They differ from programs like the First Movers Coalition because they are agreements between individual purchasers and suppliers that demonstrate potential future cash flows to reduce financial risk as an alternative to high-level commitments. The federal government could either enter into these agreements directly when applicable to standard agency procurement, or provide incentives for companies to do so for goods less often purchased directly by federal agencies.

Feed-in tariffs work by subsidizing a new technology in the market, paid for by a tax on all other market participants [102]. They were widely used for accelerating renewable energy development in many countries in the period between 1990 and 2010, with the most notable example being in German solar power production, where feed-in tariffs drastically improved the economics of residential rooftop solar [102]. This would be a way to create a known financial cushion for early movers to make their first full-scale plant more cost-competitive with existing players in the market and reduce their "green premium."

To accelerate the creation of a pilot or demonstration plant, the government can also institute policies that fast-track permits and other time-consuming steps. Many of these projects have time and cost overruns due to time spent obtaining permits or electrical grid interconnections. For start-up companies looking to scale quickly, this can be a major hurdle to obtaining funding or other key support. Policymakers could accelerate the timeline for technologies to demonstrate at scale by shortening these queue times and enabling a condensed permitting track, increasing the likelihood of investment and future projects.

(3) Early market: Generally speaking, existing U.S. policy has consisted mostly of subsidy and minimal penalties or regulation [103]. While the federal government has tried to create a market for the initial production of these decarbonized materials through the First Movers Coalition, it could go further by introducing regulation mandating the purchase of these materials under specific circumstances (e.g., projects larger than a given size or projects receiving government financial support) that could expand as the technologies become larger scale and lower cost. A form of this exists in the Federal Buy Clean Initiative with relatively lax rules, which could be expanded to create clearer buyers for early production.

As technologies expand beyond their first-of-a-kind (FOAK) projects, they will generally require large capital expenditures for repeat projects. After many of these projects have been built and demonstrated, they will have access to project finance, which provides well-proven, low-risk projects with low-cost debt financing (i.e., low interest rates). However, there is another "valley of death" that technologies of this type can face between their FOAK project (usually funded by a combination of venture capital funding and government grants) and their mass deployment stage (funded by project finance). In this period, the support of low-cost financing from government entities can have a large impact in scaling these capital-intensive technologies.

(4) Mass deployment: One major theme of current U.S. policy is technology specificity: tax credits or grants for implementing or developing specific technologies rather than for desired outcomes. This may cause investment of time and money in suboptimal technologies due to poor selection by a small number of policymakers. Another approach to industrial decarbonization could be evaluating and acting based on comparing measured or desired outcomes, such as a carbon tax or cap-and-trade system. These programs, however, have been proposed many times and have not yet proved politically viable in the U.S. [104], so other policy approaches that are similarly technology agnostic may prove more effective. One such example could be a carbon-reduction tax credit, rewarding producers for reducing the net GHG emissions (per unit produced) of their process while allowing them the flexibility to determine the best way to do so. This would have similar efficiency benefits to a market-based mechanism in that it would correctly align incentives but would more closely fit the policy structure already existing in the current landscape.

Alternatively, to encourage the mass adoption of these technologies in international markets that compete heavily on price, policymakers could also mandate standards. This would also require border tariffs or international agreements to prevent U.S. green manufacturers from being undercut by international competitors that are not in the jurisdiction of these regulations. To reduce emissions internationally, it may be desirable to encourage international manufacturers to take up these technologies and allow for even competition with U.S. manufacturers. This approach may face challenges in measuring and verifying compliance with emissions standards, as well as potential intellectual property concerns.

A big consideration of mass deployment is successful development of tangential but dependent technologies. Policymakers could focus on funding infrastructure projects that enable industrial decarbonization once it becomes clearer which technologies are more favorable. For example, both hydrogen and CCUS will require significant piping and storage infrastructure. There is already some funding for this in the IRA (i.e., Hydrogen Hubs) (2), but this could be expanded to nationwide pipeline networks for both hydrogen and CO_2, as well as regional industrial parks to centralize the storage of high-temperature heat. As another example, electrification of any of these processes will require low-GHG electricity that is sufficiently cheap to allow for competition with established producers or alternatives, underscoring the potential connections between different sectors simultaneously decarbonizing.

Finally, it is worth noting that none of the industrial decarbonization technologies considered here have reached (or even approach) mass deployment, making the policy discussion theoretical. As these technologies approach this stage, the unique gaps and opportunities in policy may become more apparent.

Conclusion

CO_2 and other GHG emissions from industrial processes represent more than a fifth of global emissions, yet these processes face a less certain path to decarbonization than other large emissions categories like transportation and electricity generation. The industrial contributors to GHG emissions consists mainly of cement, steel, and petrochemical production due to their huge scale (billions of tons per year). There exists a multitude of technological options to decarbonize each of these processes, which can be generally categorized into clean heating, carbon capture, using alternative feedstocks, and electrochemistry. While in the near term, it may be fastest and cheapest to retrofit existing plants with clean heating or CCUS, there may be more fitting technology-specific solutions that will be lower cost in the long term. For example, electrochemical approaches may prove to supplant existing high-temperature thermal processes, but these technologies are largely nascent. To support any of these decarbonization technologies to reach commercial scale, the government can provide financial, regulatory, or non-market policy. Although some such policy has recently been enacted in the form of the IRA and BIL, there remains urgency for further accelerating this scaling with regulation and demand-side intervention.

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