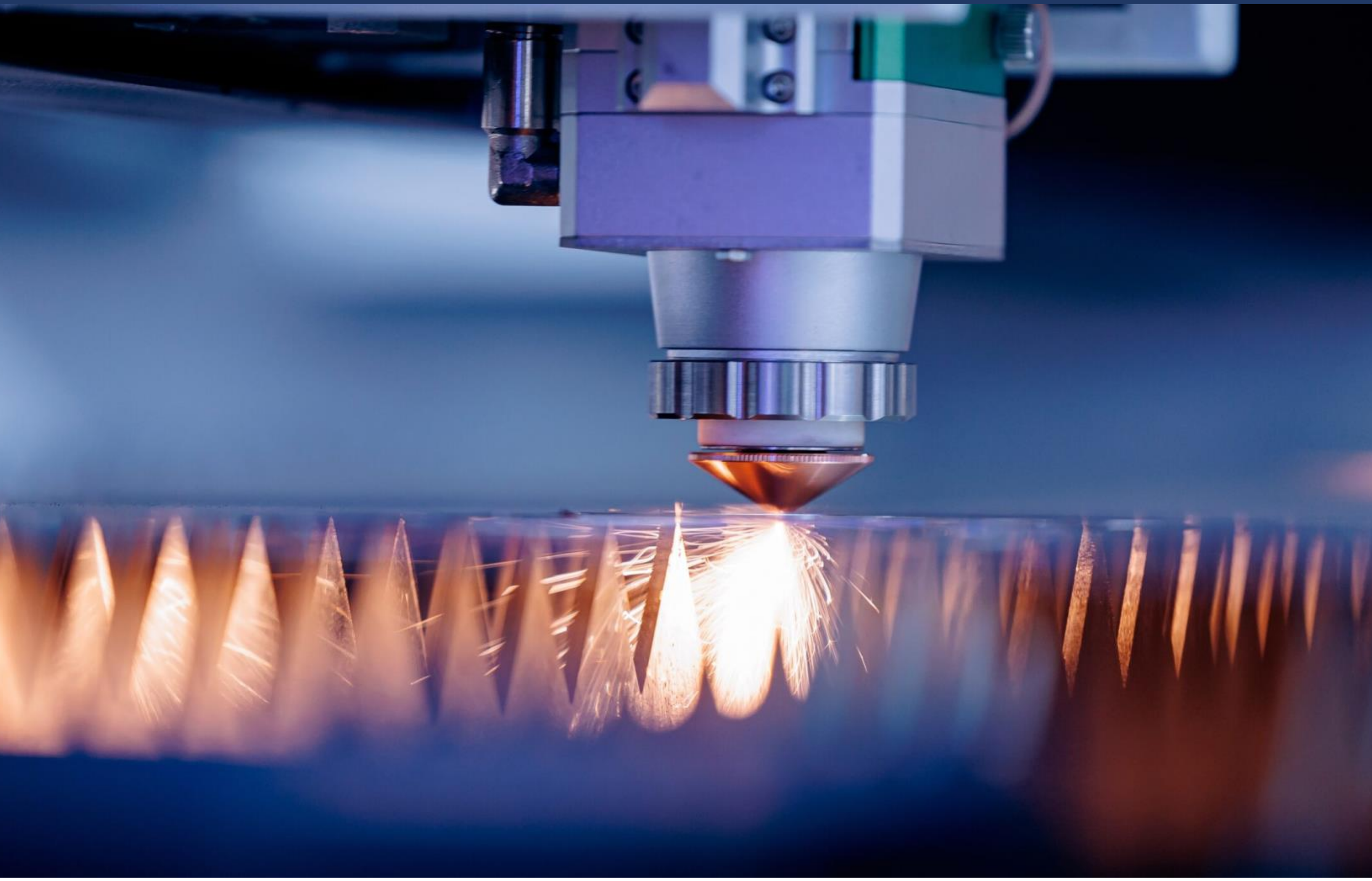

ENERGY INNOVATION POLICY & TECHNOLOGY LLC®

OVERCOMING ALL BARRIERS TO INDUSTRIAL ELECTRIFICATION

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June 2025

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ACKNOWLEDGEMENTS

The authors would like to acknowledge and thank the following reviewers for their contributions to and feedback on this report: Marco Giuli and Paul Münnich (Agora Industry); Zachary Byrum (World Resources Institute); Ali Hasanbeigi (Global Efficiency Intelligence); Blaine Collison (Renewable Thermal Collaborative); and Mike O'Boyle, Brendan Pierpont, Eric Gimon, and Xiuli Zhang (Energy Innovation). The contents of this report are the responsibility of the authors alone and do not necessarily represent the views of the reviewers. The authors also thank Greg Alvarez, Silvio Marcacci, and Shannon Stirone for their assistance in preparing and editing this report. In addition, the authors thank Mina Lee and Jack Conness for their contributions on figures and graphics.

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EXECUTIVE SUMMARY

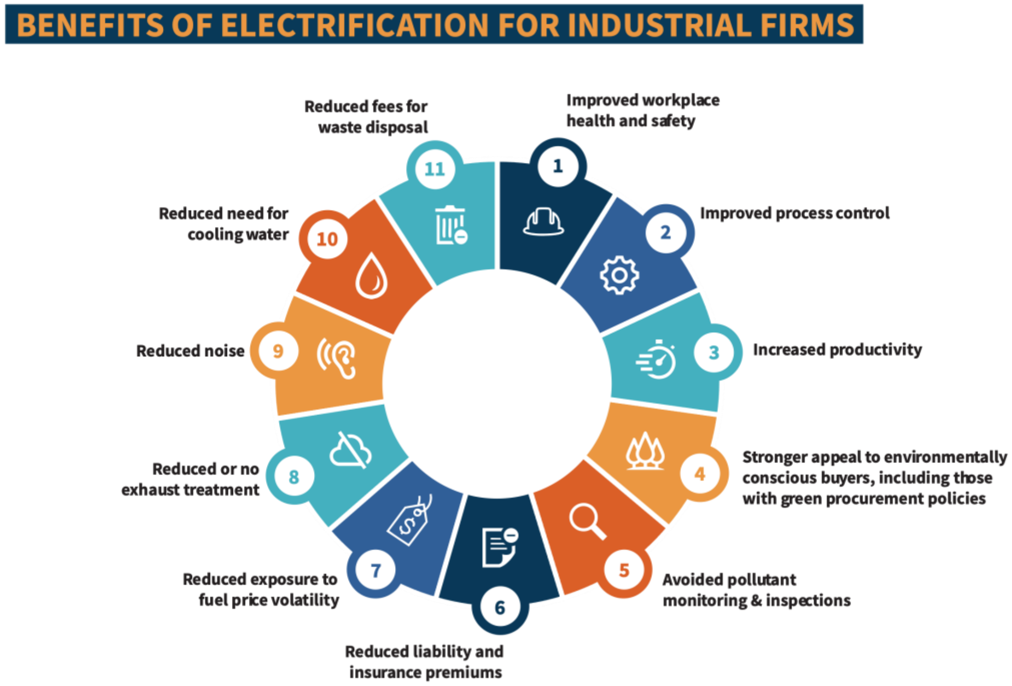
We rarely think about the concrete beneath our feet or the steel in our buildings, let alone the kilns and furnaces that create these materials. Industrial processes use huge amounts of energy, so much that the industrial sector is the largest consumer of energy in the global economy, accounting for 37 percent of global energy use in 2022.[1] Most goods and technologies in our daily lives are produced by burning fossil fuels to generate heat at varying temperatures for a range of industrial processes—such as melting metals, catalyzing chemical reactions, fabricating machinery, and more. Fossil fuel combustion produces planet-heating greenhouse gases (GHGs) and other emissions that pollute the air and harm public health, and to make matters worse, industrial emissions have risen by around 70 percent since 2000.[2]

Fortunately, industries can adopt an array of commercially available electric technologies (such as heat pumps, electric boilers, thermal batteries, and electric arc furnaces) to generate heat for the same processes. By leveraging increasingly clean power grids or directly utilizing carbon-free resources, industries can swap dirty emissions for clean electrons.

This report is the definitive resource for policymakers and other stakeholders eager to catalyze industrial electrification around the world. It provides an accessible overview of global industry, industrial heating needs, and the relevant electric technologies capable of serving industrial heat demand. It examines the comparative advantages of electrification over other pathways to decarbonize industry, outlining the pros and cons of each approach. It also discusses the primary challenges to the transition and an array of policy solutions designed to overcome the barriers to industrial electrification.

Electric technologies can decarbonize most industrial processes faster, more efficiently, and more cost-effectively than alternatives like green hydrogen, bioenergy, or carbon capture and sequestration. Electrification also provides an array of benefits for industrial firms, as detailed in Figure ES-1.

Figure ES-1. Benefits of electrification for industrial firms



Industrial electrification solutions are already underway. Companies around the world are demonstrating that electric technologies can modernize operations, improve worker safety, and meet growing global demand for low-carbon goods. Policymakers are increasingly stepping up to enact the policies necessary to overcome extant barriers.

But accelerating industrial electrification this decade requires bold policy leadership and dedication from businesses to demonstrate the value proposition of electric technologies powered by carbon-free electricity in lieu of volatile and polluting fossil fuels.

The primary barriers to industrial electrification are:

- **Economics** – Though electrification can deliver many long-term economic benefits, the higher cost of electricity relative to fossil fuels in many places and the capital expenditures needed to switch to electric technologies can be a deterrent to change. In addition, the costs to connect to the grid or disconnect from an existing fossil fuel utility can layer on additional expenses for industries. Additionally, firms that use byproducts as fuel in their processes face unique economic challenges to electrification.

- **Grid readiness** – Electric grids and utilities around the world face growing demand for electrons and tackling climate change requires a massive build-out of carbon-free electricity in the coming decades. Absent proactive policies, industrial electrification may be hindered by slow interconnection processes (for new load and clean generation) and outdated planning that fails to account for the huge demand from electrified manufacturing and other processes.
- **Technology maturity and awareness** – Even though a wide range of electric technologies have been commercially available and in use in specific applications for decades, not all have been deployed at scale or applied to traditionally fossil-fueled industrial processes. Industries, the workforce, and investors need experience with these technologies as well as confidence in industrial electrification, both of which take time.

As the industrial sector shifts into focus for policymakers and businesses around the world, a new framework is needed to unlock a clean industrial transformation. No single technology or policy will electrify all industrial processes, especially given the diversity of subindustries within the sector. But an array of all-electric technologies are capable of serving a wide range of temperature needs across the varied industrial processes (Figure ES-2).

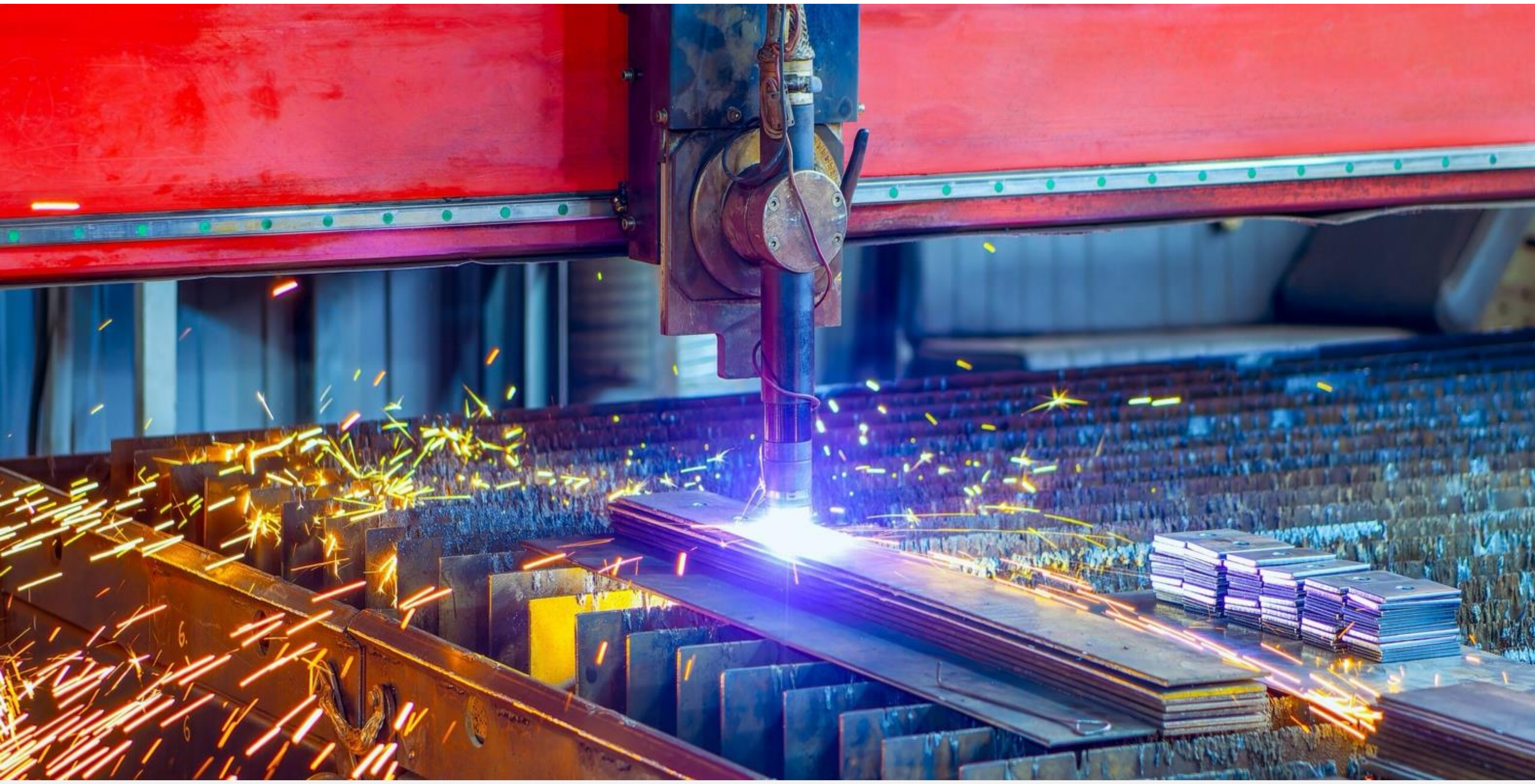
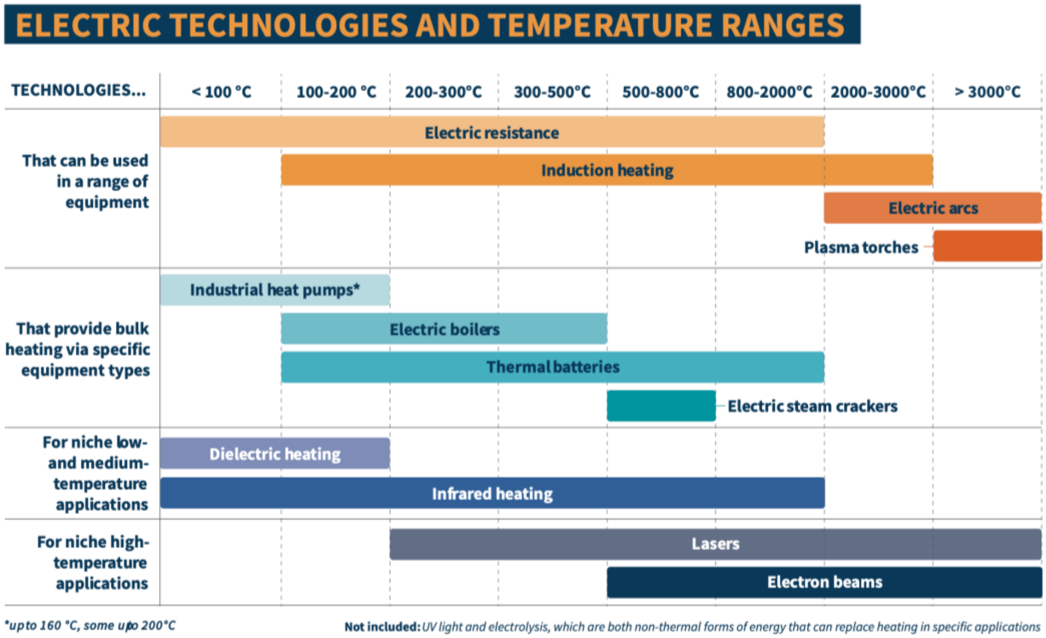


Figure ES-2. Industrial electrified heating technologies and their temperature ranges



A combination of policies will help shift industries toward electrification as the preferred alternative to fossil fuels and other competing decarbonization pathways. Policymakers will want to consider their unique policy and economic contexts, as well as the industries in their jurisdictions, as they devise comprehensive solutions to overcome barriers. This report will help guide and inform decision-makers on the menu of options as they work toward solutions, as shown in Figure ES-3.

To overcome economic barriers, we recommend:

- Policies that increase the supply of low-cost clean energy (e.g., renewable portfolio standards, incentives for on- and off-grid renewables); electricity tariff reforms (e.g., time- and location-specific rates); and policies that account for the full costs of fossil fuel combustion (e.g., carbon pricing).
- New incentives for direct electrification. These incentives should be offered in conjunction with policies to accelerate renewables deployment to reduce the near-term and long-term capital and operational costs of electrification.
- Clean heat emissions standards that help level the playing field for industrial electrification technologies, allowing them to compete with fossil fuel alternatives.
- Creative financing tools, such as green banks, to help industrial firms access electrified technologies.

To overcome grid readiness barriers, we recommend:

- Policies to encourage greater energy efficiency (e.g., energy efficiency standards) and flexible industrial demand (e.g., time- and location-specific rates).
- Interconnection and grid planning reforms that reduce the electricity demand on the grid while optimizing industrial electric loads and reducing costs for other ratepayers.

To overcome technology maturity and awareness barriers, we recommend:

- Foundational research, development, and demonstration policies to ensure continued evolution of the technologies, commercialize nascent electrification technologies, and support pilot projects and demonstrations that yield cost and performance improvements across different geographies and jurisdictions.
- Workforce training and education to support the people charged with deployment and maintenance.

Figure ES-3. Policy solutions to overcome barriers to industrial electrification

POLICY SOLUTIONS TO OVERCOME BARRIERS TO INDUSTRIAL ELECTRIFICATION

** = depends on policy design*

	Economic Barriers				Grid Readiness Barriers	Technical Barriers
	Differential between fossil fuel and electricity prices	Utility interconnection and disconnection fees	Other costs: capital costs, financing, and soft costs	Use of byproducts as fuel	Interconnection, infrastructure, and planning	Electrification technology maturity
On-grid renewable energy deployment	X				X	
Off-grid renewable energy deployment	X	X			X	
Co-location with carbon-free resources	X	X			X	
Incentives for cleanly manufactured products	X	X*	X*	X*		
Incentives for electrified equipment			X			X
Clean heat production tax credit	X		X*	X*		
Incentives for clean electricity use	X			X*		
Financing tools	X		X			X
Flexible industrial electricity demand	X	X			X	
Time- and location-specific electricity pricing	X				X	
Carbon pricing policies	X					X
Carbon border adjustment mechanisms	X					
Energy efficiency standards			X		X	X
Clean heat emissions standard	X		X			
Interconnection and planning reforms		X			X	
Exit fee reforms		X				
RD&D				X		X
Workforce training and education			X			X
Solutions for firms that burn their own byproducts				X		

WHY INDUSTRIAL ELECTRIFICATION?

We are halfway through a critical decade for climate action, and the industrial sector still lags other parts of the global economy in its efforts to meaningfully reduce GHG emissions and other harmful air pollutants. Industry is responsible for making the products and materials we rely on every day, including the technologies needed for a carbon-free future. It's also responsible for roughly one-third of human-caused GHGs when accounting for direct and indirect emissions.[i]

Despite the sector's impact, the approaches and policy pathways for industry are less understood than decarbonization strategies for other sectors of the economy.[3] Often mischaracterized as "hard to abate," the industrial sector has considerable untapped potential to reduce emissions using today's technologies while still meeting the sector's energy needs.

What is the answer?

Switching industrial processes[ii] from fossil fuel combustion to electricity (also known as direct electrification) is the most efficient solution for reducing GHG emissions from most industrial process uses—because electricity can be generated from low- to no-carbon resources, reducing and ultimately displacing the emissions from fossil fuel combustion.[4] The term "process uses" refers to the use of energy in industrial equipment, such as in boilers that generate hot water or steam for heating materials or distilling liquids; in the kilns and blast furnaces that make cement and steel; and in moving machinery such as pumps, fans, and conveyor belts.

The industrial sector is not homogenous and consists of numerous subindustries, which are categorized in Figure 1.

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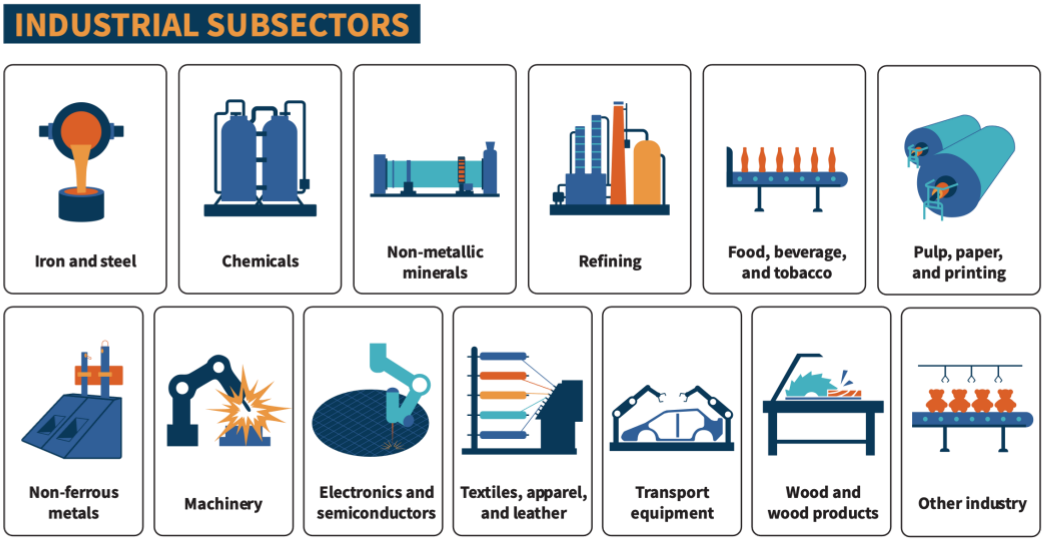
[i] Indirect emissions include purchased electricity and steam.

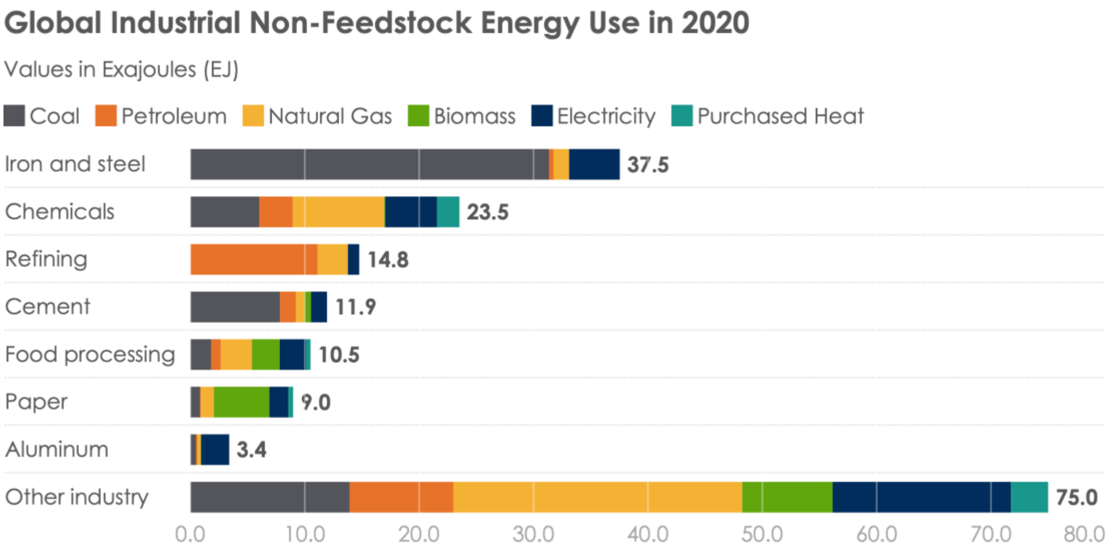
[ii] Process uses are distinct from the two other sources of industrial emissions: 1) feedstocks, which are fuels used as chemical inputs to industrial processes, such as ammonia for fertilizer, which cannot be replaced with electricity directly; and 2) non-process uses, which are not part of the manufacturing process but are required for the industry to operate, such as heating, air conditioning, and lighting of industrial facilities or vehicles used on site, like forklifts. Many of these building- and vehicle-related end uses can be electrified but fall outside the scope of this report.

Figure 1. Subindustries within the industrial sector



Energy usage requirements and sources of energy vary across these subindustries, as shown in Figure 2.

Figure 2. Subindustries within the global industrial sector and their non-feedstock energy use in 2020

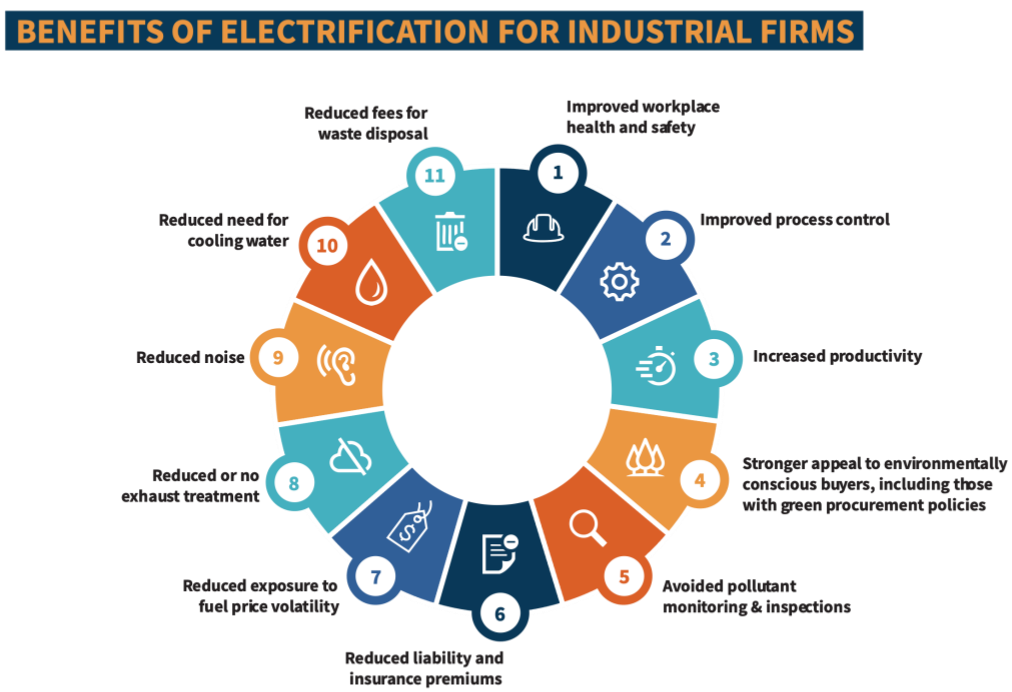


Source: Pacific Northwest National Laboratory, Global Change Assessment Model v7.1, 2024 Other industry includes non-ferrous metals other than aluminum, non-metallic minerals other than cement (e.g., glass and brick), textiles and apparel, plastic and rubber products, machinery and equipment, vehicles, electronics and semiconductors, wood and wood *products, furniture, weapons and military equipment, medical supplies, and miscellaneous goods. Non-manufacturing industries (e.g., agriculture, construction, and mining) are not shown here.*

Process heating accounts for the majority (84 percent) of industrial non-feedstock fossil fuel use, with about a third of that demand falling into a low-temperature heat range (below 200 degrees Celsius) addressable by all-electric heat pumps.[5] Other electrified technologies such as industrial thermal batteries, electric arc or induction furnaces, electric resistance heating, dielectric (radio or microwave) heating, and infrared heating can meet nearly all of the remaining, higher-temperature heating demands.

Direct electrification has many benefits: It's more energy efficient than traditional combustion because it avoids energy losses in hot exhaust gases and in water vapor that forms when fuels are burned;[6] it greatly reduces air pollution and improves public and worker health; and it creates jobs from investments in new electrified equipment (and ongoing purchases of electricity instead of fossil fuels).[7] Electrification's benefits for industrial firms are summarized in Figure 3.

Figure 3. Benefits of electrification for industrial firms



Of course, realizing these benefits and reducing GHG emissions requires continued efforts to build a carbon-free electricity grid. Fortunately, global power sector emissions are in decline and grid decarbonization is underway in nearly all major economies thanks to decades of progress and smart policies. Given the long lifetime of most industrial equipment, the present-day emissions intensity of the electric grid should not discourage decision-makers from investing in industrial electrification now. That said, electricity demand growth from EVs, data centers, electrolytic hydrogen production, and direct electrification of industry, transportation, and buildings—alongside other new loads—will require countries and utilities to thoughtfully plan and invest in future non-emitting electricity generation, grid infrastructure, and demand-side solutions while still achieving their climate and air quality goals.[8,iii]

A concerted focus on the policy pathways to enable industrial electrification will ensure the industrial sector keeps pace with the other economic sectors. The time is now for the next industrial revolution to center on deploying electric technologies and carbon-free electricity.

This report is for decision-makers around the world who want to better understand the state of industrial electrification technologies, the challenges impeding progress, and the policy solutions that can put industry on a more sustainable path. Decision-makers can use this resource to sketch out the initial contours of an industrial electrification strategy, with the understanding that additional resources may be needed to design and implement the relevant policies.

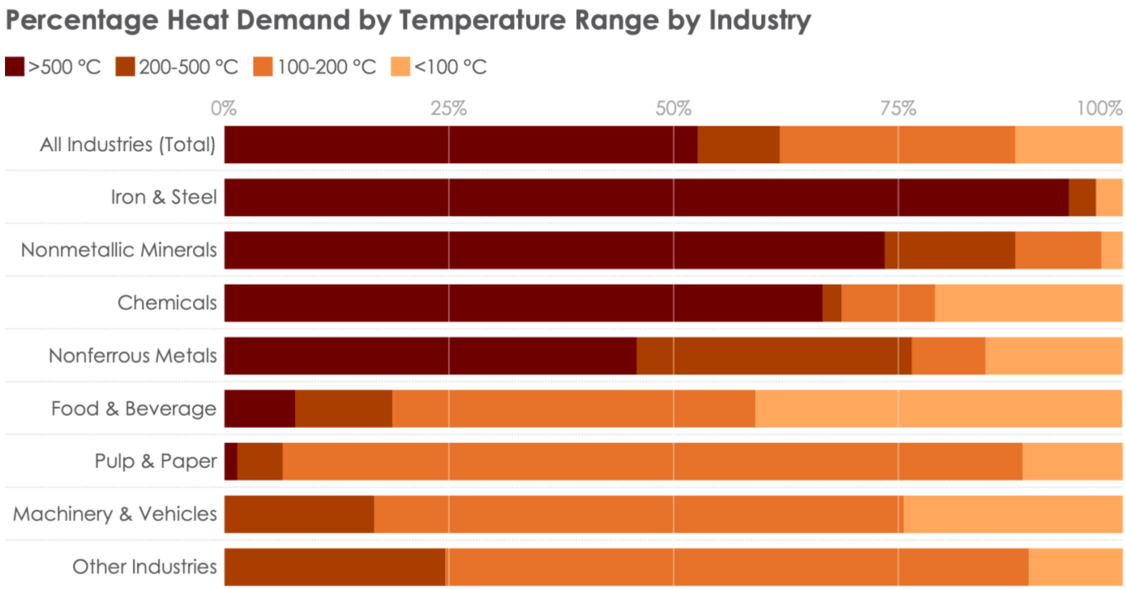
Electrification Technologies for Industrial Heat

Industries that require process heat need not rely on fossil fuels to reach requisite temperatures. While there is not a one-size-fits-all solution for industrial heat, several technologies can electrify industrial process heat across a wide range of temperatures (Figure 4). Low-temperature heat is commonly required for making food products, manufacturing pulp and paper, and fabricating machinery or vehicles from purchased metal and other materials, among other processes.[9] Most technologies to electrify low- and medium-temperature heat (< 200°C and 201-500°C, respectively) are commercially available, although more real-world deployments are needed to understand and resolve facility- and process-specific challenges. High-temperature process heat (over 500°C, but seldom more than 1,800°C)[iv] is concentrated within a

[iii] For more information on the electricity sector, visit www.energyinnovation.org.
[iv] Some niche industrial processes require temperatures up to 3,000°C, such as the manufacturing of synthetic graphite, but these applications may already be electrified, as fossil fuel combustion can struggle to reach these temperatures.

handful of industries, namely iron and steel, non-metallic minerals, chemicals, refining, and non-ferrous metals.[10]

Figure 4. Percentage of industrial process heat demand by temperature range in the European Union in 2012 [11]



While some high-temperature electrified technologies have been commercialized (such as electric arc furnaces, which are used in creating recycled steel), many technologies that can electrify high-temperature heat are still in early stages of deployment. Below we summarize the primary electric technologies capable of supporting an array of industrial processes, categorized here by their primary applications (though note that there are other ways to classify these technologies, as they are multifaceted in their use and functions).

Technologies that can be used in a range of equipment:

- **Electric resistance** involves running an electric current through a "resistor," typically a metal, metal oxide, or carbon-based material wherein electric resistance converts electricity to heat.[12] Electric resistance is a versatile technology that can power a wide range of heating equipment, including thermal batteries and electric boilers. Because it can reach temperatures as high as the chosen resistor can withstand, electric resistance can serve industry's highest-temperature heating needs.[v] However, electric resistance equipment that heats materials indirectly (i.e., uses air or steam to transfer the heat) tops out at lower temperatures.[vi]

- **Induction heating** can reach temperatures exceeding 3,000°C, far higher than most industrial processes require, but its application is limited to metals industries.[13,vii] It works by exposing electrically conductive materials to a time-varying magnetic field, generating an electric current within the material that is then converted to heat due to the material's inherent resistivity. Induction heating is a commercial technology that is already used in industries like steel, copper, and aluminum, but it has not yet reached its full deployment potential.[14]

- **Electric arcs** and **plasma torches** could decarbonize a range of industrial processes that require concentrated, high-temperature heat. Electric arcs are high-voltage electrical currents suspended in

INDUSTRIAL HEAT PUMPS: STATE OF THE MARKET

As of 2021, industrial heat pumps (IHPs) aimed at serving the needs of industrial process heating represented a relatively small share of the global heat pump market, with under a 2 percent market share and around $0.6-1 billion in sales. Energy Innovation identified 21 existing IHP manufacturers in 2022 with applications including the manufacture of chemicals, food, pharmaceuticals, and textiles, and another 26 heat pump manufacturers that produce units for large-scale commercial buildings and may be able to adapt models for the industrial market.

Most current IHP offerings support temperature ranges up to around 100°C. While the 100–200°C temperature range encompasses a large market of industrial applications, there are few firms offering solutions for those temperatures. The company Heaten claims that its HeatBooster IHP can produce temperatures up to 200°C.

Source: Jeffrey Rissman, "Decarbonizing Low-Temperature Industrial Heat in the U.S." (Energy Innovation, October 2022).

[v] For instance, the melting point of tungsten, a common material for high-temperature electric resistors, is 3,422°C.
[vi] While electric boilers top out at 500°C, they are nevertheless an important technology for decarbonizing medium-temperature heat. See the next section, "Electrified Technologies for Low- and Medium-Temperature Heat," for more.
[vii] Induction heaters can heat other materials through radiative heating (i.e., a heated metal element called a "susceptor" is placed next to a non-metallic mineral), but this reduces heating efficiency and is usually used to precisely control the precise shape or pattern where heat is applied.

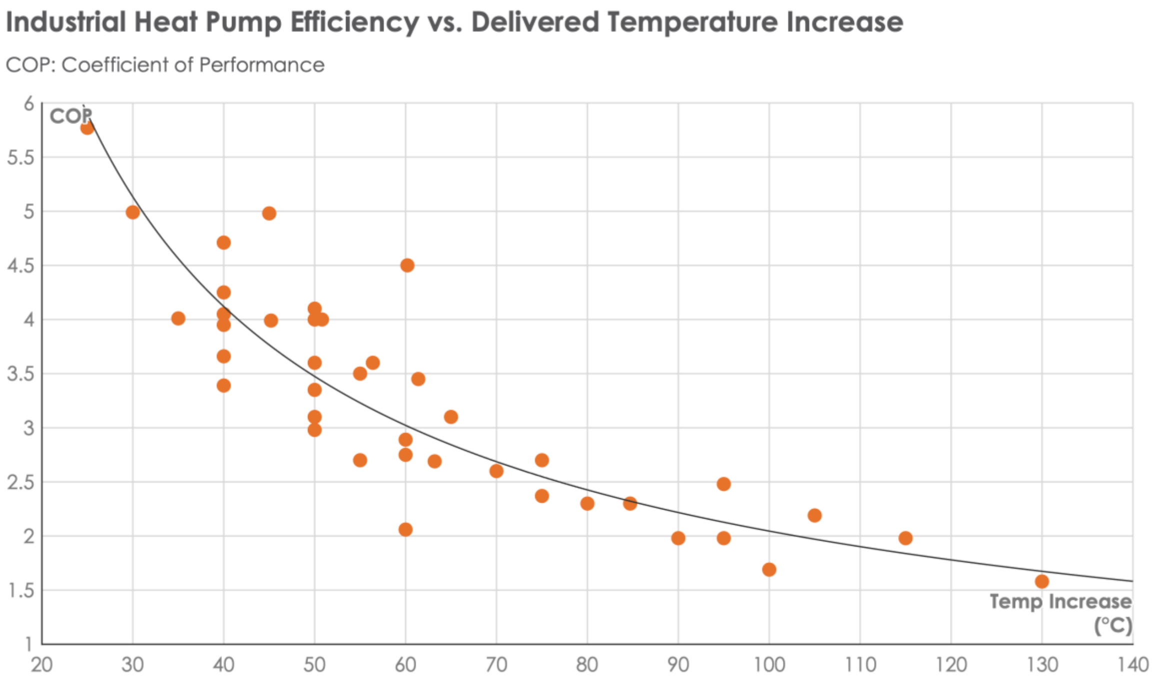
"plasma," an electrically conductive gas-like state of matter. Electric arc furnaces can reach up to 1,800°C, heating materials through radiant energy and, usually, electrical resistance within the materials themselves. Plasma torches, which transmit plasma from a nozzle, often for precision heating applications, can reach up to 5,000°C. Electric arc furnaces are used widely in the U.S. steel industry, and both electric arcs and plasma torches are commonly used for activities like cutting, drilling, and welding metals. However, the use of these technologies in non-metallic minerals industries like cement and glass is still at the research and pilot stage.

Technologies that provide bulk heating via specific equipment types:

- **Industrial heat pumps** output more energy than they use because they rely on electricity to move heat rather than converting electricity into heat.[15] Like refrigerators and air conditioners, heat pumps manipulate the pressure of refrigerant as it moves through a closed loop, absorbing heat from a source (e.g., ambient air, waste heat) and depositing it to a sink (e.g., water).[16] They are most efficient when delivering smaller temperature increases, but they are still more efficient than any alternative technology at the highest temperatures they can reach (Figure 5).[17,viii] Figure 5 data are from a survey of commercially available industrial heat pumps in 2018,[18] and maximum temperatures and efficiencies are better now due to technological advancement. Heat pumps are both technologically mature and cost competitive with conventional heating in many cases, though operational costs can vary by country and utility. Most commercialized industrial heat pumps top out at 90 to 100°C, but some options on the market can achieve temperatures of up to 165-200°C.

[viii] A heat pump's efficiency is defined by its coefficient of performance (COP), or ratio of energy output (i.e., heat) to energy input (i.e., electricity). Industrial heat pumps generally have a COP of between 3 and 4 for temperature increases of 40 to 60°C, a COP of between 2 and 3 for temperature increases of 60 to 100°C, and a COP of 1.5 for temperature increases of 130°C. The most efficient electric boilers (or any other heating technology) can have a COP of up to 1.

Figure 5. Industrial heat pump efficiency versus temperature increase[19]



- **Electric boilers** are important options where heat pumps are not viable or practical and, with efficiencies of around 99 percent, they are still more efficient than conventional boilers.[20] Electric boilers come in two types: electrode boilers, which run electrical current through water to generate heat in the water itself, and electrical resistance boilers, which use a metal or ceramic resistor to heat the water. Both types are drop-in replacements for conventional boilers and are already used in industrial settings today, but their use can be scaled up significantly. Because of their flexibility and relatively low up-front cost, electric boilers can also be deployed alongside existing fossil fuel equipment (i.e., a hybrid system) to help reduce costs and emissions, while also serving as an entry to full electrification.

- **Thermal batteries** are a unique application of electric resistance that can provide low- to high-temperature heat at lower costs than most electrified heating technologies.[21] Modern thermal batteries can convert electricity to temperatures of up to 1,700°C and store that heat for multiple hours or even days. Thus, firms can save on electricity costs by obtaining electricity when it is cheapest and converting that electricity to heat for later use, as well as by providing demand-response and grid-balancing services to the grid. Commercially available thermal batteries usually top out at 350 to 500°C, but thermal batteries storing heat at temperatures up to 1,700°C have been demonstrated to be hot enough to meet the temperature requirements of approximately 75 percent of the U.S.'s industrial non-feedstock energy demand.[22] Market research firm Solrico identified 32 companies offering modern high-temperature thermal storage, 28 of which targeted the industrial sector.[23,ix]

- **Electric steam crackers** are another electric resistance technology and are a promising option for decarbonizing the chemicals industry. Conventional steam crackers, which accounted for 26 percent of the European chemicals industry's non-feedstock energy demand in 2019, create heat above 800°C to break hydrocarbon feedstocks into chemical building blocks like ethylene.[24] Two consortia of companies are now working to develop electric steam crackers, and one of them broke ground last year with the world's first large-scale demonstration in Germany.[25]

Technologies for niche low- and medium-temperature applications:

- **Dielectric heating** and **infrared heating** are commercially available technologies for electrifying the few low- to medium-temperature heating applications that are not currently met by boilers.[26] In fact, these technologies are already used for many applications in industry. Dielectric heating technologies use radio waves or microwaves to generate heat in materials that contain polar molecules (e.g., food, ceramics, plastics, rubber) for processes like cooking, drying, molding, and curing. Infrared equipment heats an "emitter" that directs infrared heat to a target material for processes like drying and curing.

Technologies for niche high-temperature applications:

- **Lasers** and **electron beams** work best for precision applications like cutting, engraving, welding, and machining parts. Lasers apply energy to a lasing medium to release cascading photons, while electron beams involve applying electricity to a filament which gives off electrons. Both technologies are already commercially deployed in the industrial sector, but they are not energy efficient at delivering bulk heat, so they are only suited to niche applications representing a very small share of industrial heat.

Technologies to replace heat with non-thermal forms of energy:

- **Electrolysis** is a non-thermal option for electrifying certain high-temperature processes. It is already commonly used for aluminum smelting, but is currently also being explored as an option for primary steel production. A nearer-term option for decarbonizing primary steel involves using green hydrogen to

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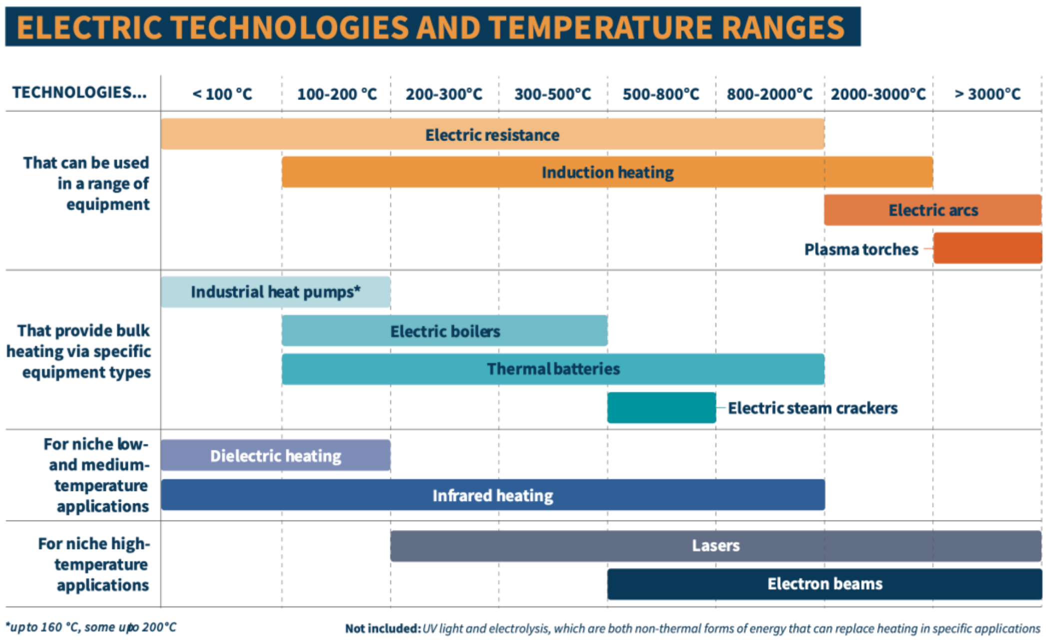
[ix] Twenty technologies supported temperatures up to 565°C, 12 of which could handle temperatures exceeding 1,000°C. Seven of the companies have operational commercial plants, 14 have demonstration plants, and six have pilot plants (several of which were still under construction as of March 2024).

chemically reduce iron ore to metallic iron, but electrolysis is a more efficient option that may be viable in the long term.

- **Ultraviolet light** is a substitute for heat that is currently used for applications like sterilizing and pasteurizing foods, curing coatings, and catalyzing chemical reactions.

Figure 6 summarizes industrial electrified heating technologies and the temperatures they achieve.

Figure 6. Industrial electrified heating technologies and their temperature ranges



Electrification Versus Alternative Decarbonization Pathways

The most prominent alternatives to direct electrification for reducing industrial emissions include green hydrogen,[27] bioenergy,[x] and carbon capture and storage

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[x] "Bioenergy" refers to energy derived from organic material originating from plants, animals, and microorganisms. This form of energy can be used for electricity generation, heating, and transportation fuels. Bioenergy includes so-called "renewable natural gas," which is methane that has been upgraded from biogas produced from organic waste materials through a process called anaerobic digestion or from thermal gasification of biomass.

(CCS). Comparing these options with direct electrification reveals the pros and cons of each pathway.[xi]

The Industrial Zero Emissions Calculator (IZEC) is an interactive and customizable tool developed by Energy Innovation. It offers a comparison of electrification with alternative industrial decarbonization technologies and scenarios in terms of their resource requirements, including clean electricity demand, electrolyzer capacity, land use, amount of carbon dioxide (CO_2) that would need to be stored using CCS, and other outputs. The IZEC's accompanying report details the relative advantages of direct electrification for reasons summarized below.[28]

Green hydrogen, produced using renewable energy, is an extremely inefficient heat source for industry.[xii] Producing it consumes a lot of electricity,[xiii] and combusting it wastes energy in the form of hot exhaust gases and latent heat in formed water vapor. Compared to direct electrification, green hydrogen requires about twice as much clean electricity per unit of heat successfully delivered to the part or material being processed.[29] Leaning heavily on hydrogen to decarbonize U.S. industry could triple electricity demand in the U.S.[30] And while burning hydrogen does not generate CO_2 emissions, it does emit harmful nitrogen oxides (NO_x) due to high flame temperatures that split atmospheric nitrogen.[31] Rather than serving as a source of process heat, green hydrogen should be reserved for its highest-value industrial uses, including as a feedstock and/or reactant in the ammonia, refining, and steel industries.

Relying heavily on bioenergy (solid biomass or biogas) for decarbonizing process heat does not increase electricity demand but presents other significant challenges.[xiv] For example, according to the IZEC, using bioenergy for around three-quarters of industrial process heat in the U.S. would require dedicating 21 percent of total U.S. agricultural land to the creation of bioenergy crops (in addition to land for any

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[xi] We do not address solar thermal here, though there are applications where it can provide low to medium heat in sunny areas with sufficient land. For more information on solar thermal for industrial uses, visit https://www.renewablethermal.org/solar-thermal/.

[xii] Hydrogen can be produced using a variety of methods (indicated by different colors to denote its method of production and emissions intensity). For example, blue hydrogen is produced from fossil fuels, primarily natural gas, but the CO_2 emissions are captured and stored using CCS technologies. In this paragraph, we focus on green hydrogen as the primary alternative for comparison with electrification.

[xiii] According to the IZEC, meeting global industrial heating needs under the high green hydrogen scenario would increase the electricity demands of the industrial sector severalfold. Depending too much on hydrogen would vastly increase the renewables needed by the grid to support its manufacture, so hydrogen should be reserved for high-value applications such as primary steelmaking and chemical feedstocks. For more information, see https://energyinnovation.org/data-explorer/the-industrial-zero-emissions-calculator/.

[xiv] Of note, dedicated biomass is grown specifically for energy production and requires dedicated land, water, fertilizer, and other resources to produce. Waste biomass, on the other hand, is a finite byproduct of existing processes (e.g., agriculture, forestry, or industry) and has other competing uses.

bioenergy used in other sectors, such as corn ethanol for transportation fuel).[32] This amounts to a land mass 25 percent larger than the state of Texas. This land would need to be supplied with irrigation and fertilizer, increasing energy and material requirements. Globally, high bioenergy usage for industrial decarbonization could also pose major threats to climate and the environment. For instance, it would naturally drive demand for internationally traded biomass, leading to deforestation, ecosystem decline, and water contamination (and regions with poor land-use protection would be especially vulnerable to exploitation). Biomass combustion also emits more fine particulates than coal and a comparable amount of NO_x, eroding air quality and public health.[33] In fact, biomass recently surpassed coal as the leading cause of premature air pollution deaths in the U.S.[34]

CCS has its own challenges, such as high capital costs to capture, transport, and inject the CO_2 underground, and it lacks proven scalability in most industrial applications.[xv] For example, relying heavily on CCS to decarbonize process heat in U.S. industry could require a capital investment of $3.3 trillion,[35] plus the energy costs to capture and store that CO_2, likely around $100 billion per year.[xvi] In addition, CCS at the industrial plant does not eliminate upstream emissions from the production, processing, and transportation of fossil fuels (including methane leakage from wellheads and coal mines).[36] Nevertheless, CCS does have a role in decarbonizing especially hard-to-abate emissions, such as process CO_2 created as a byproduct of chemical reactions and in other cases where electrification is not a feasible option.

Direct electrification does pose its own challenges, though not insurmountable ones. Although costs vary for each technology and use case, electric technologies may cost more to install (or retrofit) than swapping in combustion-based equipment (for instance, due to the potential need to upgrade electricity delivery capacity to the facility). Also, electricity can cost more than fossil fuels, so technological solutions to reduce electricity costs (such as heat pumps and thermal batteries) or efforts to reduce the cost of clean electricity (such as by increased deployment of renewables) can be important to contain operating costs. In addition, the electricity demand from industrial electrification comes on top of load growth from other sources, such as data

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[xv] Most commercial CCS today is for natural gas processing, with smaller shares in blue hydrogen, ammonia/fertilizer, and ethanol production. CCS use in subindustries such as iron and steel, cement, and pulp and paper is in earlier stages with few commercial examples. For instance, there is only one operating steelworks that employs CCS, and it does not use a blast furnace, the most common steelmaking technology.

[xvi] CCS increases energy requirements of combustion processes by about 20 percent. According to the U.S. Energy Information Administration (source and source), in the U.S. in 2022, buyers spent about $1.7 trillion on non-feedstock energy, with the industrial sector consuming about 35 percent of that total, or 30 percent excluding purchased electricity. Therefore, a rough estimate of energy costs of applying CCS to all non-electricity, non-feedstock energy use by U.S. industry would be around $100 billion per year.

centers, EVs, and electrified buildings, increasing the need for new generation, transmission, and distribution infrastructure. In the U.S., for example, electrifying all eligible industrial processes could increase electricity demand by 2.4 percent annually over the next 30 years (before accounting for non-industrial load growth).[37] For comparison, U.S. historical average annual growth rates between 1950 and today were higher, at 3.9 percent.[38] While growth rates for industrial electrification alone may be technically feasible, building new electric infrastructure takes time and must be done with attention to affordability and reliability. And, of course, new electricity demand will need to be supplied with carbon-free resources, including off-grid and co-located solutions.

A Two-Pronged Approach: Electrification and Efficiency

Advances in energy and material efficiency can significantly reduce the resource demands of industrial electrification and ease stress on the grid. For instance, achievable improvements of 25 percent in energy efficiency and 15 percent in material efficiency can offset 40 percent of the projected increase in electricity demand from electrifying all eligible industrial processes. Over 30 years, these efficiency improvements reduce the grid's required annual growth rate to serve industrial load growth in the U.S. from 2.4 percent to 1.7 percent while still achieving full decarbonization of all industrial energy and feedstock use.[39]

The efficiency improvements themselves are quite feasible: improving energy efficiency by 25 percent is aligned with the progress from 2020 to 2030 in the International Energy Agency's (IEA) Net Zero scenario[40]—a far shorter timescale than is necessary to fully decarbonize the industrial sector. The IEA estimated that using only readily available cost-effective measures would be sufficient to reduce global industrial energy intensity by 44 percent from 2018 to 2040, amounting to an annual improvement rate of 2.3 percent.[41] Historically, from 2011 to 2018, industrial energy efficiency improvements averaged 2.5 percent a year.[42] Global annual improvement in primary energy intensity has slowed in the 2020s, however, with most years outside of 2022 being closer to 1 percent.[43] Studies of specific industries have found similar untapped efficiency potentials, such as 30 percent in textiles[44] and 19 percent in iron and steel.[45] Naturally, estimates differ based on their scope and factors such as the inclusion of technical versus economic potential, feasibility, time horizon, and geographic constraints.

Material efficiency can also be improved considerably through modified design and production processes. For example, research shows that 30 percent less metal could be used in most applications without compromising on utility,[46] and similar approaches for doing more with less are possible with cement and other primary materials.[47] An array of methods to measure material intensity exist with varying strengths and weaknesses,[48] and often material footprints grow more slowly than

GDP: In an assessment of 186 countries from 1990 to 2018, every 10 percent increase in GDP related to an average national material footprint increase of 6 percent.[49] However, improvements in material efficiency will require industries to continue prioritizing innovations.

Ultimately, a two-pronged approach is necessary to optimize electrification of the industrial sector. Direct electrification outcompetes decarbonized alternatives in most process heating applications but still requires up-front and ongoing expenditures to adopt electric technologies, as well as investments in the electricity grid plus off-grid solutions. Improving both energy and material efficiency can offset some of the costs to electrify and help mitigate the scale of that grid expansion, making the transition to clean processes more attractive to industries.

BARRIERS TO INDUSTRIAL ELECTRIFICATION

To accelerate industrial electrification around the world and design smart policies to facilitate the transition away from fossil fuels, it is necessary to first understand the barriers. While each industry, jurisdiction, and geography face different contexts that may present unique challenges and pathways, the primary barriers to industrial electrification are economics, grid readiness, and technology maturity. Each is discussed in turn.

Economics

Around the world, energy-intensive industrial processes are highly sensitive to costs—both recurring operating costs (i.e., materials, labor, energy, and financing costs) and up-front capital costs (i.e., expenditures for equipment and facilities).[xvii] These costs impact the overall cost per unit of production, and businesses risk financial losses or insolvency when costs increase. In the context of industrial electrification, the cost of installing and operating electric equipment is often higher than for conventional fossil-fueled equipment, and challenging economics are currently the primary barrier to industrial electrification. Industrial customers seeking to reduce costs may be compelled to relocate to other geographies if costs for energy or feedstocks become prohibitively high. As such, the economic impact of any policy decision is front of

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[xvii] Electric technologies suitable for industrial electrification have varying capital and operating expenses because of their differences in efficiency, maturity, and suitability for specific applications. High-efficiency technologies with higher COPs, like industrial heat pumps, may have higher up-front costs but lower operational costs over time, whereas less efficient options (like electric boilers) might cost less initially but have higher energy consumption and maintenance costs. These differences should always be factored in when analyzing the economics of industrial electrification.

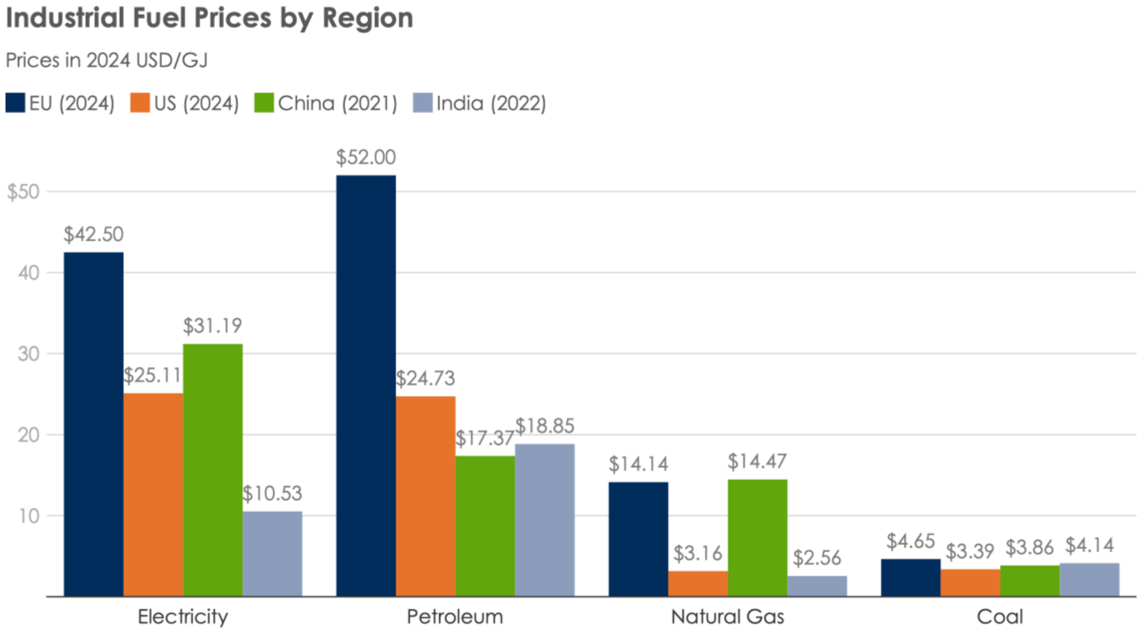
mind for policymakers motivated to retain or attract industrial jobs and economic development.

The Differential Between Fossil Fuel and Electricity Rates

While industries typically use both electricity and fossil fuels, most industrial thermal processes today rely on the combustion of natural gas (aka methane gas) or coal. And in most places, electricity can be several times more expensive per unit energy than fossil fuels, inclusive of taxes and subsidies (Figure 7).[xviii] Except in the case of some industrial heat pumps, the efficiency gains from electrification are often insufficient to overcome this wide price gap.

[xviii] In Figure 7, "coal" refers to steam coal, lower-grade coal combusted for heat and power. Metallurgical coal, a higher-grade coal used to produce coke for the steel industry, is often about twice as expensive. Note that taxes and subsidies can have a large impact on final prices. For example, India's average price paid for imported natural gas was \$8.14/GJ, 3.2 times higher than the subsidized price charged to industrial gas consumers, such as fertilizer plants. Also note that there can be wide variation in prices between subregions, such as specific EU nations or U.S. states. For instance, the EU nation with the lowest industrial electricity price charged \$20.36/GJ, roughly half the EU average, while the nation with the highest price charged \$61.82/GJ, 45 percent more than the EU average. Also note that this chart does not account for the efficiency with which each energy source is used; electricity is used more efficiently than combustible fuels.

Figure 7. Average retail cost (inclusive of taxes and subsidies) per unit energy (gigajoules, GJ) to industrial customers in the EU, U.S., China, and India. EU and U.S. data are for 2024, China data are for 2021, and India data are for 2022.[50,51,52,53,54]



This cost differential and the way energy rates are designed are currently the primary barriers to industrial electrification—although how much energy costs contribute to the total per unit product cost varies across industries. Overcoming these barriers requires a deeper understanding of how energy rates are structured and how this impacts industrial customer decision-making.

For example, in the U.S., industrial customers pay designated rates (or tariffs) for electricity and natural gas. Depending on the size of the industrial customer and the volume of energy they require, these rates may either be negotiated directly with their utility providers or subject to regulatory approval in rate cases overseen by state utility regulators (often known as public service commissions). These rates are designed to relate directly to the cost of serving these customers. If rates for industrial customers dip too far below the cost of service, then costs shift to other rate classes, like residential or small commercial customers.

Electricity rates in the U.S. consist of wholesale electricity rates as well as retail electricity rates. The wholesale electricity rate generally reflects the cost to generate and transmit electricity between power plants and direct large-scale buyers. The retail rate reflects the full cost to generate and deliver electricity to customers of the distribution utility or load-serving entity, including any ancillary charges to cover other approved costs, such as wildfire mitigation expenses or adders to support energy efficiency or low-income customer assistance programs.

Depending on the size and sophistication of the customer and the market structure, industrial consumers may have direct access to wholesale rates, or they may take service through a distribution utility via a retail rate. An industrial customer's rate class gives them access to rates that can be designed any number of ways to ensure the utilities recover the costs to serve these customers, also known as cost of service. [55]

The cost of electricity service depends on many factors but mainly relates to the variable cost of electricity generation and the fixed costs associated with building and maintaining electrical delivery infrastructure. Though, large industrial customers may have the opportunity to site their facilities in areas with smaller delivery costs or even avoid the distribution system entirely by connecting directly to the transmission system. To reflect these costs, it's common for industrial electricity rate structures to include an energy charge, based on the volume of electricity consumed. They also include a demand charge, based on the customer's electricity demand during system-wide peak demand periods, and fixed charges. These charges all pay for costs of service that do not vary with the volume or timing of electricity consumed.

Importantly, industrial electricity rates depend not only on how much electricity a customer uses but also on how much a customer uses during times of peak electricity demand. Peak demand use is often used as a proxy for the industrial user's contribution to the cost of electricity delivery infrastructure, which is sized for those times of the year (even if only a few minutes) when electricity load is at its maximum. The rate can also depend on the size of the facility, the voltage of the electric service the customer receives, and the power factor, which is a measure of how efficiently the customer uses electricity.[56]

Gas rates and gas markets are also structured around fixed and variable costs of service. For example, the largest industrial customers in the U.S. get their gas directly from transmission pipelines through sales networks known as marketers, also called independent suppliers. Marketers buy gas alongside local distribution companies (LDCs) in an open market and sell it for a profit, and they can sell gas directly to consumers or to an LDC, which is responsible for delivering the gas. Smaller industrial customers typically get their gas from LDCs or municipalities.[57] Large industrial customers located in deregulated

INDUSTRIAL ENERGY PRICES IN CHINA

The National Development and Reform Commission (NDRC) plays an important role in managing energy prices in China. NDRC employs a range of strategies, including price guidance, ceilings and floors, and subsidies. The NDRC is progressively shifting toward market-oriented mechanisms.

The NDRC divides electricity customers into four classes: residential, agricultural, general industrial and commercial, and large-scale industrial.

Residential customers have enjoyed relatively low and stable electricity rates for decades, whereas general industrial and commercial and large-scale industrial electricity rates have experienced more fluctuations over the past 20 years.

Large-scale industrial customers are subject to two-part pricing systems, with an electricity charge based on consumption and a basic electricity charge determined either by the transformer capacity or the maximum demand.

In some cases, tiered pricing and time-of-use pricing may apply, though large-scale industrial users are required to adopt time-of-use pricing whereas general industrial and commercial customers have the flexibility to choose based on their business needs.

China is heavily reliant on natural gas imports, making it vulnerable to significant fluctuations in the international gas market. The NDRC manages city-gate prices, regulates pipeline transportation fees, and promotes market-based trading through exchange centers. Industrial prices are more market-driven and subject to negotiations between suppliers and consumers.

markets may pay three separate bills: one for gas purchases, one for pipeline transportation, and one for local delivery.[58]

Depending on their rate schedule and how utility bills are structured, industrial customer gas bills may include a gas usage charge (aka commodity charge or purchased gas cost), customer charges (such as a meter charge), a transportation and distribution charge (for the pipelines needed to deliver gas), a demand charge (based on the maximum rate that gas supply is delivered to the facility), a storage charge (for the portion of supplied gas that was kept in storage), and other charges, such as riders, taxes, fees, and penalties.[59]

Industrial customers may have access to different contractual pricing options, which allow them to take advantage of fluctuating market prices and to moderate their consumption in real time to optimize savings. Some suppliers offer customers the option to pre-purchase a forecasted amount of gas, which gets sold back to the supplier at a reduced rate if not all the gas is consumed. In the context of electrification, this matters because a large industrial customer locked into a longer-term gas contract based on future forecasts or future pricing assumptions may be extremely limited in or prevented from making any changes to their operating protocols without risking heavy financial penalties.

Energy rates create economic incentives apparent in the ongoing cost of energy for electrified versus gas- or coal-derived process heat. But while gas may be currently competitive, this dynamic is not fixed on the rate side. The cost of wind and solar electricity has fallen significantly in the last decade and is projected to continue falling in the coming decades.

In electricity balancing areas with few renewables, one driver of the cost difference between electricity and fossil fuels is the inefficiency of converting fossil fuels to electricity and using that electricity versus using fossil fuels directly at the industrial facility. However, this is not necessarily true in balancing areas with abundant renewables, because renewables produce inexpensive electricity that can drive down the market price in many hours of the day. Figure 8 shows that many regions of the U.S. with large shares of renewable generation (typically onshore wind in the center of the country, and high levels of solar and battery energy storage in much of Texas and southern California) have the lowest wholesale electricity prices.[xix] The average

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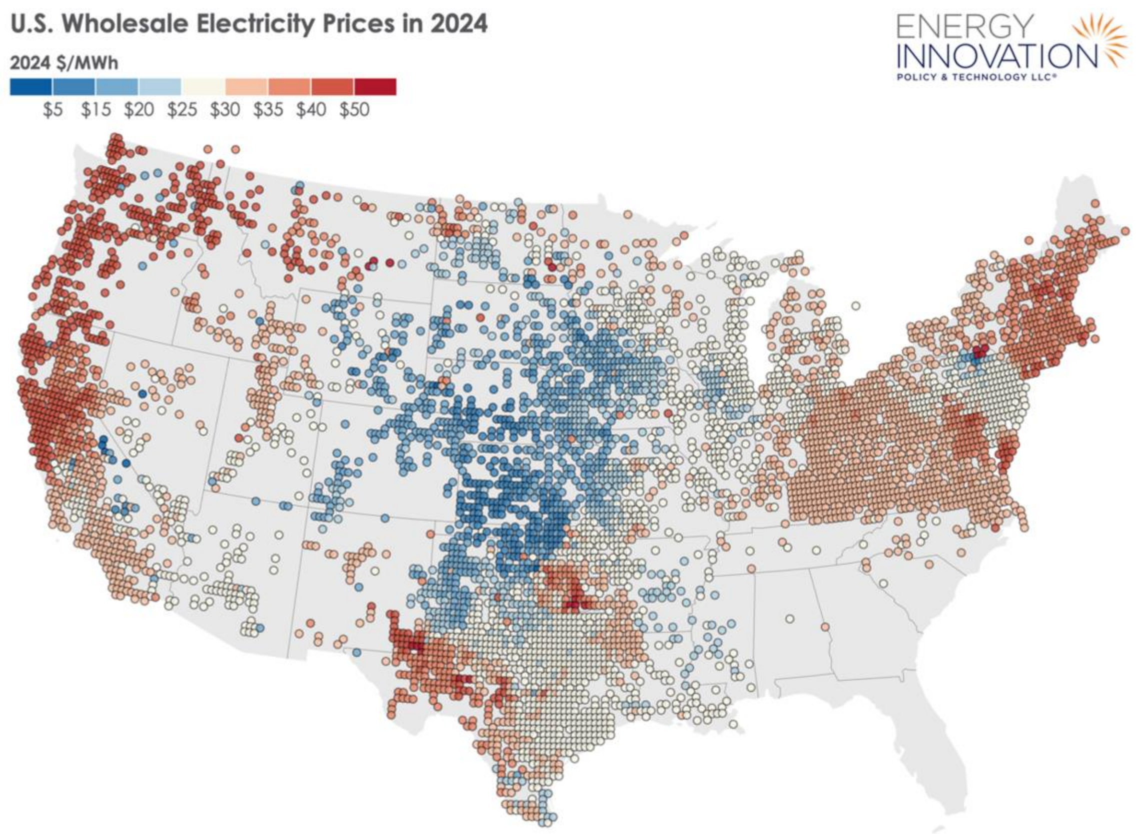
[xix] Wholesale prices vary both with time and with the specific location of an industrial customer. Some regions with large shares of renewable generation have the lowest electricity prices, as renewables produce inexpensive electricity that drives down the market price in many hours of the day. Of note, the Southeastern states do not currently operate a competitive wholesale electricity market like those managed by Independent System Operators (ISOs) or Regional Transmission Organizations (RTOs) in other regions. As such, there is limited wholesale pricing data available for this region.

wholesale price of electricity can be under $10/MWh ($2.78/GJ), which can be competitive with natural gas, particularly when considering that electricity provides industrial heat and services more efficiently than gas (even though, as noted earlier, some industrial facilities must pay retail rates). With more renewable energy deployment, more countries (and more parts of the U.S.) could benefit from lower electricity prices, helping to close the energy cost gap.

Figure 8. Average wholesale price of electricity in the continental U.S. in 2024 [60]



However, deploying more renewables is only half the equation. Differences between electricity and gas rates also arise from the underlying dynamics of rate design and energy markets, and industrial facilities' ability or inability to access time- and location-specific wholesale pricing. These elements are further complicated by utility business models, outdated principals of ratemaking, and misaligned policy directives.

Utility Interconnection and Disconnection Fees

Industrial customers seeking to electrify their heat processes may encounter other economic barriers, including costs to exit or enter a utility system. Given the size and scale of industrial facilities, and the sizable up-front investments in infrastructure required to provide energy to their facility, a large industrial customer planning to switch from gas to electricity may be required to pay exit fees to the gas utility. One gas utility in Oklahoma, for example, proposed a gas exit fee ranging from $875 to $43,750 for commercial and industrial customers.[61]

Alternatively, if a large industrial customer seeks to electrify their processes, they may incur expenses related to interconnection and may be required to make sizeable investments in additional electric grid infrastructure. In many cases, they may have to pay for grid upgrades exclusively, even if other customers will benefit down the line. Absent transparency from the utility, industrial customers may not know if and to what extent they will trigger an upgrade until after the project planning and design phase, making financial planning for electrification even more challenging.

Other Costs: Capital Costs, Financing, and Soft Costs

Although the costs for different electric technologies vary, the capital investments needed to install new electric equipment and upgrade facilities to support that equipment represents an additional economic obstacle. While capital costs are only a small portion of the lifetime costs of industrial equipment, firms may lack the capital needed to cover up-front costs. They may also struggle to obtain financing for those costs if investors perceive the technology as unproven or risky. If firms are unable to access financing and must pay for all new equipment and infrastructure up front, they may be unlikely to pursue a change.

To give a sense of the magnitude of required capital investments, all relatively technologically mature opportunities to electrify non-feedstock energy use[62] in the U.S. would shift 66 percent of non-feedstock fossil fuel demand to electricity. To estimate required capital costs, we developed a scenario that uses 2050 forecasted energy demand disaggregated by subindustry from the U.S. Energy Information Administration, that employs heat pumps to address heat needs up to 150°C, and that utilizes electric resistance, electric arc, and induction technologies to address temperatures over 150°C. This simplified scenario aims to obtain ballpark capital costs—specific costs would vary depending on technology mix and could be reduced through use of energy efficiency and material efficiency technology improvements. Also, note that ancillary costs such as installation costs and costs to increase electrical capacity delivered to the industrial facility are not included. We calculate that these measures, in aggregate, require about $289 billion in capital investment in industrial equipment by 2050 (Figure 9).[xx] However, if these investments were targeted during

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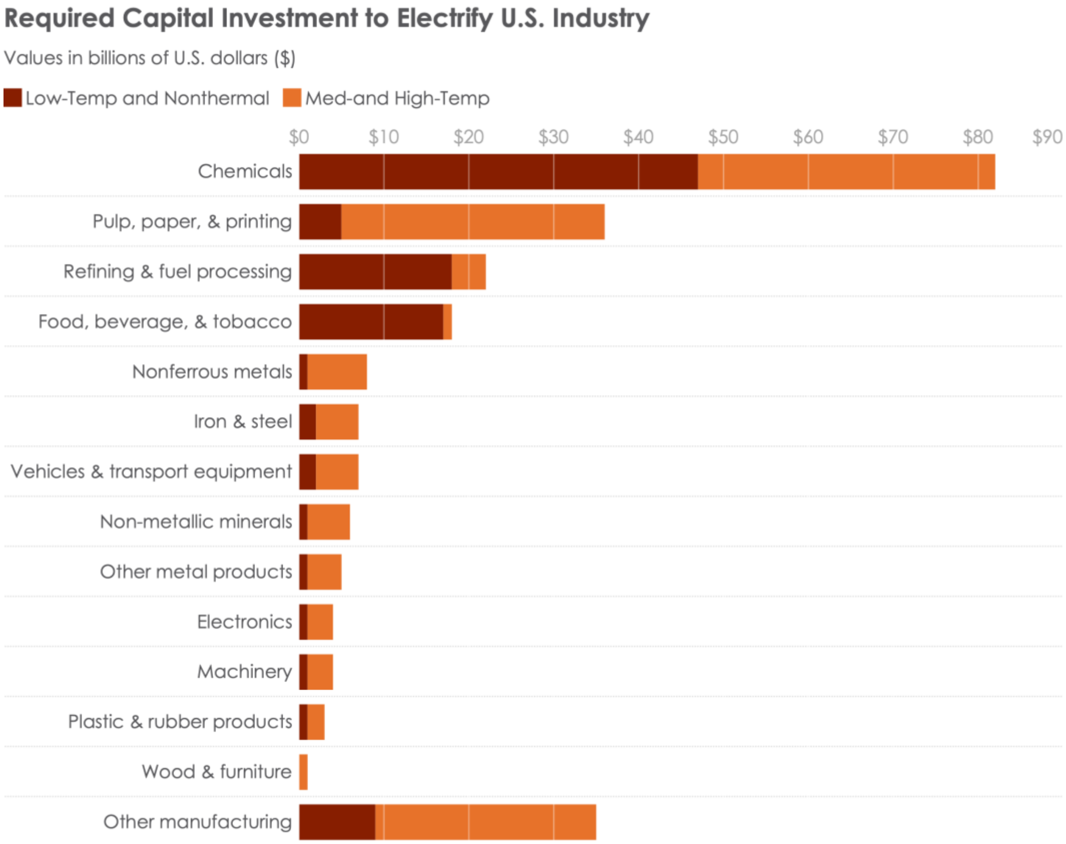
[xx] Figure 9 data are based on an Excel-based computer model, which will be published in a forthcoming World Bank Group report.

times when fossil fuel equipment needed to be replaced, the net additional cost for electric equipment might be much lower; any required capital investment in electric generation, transmission, or distribution assets would be additional.

Figure 9. Required capital equipment investment to realize all relatively technologically mature opportunities to electrify U.S. non-feedstock energy use[xxi]



The required capital investment could also be reduced with manufacturing technologies and product design changes that improve energy efficiency, material efficiency, or product longevity and repairability. For instance, a 25 percent improvement in energy efficiency and a 15 percent reduction in material demand (via material efficiency and product longevity) are achievable by 2050 in advanced

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[xxi] In general, low-temperature and nonthermal fuel-using processes are cheapest and easiest to electrify and could be addressed before medium- and high-temperature processes. However, certain industries—such as chemicals—have tightly integrated facilities where waste heat from high-temperature processes is recovered and used for lower-temperature processes. In these cases, it may be necessary to electrify higher- and lower-temperature processes simultaneously. Costs include projected increases in U.S. industrial production through 2050. Capital costs could be reduced through increased use of energy efficiency and material efficiency (discussed later in the report).

economies and would reduce the required capital (and annual energy) requirements by over 35 percent.[63] The savings potential is even greater in emerging economies with more headroom for efficiency and product longevity improvements.

Firms that electrify will also face soft costs like the time needed to train workers on new operational protocols and the use of new equipment. Additionally, companies may need to consider the local availability of skilled labor to support the retrofit or a new project. In some countries, areas with high availability of cheap renewable electricity may be in less-populated parts of the country (Figure 8), while major urban centers may have an abundance of labor but less available land on which to site a new industrial facility. Additionally, any facility seeking to have co-located renewable energy projects to support new electric load will require additional land.

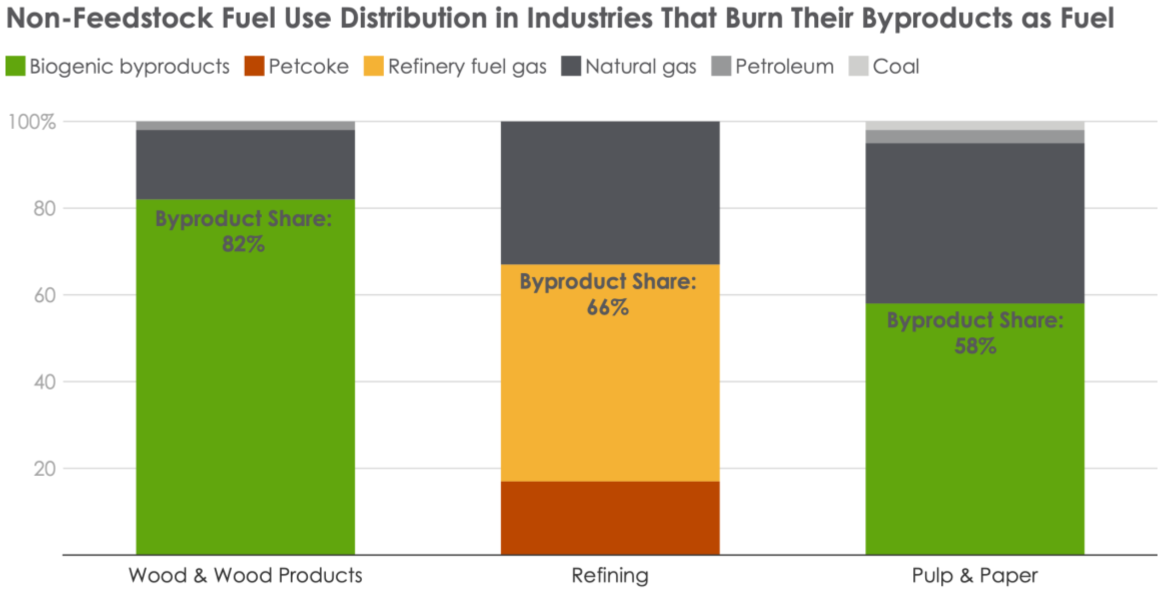
Industries that Use Byproducts as Fuel

Electrification may entail a particularly high operating cost premium for industries that obtain energy by burning the byproducts that they create on site. Industries that rely heavily on byproduct fuels—the refining industry, the pulp and paper industry, and the wood and wood products industry—collectively account for around 10 percent of the global industrial sector's emissions and around 16 percent of the industrial sector's on-site emissions from fuel combustion.[64] These industries also account for a significant share of the sector's low- and medium-temperature heat use, complicating the decarbonization of heat that would otherwise be "easy to electrify." [xxii]

A variety of byproducts such as waste gases and residual oils[65] are inevitable outputs of these industries. In refineries, process units like distillation towers, reactors, and purifiers create these byproducts; they then collect and convert these byproducts to refinery fuel gas (RFG), an energy-dense replacement for natural gas. Certain refinery process units also create a unique byproduct, petcoke, that is collected and used separately as a replacement for coal. Refinery byproducts are not only a cheap source of energy but also are difficult to sell or dispose of due to their high levels of impurities. In the forest products industries, biomass residues that result from processes like de-barking, cutting, and shaping wood are collected and burned as fuel.[66] In pulp manufacturing facilities, chemical processes that break wood down into fine pulp also create byproduct "liquors" that can be recovered and used as fuel. RFG and petcoke together accounted for two-thirds of U.S. refineries' on-site heat in 2022 (Figure 10).

[xxii] According to the U.S. Department of Energy's 2018 Manufacturing Energy Consumption Survey, these three industries account for around half of industrial process heat under 500°C in the U.S.

Figure 10. Non-feedstock fuel use distribution in industries that burn their byproducts as fuel. Purchased electricity is not shown, as it is often used for non-thermal purposes by these industries. Data are from the U.S. in 2022, but potentially similar across countries.[67]



Byproduct fuels account for around 82 percent of on-site combusted energy in the wood and wood products industry and around 58 percent in the pulp and paper industry (Figure 9). All three industries combust byproducts alongside purchased fuels, typically in combined heat and power systems (aka CHP) that deliver both heat and electricity to facilities.[68] Therefore, to electrify these facilities, it would be necessary to purchase enough electricity to not only replace the heat from combusted fuels but also replace the electricity.

Additionally, there are concerns beyond energy costs. If industrial facilities were to stop burning byproducts, they would need to convert these substances into sellable products to serve a pre-existing market or pay to dispose of them.

Given the challenges associated with displacing byproduct fuels, it may seem rational to first focus on electrifying processes that use purchased fuels and address byproduct fuels later. However, most purchased fuels are burned together with byproduct fuels in the same equipment, so this equipment cannot be electrified without contending with byproduct fuels.

Grid Readiness

Widespread industrial electrification will require a robust and reliable electricity grid capable of supporting substantially more demand. New capacity additions must also be carbon-free, and new transmission and distribution infrastructure will be necessary to transmit the electricity to new and existing industrial load centers.

Electrifying all existing, eligible industrial processes[xxiii] would require an increase in electricity generation of 35 percent in the EU, 62 percent in the U.S., 105 percent in China, and 122 percent in India.[69] The primary obstacles to scaling carbon-free electricity resources to support industrial electrification are slow and costly interconnection processes (for both new supply and demand) and grid planning that fails to account for increased load from industrial electrification.

Before construction of a new power generation resource may begin, the developer or customer must apply to the relevant utility or system operator requesting interconnection approval. According to a recent report from Lawrence Berkeley National Laboratory, active bulk-power grid interconnection requests for new generation capacity in the U.S. total 2,600 gigawatts (GW)—more than double the total installed capacity of the country's existing power plant fleet (1,280 GW). Lawrence Berkeley reports that the time required for new generation to secure an interconnection has increased by 70 percent over the last decade and is now almost five years. Interconnection costs have also increased over the last decade (but remain highly variable from region to region and from utility to utility), and interconnection

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[xxiii] Here, the term "eligible industrial processes" refers to all fossil fuel-using processes other than chemical feedstocks and fossil fuels used in primary steelmaking (predominantly coke and coal in blast furnaces, but also natural gas in direct reduced iron facilities). Unlike in Figure 9, the term is not limited to processes for which electric alternatives are relatively technologically mature. The values here refer only to the electricity needed to replace direct use of fossil fuels by industry; additional clean generation needed to decarbonize purchased electricity and steam are excluded.

request withdrawal rates remain high, at 80 percent.[xxiv,70] The same report finds that, if left unaddressed, the interconnection bottleneck will impede the pace of wind, solar, and storage deployment.[71]

Just as new power plants require permission to interconnect with the grid, so too do large new electricity-demanding facilities, and queues also exist on the demand side. Industrial electrification would increase electricity demand at a time when the grid is also facing increased demand from other sectors, including power-hungry data centers. For example, the Electric Power Research Institute forecasts that data centers could go from 4 percent of load today to as much as 9 percent of U.S. electricity consumption by 2030.[72] New manufacturing facilities, cryptocurrency mining, and electrifying the transportation and building sectors are adding pressures to the electric grid demand-side interconnection queues. Each new load addition faces costs and delays to interconnect to the grid, which impose additional soft costs that are ultimately borne by those grid customers.

Grid planning processes are another barrier to industrial electrification. Although grid planning processes vary across countries and utilities, most rely on sophisticated models to determine the most cost-effective, least-risk investments needed to ensure sufficient generation, transmission, and distribution are built to meet projected demand. If those models and forecasts fail to account for the

REAL-WORLD INDUSTRIAL ELECTRIFICATION EXAMPLES

German start-up Kraftblock implemented thermal battery storage in a PepsiCo production plant in the Netherlands. The storage system can bank heat for up to two weeks, allowing PepsiCo to leverage cheap renewable energy from North Sea windfarms during off-peak hours. The snack production facility achieved full decarbonization by coupling the battery with direct electrification of two of the site's thermal oil boilers.

Norwegian firm ENERGYNEST piloted its thermal battery with a fertilizer producer, connecting to the facility's steam grid. It also ran a successful peer-reviewed pilot test over 20 months at the Masdar Institute Solar Platform in Abu Dhabi, United Arab Emirates, that boded well for sustained, long-term performance without degradation.

Sources: Flora Southey, "Electrifying Crisp Production: PepsiCo Overcomes Green Energy Storage Issue with Thermal Battery Tech," Food Navigator Europe, May 23, 2023; and Nils Hoivik et al., "Long-Term Performance Results of Concrete-Based Modular Thermal Energy Storage System," *Journal of Energy Storage* 24 (August 1, 2019): 100735.

[xxiv] Some withdrawals are expected, as developers can submit requests speculatively and as a form of price discovery. However, long interconnection wait times force developers to submit more speculative requests, resulting in larger numbers of withdrawals that further erode the efficiency of the interconnection system (especially late-stage withdrawals that force a re-do of studies characterizing the impacts of other queued projects on the electric grid).

increased demand from industrial electrification, then the grid will not be ready to interconnect new industrial loads quickly or affordably—more expensive upgrades will be required, and more generation capacity will be needed. As noted above, industrial electrification at scale will require significant amounts of carbon-free electricity resources as well as a robust electric transmission and distribution system that can adequately manage the increased energy volume.[73]

Technology Maturity

The commercialization status of different industrial electrification technologies varies widely, but all industrial heating needs can be met by at least one existing electrified technology, if not more. Most industrial process heat under 500°C can be electrified with commercially available technologies. However, industrial firms' lack of familiarity with these technologies impedes their adoption. Certain high-temperature electrical heating technologies are also commercially available, such as electric arc furnaces for steelmaking, and lasers or plasma torches for cutting and welding. However, in other cases, technologies to electrify high-temperature heat require further development and commercialization to be ready for industrial electrification at scale.

For example, electrical resistance is a mature technology, but manufacturers of some types of industrial equipment do not offer models heated by electrical resistance.[74,xxv] Thermal batteries use electrical resistance for converting electricity to heat, and they store that heat in materials that are cheap and abundant (e.g., bricks, carbon blocks), but most industrial models are currently in the pilot and demonstration stage, save for a few early deployments.[xxvi,75]

Other technologies are even more nascent. Electric steam crackers for chemicals manufacturing and plasma torches for cement production would benefit from more real-world pilots and demonstrations to improve performance, reduce costs, and scale adoption. While electrolysis is widely commercially used in the aluminum industry, electrolytic steelmaking technologies that could slash industry's high-temperature heating needs are still at the laboratory stage.

Some technologies are fully commercialized but have not yet reached their full deployment potential, such as induction furnaces for metals manufacturing and

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[xxv] Electric resistance equipment could electrify most processes in the refining, chemicals, and pulp and paper industries and some processes in the steel and cement industries, and it is already deployed widely in the food manufacturing industry (source: Jeffrey Rissman, "Decarbonizing Low-Temperature Industrial Heat in the U.S." (Energy Innovation, October 2022).

[xxvi] Molten salt-based thermal energy storage has been deployed commercially for many years, principally at concentrating solar power plants, but these systems are much less effective and practical for manufacturers than the modern thermal batteries discussed here.

electric arc furnaces for steelmaking. Other technologies are commercially available and are used in existing industrial processes but represent niche use cases that account for a relatively small share of total industrial energy needs. These include lasers, electron beams, dielectric heating, infrared heating, and ultraviolet light.[76]

Industrial heat pumps are the most promising technology to replace lower-temperature industrial boilers (those that output up to around 165-200°C, the maximum temperature that heat pumps can reach). Industrial heat pumps have been commercialized, but they face practical deployment constraints. Global manufacturing capacity for industrial heat pumps (especially those capable of reaching temperatures over 120°C) is limited. Heat pumps are most energy efficient when they can use waste heat as a heat source (and boost it to a higher temperature), but waste heat will be increasingly scarce in a future electrified industrial sector. (Electric technologies avoid wasting heat in exhaust gases. This is generally a good thing, but it limits opportunities for waste heat recovery.) Additionally, an industrial heat pump requires more floor space to accommodate its physical footprint than a boiler of equivalent capacity, and the largest heat pumps have a lower capacity than the largest boilers, so multiple heat pumps may be needed to replace the largest boilers. Electric boilers can have footprints similar to that of fossil-fueled boilers and can reach similar temperatures, but they lack the efficiency of heat pumps, so their energy costs are higher than for boilers that run on less expensive fuels, such as coal and natural gas.

The technological maturity of a given solution impacts industrial customers' willingness to adopt and invest in it, as well as the ability to obtain financing. Moreover, building familiarity with newer technology (or established technology applied to new end uses) requires investments in workforce training.

POLICY SOLUTIONS TO OVERCOME BARRIERS

Overcoming barriers to industrial electrification will require a combination of financial incentives, regulatory standards, and other enabling policies. Recognizing the differences across geographies and industrial sectors around the world, we provide a menu of options for policymakers to consider adopting and adapting to their circumstances. Figure 10 (below) provides a summary table of which policies are best suited to address the barriers to industrial electrification, and in many cases a combination of policy actions will be necessary to overcome market inertia.

Accelerate Renewable Energy Deployment

As shown in Figure 8, the wholesale price of electricity can vary dramatically depending on location. Parts of the U.S. with heavy renewables penetration saw average wholesale prices under $10/MWh in 2023, while other regions of the country saw prices over $50/MWh (and even over $100/MWh in some spots). This highlights that one powerful way to lower the cost of electricity is simply to deploy more renewables, which generate low-cost electricity in many hours of the year, pushing down average prices.

There are a variety of policies that can accelerate renewables deployment, including incentives (such as tax credits for generating clean electricity), renewable portfolio standards or clean electricity standards (which require utilities to procure a certain percentage of their electricity from renewable sources), and ensuring that local, state, and federal policies (such as setback or environmental review requirements) do not unreasonably interfere with siting and permitting of new renewables and transmission lines. Policies to accelerate renewables deployment on the grid are outside the scope of this paper and are not detailed here.

However, industrial firms do not always have to rely solely on grid electricity: they may locate in areas where on-site renewables and storage can supply some or all of their

electricity needs. Enabling policies and incentives for on-site, distributed clean energy generation and storage make this choice more practical and cost-effective for industrial firms. Also, industries opting for on-site renewable generation reduce strain on the grid, making it easier to expand grid generation to meet the needs of all economic sectors. Incentives for on-site generation and storage are common worldwide and have proved highly effective at reducing the cost of carbon-free energy resources and scaling deployment of off-grid consumption.

Enable Co-Location with Carbon-Free Resources

Industrial facilities may be able to reduce electricity costs by producing their own clean electricity on site or by co-locating with clean electricity generation and energy storage, such as thermal batteries. In a 2023 study, Energy Innovation modeled two scenarios—one in California and another in Texas—in which industrial facilities obtained their heat from thermal batteries powered by off-grid renewables. Per the modeling results, the California thermal battery configuration cost the firm an average of $62 per MWh of thermal output, just over a third the costs of an electrified process powered by grid electricity (at retail rates). The Texas scenario resulted in costs around $35 per MWh of thermal output, or half the costs of an electrified process using grid electricity (at retail rates). In both scenarios, the thermal battery configuration nearly reached cost parity with the costs of conventional processes powered by natural gas.[77] Other emerging carbon-free technologies, such as small nuclear reactors and enhanced geothermal, could also be an option for certain facilities and locations.

A growing number of industrial facilities are co-locating with on- or off-grid renewable resources. For instance, the IEA's Renewable Energy Technology Development Technology Collaboration Programme highlights several examples, including: a Volkswagen plant in Chattanooga, Tennessee, that uses solar power through a PPA agreement with an adjacent 9.5 MW solar park (U.S.); a Tenon manufacturing facility that modified its natural gas kilns to run efficiently on geothermal steam (New Zealand); a Mitr Phol sugar mill that uses renewable cogeneration (Thailand); and a Pepperidge Farm plant that sells excess energy from its own solar PV installation back to the grid at retail prices (U.S.).[78]

Industrial facilities that benefit from off-grid renewable sources can procure electricity at lower cost than grid-connected rates from utilities but must address the variability of renewable generation.[79] Fluctuations in solar power provision caused by day/night cycles and the impact of weather patterns on wind farms could be evened out by industrial thermal batteries[80] or other storage solutions. Some facilities (with sufficient floor space) might choose to retain their fossil equipment as a backup and run it only during the longest periods of calm, cloudy days (e.g., less than 1 percent of the year) and purchase offsets or fund carbon removal projects to counterbalance the resulting emissions.

Another possibility is co-located nuclear energy. For instance, U.S. chemicals manufacturer Dow and nuclear technology company X-energy plan to deploy four small modular nuclear reactors to provide high-temperature heat and electricity to a Dow manufacturing facility in Texas, backed by over $1 billion in government subsidies.[81] In recent decades, utility-scale nuclear has frequently faced significant project delays and cost overruns. It remains to be seen if small modular reactor technology can be deployed on time and cost-effectively.

Enhanced geothermal—an advanced form of geothermal energy technology that creates its own reservoirs by injecting fluid into hot, dry rock deep below the Earth's surface to create fractures and stimulate a flow of heat—is also gaining traction in the U.S., the EU, Australia, and countries in Asia. Several companies are deploying pilot projects with promising results.[82]

Incentivize Clean Industry

The inherent efficiency of electric technologies can only partially mitigate the cost premium for electrified heat.[xxvii] Given the need for many industrial facilities to operate 24/7 or on demand, most industrial facilities cannot avoid this premium by purchasing electricity only in those hours when it is cheapest. Therefore, financial incentives will be critical for creating cost parity between industrial electrification and conventional heating processes.

Incentives—including tax credits, grants, and rebates—can be used to reduce the operating costs of electrified industry, to lower the cost of carbon-free electricity, or to help firms cover the capital expenditures associated with electric equipment. Funding for these incentives could come from taxpayer dollars (via tax credits or government grants), from other utility ratepayers (via utility rebates or special tariffs), or through fees on harmful pollution (see the discussion of carbon pricing below for one example, though fees could also be levied on conventional air pollutants).

Note that incentives that are structured as tax credits should incorporate provisions that ensure firms without tax liability can still benefit (i.e., by making the tax credit refundable or easily transferable). Nonrefundable tax credits may require industrial firms to partner with large financial institutions, which have limited capacity to

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[xxvii] There are some exceptions to this. At output temperatures under 100°C, heat pumps can be efficient enough to overcome this cost premium, depending on local fossil fuel prices. The premium may also be lower for thermal batteries, since firms can leverage their storage capabilities to selectively purchase electricity when it is cheapest and provide demand-response services to the grid.

engage in such partnerships, are only interested in sufficiently large deals, and ultimately take about half the value of the tax credit.[83]

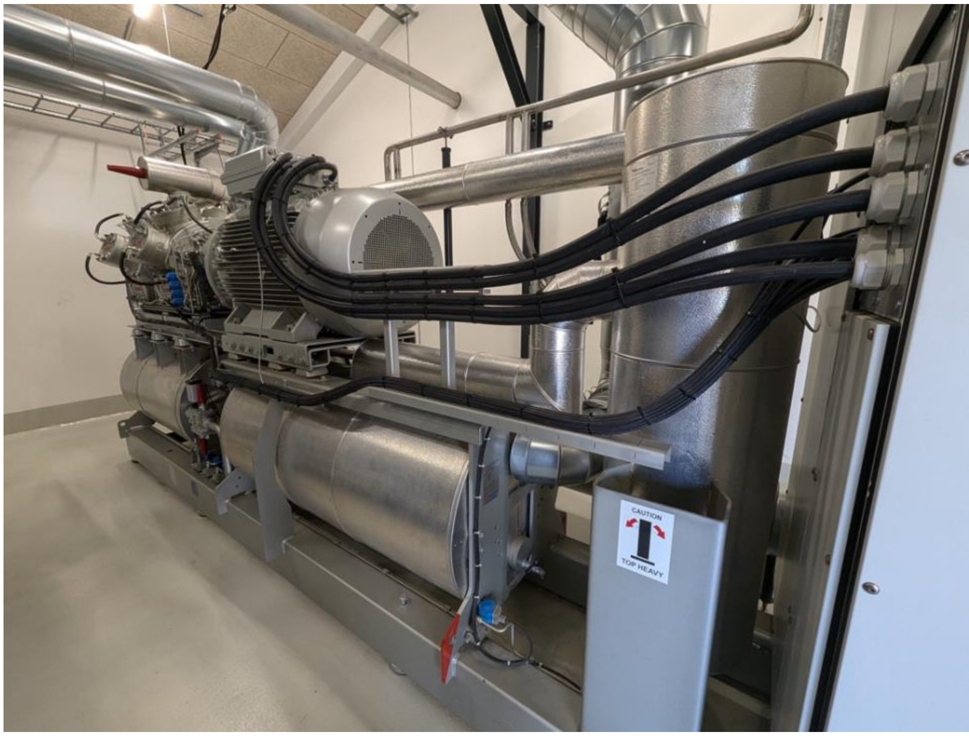
Incentives for Cleanly Manufactured Products

A country or state could adopt incentives for producing goods or materials via industrial processes that use electricity in place of fossil fuels, and the incentive could be tiered based on carbon intensity (i.e., an industrial firm whose products are manufactured using 100 percent carbon-free electricity would qualify for the maximum incentive). To determine the appropriate incentive amount, a government would need to be able to obtain accurate data regarding the carbon intensity of manufacturers' processes, so the policy must be designed and enforced with those implementation details in mind. Such incentives work well for commodities such as steel or basic chemicals, whose output is consistent across manufacturers. Internationally accepted guidelines could be established to ensure the reported carbon intensity data functions both domestically and internationally (e.g., when firms export products to regions with carbon border adjustment mechanisms (CBAMs), such as the EU).

A related mechanism for incentivizing cleanly manufactured products is a green public procurement program, also known as a "buy clean" program. Governments are major purchasers of emissions-intensive industrial products and materials, including steel and cement in public buildings and infrastructure. National, state, or local governments can commit to purchasing goods that are manufactured with lower-than-average emissions and gradually tighten the emissions threshold over time to ensure continuous improvement. They may also carve out a small percentage of their purchases to support novel manufacturing technologies that are just beginning to be deployed in the marketplace and that can achieve zero or near-zero emissions, giving these technologies a protected market that allows them to scale up and drive down costs. Many countries and subnational regions have green public procurement programs, including Denmark, France, Germany, the Netherlands, California, Brazil, South Africa, Argentina, and Mexico.[84]

Incentives for Electrified Equipment Capital

Policies that help buy down the up-front cost of new electric equipment and accompanying electric upgrades are another tool in the toolbox. Equipment rebates, akin to those that promote efficient residential appliances, can reduce the cost of equipment that meets certain efficiency or emissions intensity thresholds. The size of the rebate can be based on the margin by which the equipment's environmental performance beats the threshold.



Grants and tax credits for new or retrofit facilities can also provide money to support the purchase and installation of electrified technologies. Policymakers may attach stipulations or requirements to the public funding (e.g., data collection and reporting, creation of high-quality jobs, and ability to demonstrate public benefits). For example, in 2024 the U.S. Office of Clean Energy Demonstrations provided $6 billion to support 33 industrial decarbonization projects that promise to create significant community benefits and jobs.[85] Private funders committed an additional $14 billion to match the federal funding. Note, however, that equipment rebates, grants, and tax credits that help defray the cost of new equipment may not, by themselves, be sufficient to incentivize manufacturers to adopt electrified technologies if annual energy costs would be higher after electrification, as energy costs generally represent most of the lifetime costs of energy-using industrial equipment. Therefore, policymakers should ideally offer incentives that cover both the operating and capital cost premium for electrified industrial processes.

Clean Heat Production Tax Credit

A production tax credit (PTC) for clean industrial heat is an incentive for industrial processes that use electricity to generate heat. A PTC would reward every unit of "clean heat"—i.e., industrial process heat created without any on-site GHG or pollutant emissions—with a credit equal to the operating cost premium for electrified heat.[86] Since the operating cost premium depends on the efficiency of the heating technology, which in turn varies by temperature, the credit should ideally be calculated as a function of the temperature required by the industrial process using a smooth, mathematical function.[xxviii] The alternative approach, where the credit is fixed at a specific value per unit of heat generated, would overpay for some interventions and underpay for others.

A clean heat PTC need not explicitly exclude other sources of clean heat, but some elements of a well-designed PTC might implicitly incentivize electrification. For instance, the definition of clean heat should include conventional pollutants in addition to GHGs. This means that robust pollution control equipment would be needed before the credit would be paid out for heat from bioenergy combustion (which can emit large quantities of particulates and other conventional pollutants) and hydrogen (which creates NO_x by splitting atmospheric nitrogen). Also, the PTC should only credit heat used productively in a manufacturing process. Combustion of any fuel, including hydrogen and biomass, loses energy in hot exhaust gases and latent heat in formed water vapor, while electrification does not have those heat loss modes.

The PTC should be available for a period equivalent to the lifetime of process heating equipment, and it should come into effect one to two years after enactment to give firms enough time to invest in new equipment and production lines.[xxix] Moreover, if the PTC is designed to cover the full operating cost premium for clean heat, the authorizing legislation should prohibit firms from stacking the PTC with other incentives that could also cover those operating costs, such as the 45V tax credit for green hydrogen in the U.S., carbon contracts for difference (CCfD) in Germany, and industrial decarbonization grants in France.[xxx, 87]

Industrial firms consume a large amount of energy, mostly for heat, so a clean heat PTC with an attractive incentive amount could see large uptake (which could become quite costly to implement). Other types of incentives can be better at limiting costs, especially incentives that are funded only up to a certain amount of money and for which companies must compete by submitting proposals to the government agency administering the grant program or tax credit. Implementing a clean heat PTC would also require a mechanism to verify reported data to claim the incentive.

[xxviii] The function should be based on best-in-class, commercialized technology available in the marketplace, not customized to the unique efficiency of every industrial facility, so each facility need not collect or submit efficiency data. This also reduces opportunities for gaming the system.

[xxix] Legal parameters in the political process may require shorter periods of eligibility. For example, policies passed through the U.S. budget reconciliation process must sunset after 10 years unless revenue raisers exist to offset any expenditures beyond 10 years.

[xxx] A clean heat PTC could also be designed to cover the capital cost premium for electrified heat, but it may be difficult to embed this factor into the PTC's function, since data on the capital costs of specific industrial equipment is not widely available. An alternative approach is to offer the PTC alongside a separate investment tax credit or grant program that covers up-front capital costs.

Importantly, the emissions impact of a clean heat PTC depends on the successful passage and implementation of complementary policies, such as an industrial energy efficiency standard (explored below), that can help address non-cost barriers to decarbonizing industrial heat and incentivize energy efficiency to reduce overall energy needs. And as noted above, complementary policies to decarbonize the grid are necessary to ensure that electrified heat is emissions free in the long run.

Incentives for Clean Electricity Use

Incentives to address the price differential between electricity and fossil fuels are less common but would function similarly to incentives for products made with clean electricity. They can be implemented either by utilities or policymakers. Electric utilities can offer a discounted rate to industrial firms, subject to approval by regulators. Alternatively, policymakers can implement CCfDs, or long-term contracts in which the government agrees to pay industrial firms the difference between actual carbon prices (i.e., in jurisdictions with cap-and-trade systems) and an agreed-upon carbon price. By providing firms long-term certainty around the cost difference between clean and conventional heat, CCfDs encourage investments in clean industrial processes that are already close to cost parity with conventional processes. Germany's Klimaschutzverträge is a recent example of this policy. As of October 2024, 15 companies had signed contracts with the German Ministry for Economic Affairs and Climate Action to support their decarbonization efforts. Funding is expected to total €2.8 billion and save up to 17 million tonnes of CO_2e over the next 15 years.[88] Utilities or governments could also consider additional incentives to address other infrastructure required for electricity delivery to industrial facilities (e.g., transformers, power lines) to help reduce the costs to electrify.

To qualify as "clean electricity" that is eligible for incentives, electricity should be required to pass a three pillars test ensuring additionality, deliverability, and time-matching.[89] The three pillars test, originally developed in the context of tax credits for electrolytic hydrogen, ensures that an industrial facility switching to clean electricity reduces economy-wide emissions. Without such a test, an incentive will likely cause renewable electricity that would have gone to other customers to be redirected to the industrial facility. Additional fossil generation may then be dispatched to serve those other customers, increasing total emissions.

Create New Financing Tools

Beyond incentives to offset the up-front and operating costs of electric technologies and carbon-free electricity generation, policymakers can help firms cover the remaining costs with creative financing tools.

For example, green banks (the first of which was founded in Malaysia in 2010) are designed to provide attractive financing options for an array of clean energy measures and other sustainability improvements that may not be typically covered by traditional financing institutions.[90] The nonprofit Coalition for Green Capital has helped to establish green banks in several U.S. states as well as abroad.[91]

THE EU'S CLEAN INDUSTRIAL DEAL

The Clean Industrial Deal aims to make decarbonization a driver of economic growth and improve energy affordability throughout the EU.

According to the European Commission, the Clean Industrial Deal will mobilize over €100 billion to create an industrial decarbonization bank that will support domestic, carbon-free manufacturing.

The Commission also plans to accelerate state aid to support more renewable energy development and deployment of clean technologies across an array of industries.

Sources: European Commission, "Clean Industrial Deal," February 2025.

Green banks can support projects that utilize existing technologies that may still be unproven or possess too high a cost barrier to attract sufficient private sector funding. That said, projects still need to provide a financial return over a reasonable time at tolerable levels of risk. Green banks typically use their initial nonprofit or government funding to help spur partnerships with private capital that leverage their impact. For example, over a decade, the Connecticut Green Bank used $322 million in green bank funds to attract $1.95 billion of private investment.[92] Traditionally, green banks are "revolving funds" where repaid principal and interest on loans can in turn finance new loans to new projects. This enables an initial investment to be self-sustaining and ensure a stable future foundation for the institution.

Green banks and other financial institutions have an array of funding mechanisms at their disposal to support industrial firms interested in electrification.[93] These include co-lending with private financial institutions—sharing both the risks and rewards of the loan, aggregation of small loans to multiple projects into a bundle to sell to private investors (creating diversification and reducing risk), or selling tax-favored bonds to raise capital. Green banks may also set aside loan loss reserves that can cover some percentage of private lenders' potential losses if a project fails, partially offsetting their risk in funding green projects. More aggressively, loan guarantees can absorb a considerable portion, or even all, of the potential debt in case of a loan default; these guarantees can be used in cases when the promising project is so nascent that private sector buy-in would be otherwise untenable.

Increase Efficiency and Flexibility to Reduce Demand and Costs

While access to low-cost clean electricity is crucial for industrial firms to transition off fossil fuels, it is also necessary to find ways that production can be streamlined to use less electricity per unit of output product. Reducing energy use through the promotion of energy efficiency, material efficiency, or material substitution measures can offset demands on the grid without sacrificing productivity. A circular economy also offers multiple routes to reduce the energy and resource requirements of production and can benefit from smart policies to incentivize its growth in a way that strengthens GDP.

Energy Efficiency Standards

Energy efficiency standards can help industrial firms prioritize investments in energy efficiency ahead of other capital investments. Efficiency standards have traditionally been designed at the component level—for example, addressing the different equipment properties of motors or pumps. More progress is possible, as there are many types of industrial equipment that are not yet subject to energy efficiency standards in most or all countries. However, there is also considerable headroom to improve industrial efficiency by rethinking entire production lines (what types of equipment are selected, how equipment is integrated, and how materials and energy flow through the system) and by tweaking product designs so that goods require fewer or less energy-intensive manufacturing steps.

Standards should be designed to become more stringent over time to prevent stagnation. This gives standards the twofold benefit of phasing out lower-performing products from the marketplace while also encouraging manufacturers to continuously improve their technologies. Even so, standards tend to have cutoff values that manufacturers are not incentivized to significantly outperform. Standards can be paired with incentives (discussed earlier), which can be scaled to reward exceptionally efficient performance.

For example, energy efficiency standards for low-temperature industrial heat could remain technology neutral, which would support industries' efforts to cost-effectively electrify roughly 35 percent of their process heating needs via efficient technologies such as heat pumps.[94]

Flexible Industrial Electricity Demand

While some industrial firms operate 24/7, many others ramp their production up and down over the course of the week and year (see sidebar, "Industrial Electricity Demand Patterns"). Taken as a whole, there is significant potential for industrial firms to flexibly optimize the times at which they use electricity, which can reduce utilities' cost to generate and deliver that electricity (and they may pass some of these savings through to the firm). For instance, a recent report from Duke University showed that there is significant existing headroom on the U.S. electricity grid much of the time, and if customers could operate primarily during those periods of headroom, new infrastructure might not be needed to serve those customers.[95] In practice, this means industrial customers would aim to use electricity when wholesale electricity costs are low, which tends to be when available electricity resources greatly exceed demand—for example, when the local grid is able to meet most or all of its demand with solar resources on a sunny day, or during mild temperatures when few buildings are operating air conditioning or heating.

There are multiple ways to incentivize customers to use electricity at such times. One way is to implement daily time-of-use prices, in which electricity is more expensive during peak times, generally in the morning or evening, and cheaper during the middle of the day or night.[96] However, time-of-use pricing is generally the same from day to day, which means that variation between days is not reflected in the price. Therefore, neither the customer nor the electricity supplier is getting the most value out of the potential flexibility industry could offer. Block and index pricing is another common rate structure for flexible loads, wherein a customer buys a block of power at a fixed rate and then either buys the remainder or sells back power at a real-time price.[97]

A more direct method is to expose customers to the actual wholesale price of electricity. This method, called "real-time pricing," has proved effective in Texas,[98] where industrial customers have been able to access very cheap electricity when renewable energy production from wind energy is high.[99] It is primarily available to customers in retail choice electric markets, and is suitable mainly for sophisticated industrial customers who can manage additional exposure to not only low prices, but also high prices during peak demand times. (Thermal batteries, discussed earlier, are one technology that can make it easier for industrial firms to manage their demand and avoid buying electricity in peak hours.) For regions without retail choice markets, utilities and regulators should develop policies or rate plans that pass through real-time prices for industrial customers who opt in (because they are able to respond to such dynamic price signals).

Industrial customers can also reduce their impact on generation capacity needs by reducing electricity use specifically during peak moments during the day or year. This behavior can be incentivized by either "critical peak pricing" or an "interruptible tariff." Typically, these rates offer the customer a credit for curtailing their electricity use when called upon during peak times, but they could also give the customer cheaper overall rates if they commit to reduce their power usage during peak times.[100] These rates are designed with infrequent, high-electricity-demand events in mind, such as extreme hot or cold temperatures, for industrial customers that can decrease large amounts of demand very quickly and provide valuable demand-response services.

Lastly, customers may be able to reduce their cost of service by reducing their impact on the fixed components of grid infrastructure like transmission lines. In some regions, transmission costs are allocated similarly to capacity charges (fees based not on a customer's total electricity consumption but on their consumption at specific times). For example, many utilities allocate transmission charges via the coincident peak method, by which a customer's electricity use during a given number of the highest electricity demand peaks throughout the year determines the capacity charge the customer must pay.[101] Under this rate structure, if industrial customers can reduce use during these coincident peaks, they can reduce their cost of transmission service.

While transmission congestion and peak electricity demand are often coincident, rate designs that incentivize reduced transmission congestion without regard to system-wide electricity demand may be able to further reduce cost of service. There exist today comprehensive demand-response programs that treat industrial customers as an electricity system asset, whose demand can be ramped down by utilities (by sending price signals) when needed, to alleviate transmission congestion or help the

INDUSTRIAL ELECTRICITY DEMAND PATTERNS

Industries that operate nearly continuously—only shutting down equipment for maintenance—contribute almost half of industrial electricity demand. At the other extreme, some agricultural produce processing facilities may only operate seasonally. On average, U.S. industrial energy demand declines by 17 percent at night during the work week but drops 50 percent at night over the weekends. There is also seasonal variance. For instance, peak-hour industrial electricity demand is elevated by 15 percent in the summer compared to the winter.

While granular data for the industrial sector in other countries is more difficult to come by, an analysis of smart meter data from 21,330 manufacturing facilities in Guangdong Province, China, showed wide heterogeneity in industrial operation and energy use over the weekend. Only 23 to 27 percent of factories worked through the weekend, varying by industry (with transportation equipment factories taking the least time off); only 4 to 8 percent took both days off, with the remaining 66 to 70 percent of factories taking one day.

Though industry-sector-specific data in India was difficult to disaggregate, energy demand across all sectors swung relatively little from weekday to weekend, with Sundays averaging 5 percent less demand than Mondays. While seasonality exists in the industrial sector's energy demand in India, its impact on daily swings in load pales in comparison to residential/commercial sectors. This is evidenced by the small daily demand swings in Maharashtra, whose loads are primarily industrial, as compared to the load swings in Delhi, the nation's capital, which has almost entirely residential and commercial loads.

Sources: *Jeffrey Rissman and Eric Gimon, "Industrial Thermal Batteries: Decarbonizing U.S. Industry While Supporting a High-Renewables Grid," 2023.*

Imran Khan et al., "Segmentation of Factories on Electricity Consumption Behaviors Using Load Profile Data," IEEE Access 4 (November 22, 2016): 8394–8406.

Grid-India, "Report on Electricity Demand Pattern Analysis, Volume 1," Grid Controller of India Limited, December 2023.

utility with ancillary services, such as frequency regulation and voltage control.[102] If such comprehensive demand-response programs become sufficiently sophisticated and reliable for reducing transmission congestion and providing other services, utilities could have the confidence to forgo some costly grid investments.[103]

Time- and Location-Specific Electricity Pricing

Thermal batteries enable an industrial firm to purchase electricity in the hours when it is cheapest (when there is oversupply on the grid) and to avoid buying electricity in hours when it is scarce and expensive. This helps grid regulators balance the grid, and it can even create financial savings for utilities and grid operators by enabling them to profitably sell excess electricity from renewables that otherwise would have been curtailed. Utilities can pass along some of these savings in the form of lower rates for other customers, and it incentivizes utilities to develop more renewables in areas that today are subject to high curtailment rates, where additional wind or solar might not be profitable. Thus, thermal batteries can create a virtuous cycle that incentivizes further renewable energy deployment and generates savings for industrial firms, utilities, and other electricity buyers.

However, utilities and grid operators typically do not allow industrial firms to pay time- and location-specific wholesale rates. Even time-of-use rates often levelize electricity prices into multiple-hour-long blocks, whereas thermal batteries benefit from rates that are updated to reflect the true value of electricity every 15 minutes or even more frequently.

A utility, with regulatory approval, can create a new rate class for highly flexible industrial loads that charges the true cost, or something akin to a real-time wholesale rate, to generate and deliver electricity to the facility in every 5- or 15-minute increment. Since the industrial facility would only utilize grid infrastructure (such as transmission) at times when spare capacity is available, a discount on ancillary charges (i.e., cost adders above the wholesale price) to maintain grid infrastructure can be justified.

Adopt Carbon Pricing Policies

Today, many countries subsidize fossil fuel production or fossil fuel use by industry. Ending these subsidies is necessary to ensure a fair playing field (and is complementary to carbon pricing). We recognize such an action faces political challenges around the world, but doing so would accelerate the transition to clean electricity and correct skewed economics that favor fossil fuels over direct electrification. Carbon pricing can encourage industrial electrification by accounting for the full costs of fossil fuel combustion, thereby reducing the cost gap between electrified heat and fossil-based heat. It may also lower demand for emissions-intensive goods if producers pass their compliance costs on to consumers, though costs are not always passed on, especially for commodities.[104,xxxi,xxxii]

While specific policies vary in design, carbon prices generally work by charging entities a fee for emitting GHGs, requiring them to pay for the social costs of that pollution. Rather than requiring firms to reduce emissions or adopt certain technologies, carbon pricing changes the cost-benefit calculus that firms face when selecting process heating technologies. To date, global carbon prices levied on the industrial sector have often been modest, so they are only effective at advancing technologies that are marginally more expensive than conventional alternatives (and sometimes, the industrial sector has been exempted from carbon pricing entirely). This means that carbon pricing alone is likely to be insufficient to drive industrial electrification unless significantly higher prices are charged.

Although carbon pricing is technology neutral, it would likely incentivize electrification over switching to cleaner combustible fuels (such as green hydrogen or biomethane) in many industrial processes. This is due in part to the efficiency of electrification compared to fuel combustion at all temperature levels, the commercial viability of many low- to medium-temperature electrified heating technologies, and the availability of electricity and its enabling infrastructure compared to low-carbon fuels.

Policymakers can choose between two main forms of carbon pricing—carbon taxes and cap-and-trade—or they can create hybrid schemes that combine elements of both. A carbon tax charges emitters a fixed fee for every metric ton of CO_2-equivalent

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[xxxi] Market prices for commodities are set by the marginal producer, or the producer with the highest production costs who nevertheless sells the product at a price the consumer will pay. Commodity prices will only increase to the extent that a carbon price raises marginal producers' production costs. Since marginal producers are typically the cleaner producer, many commodity prices will remain the same or increase only slightly.

[xxxii] This may be an unwanted consequence of carbon pricing from an economic and social perspective, especially if it disproportionately burdens lower-income consumers.

(CO_2e)[xxxiii] that they emit. Regardless of the fee chosen (e.g., it could initially be based on the social cost of carbon), it should ramp up over time to eventually incentivize net-zero emissions. This policy provides certainty to emitters around the cost of emitting GHGs, allowing them to plan their near- and long-term compliance efforts. However, it does not provide certainty around the level of emissions reductions that will occur, since it leaves each emitter free to decide whether to pay the fee or abate their emissions.

Cap-and-trade policies typically require entities to purchase permits to pollute above a certain limit (and small emitters, below that limit, can often be covered by requiring fuel suppliers to buy permits to cover the anticipated emissions from the fuels they sell). Permit prices are typically decided via auction, and entities with high abatement costs may buy permits from those with lower abatement costs. Therefore, permit prices tend to reflect the marginal costs of abatement, minimizing the costs of compliance at the expense of price uncertainty for firms. Since the number of available permits typically ramps down to zero over time, cap-and-trade systems also create certainty around emissions reductions. Despite these benefits, the complexity of holding auctions and administering permits (e.g., whether to allow banking of permits, whether to link multiple jurisdictions, whether to allow carbon offsets and how to vet them) can create loopholes, and community advocates may oppose permit trading insofar as it could prolong the life of polluting facilities in certain areas.

Since many industrial firms face high costs of abatement and create politically valuable co-benefits like jobs, carbon pricing faces uniquely high political obstacles. In the U.S., a proposed federal cap-and-trade system buckled amid economic concerns in 2009, and other countries that do have national carbon prices typically offer exemptions for industrial emissions. The EU emissions trading system (ETS) grants trade-exposed industries "free allocations" that allow them to emit some GHGs.[xxxiv] China's ETS does not cover heavy industry at all, but this is expected to change in the next few years.[105]

Pragmatically, the best carbon pricing system is the one that is politically viable. Cap-and-trade systems have proved popular globally, likely because they can preserve the competitiveness of firms that offer economic and social co-benefits. In fact, they represent all subnational carbon pricing policies in the U.S., from state-level policies in California and Washington to the Regional Greenhouse Gas Initiative that covers 11 Northeastern states. If expanded to cover industrial emissions, these cap-and-trade schemes would cover up to 12 percent of energy-related industrial carbon emissions in

[xxxiii] CO_2e is a metric that expresses the climate warming potential of various GHGs (e.g., CO_2, methane, and NO_x) in terms of the climate warming potential of CO_2.
[xxxiv] These free allocations will phase out by 2034.

the U.S. Regional Greenhouse Gas Initiative states.[106,xxxv] States like Colorado and Oregon with ambitious climate policies may also be fertile grounds for new carbon pricing policies that include the industrial sector.

Complementary policies can safeguard against the downsides of carbon pricing, making it more politically viable.[107] For example, incentives like a clean heat PTC (discussed earlier) or subsidies based on positive traits the government wants to encourage (e.g., creation of high-quality jobs or contribution to GDP) can offset the financial burden posed by a carbon price. Such countervailing subsidies can be used instead of "free allocation" of permits to maintain firms' competitiveness without dampening the policy's signal to industrial firms to decarbonize.

Carbon Border Adjustment Mechanisms

Carbon border adjustment mechanisms (CBAMs) can protect domestic industries from competition from foreign firms that are not subject to a carbon price. A CBAM charges a fee on imported goods based on the carbon that was emitted when those goods were manufactured (the "embodied carbon" in the imported goods). This prevents firms from getting an advantage when selling inside the regulated area by producing goods in places with weaker or absent environmental regulations, like carbon pricing. Similarly, the CBAM rebates the cost of the carbon price to domestic firms that are exporting their products to places without carbon pricing, so their exports are not put at a disadvantage relative to other products available in those countries. A CBAM improves the financial efficiency of carbon pricing and can create an incentive for firms outside of the regulated area (i.e., in a place without carbon pricing) to cut their emissions. However, it does rely on an internationally accepted, verifiable standard for measuring and reporting embodied emissions. In October 2023, the EU adopted a CBAM with the objective to reduce carbon emissions, put a fair price on the carbon emitted during the production of carbon-intensive goods imported into the EU, and encourage cleaner industrial production through a methodology for calculating embedded emissions according to the Paris Agreement and the EU Fit for 55 package.[108]

A CBAM need not be used only in the context of carbon pricing. It can also offer financial protections to domestic firms when other policies are in place that might raise industry's costs, like a clean heat emissions standard. The following section explores this type of policy in more detail.

[xxxv] Energy-related CO_2 emissions from the industrial sector in these 13 states represented around 12 percent of those emissions in the entire U.S. in 2022.

Enact Emissions Standards

As noted above (with respect to energy efficiency standards), standards help to overcome the non-cost barriers that prevent firms from decarbonizing even when there is cost parity between conventional technologies and clean alternatives.[109]

However, energy efficiency standards alone may not always drive lower conventional pollutant emissions (e.g., particulates, sulfur oxides, NOx); facilities may run more efficiently but throttle down their exhaust treatment systems to continue to narrowly comply with any relevant emissions standards. Also, the only way to use energy efficiency standards to achieve full decarbonization is to set them so stringently (e.g., near 100 percent) that combustion technologies cannot compete, and this would unintentionally exclude the combustion of clean fuels like green hydrogen and biomethane. Therefore, there is a place not only for energy efficiency standards but also for emissions standards.

Unlike today's energy efficiency standards, today's emissions standards generally operate at the scale of the facility, rather than individual pieces of equipment, and thus support a flexible range of decarbonization strategies for compliance.

For primary products such as commodities whose outputs can be easily quantified in common units across manufacturers, GHG emissions intensity thresholds can be set for the allowable CO_2e per unit of product. Cement, steel, and major chemicals like ammonia are responsible for the majority of industrial emissions and have only limited differentiation (e.g., there are different grades of steel, but steel of similar grade is comparable across manufacturers), making per-unit-product thresholds a promising approach. Products like steel and ammonia are typically inputs into other, downstream products—if a standard is imposed on the "upstream" materials that went into a product, it may not be necessary to set a standard on the heterogeneous "downstream" products made from that material, if the lion's share of the energy and emissions are encompassed in the upstream steps.

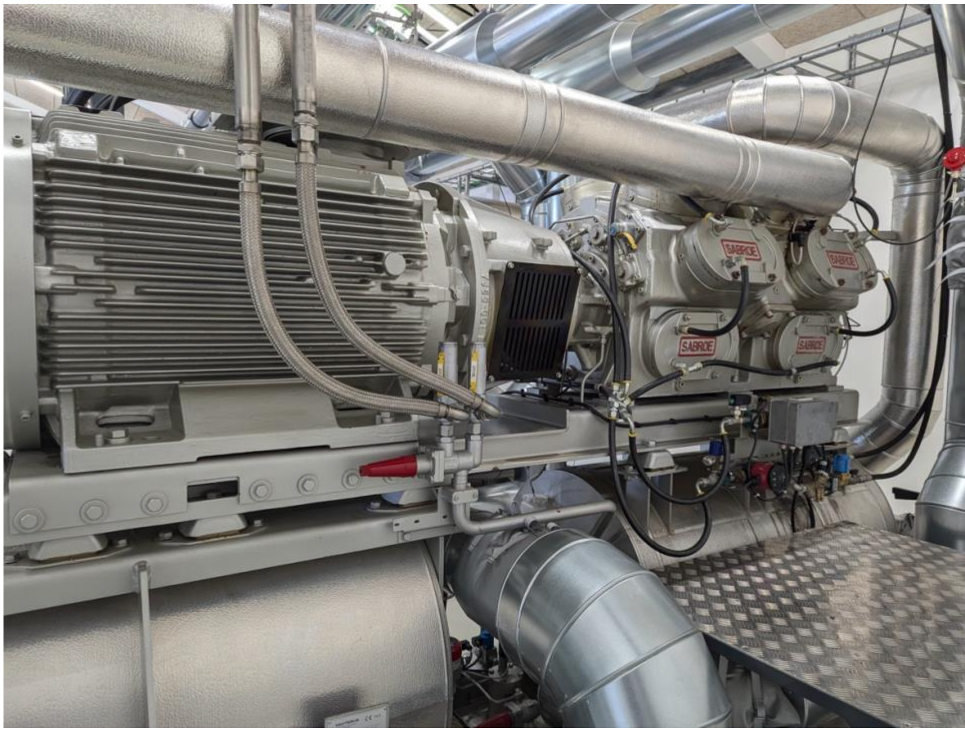
More specialized or "differentiated products" often exhibit qualitative differences between the designs of each manufacturer that make product-based thresholds more difficult to establish. One approach is to hold manufacturers to improvement upon a historical baseline (ideally one instituted before knowledge of the benchmark, to prevent artificially inflating the baseline measurement to make compliance easier).

Canada's Output-Based Pricing System is a carbon intensity standard that in some provinces is superseded by more specific rules, such as Ontario's Emissions Performance Standard. Ontario's strictures have sector-wide emissions intensity thresholds for specific commodities, while other less common products such as glass and nylon are regulated through facility-specific standards that are pinned to historical baselines. Noncompliant products are billed an escalating amount for each ton of excess emissions, reaching CAD $170 per metric ton of CO_2e by 2030.[110]

Clean Heat Emissions Standard

An emissions standard for clean industrial heat could complement and strengthen the effectiveness of financial policies like a clean heat PTC or a carbon price. A clean heat emissions standard would place declining limits on allowable GHG and pollutant emissions from industrial process heat.[111] The standard should be technology neutral, allowing firms to select the most cost-effective and practical energy sources, equipment, and/or processes that comply with the emissions requirements. The standard could incentivize electrification over fuel-switching to low-carbon fuels by excluding emissions associated with purchased electricity from the declining emissions limit (though such a standard should be accompanied by other policies aiming to decarbonize the electricity sector).

To achieve meaningful emissions reductions, the standard should cover heat from both new and existing equipment. The precise timeframes may vary depending on the country and the temperature level of industrial heat produced, given the differences in technological maturity of different heating technologies. For instance, in high-income countries, the emissions limit for most new equipment should decline to zero 10 to 15 years after enactment. Given the long lifetimes of industrial heating equipment, the limit for most existing equipment should decline to zero 30 to 40 years after enactment. The standard should begin declining two to three years after enactment to give firms enough time to invest in new equipment and production lines.



While no major economies have set strict emissions limits on each unit of industrial heat, some indirectly regulate emissions from industrial heat. For example, the EU's Industrial Emissions Directive limits emissions of conventional pollutants from certain industrial installations,[112] and the U.S. Environmental Protection Agency's New Source Performance Standards limit GHG and pollutant emissions from certain new or modified industrial heating equipment.[113]

An emissions standard on industrial heat is more likely to face political opposition than financial incentives for clean heat. Policies like a CBAM that shield firms from negative competitiveness impacts, as well as incentives (of the types discussed above), may increase political appetite for a standard.

Reform Utility Interconnection and Planning

Solutions to increase the clean generation capacity on the grid and enable expedited interconnection of new industrial electrification load will play central roles in enabling long-term industrial electrification growth. We discuss each in turn.

An underutilized approach to increasing capacity on a constrained electricity grid is a novel concept known as surplus interconnection—a process by which interconnection infrastructure already in use can be further leveraged to add more resources. Recent research by the University of California, Berkeley, shows that nearly 1,000 GW of new clean electricity resources could be quickly added to the grid using surplus interconnection.[114] For example, a power plant that is already in operation is typically not running 100 percent of the time. When it is not running, that interconnection tie is not in use. So, if there were additional resources that could use the same interconnection tie, they could provide power to the grid when the original power plant is not running. In the U.S., grid operators are required to allow surplus interconnection under Federal Energy Regulatory Commission (FERC) Order 845, but not every region of the country is taking full advantage of this opportunity.[115]

Relatedly, generator replacement offers another means to fast-track the interconnection of new generation resources. By re-using interconnection infrastructure at retired or retiring power plants for new electricity generation projects, utilities could offer space on the grid for new generators, instead of placing them at the end of the interconnection queue, as is currently the practice in many regions. For example, the U.S. coal fleet is down to 188 GW from its high of 318 GW,[116] and another 80 GW is expected to retire by 2030.[117] While some of these sites have already been re-used, functioning generator replacement processes could free up to 200 GW of interconnection capacity for new electricity generation. Other countries may have similar untapped opportunities.

Adding more transmission capacity faster is another important solution, though building new transmission lines, particularly regional and interregional lines, can take five to fifteen years.[118] Fortunately, grid-enhancing technologies and advanced conductors (aka reconductoring) offer an interim solution to increase capacity on the grid while new lines are being built. Grid-enhancing technologies such as dynamic line ratings and advanced topology control can come online in just a few months, adding up to 30 percent capacity on an existing line.[119] Reconductoring a transmission line with an advanced conductor by replacing the wire while leaving the rest of the line's infrastructure in place can up to double the capacity of an existing line within 18 to 36 months.[120]

Improvements to interconnection processes—wherein grid operators study and approve new resources for interconnection—are another underutilized tool in the toolbox. For instance, most interconnection requests require a detailed study of a new resource's impact on the grid from an energy and capacity standpoint. Processes that prioritize the energy requirements for interconnection while leaving the capacity requirements for broader grid planning, a process known as "energy-only interconnection" or "connect-and-manage," can significantly reduce the costs and timelines for interconnection without compromising grid reliability.[121]

Lastly, proactive grid and transmission planning are a long-term solution to enabling more industrial electrification and ensuring grid infrastructure is built to meet future electricity demand. For example, some studies estimate that transmission systems in the U.S. will need to grow 60 percent from today's levels by 2030 and 300 percent by 2050.[122] FERC Order 1920, finalized in 2024, requires transmission planning regions to improve their regional planning processes, which will require proper enforcement to be effective.[123] States can form transmission authorities, like the New Mexico Renewable Energy Transmission Authority, to aid in the planning and financing of transmission to support other policy goals.[124]

To facilitate expansion of the distribution system to accommodate industrial electrification and minimize the unpredictability of grid upgrade costs, utilities can publish public hosting capacity maps that indicate available capacity at different points on the distribution system. Provided they are developed with accurate assumptions and methodologies, these maps can help inform industrial firms about local grid conditions and the likelihood of a necessary grid upgrade to accommodate an electric upgrade.[125] Utilities can also offer firms coordinated assistance at the planning and design stage of an electrification project, answering questions about existing grid capacity and options to mitigate grid upgrade costs. Regulators can establish directives or incentives that encourage utilities to provide these resources, and industrial customers can engage in regulatory proceedings to highlight the types of information and assistance that would be most helpful.

Where grid upgrade costs cannot always be meaningfully mitigated or avoided, policymakers and regulators should consider adopting mechanisms to spread the costs of grid upgrades fairly among multiple customers, assuming the upgrade will benefit multiple customers. Utilities can either spread costs among groups of

customers looking to increase their load at the same time, reimburse the customer that triggers the upgrade by charging other customers that benefit from it down the line, or socialize the cost of the upgrade through modified line extension policies or temporary incentive programs.

Exit Fee Reforms

Industrial customers seeking to switch from using natural gas to electricity may be liable for costly penalties for breaking a contract with their utility or gas supplier. Sometimes referred to as early termination fees or exit fees, these fees can be a serious financial hurdle locking customers into existing fossil fuel systems. In some places, exit fees are used to cover costs unrelated to the industrial customer, such as debt incurred during extreme weather events.[126] Policymakers may restrict utilities' ability to charge exit fees only to situations where, for instance, the utility previously paid for an expansion of its gas infrastructure to serve an industrial facility, and the facility switched away from gas within 10 years of the system expansion. In such cases, the fee should be limited to the remaining undepreciated value of the assets the utility paid for, and only to the extent those assets provide capacity specifically to serve that industrial customer and not other customers. This issue would benefit from additional research to identify best practices.

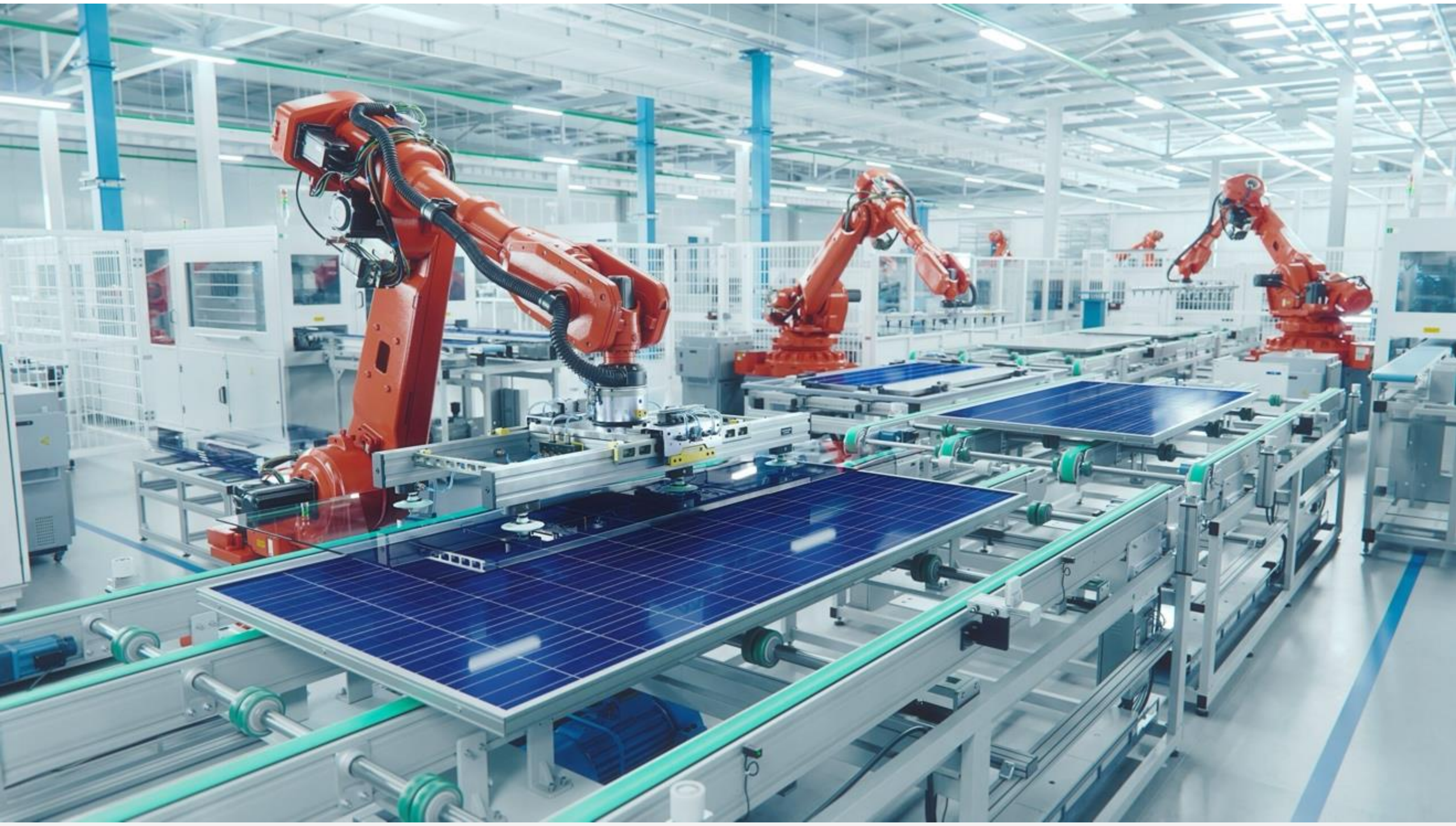
Fund Research, Development, and Demonstration

Research, development, and demonstration (RD&D) policies fulfill a crucial niche among the strategies for growing a decarbonized and electrified industrial sector, as they foster technology development at stages too early to attract sufficient private investment (from the laboratory all the way through early commercial deployment). Government-funded research support has enabled the development of everything from the internet and GPS systems to many vaccines. In the case of solar photovoltaics, U.S. government support in the 1970s, at what would become the National Renewable Energy Laboratory, enabled costs to fall enough that the solar industry eventually became a flourishing global sector.[127]

While government labs and research grants are one route to supporting RD&D, the onus is not solely on governmental agencies. Rather, government labs work best in partnerships with private firms and academic institutions, drawing on rich sources of expertise and market knowledge. Private firms can provide cost-sharing support while receiving favorable intellectual property licensing terms or ownership. For example, the engine manufacturer Cummins has partnered with the U.S.'s Sandia National Laboratories in 50-50 cost-sharing agreements, taking advantage of Sandia's combustion research facility.[128] Clean industrial RD&D can also be supported by climate and energy agencies such as the EU Innovation Fund or the U.S.'s Advanced Research Projects Agency-Energy.

Governments can also help create independent or quasi-independent research organizations that derive most or all of their budget from research partnerships and licensing agreements. Fraunhofer-Gesellschaft in Germany is one such organization, a network of 76 research institutes employing more than 30,000 people with an annual budget of approximately €3.4 billion in 2023. Fraunhofer has produced an array of energy-relevant technologies, such as green hydrogen production equipment and efficient voltage converters.

Support for pilot projects can show that clean manufacturing is financially and technologically viable. In 2024, the U.S. Office of Clean Energy Demonstrations



awarded $6 billion in funding for 33 industrial decarbonization projects, covering the manufacturing of everything from cement and steel to beverages and ice cream.[129]

Ultimately, the resources currently devoted to industrial decarbonization and electrification RD&D by governments are relatively minor, and insufficient to meet our global net-zero goals. Stronger policy support for such efforts is required to develop promising clean technologies that can be cost-effectively scaled in the near future.

Support Workforce Training and Education

A skilled workforce is critical for installing, operating, and maintaining electrified heating technologies. The public sector should play a leading role in developing an electrification-ready industrial workforce, which will increase the effectiveness of industrial electrification incentives and ensure that labor needs are quickly and efficiently met as they arise.[130]

Generally, operating an electrified industrial facility will require a similar amount of labor to operating an emitting industrial facility, and the skills of existing manufacturing workers would often require only minor training to transition to utilizing electrified equipment. This can ease the transition pathway for existing facilities. However, particularly when building a new facility, a firm may need to assess whether there is a gap between existing trade and engineering skills in a region or sector and the skills that will be necessary at the facility.

Governments can help develop a skilled industrial workforce near present or future concentrations of industrial activity. Policies can aim to upskill and retrain existing workers in industries that are projected to scale down (e.g., coal mining) or can provide an education pathway for students at trade schools, community colleges, and universities.

Two categories of policies can work together to expand and upskill the workforce for industrial electrification: direct job training, which provides workers with the skills they need to take on new jobs, and other enabling support, which makes training programs and job opportunities accessible and attractive to workers.[131]

Governments can support direct job training programs outside of the workplace (off-job training) and within the workplace (on-job training). In the realm of off-job training, governments can create or support basic education or vocational programs for students who are interested in industrial electrification. The U.S. Department of Energy (DOE), for example, runs university-based Industrial Training and Assessment Centers that teach energy efficiency and sustainable manufacturing concepts to science, technology, engineering, and mathematics students.[132] As part of their learning process at these centers, students help faculty identify energy- and emissions-saving opportunities at U.S. manufacturing sites. Governments can also support off-job training around soft skills (e.g., language proficiency, time management) that are broadly relevant to all jobs, including industrial electrification jobs.

On-job training can be a strong complement to off-job training, especially for trade and engineering roles.[133] Some governments fund training and certification programs for workers. For example, Australia runs a Vocational Education and Training system

that upskills and reskills workers across a variety of industries,[134] and several DOE programs teach industrial workers how to run energy management systems that reduce facility-level energy use. Another promising approach is apprenticeship programs, which provide structured, hands-on experience under the supervision of skilled workers. While firms and unions are best suited to run these programs, governments can offer funding and technical support to entities that establish electrification-specific programs. Germany, for example, has successfully promoted apprenticeships for a range of manufacturing jobs by covering tuition costs, standardizing curricula for various job types, and ensuring apprentices earn official certificates on completion of their programs.[135] Governments that are funding constrained can indirectly support apprenticeships by supporting pre-apprenticeship programs that prepare students and workers for formal apprenticeships, familiarizing them with industrial electrification work and the relevant skills.[136] Finally, governments can help upskill current industrial workers by providing tools and resources to keep them up to date on new electrified technologies. For example, the DOE's Better Plants and Industrial Technology Validation Pilots programs leverage expertise from federal laboratories to offer tools and educational materials that help industrial facilities adopt new technologies.[137]

Initiatives to upskill people for industrial electrification jobs will only succeed if sufficient jobs are available that will take advantage of students' and workers' new skills, enough people are interested in those jobs, and those individuals have the means to participate in training programs.[138] Governments should therefore implement other enabling policies to make jobs more attractive to workers and training opportunities more accessible to potential workers.

For example, governments can coordinate with private industry to ensure that training program locations and training programs are matched with firms' anticipated needs. Governments can also help make these jobs more attractive to prospective workers by tying incentives and subsidies for industrial firms to minimum requirements associated with the pay and benefits offered to workers. They can also enact laws to protect collective bargaining rights and provide robust social services to remove obstacles to labor force participation (e.g., childcare).

To make training opportunities more visible and accessible to potential workers, governments can publish the relevant information online in a centralized and easy-to-navigate format (e.g., skills taught, relevant job opportunities, logistics, eligibility criteria, application process). In addition to this broad outreach, governments may conduct targeted outreach to—or establish dedicated programs for—individuals who are less likely to seek out industrial jobs on their own. This includes individuals historically excluded from manufacturing jobs and workers who have been displaced in the energy transition.

Create Solutions for Firms that Burn Their Own Byproducts

Policies designed to incentivize electrification of the industrial sector will be ineffective for industries that burn their own byproducts. As such, additional targeted policies are needed to encourage electrification, especially for the refining and forest products industries.

Given that refinery byproducts (RFG and petcoke) are difficult to sell or dispose of safely, refineries must find a way to mitigate GHG emissions from their use. Retrofitting the combustion of these byproducts with CCS would be expensive and impractical at most refineries, given that combustion units and their exhaust streams are typically small and widely dispersed throughout a facility.[139] Therefore, the best option may be to reform RFG into blue hydrogen, since capturing and storing the CO_2 would be easier at a single, centralized steam reformer than at numerous small, combustion sources throughout the refinery. Since refineries require hydrogen for various processes (such as hydrotreating, hydrocracking, and desulfurization), the hydrogen can be used on site, avoiding the need for hydrogen transportation infrastructure. Petcoke can be gasified with carbon capture, producing blue hydrogen, or it can be chemically converted to sellable products such as electrodes or graphene materials.[140]

Governments can invest in RD&D for relevant conversion processes and technologies, either in government labs or through grants to universities and private labs. Once those processes are near commercial-ready, governments can encourage their deployment through a PTC, CCfDs, public procurement, and/or advance market commitments for such products, ensuring that byproduct conversion yields similar economic benefits to byproduct combustion. Once refineries redirect their byproducts away from combustion, policies like a clean heat PTC that aim to make electrified heating cost competitive will be effective.[xxxvi]

Byproducts in the forest products industries can be sold as energy sources for applications that cannot easily be electrified today, such as high-temperature industrial heating and heavy-duty transportation. They can also be used as feedstocks by the chemicals industry to produce building block chemicals such as methanol, olefins, and aromatics.[141] Black liquor can be used directly as an energy source, while wood residues can be transformed into energy-dense wood pellets for easier transportation and sale.[142] Both black liquor and wood pellets can also be gasified to produce syngas, which can be converted into low-carbon fuels and chemicals. Governments can help redirect these byproducts to targeted energy or chemical feedstock applications through incentives and standards that promote clean energy consumption. One example of such a policy is the EU Renewable Energy Directive, which promotes increasing shares of renewable energy (e.g., biomass) in European electricity and heating systems.[143] This policy made Europe the world's largest consumer of wood pellets in 2022, but those pellets were used for low-temperature applications in the residential, commercial, and industrial sectors. Future policies should only incentivize wood pellet usage for high-temperature or chemical feedstock applications where electrification is particularly difficult. To grow clean feedstock use, governments can invest in RD&D for the relevant chemical processes and make advance market commitments to procure the resulting products.

[xxxvi] Refineries that follow this path may still rely on green hydrogen for some of their industrial heat, since the enabling infrastructure will already be present due to the centrality of hydrogen in many refining processes.

CONCLUSION

Direct electrification is the best approach for putting the industrial sector on a fast-track path to reduce harmful climate emissions and air pollutants, increasing energy security while also accelerating technology innovation and evolution of the workforce. The next industrial revolution will hinge on the adoption of thoughtful policy solutions that overcome the known barriers to electrification.

Policymakers should target the solutions best suited to address their specific context and circumstances, but ideally all should start with consideration of the policies designed to overcome economic barriers as summarized in Figure 11.

Figure 11. Policy solutions to overcome barriers to industrial electrification

POLICY SOLUTIONS TO OVERCOME BARRIERS TO INDUSTRIAL ELECTRIFICATION

	Economic Barriers				Grid Readiness Barriers	Technical Barriers
** = depends on policy design*	Differential between fossil fuel and electricity prices	Utility interconnection and disconnection fees	Other costs: capital costs, financing, and soft costs	Use of byproducts as fuel	Interconnection, infrastructure, and planning	Electrification technology maturity
On-grid renewable energy deployment	X				X	
Off-grid renewable energy deployment	X	X			X	
Co-location with carbon-free resources	X	X			X	
Incentives for cleanly manufactured products	X	X*	X*	X*		
Incentives for electrified equipment			X			X
Clean heat production tax credit	X		X*	X*		
Incentives for clean electricity use	X			X*		
Financing tools	X		X			X
Flexible industrial electricity demand	X	X			X	
Time- and location-specific electricity pricing	X				X	
Carbon pricing policies	X					X
Carbon border adjustment mechanisms	X					
Energy efficiency standards			X		X	X
Clean heat emissions standard	X		X			
Interconnection and planning reforms		X			X	
Exit fee reforms		X				
RD&D				X		X
Workforce training and education			X			X
Solutions for firms that burn their own byproducts				X		

Policymakers should prioritize a combination of incentives to increase deployment of renewable and carbon-free electricity (to reduce the cost differential between fossil fuels and electricity) and incentives to encourage clean industry and electrification. Addressing both simultaneously will reduce the near-term and long-term capital and operational costs of electrification. Creative financing tools will help fill market gaps so that industrial firms have access to electrified technologies.

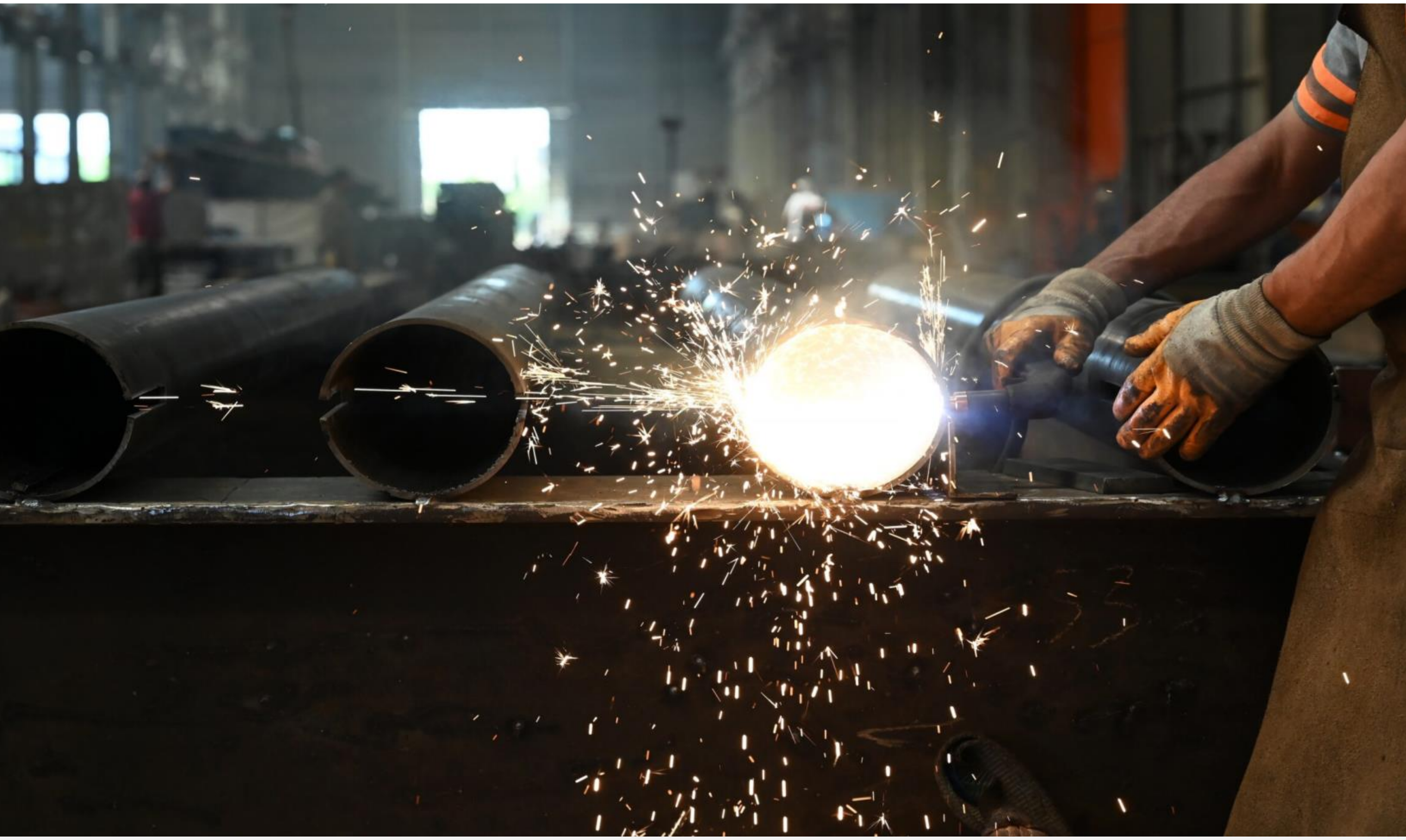
The suite of selected policies should be designed to address and minimize the high price of electricity relative to conventional fuels. Three types of policies can reduce the energy price premium for electrified processes: (1) policies that increase the supply of low-cost clean energy (e.g., renewable portfolio standards, incentives for off-grid renewables); (2) electricity tariff reforms (e.g., time- and location-specific rates); and (3) policies that reflect the full costs of fossil fuel combustion (e.g., carbon pricing).

Policies to improve grid readiness are another essential element of an industrial electrification policy package. They are especially important given that EVs, building electrification, and data centers are collectively poised to impose an unprecedented increase in electricity demand in many countries. Policies to encourage greater energy efficiency (e.g., energy efficiency standards) and flexible industrial demand (e.g., time- and location-specific rates) combined with interconnection and grid planning reforms can reduce the electricity demand on the grid, while also optimizing industrial electric loads and reducing the costs for other ratepayers. Policies to expand and modernize the grid are also crucial but outside the scope of this report. Clean heat emissions standards can help level the playing field for industrial electrification technologies over time, allowing them to compete with fossil fuel alternatives.

All policy approaches should include foundational RD&D policies and workforce training and education—necessary to ensure the technologies' continued evolution and to support the people charged with their effective deployment and maintenance. RD&D policies can help to commercialize nascent electrification technologies, and pilot projects and demonstrations can yield technology cost and performance improvements across different geographies and jurisdictions. Wherever the political and budgetary appetite for RD&D investment exists, it should be targeted to high-temperature electrified technologies that can address a large portion of industrial emissions, such as thermal batteries, electric steam crackers for chemicals production, plasma torches for cement making, and electrolytic steelmaking technologies.

Many of these policies can be pursued in tandem but sequencing them can maximize their chances of success. Policies to narrow the price premium for electricity should be the top priority, followed by policies to cover the remaining cost premium and address other economic barriers. Since industrial electrification will grow steadily over time, policies to boost grid readiness should be given sustained attention as economic incentives begin to shift the market from early adopters to more widespread uptake. While RD&D policies need not be as carefully timed, early-stage technologies often take multiple decades to reach the market, so earlier RD&D investments are likely to yield greater benefits than later ones.

Industrial electrification can create high-paying jobs and support economic development, while bolstering grid reforms that benefit other economic sectors. Ultimately, there is no one-size-fits-all policy package for electrifying the industrial sector, as each industry and region has its own challenges and priorities. These policy options offer a starting point for those interested in revitalizing and modernizing their region's industrial base.



APPENDIX

Industrial Context: China

Manufacturing accounted for 61 percent of China's total energy-related CO_2 emissions in 2021, with nearly three-quarters of that industrial energy demand consumed for process heating.[144] This is almost entirely supplied by fossil fuels such as coal, coke, and natural gas, and represents approximately 20 percent of global energy-related CO_2 emissions (around 6.7 $GtCO_2$).[145] Four industries make up around 90 percent of China's industrial heat energy demand: ferrous metals (iron and steel), chemicals, non-metallic minerals (cement and glass), and petroleum refining and coking. Iron and steel and cement production require very high temperatures, and temperatures above 1,100°C account for 34 percent of the country's industrial heat energy demand.[146]

The National Development and Reform Commission (NDRC) is the primary governmental body for electricity and renewables decision-making. Two state-owned utilities provide most of the country's power: China State Grid and China Southern Grid. China has its own market-tradable renewable energy certificates for tracking generated renewable energy, Green Energy Certificates.[147] China's voluntary carbon market has its own China Certified Emission Reduction certificates managed by the Ministry of Ecology and Environment, while the Green Energy Certificates are issued by the National Energy Administration under the NDRC.[148]

Most manufacturing is in populous eastern provinces of China where little surplus renewable electricity is available. Meanwhile, eight western and northwestern provinces host nearly half of China's wind and solar capacity but contribute only around 12 percent of the country's GDP.[149] To balance these geographic supply and demand problems, China needs to expand its inter-provincial electricity trading, which in 2022 accounted for only 12 percent of electricity sales, primarily in the form of long-term contracts as opposed to dynamic transactions to aid in grid rebalancing.[150] China launched a pilot inter-provincial spot power trading program in 2023, with plans to expand nationally by 2030.[151]

Electricity cost is a central challenge to industrial electrification in China, where industrial entities pay 40 percent more than residential customers.[152] Electricity costs the average industrial firm 635 yuan/MWh ($93.6/MWh), compared to coal at just 134 yuan/MWh ($19.8/MWh) and natural gas at 337 yuan/MWh ($49.6/MWh). Despite this hurdle, industrial heat pumps are still cost competitive with fossil fuel alternatives in China[153] and could meet up to 15 percent of the country's industrial heat demand.[154] Greater scrap recycling in electric arc furnaces has a role to play in cutting fossil fuels from China's iron and steel industry, while industrial thermal batteries could be cost-effective at supplying high-temperature industrial heat up to 1,700°C.[155] This is due in part to the considerable price swings in intraday grid electricity pricing in China, especially in populous provinces such as Guangdong and Shandong; a July 2021 policy aimed for a ratio of four-to-one between peak and valley prices.[156] Industrial firms equipped with thermal batteries would be able to purchase grid electricity at just 34 percent of the cost they would pay if drawing on electricity evenly throughout the day.[157]

Industrial Context: United States

Manufacturing in the U.S. increased rapidly with industrialization in the late 19th century, with manufacturing making up roughly a third of all non-farm jobs by 1910 and peaking at 39 percent in 1944 (driven by World War II).[158] Since then, there has been a steady decline in manufacturing's share of the U.S. economy, as the country re-oriented toward services, finance, and technology.[159] In 2024, just 8 percent of U.S. non-farm jobs and 10 percent of value added (contribution to GDP)[160] came from manufacturing, a smaller share than in 1870.[161]

The U.S.'s largest industrial energy users are chemicals and refining, accounting for 43 percent and 21 percent of non-feedstock industrial final energy use in 2022 respectively.[162] The next highest industries are pulp, paper, and printing (9 percent); food, beverage, and tobacco (6 percent); and iron and steel (5 percent), with no other subindustry consuming more than 2 percent. Chemicals and refining dominate the U.S. industrial mix because they rely on petroleum and natural gas as fuels (burned for energy) and feedstocks (transformed into output products like gasoline or plastics). These energy sources are comparatively inexpensive in the U.S. due to the country's large reserves and the dramatic expansion of unconventional oil and gas extraction (using techniques such as hydraulic fracturing and horizontal drilling) since 2010.

Certain regulations limit industrial firms' environmental impacts. Notably, the Environmental Protection Agency has statutory authority to set limits on the emissions of certain pollutants from large industrial facilities, which are often required to monitor and maintain records of their emissions. Non-compliance may result in fines or other penalties. In some cases, new industrial facilities may be required to conduct environmental impact assessments to obtain permits.

The Inflation Reduction Act, enacted in 2022, sets forth numerous policies designed to stimulate a clean industrial renaissance and attract businesses to build new factories and facilities in support of the clean energy economy. The law has supported over $600 billion in investments and created more than 400,000 jobs.[163]

Industrial Context: European Union

The EU is home to a large share of global industry, accounting for nearly 15 percent of the global industrial sector's added value in 2021.[164] European industry generated 492 million metric tons of CO_2 in 2022, making it the third-highest emitting sector of Europe's economy.[165] It also consumes 23 percent of the EU's final energy, nearly half of which is used for process heating.[166] Only 4 percent of European industry's process heat is electrified today, with nearly three-quarters of it coming from the combustion of natural gas, coal, and other fossil fuels.

The most fuel-intensive subindustries in Europe—iron and steel, chemicals, and non-metallic minerals—rely heavily on high-temperature heat.[167] Still, a significant portion of their process heat is under 500°C and can be electrified with commercially available technologies, including 40 percent of process heat in the iron and steel industry, over 70 percent in the chemicals industry, and nearly 20 percent in the cement industry. Moreover, a large portion of process heat in the chemicals, food and beverage, and plastics and rubber industries can be electrified with highly efficient heat pumps.

The European electricity market is liberalized and fully interconnected, with significant cross-border energy flows.[168] EU-level rules coordinate electricity generation, distribution, and storage across the Union, while member states implement those rules via direct regulation of national electricity markets, whose structures vary. EU-level rules reflect Europe's commitment to climate neutrality by 2050, codified by the EU Green Deal that all member states approved in 2019.[169]

Downstream from that target is an ETS that caps allowable emissions of GHGs from various entities, including all industrial firms by 2034.[170] Additional policies include a CBAM to protect ETS-covered industrial firms from foreign competition, as well as directives that mandate clean energy deployment, energy efficiency interventions, and reductions in industrial emissions.[171] Moreover, EU policymakers are currently pursuing electricity market reforms that would encourage industrial electrification, such as through long-term renewables contracts, dynamic electricity pricing, and demand-response programs.[172]

The Green Deal also requires EU's 27 member states to develop national strategies and policies to achieve EU climate targets.[173] Several countries have their own carbon taxes on top of the ETS, and some have established dedicated incentives for industrial decarbonization. For example, Germany's CCfD program covers the operating cost premium for green technologies via bespoke contracts between the national government and firms, and Denmark runs a $500 million funding pool for the acquisition and installation of industrial decarbonization technologies.[174] Many countries have also banned, or are planning to ban, certain fossil fuel-fired heating equipment.[175]

Industrial Context: India

As India rapidly industrializes, it relies on both fossil fuels and clean energy to meet its skyrocketing energy demand.[176] Coal, oil, and natural gas each accounted for 46 percent, 24 percent, and 5 percent of the country's total energy supply in 2022, respectively, and India does not plan to reach carbon neutrality until 2070, far later than any other major emitter.[177] However, nearly half of its electricity generation capacity comes from renewables, and its corporate renewable energy procurement market is highly developed.[178] Industrial electrification in India is therefore possible, but important barriers do stand in its way.

India's industrial sector emitted 607 million metric tons of CO_2 in 2022 and is on track to become the country's highest-emitting sector by 2040.[179] This is mainly due to its reliance on coal, which is expected to nearly double by 2040.[180] India's highest-emitting subindustry is iron and steel, as most iron is made in coal-fired blast furnaces and direct reduced iron furnaces. Rather than switch to green-hydrogen-based direct reduced iron and scale up electrified steelmaking (which already represents half of Indian steelmaking), India's government plans to scale up coal-based ironmaking in the coming decades.[181] India also has a vast informal industrial sector, accounting for 97 percent of the country's industrial enterprises, 71 percent of its industrial workers, and 40 percent of its gross value added from industry in 2016.[182] The informal manufacturing of products like bricks, basic metals, textiles, and food products also relies heavily on coal, and it created around 105 million metric tons of unreported CO_2 emissions from on-site fuel combustion in 2015 and 2016.

Grid management challenges are another barrier to industrial electrification in India. India has one unified, national grid that is overseen by the prime minister.[183] Various federal ministries manage and finance energy generation, and they also set broad policies around issues like electricity tariffs, market structures, transmission, and grid security. States enforce those policies and manage intrastate electricity generation, transmission, and distribution. Federal and state regulators are facing a variety of challenges, including lagging infrastructure investments that have made power outages a daily or weekly occurrence for most customers, as well as financial and planning setbacks due to uncertain electricity supply and demand. Moreover, industrial customers face electricity tariffs that are around 70 percent higher than those of residential and agricultural customers.[184]

If Indian industry is to electrify in the coming decades, the government must amend national strategies that seek to expand coal-based equipment and pursue policies that incorporate all industrial activities into the formal economy. Additionally, as rising economy-wide electricity demand continues to strain India's grid, off-grid renewables may play an important role in electrifying Indian industry, especially given existing federal subsidies and bonds for renewable installations.[185] Facilities that do remain grid-connected can deploy industrial thermal batteries to offer much-needed flexibility to the grid. Finally, India's forthcoming national carbon market will bring fossil fuel prices closer to the high electricity prices that industrial customers face.[186]

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