DECARBONIZING INDUSTRY IN THE U.S. AND CHINA

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Jeffrey Rissman, Energy Innovation*
Hongyou Lu, Lawrence Berkeley National Laboratory*
Al Armendariz, Climate Imperative*
Qi Zhang, Northeastern University (China)*

* Organizations are noted for affiliation purposes only. This paper represents authors' views, and not necessarily those of their institutions.

BACKGROUND AND CHALLENGES

It is hard to overstate the importance of the industry sector in the transition to a clean, sustainable economy. Industry produces the materials and products we rely on every day, including the innovative technologies essential to eliminate greenhouse gas (GHG) emissions, such as solar panels, wind turbines and electric vehicles, etc. Yet industry itself is a major GHG emitter. Including emissions from electricity purchased by industry, the industrial sector is responsible for around 60% of China's GHG emissions (International Energy Agency, 2021; World Resources Institute, 2022) and 30% U.S. emissions (International Energy Agency, 2021; U.S. Environmental Protection Agency, 2022). Therefore, industry must adopt technologies and processes to cut its own emissions to zero, while continuing to support millions of high-quality jobs and produce the technologies needed to decarbonize all sectors of the economy. Strong action to decarbonize industry will be essential if China and the U.S. are to meet their commitments to achieve net zero GHG emissions in the 2050-2060 timeframe.

In China and the U.S., the largest-emitting industries are iron and steel, non-metallic minerals (i.e., cement), and chemicals (Figures 1 and 2, next page). Some emissions-reducing technologies are specific to these industries. In other cases, cross-cutting approaches such as energy efficiency, material efficiency, and electrical heating can be applied in more than one industry.

Industrial equipment lifespans are measured in decades, so even after enacting policies to accelerate the deployment of clean production technologies, it may take years before all of the existing, polluting equipment is replaced or upgraded. This long turnover time makes it urgent for industries to begin deploying clean technologies as soon as possible.

Due to the urgency of the issue, this paper primarily emphasizes technologies and policies that are either already readily available or that can be deployed and scaled up in China and the U.S. within the next 10 years, such as energy efficiency, material efficiency, circular economy, and direct electrification of industrial heat. This paper also highlights the need for demonstration facilities for addressing emissions from the top-emitting industries, such as innovative ways to produce zero-carbon primary steel or novel cement chemistries, in the next decade.

Done right, a transition to clean industry will not only reduce GHG emissions: it can also strengthen the economy, reduce air pollution-related illnesses and deaths, and secure the clean energy technological leadership of both countries.

Figure 1 | China GHG Emissions by Industry and Emissions Type in 2019

(Gütschow et al., 2019; International Energy Agency, 2021; Joint Global Change Research Institute, 2018; U.S. Environmental Protection Agency, 2014, 2021).

RECOMMENDED TECHNOLOGIES AND TECHNICAL APPROACHES

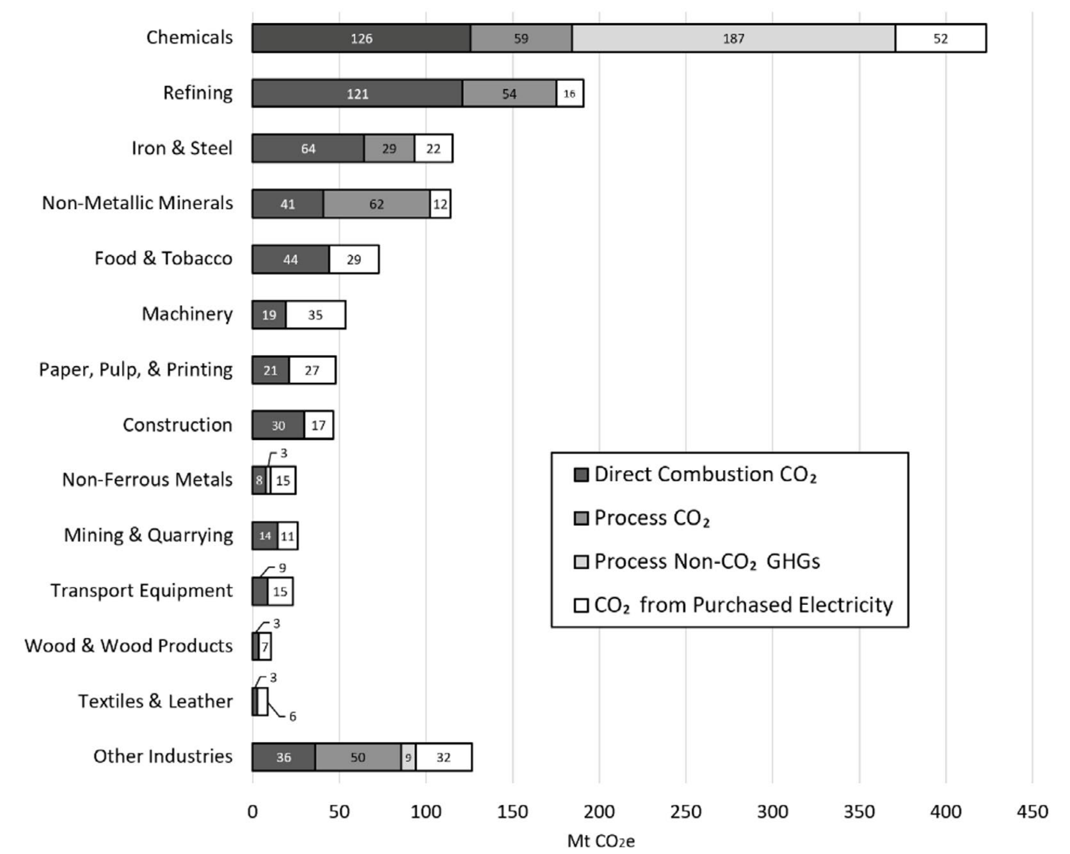
Material Efficiency and Circular Economy

Materials such as cement, steel, aluminum, copper, and plastics are critical for modern societies to build cities, develop infrastructure, and provide food, shelter, transport, medical care, and other services. Extraction, processing, and manufacturing of these materials have significant environmental impacts, accounting for about 50% of global GHG emissions (IRP, 2020a). In China, for example, cement and steel production accounted for 13.5% and 15% of the country's total CO_2 emissions in 2020 (China Securities News, 2021; Economic Information Daily, 2021).

Global demand for materials has outpaced population growth and has coincided with economic development. Since 1970, global material extraction has tripled, while the global population almost doubled (UNEP, 2016), and global gross domestic product (GDP) increased nearly fivefold (IEA, 2019a). In the future, growth in material demand is expected to continue, with some experts seeing per-capita global material demand doubling by 2060 (IRP, 2020a).

Therefore, decoupling material demand and environmental impacts is imperative to achieve climate goals. There are many technologies, practices, and measures to achieve decoupling. Many of the practices are cost-effective and can be implemented in the near term, across the value-chain of the materials and products in design, production, use, and reuse/resale stages.

Figure 2 | U.S. GHG Emissions by Industry and Emissions Type in 2019



(Gütschow et al., 2019; International Energy Agency, 2021; Joint Global Change Research Institute, 2018; U.S. Environmental Protection Agency, 2014, 2021).

Material design: improve design and use lightweight materials

When designing products, measures can be taken to reduce or eliminate the use of materials. For example, studies show that food and consumer goods packaging can be reduced by more than 20% without compromising functionality (Material Economics, 2018). Some products can be delivered digitally (video, books, etc.), and digital services can reduce the need for transportation, reducing demand for material-intensive vehicles and infrastructure. In building construction, reducing over-specification in the design process can lead to 20% cement reduction in structural elements (Shanks et al., 2019) while variable cross-section steel beams can save about 30% of the steel in a standard beam (Carruth et al., 2011).

Material production: additive manufacturing, prefabrication and improved production yields

In the production stage, additive manufacturing (also known as 3D printing) has been demonstrated in aerospace, medical, and automotive industries using a variety of polymers and metals, such as steel, aluminum, nickel, and titanium alloys. Additive manufacturing puts material only where it is needed and can create complex shapes that achieve high strength with less material, with potential material reductions up to 90% (Huang et al., 2016). Prefabrication and modular construction can reduce material use by assembling building elements in factories where processes can be standardized and material waste avoided (IRP, 2020b). China has set a target of 40% prefabricated elements in new urban buildings by 2030 (MOHURD & NDRC, 2022). In the automotive industry, sheet metal yield can be increased from 56% to 70% by incorporating material-saving best practices in design and production stages, which can reduce CO_2 emissions and costs by more than 25% (Horton & Allwood, 2017).

Material use: substitution and extending lifetime

Sometimes, energy-intensive materials can be replaced with lower-impact materials. In regions with sustainable wood resources, engineered wood can offset concrete and steel demand in buildings. For example, concrete has been replaced with engineered wood products, such as glue-laminated beams and cross-laminated timber, in buildings up to 25 stories (Willcoxon, 2022). Mass timber can reduce a building's concrete use by 25-42% (Churkina et al., 2020). About 25% of plastics used in packaging can be replaced with fiber-based alternatives, while 5% of the plastics in structural elements can be replaced with bio-composites (Material Economics, 2018).

Extending product lifetime through improved material performance and integrated structural design with durability modeling can have significant material and environmental savings (Milford et al., 2013). For example, building lifetimes in China are less than half that in the U.S. and Europe. Doubling the current building lifetime in China can reduce cement and steel demand by 20% by 2060 (Lu et al., 2022).

Reuse, Sharing, Remanufacturing, and Recycling

When a product is no longer needed by its current owner, the best option is to reuse it by selling or transferring it to a new owner, avoiding the emissions and costs of making a new product. Companies can design products to facilitate transfer and run buy-back programs, purchasing, refurbishing, and reselling their old products. Sharing systems, such as libraries that loan not only media, but also tools, gardening equipment, and other products, reduce the need for individuals to purchase products they seldom use.

Remanufacturing refers to deconstructing and re-using a product's components. For example, when decommissioning a building, steel beams can be reconditioned and used in new buildings (Dunant et al., 2019). When buildings are designed for disassembly, structural elements such as columns, beams, and hollow-core slabs can be reused in new construction projects, with the potential to cut concrete demand by 68% (Cao et al., 2021). Remanufacturing vehicle parts can also reduce energy and material demand. Studies found that remanufacturing a diesel engine can reduce 90% energy demand and save nearly 70% of embodied emissions compared to producing a new engine (Liu et al., 2014; McKenna et al., 2013).

Recycling materials can save energy and GHG emissions, depending on the material. Recycling is best suited to metals, especially aluminum, as well as paper (which avoids methane emissions from decomposing paper in landfills). Recycling glass has benefits, but they are smaller, since the energy to recycle glass is not much less than the energy to make new glass. Contrary to marketing claims of plastic manufacturers, most plastic is not well-suited to recycling, as only a few types of plastic can be cost-effectively recycled, and even "recycled" plastic is usually downcycled (re-used in a lower-grade product and then trashed).

Energy Efficiency

Energy efficiency is one of the most cost-effective means of reducing industrial GHG emissions. Efficiency also makes it faster and cheaper to shift to a net zero economy by reducing the amount of clean energy generation required to supply industry. Even after years of efficiency improvements, many opportunities remain. Researchers believe an efficiency improvement rate around 2.4% per year is possible in the coming decades (International Energy Agency, 2018; U.S. Department of Energy, 2016). China and the U.S. recognize the importance of improving energy efficiency. In October 2021, China announced energy efficiency would be a key measure to mitigate CO_2 emissions in key industrial sectors and set a goal for 30% of industrial capacity to reach international energy efficiency benchmark by 2025 (National Development and Reform Commission of China, 2021), while the United States Department of Energy's Better Plants initiative aims at reducing manufacturers' energy intensity by 25% over ten years (U.S. Department of Energy, n.d.).

Industrial energy efficiency improvements can happen at three scales: individual pieces of equipment, entire facilities, and beyond-facility measures such as business practices and product design. At the scale of individual equipment, there are hundreds of cost-effective, commercialized, energy-saving technologies and practices available for industries. For instance, manufacturers can use more forming processes, such as casting and forging, and fewer machining processes, such as drilling and grinding, which waste material. For electric motors and pumps, industries can use variable frequency drives, which adjust their speed and torque to match the load. Facilities should avoid the use of compressed air systems, which have typical efficiencies around 10% (Galitsky & Worrell, 2008). Instead, use fans for cooling; brushes, blowers, or vacuum pumps to clean parts and remove debris; and electric motors or hydraulics to move machines.

At the scale of entire facilities, efficiency relates to the choices and sizing of equipment, how different machines are connected, and how energy and materials flow between them. One important technique is to ensure machines are sized correctly for their loads, so they run at their optimal design capacity. An over-sized piece of equipment (such as a pump or boiler) must ramp its operation up and down, wasting energy. Another facility-scale technique is waste heat recovery, which uses the heat from an industrial process to power another process or to pre-heat and dry materials before they enter a furnace, boiler, or kiln. Waste heat recovery is particularly useful for industries that produce high temperatures, such as iron and steel and cement-making. Pressurizing exhaust gases increases their temperature, making it easier to extract its heat using a heat exchanger (U.S. Department of Energy, 2003). Other facility-scale options include the direct use of solar energy for heat (i.e., without first converting the sunlight into electricity) and automation (using robots to complete tasks more quickly, such as welding, which limits the amount of time a welding torch is active and consuming energy).

Beyond the facility, companies may optimize their supply chains, redesign products to be easier and less energy-intensive to manufacture, and adopt corporate decision-making frameworks that ensure energy efficiency investments are properly considered and their benefits recognized. These benefits often go beyond energy savings and can include increased productivity, reduced exposure to energy price volatility, reduced capital costs and associated insurance premiums, reduced maintenance costs, reduced waste generation and disposal fees, and improved workplace health and safety (Russell, 2015).

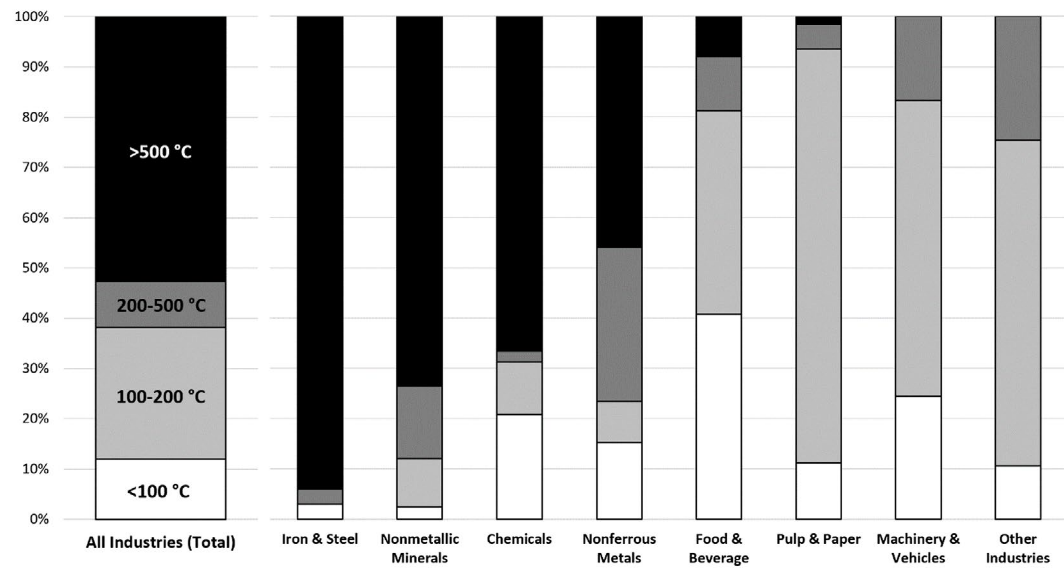
Direct Electrification of Industrial Heat

One of the most powerful methods of reducing industrial emissions is to replace fossil fuel combustion with electrified equipment. Electricity-using equipment reduces emissions as the power grid progressively achieves greater shares of renewables. Due to the long turnover time of industrial equipment, it is important to deploy electrified technologies today, not wait for the electricity grid to become fully decarbonized.

The vast majority of industrial fossil fuel (excluding feedstocks) is used to generate heat for equipment such as boilers, furnaces, kilns, distillation columns, etc. In the U.S., 91% of non-feedstock industrial energy use is for boilers and other process heating (U.S. Energy Information Administration, 2021). The key to electrifying industry is to use electrical technologies to supply heat in sufficient quantity and at the temperatures required by industry. Figure 3 shows heat demand by temperature range for industry in Europe. The temperature ranges for each individual industry are likely the same in Europe, China, and the U.S., though the total will vary by geography due to different distributions of industries in each region.

To supply temperatures up to around 165 °C, the most efficient technology is an industrial heat pump. A heat pump moves heat rather than creating it, like a refrigerator operating in reverse. Heat pumps are often between 1.5 and 5 times more efficient than creating heat (such as via an electric resistor), with declining efficiency when heat pumps are configured to deliver larger temperature increases.(Arpagaus et al., 2018) Heat pumps can supply almost all of the heat

Figure 3 | Industrial heat demand by temperature range in the European Union (EU28) in 2012



(Fraunhofer Institute, 2016).

required by certain industries such as food and beverage processing, pulp and paper, producing machinery and vehicles (from purchased materials), and other light manufacturing.

For temperatures above what a heat pump can supply, electric technology options include electrical resistance heating, inductive heating (heating conductive materials by exposure to a varying magnetic field), electric arcs and plasma torches, dielectric heating (using radio waves or microwaves to excite polar molecules, such as water), infrared heating, lasers, and electron beams. There also exist electrical alternatives to heating, such as using UV light to cure epoxies and resins or using electrolysis to chemically break down substances.

In China and in the U.S., electricity costs several times more than coal or natural gas per unit of energy. However, electricity can deliver heat to the material or part to be processed more efficiently (with lower heat losses), which helps to compensate for its higher cost. For instance, a large share of the heat from combustion of fossil fuels in an industrial furnace is lost in hot exhaust gases or to evaporate moisture formed during combustion (Bureau of Energy Efficiency, n.d.). Electrical technologies do not produce combustion exhaust gases and do not need to evaporate water in or created by fuel, eliminating these major causes of heat loss.

Even greater efficiency gains can be achieved by rethinking processes to best use electricity rather than simply swapping components. For example, fossil fuel boilers producing steam can be over 90% efficient, though typical industrial boilers in China are 70-79% efficient (United Nations Industrial Development Organization, 2014). But some heat is lost in other parts of the steam system, such as steam distribution and condensate recovery, and only 75% of the heat in steam can be extracted using a heat exchanger, so the total system efficiency in China is typically around 50%. An electrical boiler could achieve fuel-to-steam efficiency of near 100%, but it would still suffer losses in other parts of the system. Replacing the entire steam system with an electrical alternative could offer greater efficiency gains. In addition to GHG reduction, electrification brings social, economic, and environmental benefits by reducing fossil fuel consumption, reducing non-energy costs, improving safety and lower air pollutant emissions (Rightor et al., 2020).

Lastly, direct industrial heat electrification can be coupled with demand side management and energy management practices, to improve utilization efficiency of electricity at industrial facilities and better load management.

Hydrogen for Chemical Feedstocks and Primary Steelmaking

Today, chemical manufacturing and primary steelmaking rely heavily on fossil fuels, not only for high-temperature heat, but also as inputs to chemical reactions involved in making iron and chemicals. Zero-carbon hydrogen can meet these process needs without CO_2 emissions. The most mature zero-carbon hydrogen production technology is water electrolysis, where water is split into hydrogen and oxygen in an electrolyzer. Alkaline electrolysis, the most commercialized form of water electrolysis, has an energy efficiency of 63-70% today and is expected to increase to 80% in the future (IEA, 2019b).

Zero-carbon hydrogen will play an important role to decarbonize hard-to-abate industrial sectors. A synthesis study of seven China-focused energy models found that zero-carbon hydrogen is expected to represent 3% to 18% of final industrial energy use in China by 2050 in the models' 1.5 °C scenarios (Energy Foundation China, 2020). In the U.S., zero-carbon hydrogen could contribute about 10% of industrial final energy use by 2050 (Horowitz et al., 2022).

Hydrogen applications in the steel industry have attracted significant interest. In China, Baowu Steel and Jinnan steel have pilot projects using hydrogen-rich syngas in blast furnaces. A number of Chinese companies, such as Baowu Steel, Hebei Iron and Steel Group, Jianlong Steel, and Jiugang Steel, are developing projects to test using hydrogen in the direct reduction of iron. In the chemicals industry, hydrogen can be an alternative to fossil-based feedstocks. For example, CO_2 hydrogenation to produce methanol has been piloted in China (BJX Net, 2021).

Minor Use of Carbon Capture and Storage

Large quantities of industrial CO_2 emissions can be eliminated through techniques such as energy and material efficiency, material substitution, and electrification of heating. This should be done wherever possible, as it is less expensive to prevent the formation of CO_2 than to manage it after it has been created. However, in cement-making and steelmaking, it is difficult to completely eliminate CO_2 emissions with technologies available now or in the next 10 years. For instance, more than half of the CO_2 emissions from the cement industry result from the underlying chemical processes of manufacturing, not the burning of fuels to produce energy (IEA, 2018). To help decarbonize these industries, policymakers could consider promoting carbon capture and storage (CCS) to mitigate CO_2 emissions, especially non-energy emissions (IEA, 2021). (Heat for cement-making can be provided by electrical plasma torches.)

In carbon capture, stack gases are purified of contaminants and the CO_2 is separated to create a high concentration CO_2 stream. This is followed by storage, where CO_2 is injected into appropriate underground reservoirs. For CCS to serve as a viable GHG mitigation strategy, the captured CO_2 must be prevented from entering the atmosphere for hundreds or thousands of years (Kelemen et al., 2019). The geological conditions should favor the mineralization of the CO_2 into solid carbonate materials to create permanent underground storage.

The deployment of CCS by the cement industry will require the construction of CO_2 capture systems at the cement plants, compression equipment to pressurize the CO_2, pipeline networks to transport the CO_2 to the storage sites, and finally injection and monitoring systems. These systems will enable cement manufacturing to reach deep decarbonization when used alongside electrification, material efficiency, and energy efficiency (Plaza et al., 2020).

Another potential use of CCS exists in the steel industry at newer blast furnace/basic oxygen furnace (BF/BOF) steel plants (those with 10 or fewer years of operation with many years of remaining life). For older BF/BOF plants that have been in service 10+ years, the economics likely favor a transition away from coal-based iron and steel production rather than capital investment for CCS infrastructure.

Policymakers should be cautious about using captured CO_2 in products rather than sending it to long-term underground storage. The climate benefits of carbon capture will be reduced or eliminated by utilization of the CO_2 in a manner that releases the carbon back into the environment. This can happen if the CO_2 is incorporated into a product that releases carbon when used (e.g., fuels, fuel additives, fertilizers, etc.), a product that chemically degrades over time, or a product that is burned at end of life (such as some plastics).

Avoidance of Nitrous Oxide and F-Gas Emissions

Some industries produce non-CO_2 GHGs, especially nitrous oxide (N_2O) and fluorinated gas (f-gas) emissions. N_2O from industrial facilities is primarily a byproduct of nitric and adipic acid production. It can be inexpensively eliminated through thermal or catalytic destruction, forming N_2 and O_2. F-gases are primarily used as refrigerants (the working fluid inside refrigerators, air conditioners, heat pumps, etc.) and propellants, though there are many other, smaller uses for f-gases. In new products, f-gases can be replaced with less-harmful alternatives, such as hydrocarbons, ammonia, or CO_2. (Although CO_2 and some hydrocarbons are GHGs, they are much less powerful than f-gases at causing warming.) For f-gases already in use, at the end of equipment life, old refrigerators, air conditioners, etc. should be collected and the f-gases removed and safely destroyed or recycled, rather than letting the f-gases enter the atmosphere when equipment is scrapped.

Industry-Specific Technologies

Several commercial and pilot-scale technologies are alternatives to traditional fossil-fuel based iron, steel, and cement production. For iron and steel, direct reduction (DRI) is a mature technology that has been used globally for several decades with natural gas in shaft kilns or coal in rotary kilns (Global Energy Monitor, n.d.). However, hydrogen can be used instead of these fossil fuels. A new hydrogen-DRI facility called HYBRIT, in Sweden, is the first zero-carbon primary steel facility in the world. It is currently undergoing pilot testing, with commercial-scale production anticipated in 2026 (HYBRIT, n.d.). Molten oxide electrolysis (MOE) is another novel concept for the production of iron in which electricity replaces fossil fuels for the reduction of iron ore (Boston Metal, n.d.). The most advanced MOE developer, Boston Metal, has plans for commercial scale deployment as soon as 2026 (Temple, 2018).

Innovative low-carbon concrete formulations that use novel cements, including alkali-activated, magnesia, and sulfoaluminate cements, have been tested (Phair, 2006). Another low-carbon strategy for concrete is increasing the use of supplementary cementitious materials (SCMs), such as blast furnace slag, fly ash and natural pozzolans (Van Dam, 2013). Some SCMs are commercial and used widely in some regions. Concrete carbon mineralization, also known as CO_2-cured concrete, is a new strategy being investigated for carbon dioxide storage in cured concrete (Sant, 2019).

GHG REDUCTION POTENTIAL AND CO-BENEFITS

To quantify the emissions, financial, and public health impacts of this paper's recommendations, a Clean Industry Scenario was developed using the Energy Policy Simulator (EPS) version 3.4 for China and the U.S.[1] and the results were compared to an Existing Policies Scenario which includes no new action by policymakers to reduce industrial emissions.

The following actions were tested for both the U.S. and China, with each measure phasing in linearly from 2023 to 2050. While the same settings were used for both countries to ensure comparable measures are undertaken, this implies different absolute amounts of technical action, because the measures are set as percentages and China's industrial sector is larger than the U.S. industrial sector and uses different fuels, so technical potential varies between China and the U.S.

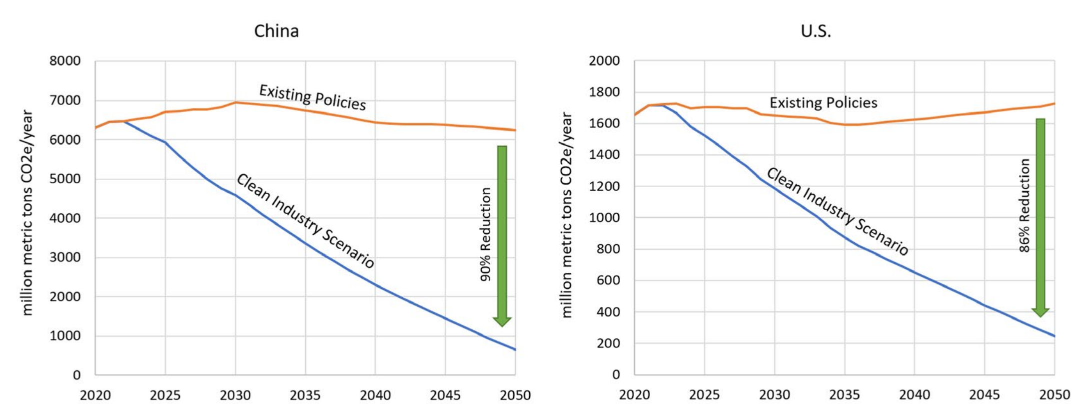
- 25% improvement in energy efficiency, plus 100% of potential achieved for cogeneration and waste heat recovery

[1] The EPS is a free and open-source computer model developed by Energy Innovation and China's Innovative Green Development Program (iGDP). Details about the simulator and how it works can be found in the EPS documentation at https://us.energypolicy.solutions/docs/

- 100% electrification of low-temperature industrial heat via heat pumps
- For industries other than iron, steel, and chemicals, 100% electrification of medium-to-high-temperature heat via technologies such as electric resistance, induction, electric arcs, and plasma torches
- For iron, steel, and chemicals, medium-to-high heat provided by 50% electricity and 50% green hydrogen combustion
- 100% of technical potential achieved for avoidance of fluorinated gas (f-gas) emissions via substituting safer gases, recycling, or destroying f-gases
- 100% of technical potential achieved for capturing or destroying leaking methane (CH_4) from natural gas production, processing, transmission, and distribution, as well as from natural gas-using industrial equipment
- 100% of technical potential achieved for destruction of nitrous oxide (N_2O) formed by industrial processes
- 100% of technical potential achieved for replacing cement clinker with other cementitious materials and fillers
- For non-metallic minerals, iron and steel, and chemicals, 80% of non-energy CO_2 emissions captured and stored

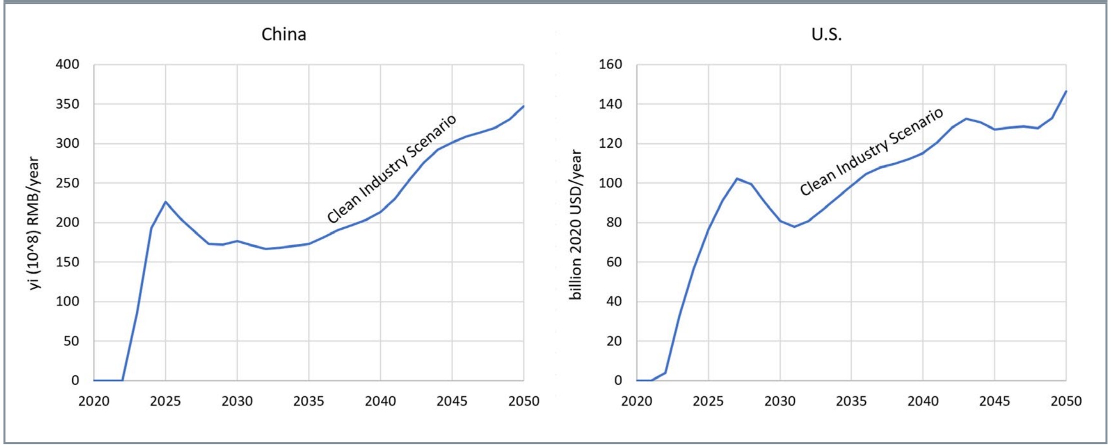
The Clean Industry Scenario shows dramatic reductions in direct industrial GHG emissions of 86% in the U.S. and 90% in China in 2050 compared to the emissions in the Existing Policies Scenario (Figure 4). For each country, two of the three measures that deliver the greatest abatement are electrification (and minor use of green hydrogen) for industrial heat, and carbon capture for CO_2 process emissions. In China, the third practice is prevention of f-gas emissions since China is a major manufacturer of refrigerants and propellants, while in the U.S., the third practice is prevention of methane leaks since the U.S. is a major natural gas producer.

Figure 4 | GHG mitigation potential from scenario analysis for China and U.S.



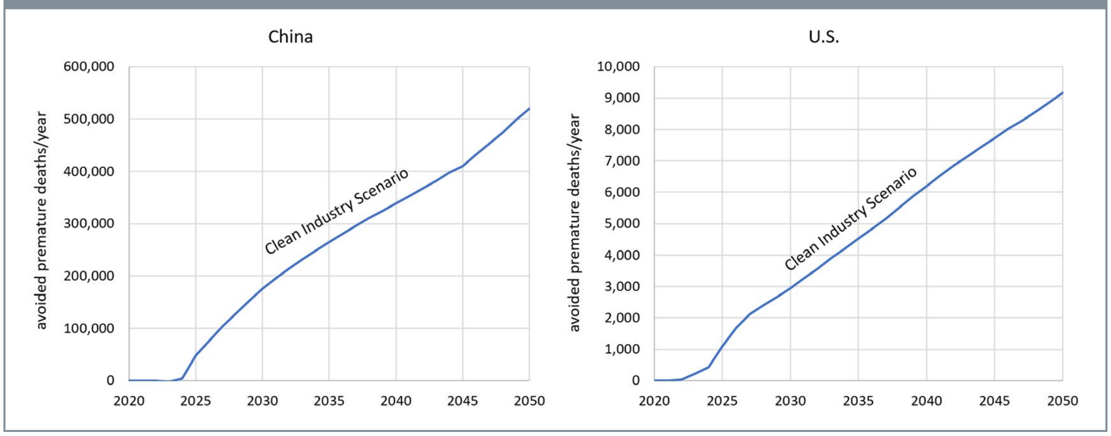
The Clean Industry Scenario boosts each countries' GDP. In 2050, China's GDP is increased by 350 yi (one yi is 10^8 renminbi) and the U.S. GDP is increased by $146 billion. Cumulatively from 2023-2050, China's GDP is increased by around 6,230 yi and U.S. GDP is increased by $2.9 trillion (Figure 5). The largest GDP impact is due to investments in the construction of new, state-of-the-art industrial facilities and capital equipment, which create jobs in industries such as equipment manufacturing, construction, and the making of constituent materials. Second, the increase in efficiency and the shift to electricity (which is used more efficiently than fossil fuels) saves money for businesses, which can be spent in ways that boost the economy, such as paying workers, buying materials, and increasing production.

Figure 5 | Change in GDP Caused by Clean Industry Scenario vs. Existing Policies Scenario[1]



[1] These graphs show the change caused by the technical measures in the scenario, not the total industrial contribution to GDP or value added. Total GDP is much larger and is projected to grow smoothly from 2023-2050. It is not shown here because changes caused by the scenario would be very difficult to see if graphed together with total GDP or value added.

Figure 6 | Avoided premature deaths



The Clean Industry Scenario causes a modest increase in imports and drop in exports of manufactured goods, as some manufacturers attempt to avoid paying for equipment upgrades. Supporting these manufacturers through retooling grants and access to low-cost financing, and/or a "buy local" policy requiring a percentage of goods to be made in-country, can counteract this effect, greatly increasing GDP (and job) creation without hampering emissions abatement.

A transition to clean industry will save lives by reducing emissions of pollutants harmful to human health, such as particulate matter, nitrogen oxides, and sulfur oxides. As industry becomes cleaner, the number of avoided premature deaths grows each year, reaching 520,000 avoided deaths in China and 9,160 avoided deaths in the U.S. in 2050 alone (Figure 6). China sees larger benefits because of its higher population and because 45% of China's industrial energy needs are met with coal, which emits high levels of pollutants, whereas coal makes up only 6% of U.S. industrial energy consumption (International Energy Agency, 2021). There are also fewer nonfatal health impacts. In 2050, China avoids 670,000 nonfatal heart attacks, over 14 million asthma attacks, 250,000 emergency room (ER) visits for respiratory issues, and over 50 million lost workdays. The U.S. figures are 12,000 nonfatal heart attacks, 283,000 asthma attacks, 4,400 respiratory ER visits, and 914,000 lost workdays avoided.

The monetary benefits of preventing lost workdays, illnesses, and deaths are not included in the GDP calculations above, so the GDP benefits will be even greater if public health impacts are factored in.

POLICY RECOMMENDATIONS

Financing for Clean Industry

For some manufacturers, the costs to buy new machines and retool factories can be a barrier to uptake of new, clean production processes. These firms often struggle to find affordable financing in the private market because their technology is too new and risky, or there are concerns about the product's competitiveness. Government can help overcome these barriers by using policy to improve industrial firms' access to low-cost financing for process improvements.

Government may use green financing mechanisms directly, or it may form a green bank, an independent or quasi-independent entity to handle this work. A green bank is initially capitalized by government appropriations, but thereafter, it operates as a self-sustaining fund where payment of principal and interest on loans finance new loans to other recipients. This makes green banks more robust and long-lasting than programs that rely on annual infusions of government money.

One way to amplify the effect of green financing is to use public resources to leverage as many private-sector dollars as possible for clean industrial projects. Key public financing approaches include:

- Co-lending: partnering with a private financial institution to loan money to a qualifying project, sharing the risks (and rewards). The government agency or green bank may have expertise in evaluating clean industrial projects, assisting the private financier with loan underwriting.
- Aggregation: bundling many small, industrial projects loans, then selling the bundled loans to private investors. Bundles are attractive to investors because they provide diversified holdings and help investors avoid the need to evaluate numerous small projects.
- Loan loss reserves or loan guarantees: covering a share of private lenders' losses, when they invest in qualifying clean industrial projects that later default on their loans. Government should not cover 100% of the losses to ensure private lenders still evaluate projects with proper due diligence.
- Bond sales: a government agency or green bank can raise money for qualifying, clean industrial projects by selling bonds. While most financing mechanisms rely on large corporate lenders, the sale of bonds unlocks financing from individual and institutional bond investors, diversifying the sources of financing available to clean industrial projects.

These lending mechanisms work well alongside other financial policies, such as tax credits or subsidies for clean industrial technology or clean production, as many of the private investors that partner with a government finance agency or green bank are motivated, in part, by these incentives.

GHG Emissions Trading Systems

An emissions trading system (ETS) puts a monetary value on the right to emit GHGs (including, but not limited to, CO_2). China has a national ETS that currently covers the power sector with the anticipation to expand to building materials, steel, and other energy-intensive sectors, while 14 U.S. states have implemented an ETS at the state or multi-state level covering the power sector and, in some states, industry sectors. This paper discusses how to design ETS systems to reduce industrial emissions efficiently and cost-effectively. U.S. and Chinese policymakers can consider these guidelines when strengthening or expanding domestic ETS policies.

An ETS incentivizes emissions reduction through three mechanisms: technology switching, demand reduction, and smart use of government revenue from selling emissions permits. Technology switching involves industries using lower-emitting manufacturing processes to produce goods to reduce their need for emissions permits. When clean technology is close in cost to dirty technology, industries can affordably switch to cleaner technology and avoid paying the carbon price. This makes carbon pricing an inexpensive and powerful policy for instances when clean technology is relatively mature and only needs a little help to outcompete dirty technology.

Demand reduction involves making goods more expensive, so people buy less of them. Generally, demand reduction is not the main mechanism by which a policymaker wishes carbon pricing to operate, because it has a high cost-per-ton-CO_2e abated, resulting in low economic efficiency. High prices can be a burden on consumers and may impact economic growth. When technology switching is expensive or impossible, a carbon price will act primarily through demand reduction. Therefore, carbon pricing is not the best choice when clean production pathways are technologically immature.

The third mechanism is smart use of government carbon pricing revenues. Among the best uses are programs that reduce industrial GHG emissions, such as research and development funding, cost-sharing for demonstration and early commercial deployment, and capitalizing green banks (discussed above). Revenues may also fund industrial energy efficiency upgrades, particularly for small manufacturers for whom the initial capital investment can be a significant barrier.

Emissions permits should have a price collar: a floor below which the price of a permit is not permitted to fall, and a ceiling, where the government prints and sells more permits to prevent prices from exceeding the maximum level. The price floor is particularly important, because experience from carbon pricing systems in Europe and the United States have shown that emissions reductions are often cheaper than regulators anticipated, so without a floor, permit prices could be too low to properly incentivize a transition to clean industry. If firms are allowed to bank permits (store them for use in a future year), then a robust price floor becomes even more crucial. A price ceiling should be high enough that it is unlikely to be reached in the short term, but a ceiling may become relevant closer to 2050, because the cost of abating the last few percent of emissions from industry may be higher than the cost of avoiding easier-to-abate GHG emissions over the next 10-20 years.

One of policymakers' major concerns with carbon pricing is the possibility of leakage: that the policy will reduce the growth of domestic industrial activity and increase industrial activity and emissions in countries without carbon pricing. To date, policymakers have addressed leakage by exempting some or all industrial facilities from the carbon pricing system, or they distribute free permits to domestic manufacturers. These techniques may reduce leakage, but they also dampen or eliminate the incentive to decarbonize, reducing the effectiveness of the carbon pricing policy. A better approach is to charge the carbon price on all firms for each unit of GHGs they emit, but to provide counterbalancing subsidies to domestic manufacturers linked not to emissions, but to positive traits the government wishes to encourage, such as the firms' contribution to GDP or the number of high-quality jobs the firm provides. This subsidy can help to offset the carbon pricing fees, so the domestic industry remains competitive. Since the subsidy does not allow free emissions, it does not reduce the policy's incentive to decarbonize.

GHG Emissions Standards

The U.S. and China have experience using standards to reduce emissions of conventional air pollutants, providing expertise they may apply to cutting GHG emissions. One study found U.S. Clean Air Act programs and regulations have a benefit/cost ratio of 30-to-1 (U.S. Environmental Protection Agency, 2011). Since 2013, policy in China has reduced conventional air pollution by 40% nationwide and by 50% in Beijing, adding 2-4 years to residents' life expectancy (Air Quality Life Index, 2022).

GHG emissions standards can be set as carbon intensity thresholds (CO_2e/unit product) for commodities, such as particular grades of steel, types of cement, or bulk chemicals such as ammonia. For differentiated products (non-commodities), each producing facility can be required to report and reduce its emissions relative to its own historical baseline.

Emission standards can provide a long-term signal that drives innovation if they are properly designed. The most important design principle is to drive continuous improvement over many years. If standards do not become tighter over time, they lose their ability to shift the market toward greener technologies. Therefore, standards should contain a formula that specifies when and how future increases in stringency are automatically calculated. This will provide transparency, timeliness, and resistance to political interference.

Standards should have simple designs and be outcome focused. Complicated standards that make many distinctions between different types of equipment and specific uses are more difficult to write and more prone to loopholes. Facility-wide standards limiting GHG emissions per unit output are simpler than standards on each piece of manufacturing or fuel-burning equipment.

Standards must apply to any product sold in the regulated market, whether imported or produced domestically, to avoid giving unfair competitive advantage to higher-carbon foreign producers. For standards set per unit material (such as steel), importers should be required to disclose the embodied carbon in their imports. For standards governing the performance of imported machinery, such as industrial boilers, imported products' performance should be tested and subject to audits.

Policymakers should also consider sales-weighted, tradable emission standards. These types of standards specify the minimum performance of the sales-weighted average of all units sold by a manufacturer. Manufacturers may sell some units that fail to meet the standard if they compensate by selling enough units that exceed the standard. An example of a sales-weighted standard is the U.S. corporate average fuel economy (CAFE) standard for light-duty vehicles, which has allowed credit trading amongst manufacturers since 2011 (He, 2014). Tradable, sales-weighted standards may be applied in addition to or instead of traditional standards that impose firm, minimum requirements on emissions from each piece of equipment.

Finally, policymakers should consider establishing a standard governing allowable "embedded emissions" (production-related emissions) in imported parts and materials. These standards prevent a loophole where domestic firms may import their carbon-intensive inputs in order to continue selling emissions-intense products in the regulated area. To comply with the standard, domestic firms may pressure suppliers to reduce their GHG emissions, or they can switch to suppliers already using cleaner processes. Suppliers wishing to sell into regulated markets may choose to adopt cleaner production processes.

Equipment Fees, Rebates, and Feebates

Industrial facilities utilize a variety of industrial equipment, ranging from boilers and furnaces to compressed air, motors, and fans. Some types of equipment are used widely across many industries. Incentivizing procurement of energy-efficient, low-carbon models of the most widely used, energy-consuming pieces of equipment can have significant energy and cost-saving impacts across industries. In addition, accelerating the adoption of clean and energy-efficient industrial equipment does not have to wait for breakthrough innovations, as there are cost-competitive, commercialized technologies on the market, and policy can help the cleanest options gain market share.

Fiscal incentives, such as equipment fees, rebates, and feebates can reduce the investment cost of energy efficiency faced by industrial facilities. For example, low-performing and inefficient industrial equipment will face a fee when sold to customers. Equipment rebates reward high-performing and efficient industrial equipment. Equipment feebates combine a fee and a rebate in a single policy, where a tax will be levied on the lowest performing equipment, and the tax revenues are used to incentivize purchasing the cleanest equipment. When setting up the thresholds for fiscal incentives, it is important to make sure thresholds are "high enough to be effective and provide sufficient incentive for action, while ensuring that they are not so high that industries close down or relocate" (Price et al., 2005). The thresholds also need to be regularly updated to keep up with improving technology in the marketplace and avoid stagnation. Other fiscal incentives such as tax deductions, tax rebates, accelerated depreciation, tax exemption, or tax credits tied to specific energy-efficient and low-carbon technologies have also been used in many industrialized countries (World Energy Council, 2008).

Fiscal incentives can also be combined with other energy efficiency and decarbonization policies (e.g., minimum energy performance standards, equipment labels, energy assessments, green financing, technology lists and awards, carbon emission trading schemes, green procurement) in an integrated energy efficiency or GHG emission mitigation program, as seen in many European countries (Price et al., 2005).

Circular Economy Policies

Both the U.S. and China have adopted policies to support a circular economy, where each product or material is put to its highest and best use through measures such as product longevity, sharing systems, redistribution/resale, remanufacturing, and recycling. China enacted the Circular Economy Promotion Law in 2008 (Circular Economy Promotion Law of People's Republic of China, 2008) and developed policies to promote reuse of waste materials (Mathews & Tan, 2016). In the United States, the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) has stimulated corporate recycling and resource recovery initiatives (Zeng et al., 2022).

Domestically, both countries can strengthen their circular economy programs by closing loopholes and addressing gaps in regulations. For example, both countries can improve repairability of products via right-to-repair legislation, including mandatory standards for product durability, repairability, and availability of replacement parts and manuals (van der Velden, 2021). Extended Producer Responsibility, principles that shift some responsibility for end-of-life products to manufacturers, can be strengthened by developing binding mechanisms, providing incentives to enterprises, and expanding coverage to more industrial products (Leal Filho et al., 2019). Higher recycling targets should be established for key materials such as steel, aluminum, paper, and glass, accompanied by recycling requirements for businesses and households, plus requirements for producers to use more easily recyclable materials in their products (Zeng et al., 2022).

Additionally, countries should work to standardize the documentation and disposition of industrial wastes. Governments can require industries to document the type, quantity, destination, and other attributes of waste they produce. Policymakers may build robust waste collection networks that are supported by online tracking of waste and recycled material flows. Waste management companies should be urged to introduce technologies that improve recycled material quality and yield, while lowering recycling energy requirements, such as low-temperature solid-state extrusion of polyethylene plastic (Guo et al., 2006).

Green Public Procurement

Governments are important buyers and funders of industrial products, especially the materials that go into infrastructure, government buildings, military equipment, vehicles, etc. Public procurement accounts for an average of 12% of GDP in OECD countries and up to 30% in non-OECD countries (UN Environment Program, 2017), so government procurement represents a large and lucrative market for industrial suppliers.

A Green Public Procurement (GPP) program leverages government's buying power by establishing an emissions intensity standard that must be met by products sold for government-funded projects. The GPP program establishes a more stringent standard for products sold to the government to create a lead market for industrial goods produced using clean manufacturing technology, so clean production processes can scale up and clean manufacturers can drive down their costs through learning and returns-to-scale.

It may not be practical for a GPP program to cover every type of product the government buys. Therefore, policymakers should prioritize establishing GPP criteria for products whose production generates significant GHG emissions, for which commercialized alternatives offer large abatement potential and are available at an acceptable cost to government, where green options provide co-benefits such as jobs in low-income communities or reduction of conventional pollutants, and where these green alternatives have large potential for cost improvement through returns-to-scale. A GPP program may create a “carve-out” for products made with highly innovative, zero-carbon technologies, such as primary steel made with green hydrogen or iron electrolysis, novel cement chemistries, etc. A carve-out is a higher performance tier for which the government is willing to pay a higher price per unit product to help manufacturers develop cutting-edge, clean processes.

Once many suppliers can provide cleanly-made products that qualify for a GPP program, the government can run a “reverse auction” to determine the price it will pay. Each firm enters a bid indicating the lowest price it will accept and the quantity of product they can supply. Government agrees to pay the lowest price that will secure sufficient product from all suppliers. Suppliers compete to drive down their costs and secure contracts to sell to the government. This mechanism is best used for commodity products, such as steel or cement, where the end product is the same from all suppliers and only the production process varies.

Finally, note that GPP programs are a type of standard, so all the design principles regarding standards (discussed above) also apply to GPP programs.

GHG Emissions Disclosure

A requirement for companies to disclose to the public, customers, and the government the amount of GHG emitted to make their products is an enabling policy that supports the other strategies described in this paper. Disclosure requirements can accelerate industrial decarbonization via several mechanisms:

- First, a company facing a disclosure requirement must understand where its emissions are coming from, which often involves an audit of energy-consuming equipment and industrial process steps. Such audits often identify cost-effective ways for firms to save energy.
- Second, accurately reporting emissions is an enabler of other policies. It helps the government determine a firm’s liabilities under carbon pricing, whether the firm is complying with GHG emissions standards, whether its products qualify for green public procurement programs, etc. Disclosure is also needed to allow for export to regions with carbon border adjustments, such as the EU.
- Third, reliance on high-emissions processes is a financial liability due to growing public and government recognition of the need for industries to decarbonize. Emissions disclosure requirements give investors data they need to make informed decisions. Disclosure helps align companies’ objective to increase shareholder value with society’s need to eliminate GHG emissions.
- Fourth, requirements for complete and accurate environmental disclosures can combat greenwashing, the practice of presenting business operations or products as environmentally friendly (for example, by using terms such as “green” or “eco-friendly” without delivering real corresponding environmental benefits). The government and the media can call attention to instances when marketing claims are contradicted by disclosed data.

To ensure accuracy and comparability across companies in different industries and countries, it is important that GHG reporting comply with an international standard. The leading entity managing environmental disclosures is CDP, a non-profit founded in 2000 with offices worldwide. CDP works with companies to help them accurately disclose their emissions (including emissions embedded in materials and parts they purchase). Over 13,000 companies disclose data through CDP (CDP, 2022).

A related organization is the Science Based Targets initiative (SBTi). SBTi helps companies set verifiable targets for future emissions abatement that are compatible with a trajectory limiting global temperature rise to 1.5 °C. SBTi staff review companies’ targets against detailed technical criteria to ensure validity and methodological robustness, including customized industry-specific criteria for a dozen industries (Science Based Targets Initiative, 2022b). As of early 2022, over 1,300 companies have targets approved by SBTi, and more than 1,500 others have publicly committed to set a target and get SBTi approval within two years (Science Based Targets Initiative, 2022a).

Governments are increasingly mandating companies disclose their emissions and climate-related risks. In 2022, the UK became the first G20 country to establish a reporting requirement. UK-registered businesses with over 500 employees and £500 million in revenue will be required to report on their climate impacts (Task Force on Climate-related Financial Disclosures, 2017; UK Government, 2021). Similarly, in 2022 Japan began requiring large businesses to report their emissions. New Zealand enacted a reporting requirement in 2021, which will come into effect in 2023 (Duran, 2021). A European Union reporting requirement will begin in 2024. Other countries with forthcoming GHG reporting requirements include Brazil, Singapore, and Switzerland.

GHG Emissions Labeling

Labeling involves putting notices on a product's packaging and digital store listings indicating its environmental performance. Labels disclosing the energy efficiency of energy-consuming products, such as automobiles and appliances, are common globally. Examples include the China Energy Label, U.S. EnergyGuide, and EU Energy Label. However, today these labels do not disclose the greenhouse gas emissions that occurred during the manufacture of a product or its materials. Labels must disclose these emissions if the labels are to be helpful in decarbonizing industry.

Most emissions involved in making a product, such as a computer, occur during the production of its constituent materials, like aluminum, copper, glass, plastic, etc. Since the product manufacturer is rarely the maker of its constituent materials, labels must disclose all emissions, including embedded emissions in purchased materials, to be useful.

Labeling should use a uniform, scientifically-sound, and government-mandated emissions accounting methodology, ideally based on international standards and compatible with reporting through CDP. Labels and claims that do not comply with these standards should be prohibited. For example, there are more than 450 types of eco-labels on consumer products, most of which provide no meaningful guidance, as there are no standards for or verification of the claims being made (Atkinson, 2014).

A robust, government labeling system helps highlight top performers, steer corporate and household purchasers toward more environmentally friendly options, assist governments in reaching national greenhouse gas emission targets, and makes it easier for businesses and local governments to implement green procurement policies.

OPPORTUNITIES FOR CHINA-U.S. COOPERATION

Global coalition to accelerate industrial heat electrification

The United States and China can lead a global coalition on industrial heat electrification to accelerate the adoption of electrotechnologies in industry. Technology guidebooks and catalogs can be developed to increase local government and industry awareness of the benefits of industry electrification. Large-scale demonstration projects of key electrotechnologies can test and validate technological feasibility, and their results can be publicized to illustrate the feasibility of electrifying various industries. Model voluntary or mandatory electrification standards can be developed, which can be adopted at national or subnational levels. Joint U.S.-China research, development, and deployment (RD&D) programs leveraging the technical expertise and manufacturing experience of each partner, supported by funding, policies, and exchange programs, can refine and commercialize technologies for high-temperature heat electrification.

Develop and harmonize GHG emission accounting standards on industrial products

One of the important industrial decarbonization measures is to create market demand for low-carbon materials and products. To improve policy effectiveness and mitigate any potential carbon leakage, it is critical to develop, harmonize, and implement methodologies and standards on carbon emission accounting (Hasanbeigi et al., 2019). Harmonized emission accounting standards increase data quality and consistency. The United States and China can adopt international standards related to environmental product declarations (EPDs) such as ISO 14025 Type III environmental declarations, require best practice reporting, and set up disclosure requirements on industrial products (Carbon Leadership Forum, 2020). The United States and China can set up committees to participate in the EPD development process.

If China and the U.S. strengthen and harmonize energy efficiency and GHG emissions standards for industrial equipment, equipment manufacturers would be able to design highly efficient equipment that complies with regulations in two large markets. This allows equipment manufacturers to reduce production and logistics cost and complexity by reducing the number of models they must manufacture and ship. Benefits would be felt worldwide, as equipment manufacturers might choose to bring all of their equipment sales globally up to the standard, even for products sold outside of the U.S. and China.

Linked Carbon Market (ETS)

The U.S. and China could create a linked ETS market with robust, uniform standards for emissions accounting, permit auctioning, verification, and trading. Additional countries that adopt equally robust carbon pricing would be invited to join. A uniform carbon market would help overcome resistance to carbon pricing by ensuring companies face a level playing field, addressing concerns that carbon pricing gives foreign firms a competitive advantage.

Joint "First-of-a-Kind" technology demonstration projects for industry decarbonization

Fully decarbonizing the industrial sector requires breakthrough technologies, such as novel medium-to-high temperature heat electrification in cement manufacturing, hydrogen-direct reduced iron or molten oxide electrolysis for steelmaking, and CCS applications in industry. Some of these technologies are in early stages of research and development, while others, such as industrial CCS, require significant investment and technology demonstration. Market adoption of these technologies face barriers, such as costs, perceived risks, geographic challenges, infrastructure needs, and complexity of integration with existing industrial processes.

The United States and China can jointly develop "First-of-a-Kind" projects to demonstrate industrial applications of these yet-to-be commercialized but high-abatement technologies. The joint projects can build upon the technology and know-how from the U.S. Department of Energy national labs and the Chinese Academy of Sciences and universities. The joint projects can build upon and go beyond the previous successful program of the U.S.-China Clean Energy Research Center (2011-2020), which focused on research and development of early technologies and did not cover carbon-intensive industrial sectors. New projects should emphasize industrial deep decarbonization technology demonstration, testing, validation, and partnerships with industry.

Clean Materials Free Trade Agreement

hina and the U.S could create a Clean Materials Free Trade Agreement, where trade proceeds without tariffs, quotas, or other barriers for commodities like steel, non-ferrous metals, cement, etc., if those materials were made with very low or zero GHG emissions. A clean materials free trade zone would create incentives for high-carbon manufacturers to innovate and adopt low- and zero-carbon technologies like hydrogen-DRI for steelmaking or CCS and electrification for cement manufacturing. The agreement could be opened to other countries as well to expand benefits globally. Once a clean materials agreement is established, it could ultimately be expanded to include equipment made from clean materials, especially equipment that is important for industrial decarbonization or clean energy generation, such as hydrogen electrolyzers, solar panels, industrial heat pumps, etc.

Joint Clean Industrial Funding Entity

Another key cooperation opportunity would be to establish a new joint funding entity, the U.S-China Green Bank (USCGB). The USCGB would help clean industrial projects in both countries secure affordable financing. It would use the full array of financing and lending tools common to green banks, such as co-lending, loan loss reserves, loan guarantees, and bond sales. The USCGB's seed capital could be provided equally by the U.S. and Chinese governments, perhaps in installments over a number of years. The USCGB would be a fully independent, self-sustaining, non-profit organization with a mandate to use its funds to maximally lever private investment into clean industry, accelerating the transition to a net-zero economy.

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