CLEAN INDUSTRIAL HEAT: A TECHNOLOGY INCLUSIVE FRAMEWORK

C2ES CENTER FOR CLIMATE AND ENERGY SOLUTIONS

by

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INTRODUCTION

While greenhouse gas emissions from the industrial sector have declined over the last 20 years, they are projected to increase through mid-century, fueled by low prices for energy, particularly natural gas and natural gas liquids.[1] Under a business-as-usual scenario, the sector is expected to become the largest source of greenhouse gas emissions in the United States over the next ten years.[2]

Decarbonizing the industrial sector is generally considered more technically challenging than in the building and transportation sectors, as it concerns emissions not only from heat and power but also from products and processes. The wide range of diversity among its subsectors—including manufacturing, mining, and construction—only adds to the decarbonization challenge. Additionally, implementing decarbonizing policies in an internationally competitive sector is economically challenging, but doable.

This brief focuses on the challenge of heat for the industrial sector. Worldwide, heat makes up roughly three-quarters (74 percent) of energy demand for industry and accounts for more than one-fifth of total (all sectors) global energy consumption.[3] Today, most industrial heat production comes from the combustion of fossil fuels; 45 percent is produced using coal, 30 percent with natural gas, 15 percent with oil, and 9 percent with renewable energy.[4]

In order to fully decarbonize the United States economy by mid-century, it will be necessary to find ways to reduce heat energy-related emissions from the industrial sector. However, doing so presents many challenges. Many industrial processes require sustained levels of heat that are difficult to generate physically and economically without burning fossil fuels.[5] This is a cross-cutting problem across multiple sectors. Solutions for industrial heat will have wide ranging applications, helping to decarbonize the entire economy.

Industry needs heat energy to produce a vast array of products— from ordinary household goods to steel for building structures and car parts. Making certain materials like metals, cement, and glass requires temperatures greater than 1,100 degrees C (2,000 degrees F). About half of industrial heat is used for low- or medium-temperature processes (below 400 degrees C or 750 degrees F), while the other half is used for high-temperature processes.[6] There are also a range of technical heat requirements such as maintaining constant temperatures (i.e., low heat flux) for production.

This brief presents several pathways that can enable large-scale deployment of clean industrial heat. First, it identifies the scale of the industrial emissions challenge, focusing on heat-related emissions from industrial processes. Next, it defines a clean heat technology-inclusive approach and the criteria needed for success. Then, it lays out rationale of why technology-inclusive strategies make sense, and evaluates the strengths and weakness of technologies. Then, it highlights current demonstration projects, followed by key insights from interviews with members of the C2ES Business Environmental Leadership Council (BELC) and the Renewable Thermal Collaborative (RTC). Finally, it provides recommendations for developing a technology-inclusive approach to decarbonizing industrial heat.

UNDERSTANDING THE CLIMATE CHALLENGE OF HEAT

Direct emissions from industry are responsible for about 22 percent of global carbon dioxide emissions.[7] About 40 percent of this (equivalent to roughly 10 percent of total global carbon dioxide emissions) comes from industrial heat production (**Figure 1**).[8] In the United States, about 43 percent of industrial emissions (i.e., direct and indirect emissions) come from burning fossil fuels to produce heat or steam.[9]

Industry uses heat for many diverse processes including hydrocarbon cracking (i.e., refining), ore reduction, drying, washing, cooking, sterilizing, preheating boiler feed water, and other process heating applications (**Table 1**). High-temperature heat is required for processes such as converting iron ore to metallic iron to produce steel (1,200 degrees C), and the calcination of limestone to produce cement (1,400 degrees C).[10] Low- and medium-temperature heat is often produced using boilers in other less energy-intensive industries. A broad collection of clean heat strategies will be needed to address these emissions.

Even though the industrial sector is diverse with many unique processes, many lower-temperature sub-industries can make use of an expanding array of cleaner heat technology pathways. Though these technologies are technically available, most are not cost-effective or commercially available and are not yet being adopted.

BOX 1: Key Insights

- The industrial sector is on track to become the largest emitting sector by 2030; industrial heat-related emissions from fossil fuel combustion are substantial.
- Heat needs vary across industries; many clean solutions are needed.
- Clean heat solutions exist for low- and medium-temperature applications, still there are challenges with cost-effectiveness, fuel availability and providing steady, uniform temperatures.
- Fewer clean thermal pathways exist for high-temperature processes; greater investment is needed to demonstrate solutions, lower costs and make them accessible.
- Companies need more tools to reduce their emissions; expanding clean thermal technologies can help them set heat-related emission reduction goals and undertake tangible actions sooner.
- Taking a portfolio-based, technology-inclusive approach can support all technologies, wherever they are on their development timeline, and reduce the risk of not having viable, affordable, and accessible clean heat solutions available in order to tackle climate change.

On the other end of the spectrum, medium- and higher-heat sub-industries will require unique solutions, not yet commercially or technically available.

TECHNOLOGY INCLUSIVE APPROACH

A technologically-inclusive approach includes all clean heat sources, clean fuels, and promotes electrification of heating (using only non-emitting electricity sources) to the largest extent possible. Additionally, this approach makes use of carbon, capture, utilization, and storage (CCUS) technology because not all industrial heat-related activities can easily or pragmatically be reinvented before mid-century, and there are also process emissions (during product conversions), regardless of the heat source, that must be captured. For a technological-inclusive approach to be successful, effective clean heat solutions must exist for every industrial need. As a practical matter, these solutions must become more affordable over time, so they can be widely deployed in order to fully decarbonize the global economy.

Solutions must exist

To meet a range of specific industrial requirements and reduce climate impact risk, it is pragmatic for policymakers to adopt a portfolio or technology-inclusive approach to clean heat. An inclusive, diversified approach can increase optionality and substantially reduce the risk of not having technological solutions available. Historically, it can take years for a technology to become mature or commercially available; investments (public and private) in many promising clean technologies are needed immediately to accelerate development and realize the emissions benefits as soon as possible.

Costs and competitiveness

Industry has multiple heat needs and stringent cost needs. To help address cost concerns, a portfolio approach that supports all technologies, wherever they are in their development timeline is needed.

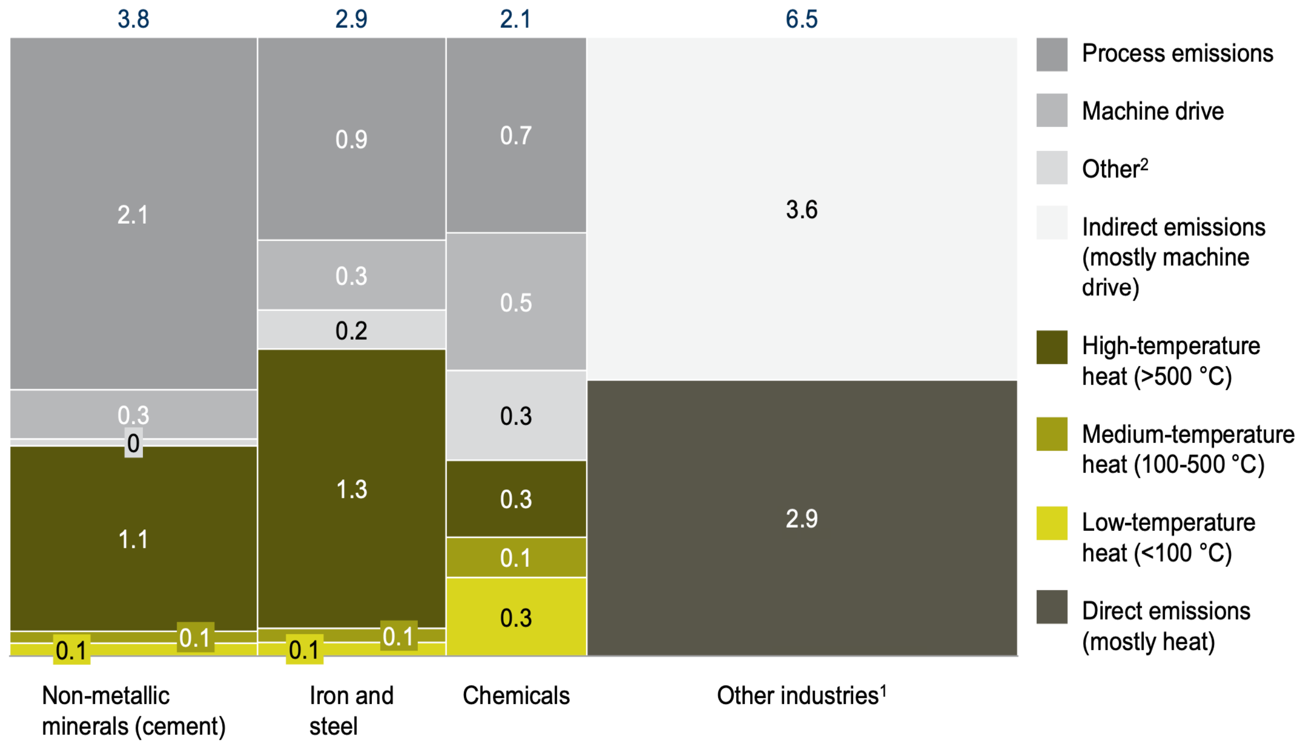
Clean heat technologies currently exist but are not widely deployed for a host of reasons. For example, deploying cleaner technologies might require building new facilities, disruptive retrofits (affecting production), or purchases of costly new equipment. Since the industrial sector is highly competitive (domestically and internationally) with tight profit margins, the relatively low cost of maintaining the current (polluting) technologies is a major factor influencing business decisions related to industrial heat. Also, there are only a few jurisdictions in the United States where there is a cost (i.e., price on carbon) for polluting. So, there is little financial incentive for facilities to migrate to cleaner heat technologies. And, for well-established industrial processes, there is a perceived risk or bias around technologies that are not already widely deployed or accepted.[11]

For high energy-intensity, high-temperature, large industrial emitters (e.g., petroleum refining, metal making, cement, petrochemicals, glass and ceramics), clean heat alternatives are not readily available. Here, research, development (i.e., innovation) and demonstration projects are needed to make cleaner heat pathways accessible and dramatically reduce emissions. In the interim, many companies are working to improve current process efficiency and procuring clean electricity, whenever possible.

There are also valid concerns from companies about international competitiveness (i.e., foreign competitors) and carbon leakage that must be addressed. National industrial decarbonization policies (e.g., carbon pricing) can impact companies' ability to maintain market share and reduce their profits, particularly when their overseas competitors do not face the same costs.[12] Another source of competition is coming from some forward-thinking governments (i.e., European Union) that are already investing in decarbonizing industry, and U.S. companies risk falling behind. Additionally, carbon leakage, wherein industrial production is displaced from one country to another (along with any associated emissions) is a concern. Shifting production (and associated emissions) to other countries is not a climate solution.[13] For example, increasing imports and/or decreasing exports of energy-intensive industries (e.g., steel) in Organization for Economic Cooperation and Development (OECD) or developed countries is often offset by an increase in production in countries with less stringent climate policies.[14] Policy can be designed to anticipate these dynamics and help domestic industries transition to lower carbon products and processes.[15]

Innovation is already happening in many areas, including from clean heat sources, clean fuels, and the electrification of heating. Reducing the cost of these technologies and creating a wide variety of viable options will enable industry (in the United States and globally) to deploy clean heat solutions in all circumstances and achieve our climate goals.

FIGURE 1: Billion metric tons of carbon dioxide per year, per emission source, 2014



Note: 40 percent of global industry emissions are related to fuel combustion for heat.

[1] Includes food and tobacco, construction, mining, machinery, nonferrous metals, pulp and paper, transport equiptment, textiles and leather, wood and miscellaneous industry.

[2] Includes emissions related to electrochemical processes, process refridgeration and cooling, and all emissions from non-process energy use, such as on-site transport and facility HVAC.

Source: McKinsey & Company, Decarbonization of Industrial Sectors: The Next Frontier, 2018.

CLEAN THERMAL PATHWAYS

Since all technologies have technical, cost, and feasibility challenges, a technology-inclusive approach makes sense. There are no one-size-fits-all solutions; each clean heat technology has its strengths and weaknesses. For example, there are commercial technologies available at reasonable costs that offer a free fuel source such as solar thermal. However, solar thermal has temperature, geography, land use, and intermittency constraints. Other technologies such as advanced nuclear can reach temperatures of around 850 degrees C, which is not high enough for traditional steel, cement or glassmaking, and has public acceptance issues to overcome. However, nuclear is capable of providing consistent temperatures around the clock in any geography.

As noted earlier, about 43 percent of U.S. industrial emissions (direct and indirect) come from burning fossil fuels to produce heat or steam.[16] Indirect emissions are the result of electricity generated offsite, transported to, and consumed by industry. The U.S. electric power sector has become significantly cleaner since 2005; as a result, indirect emissions attributable to the industrial sector have fallen 39 percent.[17] Therefore, finding ways to increase the amount of electricity used for heating (i.e., electrification of heat) is a logical pathway to reducing heating-related emissions.

Ostensibly, electrifying all industrial heat consumption (using only clean electricity sources) seems like a reasonable endeavor. However, total electrification of industrial heat would require a huge transformation and major upgrades to electrical transmission and distribution infrastructure. In 2019, total U.S. electricity generation was 4,127 billion kWh (or around 15 EJ). At the same time, the industrial sector consumed 10,268 billion cubic feet of natural gas (or around 11 EJ).[18] Total or even significant electrification of industrial heat would require unprecedented upgrades to the U.S. electricity grid to be able to handle such a huge load increase. A recent report from the National Academies of Science, Accelerating Decarbonization of the U.S. Energy System, recognizes this challenge and notes the importance of CCUS for developing low- zero- and carbon-negative fuels, as well as transitioning to low-carbon heat sources to decarbonize industry, among other things, where industrial processes cannot be practically electrified.[19]

In order for industrial companies to transition to lower emissions, clean heat substitutes must be available that not only function as well as their existing emitting sources, but they must do so at a reasonable cost. Clean thermal pathways must be capable of achieving the range of temperatures demanded by each industrial process. The temperature required depends on the nature of the process; it can exceed 1,400 degrees C (2,500 degrees F) for industries such as steel and cement. However, two-thirds of process heat used in U.S. industry is for applications below 300 degrees C (572 degrees F) (**Figure 2**).[20] In the food, beverage, tobacco, transport equipment, machinery, textile, and pulp and paper industries, the share of heat demand at low- and medium-temperatures is about 60 percent of the total heat demand.[21] Additionally, maintaining uniform temperatures is critical for many industrial processes; clean heat alternatives that are capable of maintaining steady temperatures (i.e., low heat flux) are highly advantageous.[22]

Substitution of cleaner, lower carbon fuels like biomass and biofuel, hydrogen, renewable natural gas, and carbon dioxide-derived synthetic hydrocarbons can significantly lower or eliminate heating-related emissions, particularly when they are coupled with CCUS. Furthermore, adoption of clean heat sources like solar thermal, geothermal and nuclear can significantly contribute to industrial decarbonization (**Figure 3**).[23]

This brief identifies the full range of technologies capable of providing clean heat for low-, medium-, and high-temperature applications. The opportunities and challenges for clean heat sources, clean fuels and the electrification of heat are discussed in greater detail in the following section. The ability of industrial companies to adopt these technologies and transition to cleaner heat will depend on a number of factors (i.e., technological, economic, social and political), including cost competitiveness, scalability, and public acceptance, among other things.

Clean heat sources

Solar Thermal

Currently, the only solar thermal technology capable of producing temperatures high enough for industrial processes is concentrated solar power (CSP).[24] Typically, CSP involves the use of mirrors or lenses to focus sunlight onto a receiver (e.g., a tube filled with a working fluid), which absorbs the resulting energy. This energy can then be used to heat water and produce steam, turning a turbine and generating electricity, or the heat generated can also be used directly for industrial processes.[25]

Opportunities

While solar power has typically been unable to generate heat at the temperature levels required for the most energy-intensive industrial processes, new approaches by companies like HelioGen have been able to achieve generation of temperatures up to 1,000 degrees C. Thus, with future development, CSP technology could be used to power most industrial processes. Low operating and fuel costs could make CSP more economically viable than other heat generation options.[26] To some extent, the intermittency problem inherent to solar energy can be mitigated through the use of storage technologies, such as molten salt storage.[27]

Challenges

Concentrated solar power has very specific climatic requirements for its use. These include high levels of direct solar radiation, low rainfall and cloud cover, and access to groundwater resources for cooling purposes. These requirements impose significant geographic constraints on where CSP technologies can be deployed.[28] Like other solar power technologies, CSP must rely on sufficient energy storage capacity to ensure reliable delivery of energy in periods where the sun is not shining. The technology used for energy storage for CSP is molten salt thermal storage. This is only able to hold temperatures up to 560 degrees C, making it unsuitable for use in higher-temperature processes. Even with the use of molten salt storage, CSP's energy output would still be subject to a degree of seasonal variability, e.g., a higher sun angle and longer light duration provides more energy per hour during the summer.[29]

TABLE 1: Assessment of Clean Heat

INDUSTRY SUB-SECTOR	REPORTED CO_2 EMISSIONS [MMT-CO2E]	INDUSTRY PROCESS-HEAT TYPE/PURPOSE	PROCESS HEAT TEMP (C)	AVERAGE PLANT HEAT USE [TJ/DAY]*
Petroleum Refineries: Gasoline, Diesel, Kerosene	124	Combustion gases/atmospheric crude fractionator and heavy naphtha reformer	600	8.23
Iron and Steel Mills	51	Combustion gases/coke production	1,100	2.42
		Combustion gases/steel production	1,700	
		Electricity/steel production	2,200	
Paper Mills	32	Steam/stock preparation	150	21.1
		Steam/drying	177	
Paperboard Mills	24	Steam/stock preparation	150	21.1
		Steam/drying	177	
Pulp Mills	12	Combustion gases/electricity production	800	0.67
		Steam/wood digesting, bleaching, evaporation, chemical preparation	200	1.15
		Steam/evaporation, chemical preparation	150	2.56
All Other Basic Chemical Manufacturing	21	Combustion gases/primary reformer; Steam/methanol distillation	900	12.9
Ethyl Alcohol Manufacturing	18	Combustion gases for steam/byproduct drying (corn dry mills)/pretreatment and conditioning (lignocellulosic processes)	266	1.76
		Steam/distillation	233	
		Steam/electricity production	454	
Plastics Material and Resin Manufacturing	17	Steam/distillation	291	10.6
Petrochemical Manufacturing	16	Combustion gases/cracking furnace	875	2.37

INDUSTRY SUB-SECTOR	REPORTED CO_2 EMISSIONS [MMT-CO2E]	INDUSTRY PROCESS-HEAT TYPE/PURPOSE	PROCESS HEAT TEMP (C)	AVERAGE PLANT HEAT USE [TJ/DAY]*
Alkalies and Chlorine Manufacturing, Chlorine, Sodium Hydroxide	13	Steam/drying	177	4.26
Nitrogenous Fertilizer Manufacturing	8	Combustion gases/primary steam reforming	850	7.03
Wet Corn Milling, Starch, Corn Gluten Feed, Corn Gluten Meal, Corn Oil	18	Steam/steeping	50	8.06
		Steam/drying	177	
Lime and Cement, Lime, Cement	10	Combustion gases/heating kiln	1,200–1,500	12.45
Potash, Soda, and Borate Mining	6	Steam/calciner, crystallizer, and dryer	300	26

The National Renewable Energy Laboratory (NREL) compiled greenhouse gas, process heat temperature, and average plant heat consumption data for fourteen key industries with the highest annual emissions.

*Note that 1 terajoule (TJ) is roughly equal to the energy consumed (i.e., jet fuel burned) by a 737 aircraft on a transatlantic flight.

Source: U.S. EPA GHG Reporting Program, The National Renewable Energy Laboratory.

Geothermal

Geothermal technology accesses heat generated naturally beneath the Earth's surface. This heat can be carried to the surface through water or steam, and can then be used for heating, cooling, or generating renewable electricity.[30] In the United States today, geothermal capacity (i.e., 2.5 GW) is used primarily for electricity.[31]

Opportunities

Geothermal is a highly reliable source of energy, as it is not affected by seasonal or weather changes. It requires no fossil fuels and, depending on the plant type, produces up to one-sixth the carbon dioxide of a similarly sized (i.e., by energy output) natural gas power plant.[32] Typically, geothermal power plants make use of dry steam or hot water wells between 150 degrees C and 370 degrees C. The current level of geothermal energy use remains far below the technical potential worldwide. A recent U.S. Department of Energy report found that geothermal energy capacity could increase by as much as 26 times by 2050.[33] Finally, advanced drilling technologies developed for the oil and gas sector can be applied to help bring down the costs of geothermal.

Challenges

While cleaner than many other forms of energy production, geothermal energy is not entirely free of environmental consequences. The removal of steam from reservoirs and the return of water from power plants may cause subsidence and tectonic instability, resulting in earthquakes.[34] As mentioned above, geothermal energy also results in carbon dioxide emissions, albeit at a lower level than fossil fuels. It also results in emissions of other gases, such as sulfur dioxide and hydrogen sulfide.[35]

Geothermal energy also faces obstacles to become cost-competitive with other forms of energy. While investment in geothermal might pay off over time, high up-front costs present a major barrier to adoption of the technology.[36] Location is also a constraint to where geothermal energy can be economically deployed. Tectonic hot spots are the only locations where high-temperature heat can be easily extracted. However, geothermal energy can be accessed virtually anywhere on Earth with the capability of drilling deep enough or using milder heat closer to the Earth's surface.[37]

Nuclear

Nuclear power is responsible for the largest amount of zero-carbon heat produced in the world today, and the largest producer of nuclear power is the United States. If new nuclear plants could be co-located with industrial facilities (i.e., combined heat and power), they could provide enough heat to power certain industrial processes.[38]

Opportunities

As a highly energy dense source, nuclear has a very small land footprint. Small modular reactors (SMRs and advanced fission reactors have the potential to generate temperatures up to 850 degrees C. This is more than twice the level produced by existing nuclear power plants and creates opportunities for nuclear to be used for low- and medium-temperature process heat.[39] Several SMRs and advanced reactor designs will be deployed in the next five to ten years. Newer reactor designs are inherently safer and create far less waste than the current generation of nuclear plants.[40] Existing nuclear reactors, some of which are economically challenged, could generate non-power related revenue by producing hydrogen (through thermochemical or high-temperature electrolysis of water) for industrial heat, transportation, energy storage, and other purposes.[41]

Challenges

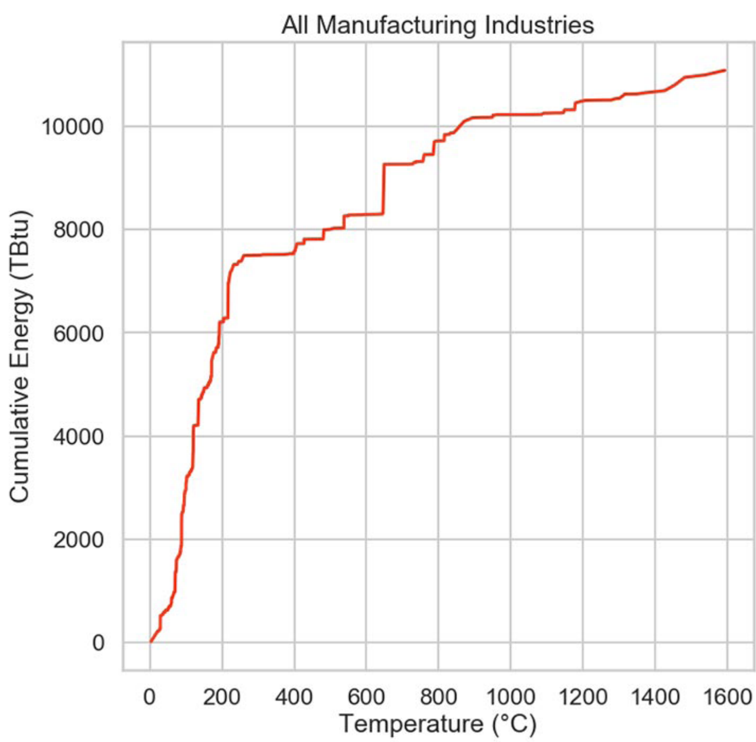
Heat generated by conventional nuclear reactors cannot achieve temperatures that are high enough for many industrial processes. However, future advanced nuclear technologies will be able to generate heat at much higher temperatures.[42] Yet these first-of-a-kind plants remain relatively expensive and more than five years away from first deployment. Nuclear power continues to face social issues; it will be difficult to gain public acceptance for positioning new reactors close to factories and populations. Additionally, critics of nuclear technologies contend that even new reactors do not adequately address safety, proliferation and waste storage issues.[43] Existing nuclear plants are also struggling to stay open due to declining energy market revenue, driven by persistently low natural gas prices and declining costs of renewables.[44]

Clean fuels

Hydrogen Combustion

Hydrogen is a naturally plentiful resource, but in order to be harnessed for energy it must be separated from other elements, which can create greenhouse gas emissions. Most hydrogen today is extracted from natural gas through a process called steam methane reforming.[45] There are multiple ways to produce hydrogen, but the

FIGURE 2: Cumulative process heat demand in the United States by temperature, 2014



Source: The National Renewable Energy Laboratory, Solar for Industrial Process Heat Analysis, 2019.

two most promising new methods are "blue" hydrogen and "green" hydrogen. Blue hydrogen refers to hydrogen produced by steam reforming of natural gas, combined with CCUS to prevent carbon dioxide emissions. Green hydrogen is produced using electrolysis, powered by clean sources of electricity like wind, solar, hydro, and nuclear (sometimes referred to as "pink" hydrogen), to extract hydrogen from water (i.e., using an electrolyzer). While green hydrogen relies on clean electricity in order to be a zero-carbon option, both technologies have the potential to produce a clean (i.e., producing only heat and water as byproducts), combustible gas capable of reducing industrial heat-related emissions.[46]

Opportunities

Excess clean electricity, or curtailed production of renewable or nuclear power, could be used to power electrolysis, the process of breaking down water molecules into hydrogen and oxygen.[47] Thus, hydrogen could effectively be used to store energy that would otherwise have been wasted. Hydrogen is also capable of producing extremely high temperatures (up to 2,800 degrees C) when combusted, enough for any industrial process.[48] To reduce emissions, hydrogen can be safely blended with natural gas and transported in existing natural gas pipelines at low concentrations, between 5 and 15 percent hydrogen by volume.[49] With many industrial facilities already consuming large quantities of natural gas, hydrogen blending offers a meaningful decarbonization pathway.

Challenges

Current methods of hydrogen production are very carbon-intensive, meaning that it must be produced with CCUS or by using electricity from clean sources before it can be useful for decarbonization.[50] Challenges exist with scaling production of green hydrogen, particularly around designing cost-effective and durable electrolyzers. Additionally, storing and transporting hydrogen can be challenging. Because its molecules are small, leakage can be a problem. Therefore, systems (i.e., pipelines, storage containers) need to be specifically designed for hydrogen, as it readily reacts with materials including metals, causing embrittlement and cracking. To encourage much greater use of hydrogen (i.e., blending beyond 20 percent), a dedicated, purpose-built pipeline network (e.g., similar to the current natural gas network) will likely be needed to deliver the gas to industrial (and other) consumers. A rigorous examination of the impact of hydrogen blending on the existing U.S. natural gas infrastructure is just commencing.[51] As of 2019, 20 percent of natural gas pipelines can already transport hydrogen with minimal adjustments needed.[52] Additionally, there are higher barriers to utilizing hydrogen for steel and cement production than in other subsectors, as it would require redesigning plants constructed with the use of fossil fuels in mind.[53] Hydrogen like other gases, e.g., natural gas or propane is also highly combustible and can present a safety risk. Finally, hydrogen burns invisibly, and is both colorless and odorless, making leak detection difficult.[54]

Biomass and Biofuel Combustion

Biomass is wood, waste and other organic material that is burned to produce heat and electricity.[55] Biofuels like ethanol and biodiesel are produced from biomass materials and can be blended with traditional fuels or consumed on their own.[56] Biofuels have the ability to produce temperatures up to 2,200 degrees C when burned, more than enough for most industrial processes, and biomass (i.e., wood chips) can reach temperatures up to 1,100 degrees C (**Figure 3**).[57] While burning biomass does produce carbon emissions, it can be a net-zero source (with proper land use practices) because the feedstocks remove carbon dioxide from the atmosphere as they are grown.

Opportunities

Biodiesel has the ability to produce heat up to 2,200 degrees C, enough for almost any industrial application.[58] As a liquid, biofuels can be transported easily via truck, rail or pipeline without upgrades to traditional equipment (i.e., that currently ships liquid fossil fuels). Because biomass can be a carbon-neutral energy source, it also has the potential to become carbon-negative through the use of CCUS technology.[59] Unlike many other potential clean heat technologies, the biomass industry is already mature, with a market capable of transporting biomass over long distances.[60] For example, the United States is the largest exporter of wood chips with nearly all shipments bound for Europe.[61]

Challenges

Similar to fossil fuels, biomass releases carbon dioxide when burned. However, the feedstocks for biomass absorb carbon dioxide from the atmosphere, meaning that the carbon dioxide released in combustion was already in the natural carbon cycle, as opposed to fossil fuels dug up from underground geological formations.[62] Biofuels can be a low-carbon fuel source, but they have the potential to result in greenhouse gas emissions if the production of biomass causes changes in land use.[63] There is also variability in emissions from different biomass feedstocks; depending on the net greenhouse gases emitted across the entire life cycle, the biomass conversion process may be considered carbon neutral, carbon negative, or carbon positive. Crops grown for biomass can also compete for land with food crops, which can result in an indirect increase in net emissions if, for example, this results in deforestation.[64] Finally, biofuels can oxidize and degrade, depending on how they are produced and stored; additives can be used to prevent breakdown and increase stability.[65]

Carbon Capture, Utilization, and Storage (CCUS)

Because of its ability to decarbonize fossil-intensive sectors and generate net-zero or net-negative emissions, CCUS will be necessary for achieving full decarbonization by mid-century.[66] CCUS is a proven technology for reducing industrial emissions; it allows for decarbonization without altering underlying industrial processes, when new, lower emission processes can be challenging to devise. CCUS can be used to capture carbon dioxide from industrial processes and fossil fuel combustion (used for heating and/or electricity), and then either permanently stored or used to produce other carbon-based products. Commercial-scale projects exist in the industrial sector for hydrogen (derived from natural gas) production, fertilizer production, and ethanol production.[67] Carbon capture technology will likely be essential for decarbonizing the power sector by eliminating emissions from firm, dispatchable fossil fuel plants. When combined with bioenergy, CCUS can even result in negative emissions by effectively removing carbon dioxide from the atmosphere on a lifecycle basis.

Opportunities

CCUS is one of the clean heat technologies that is most ready for wide-scale deployment today.[68] Tax credits for carbon capture technology, such as Section 45Q of the U.S. tax code, have made deployment of these technologies more financially viable.[69] CCUS is particularly important for decarbonizing the industrial sector, as chemical reactions that occur in manufacturing processes (e.g., steel and cement) produce carbon dioxide.[70] In the absence of CCUS, completely new processes for these industries must be devised and deployed by mid-century.

Challenges

Electricity inputs required for carbon capture mean that low- or zero-carbon electricity is necessary for CCUS to be a viable way to reduce emissions. Another challenge associated with CCUS is that it requires investment in capital-intensive infrastructure assets. Creating a network of pipelines connecting sources of carbon dioxide to locations where it will be utilized or stored will cost hundreds of millions of dollars to appraise, build, and develop.[71] In addition to cost, there are also safety concerns associated with carbon dioxide transport and storage. Also, emission reductions currently have little to no value in most markets. And, although CCUS technologies are well established, there is often a perceived risk due to the limited application in most industries. These concerns can limit investment in CCUS projects.

Electrification of Heating

Electrification is the process of introducing electricity (to power or heat) in the first instance or as a substitute for other technologies. Electric arc furnaces, used in the steel industry for decades, are probably the largest and most well-known example of electrical heating. Also, electricity is used for extracting pure aluminum from alumina, an intermediate oxide, created from bauxite—a naturally occurring ore that is mined. However, a number of nascent technologies are emerging as potential ways to electrify industrial processes, including resistance heating, infrared heating, microwaves, and induction. When the electricity is generated by clean energy sources, it can provide a fundamentally clean source of heat.[72]

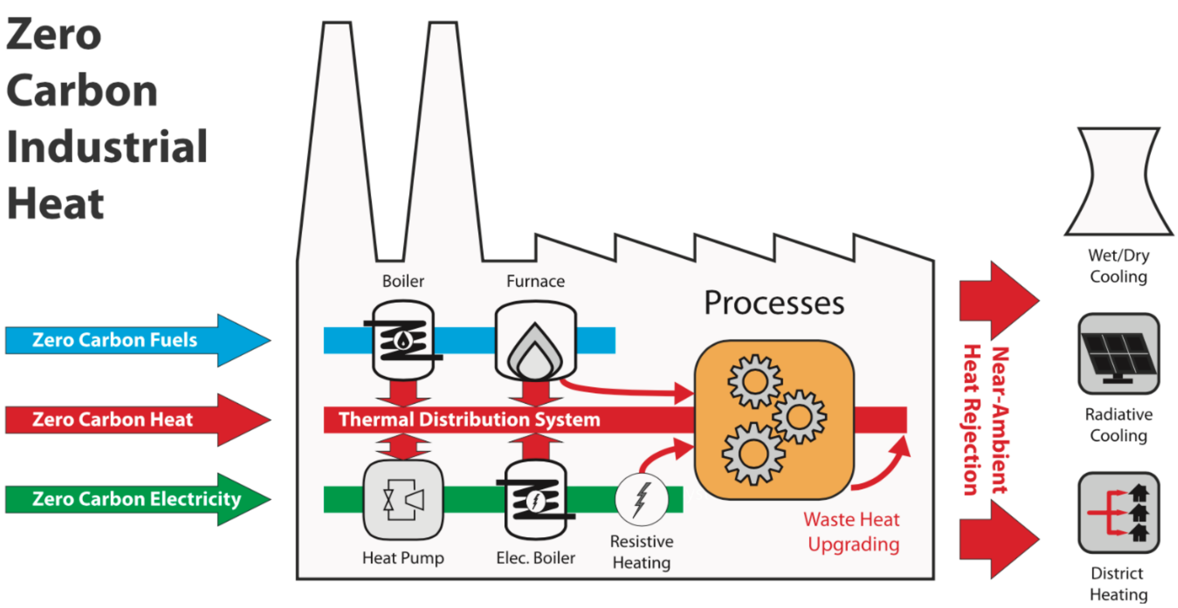
Opportunities

The transition to cleaner electricity sources in the power sector is creating a resource for a low-emission source of heat for industrial decarbonization. With costs of renewable electricity and energy storage declining and with appropriate support for existing nuclear and hydropower, it may be possible to mostly decarbonize electricity generation at a reasonable cost within the next two decades.[73] Notably, total electricity generation must increase to support a significant increase in electricity consumption from industry and other sectors, e.g., transportation and buildings. If clean electricity prices drop below those of fossil fuels, electrification could actually save industries money in the long term.[74] A key advantage of electrical heating systems are their greater ability to control the exact temperature levels compared to traditional, combustion-based process heating techniques.[75] Electric resistive heating is capable of reaching temperatures of 1,800 degrees C.

Challenges

An increase in electrification will require a significant build-out of power sector infrastructure and put heavy demands on the electricity grid.[76] There will be social resistance (i.e., NIMBYism) and lengthy environmental reviews for new projects, though infrastructure projects related to all clean heat sources and clean fuels will face this challenge as well. Additionally, the carbon footprint of electrification can vary widely depending on factors such as fuel sources and approaches to addressing resource variability.[77] Seasonal and regional variation of renewable energy resources present challenges to electrification in the absence of sufficient energy storage and other sources of firm capacity.[78] Furthermore, some geographies naturally have more favorable conditions for wind and solar energy, so widespread deployment of these technologies will require much greater high-voltage power transmission capacity. Therefore, the costs of electrification could be prohibitively high in some regions relative to fossil fuel combustion without some form of policy intervention.[79] Finally, the use of electricity as a heating source can be expensive, and it must be continuous in order to maintain the necessary temperature (e.g., aluminum production).

FIGURE 3: A schematic representation of technologies to enable zero-carbon industrial heat



Source: Thiel and Stark, To decarbonize industry, we must decarbonize heat, 2020.

TABLE 2: U.S. Industrial Sub-Sector Emissions and Heat Use

PATHWAYS	STREGNTHS/ OPPORTUNITIES	WEAKNESSES/ CHALLENGES	MULTI-SECTORAL APPLICATIONS	COSTS & READINESS
CLEAN HEAT SOURCES				
Solar thermal	• Clean heat source • Zero fuel cost	• Intermittent source • Large land footprint • Limited temperature range • Geographically constrained	• Limited to low-temperature applications	• Mature technology • R&D required for high-temperature applications
Geothermal	• Dispatchable heat source • No fuel costs • Small land footprint	• Challenging drilling depths • Induced seismicity • Low-level carbon emissions	• Very limited applications	• High up-front costs • R&D required to evaluate the potential and access to high temperature
Nuclear	• Dispatchable energy source • Zero-emissions associated with energy generation • Very small land footprint	• Limited temperature range	• Limited to low- and medium-temperature applications	• High up-front costs • RD&D required for advanced nuclear technologies
CLEAN FUELS				
Hydrogen	• Zero-emissions when combusted • Can be stored for long periods • Can attain very high temperatures; suitable for use in most industrial applications	• By-product CO2 from methane reforming • High costs and heat demand of electrolysis • Significant infrastructure is needed	• High potential for use in all economic sectors	• Relatively high production costs. • R&D necessary for transport and combustion stability and control.
Biomass and biofuels	• Lower carbon-intensity than fossil fuels • Biofuels can attain very high temperatures; suitable for use in most industrial applications	• Changes in land use • Limited quantities of biomass and biofuels • Limited temperatures for biomass	• Flexible feedstock for multi-sectoral applications	• Relatively low production costs • Mature industry
OTHER				
CCUS	• Allows decarbonization without altering industrial processes • Can capture process emissions in addition to heat-related combustion emissions	• Requires retrofits • Depends on limited carbon markets or the prospects of carbon pricing • Limited by lack of infrastructure (i.e., pipelines) • Limited by availability of viable geologic storage sites.	• Suitable for multi-sectoral applications, especially in energy-intensive industries	• Requires investments in capital-intensive infrastructure assets
Electrification	• Can be zero-emission energy source, depending on the electricity mix	• Depends on availability of clean electricity • Requires major upgrades in the grid	• Hard to adopt in energy-intensive and high-temperature applications	• Significant infrastructure upgrades will be required, especially for energy-intensive applications

CURRENT DEMONSTRATION PROJECTS

With a large variation in potential costs, challenges, and uncertainties, it is necessary to pursue a portfolio of clean thermal technologies for industrial heat decarbonization. Demonstration projects are one tool used to gain a better understanding of technology costs and the time horizons for achieving clean energy targets. Going through the real-world project management exercise of learning-by-doing can help identify technology hurdles, areas where further basic research is required, and many other areas for improvement, which can significantly drive down the cost of subsequent projects. Successful demonstrations build confidence in the industry, enhance understanding of materials and supply chain needs, and help with future financing and policy design. Notably, the track record for estimating the costs of future technology is mixed; experts can wildly overestimate costs and the time frame for achieving desired environmental goals. For example, sulfur reduction technologies at power plants proved, within a few years, to be ten times cheaper than experts predicted shortly before sulfur emission trading began.[80]

Lessons from the following (see below) three demonstrations in high-temperature, hard-to-decarbonize industrial sub-sectors (i.e., steel, cement, and chemicals) should help focus policymaker's attention on many of the remaining hurdles to making these products with far fewer greenhouse gas emissions.

STEEL

The global steel company SSAB joined forces with LKAB (Europe's largest iron ore producer) and Vattenfall (one of Europe's largest energy companies) to create HYBRIT—an initiative that endeavors to revolutionize steelmaking.[81] The HYBRIT technology aims to replace coking coal, traditionally needed for ore-based steelmaking, with fossil-free electricity and hydrogen. The result will be the world's first fossil-free steelmaking technology, with virtually no carbon footprint. The initiative is expected to reduce Sweden's carbon dioxide emissions by 10 percent and Finland's by 7 percent. The project is currently at the pilot plant trials stage. Commercial volume plant trials are scheduled by 2025 and the production of fossil-free steel is expected by 2026.

Another public-private partnership is already producing zero-carbon steel in the United States. Utilizing technology developed at MIT with support from NASA and private funders, Boston Metal devised a method for making emissions-free steel using molten oxide electrolysis (MOE).[82] With additional funding from the Department of Defense, Department of Energy, and the National Science Foundation the company is expanding beyond laboratory-scale production into the metals market.[83]

CEMENT

LafargeHolcim is partnering with Svante Inc. (a provider of carbon-capture technology), Oxy Low Carbon Ventures (OLCV is a leader in carbon management and storage), and Total to assess the viability and design of a commercial-scale carbon-capture facility at the Holcim Portland Cement Plant in Colorado.[84] The project has received a $1.5 million grant from the U.S. Department of Energy to research and develop a cost evaluation of the facility designed to capture up to 725,000 tons of carbon dioxide per year directly from the cement plant, which would be sequestered underground permanently by OLCV. The project is expected to actively capturing and sequestering carbon by 2024.

CHEMICALS

BASF has a Carbon Management Research and Development (R&D) Program through which they are developing technologies that focus on decarbonizing base chemical production, which accounts for 70 percent of the emissions of the chemical industry.[85] These solutions include hydrogen production and developing the first ever electric heating concept for steam cracking.[86] If steam cracking could be powered with electricity from renewable sources rather than natural gas, the carbon dioxide emissions from the process could be reduced by 90 percent.[87]

COMPANY INTERVIEWS

C2ES interviewed five industrial companies with a wide range of heating needs to assess how they are thinking about reducing emissions from their processes. Companies are concerned about climate change and are looking at many options for reducing emissions. With regard to industrial heat, they find that all current solutions have technical, economic or feasibility challenges. Broadly, companies want policy to help solve these issues. The following is a summary of how these companies are thinking about clean thermal technologies, emission targets, and related policy, among other things.

COMPANY CONSIDERATIONS ON TECHNOLOGIES

Currently, there is a lot of focus on industrial energy efficiency. All of the companies interviewed are looking at their existing production processes and assessing where they can make improvements.

Unsurprisingly, costs are a key consideration. Projects that have positive returns on investment and short payback periods have higher rates of implementation. One example of this type of projects is harnessing heat from existing processes (i.e., heat recovery) and using it productively, rather than letting the heat escape into the ether.

Additionally, fuel availability, proximity to renewable thermal sources, and transportation are essential concerns for companies. For example, the quantity of commercial renewable natural gas supply is a key concern. For one high-temperature industrial company, renewable natural gas is not only a lot more expensive than natural gas, but it would not qualify as a viable option due to the enormous quantities that they currently consume.

Interestingly, one lower- to medium-temperature manufacturer looked into electric boilers as an alternative to natural gas boilers and determined that power infrastructure was a real hurdle. Their utility would not be able to supply all of the additional electricity they calculated that they needed. Presumably, significant infrastructure upgrades could overcome this challenge.

Greenhouse gas targets

Companies have set a variety of emissions reductions targets to achieve decarbonization goals. A clean heat technology-inclusive approach can help increase this ambition by commercializing new solutions, reducing the costs of new and existing technologies such that they can be realistically planned for, implemented and deployed.

An emerging trend for companies (including those in high-temperature industries) is setting a net-zero carbon emissions goal, often with a target date of 2050. These companies have typically focused on reducing overall emissions without specifying how much reductions are associated with heating and cooling needs. High-temperature companies noted that solutions are just not yet commercially or readily available for them to attach any material goals to. Though, no interviewed company has established a specific thermal-related emissions reduction target. Some company goals may have a manufacturing or energy efficiency focus, while others may call out renewable electricity as part of the goal. Companies are demonstrating a willingness to reduce their emissions over the next several decades, but also state a need for flexibility in how they meet their targets and a desire for commercial-ready technologies to abate their fossil fuel footprints.

Communicating clean thermal transition internally and externally

Within companies, sustainability conversations on greenhouse gas emission reductions have largely focused on addressing emissions from electricity and not from thermal sources. Heating and cooling emission footprints are still a relatively new part of internal discussions. So, there is a critical need to educate different business units in order to gain traction on cleaner thermal initiatives. Additionally, there is a need for sustainability and commercial teams to communicate internally and align incentives that consider both business growth and emission reduction opportunities.

Externally, companies consistently expressed the importance of public perception and reputation regarding the technologies used at their facilities. Public education about how a company will implement potential new heat-related technologies is important to the project development process to ensure positive engagement with the community. This may include a thoughtful outreach strategy to educate the public on the environmental and economic benefits of the new technology.

Technology Availability and Attributes

Companies were concerned with availability of cleaner fuels like biomass and renewable natural gas. Are there commercial-scale quantities available? Is there resource adequacy, i.e., do substitutes perform as well as the fossil fuels they replace? And, how close, i.e., what is the proximity of these resources to our facilities? There was also a temporal component to these questions, i.e., what is the present situation and what will supplies look like in the future?

In the case of biomass, this means ensuring a consistent supply of wood products capable of providing a guaranteed amount of thermal energy (i.e., load). For solar thermal, companies need to factor in how intermittency in solar radiation will affect operations. Intermittency is a challenge with implementing new clean thermal projects since many companies still depend on a fossil fuel-based back up energy source to avoid process interruption. For renewable natural gas, companies expressed a need for that supply to be sited near a biomass feedstock.

CCUS may be the most viable option for high-heat industries, since it can help alleviate many of the concerns raised above. However, companies expressed degrees of hesitation with CCUS regarding lack of infrastructure and other issues, (i.e., pipelines, carbon utilization, and geological sequestration near facilities).

Energy Assessments at Facilities

As a starting point for assessing heating needs, several companies conducted energy audits and pinch analyses, a technique for analyzing how heat flows throughout an industrial process.[88] These activities have informed companies how to optimize their energy use (e.g., heat recovery projects), who also expressed the need to measure and benchmark current energy consumption prior to assessing new technology installations. Other assessments include investigating opportunities to improve energy efficiency and implement heat recovery, a relatively low cost and developed method of using heat from a variety of equipment throughout an industrial facility. Companies have also considered electric boilers as a heating alternative to fossil fuel sources, but in some cases found the facility's local utility would not adequately provide the needed electricity for the process.

Manufacturing Process Modifications

Companies have varied approaches on how to modify industrial processes at their facilities, and this represents a major barrier to implementing clean heat solutions.

Depending on the manufactured product(s) and company practices, there may be limited flexibility in how facility modifications can occur. Some companies find it challenging to adopt a process change since it may have to be instituted worldwide at facilities producing similar products. Therefore, process modification presents challenges for companies aiming to do a pilot project or make one-time changes; they also need to think broadly about how to scale up alterations across global locations, which have varying degrees of clean thermal resource availability and adequacy (or no access to them at all).

Policy

While a more in-depth analysis on how policy approaches can further accelerate clean thermal are discussed in the RTC's paper Low-Carbon Renewable Thermal Technology Solutions, companies expressed the importance of supportive policies at the local, state, and federal level and the crucial role they can play in enabling clean thermal technologies.

The price of incumbent fossil fuels for heat and electricity are an essential part of internal decision making and a higher price for natural gas or coal can incentivize the switch to cleaner alternatives. Companies expressed support for both internal and external carbon pricing. Internal carbon pricing can demonstrate renewable thermal investments' value to senior leaders within companies while also potentially providing a capital investment fund that can be used towards sustainability-oriented projects across an organization.

Other supporting policies that help accelerate clean thermal technologies include a thermal renewable energy credit, or T-REC, low carbon fuel standards, local and regional financial incentives, and both biomass quality and greenhouse gas accounting standardization. In the case of CCUS, a lowering of the carbon capture threshold could expand eligibility for more industrial facilities to benefit from tax incentives such as 45Q.

Finally, since companies typically operate across different regulatory regimes, policy environments can drastically vary depending on location. Some regions and states allow more flexibility in their permitting which can accelerate a company's ability to implement new technologies, while others require substantial time and monetary investments to institute changes (if allowed at all).

Costs

Companies often discussed how costs were a key consideration in whether a clean thermal project was implemented, and how both policy and overall project economics can satisfy ideal conditions for a project to be greenlit. One tool to assess a project's costs and benefits are to evaluate its net present value, or NPV. Projects that demonstrate a positive NPV have typically moved forward, especially ones with a shorter payback period which allows companies to recuperate on their investments faster. Other cost considerations include factoring in the opportunity costs of disrupting manufacturing processes and the lost revenue associated with such capital investments.

RECOMMENDATIONS/TAKEAWAYS

The industrial sector is on track to become the largest emitting sector by 2030. As industrial demand continues to expand, more and better clean heat substitutes for current emitting technology are needed.

Clean heat solutions currently exist for low- and medium-temperature applications, but there are challenges with fuel availability, intermittency, geography and public acceptance, among other things. Low-carbon fuels like biomass, renewable natural gas, and other biofuels are good substitutes, but their quantities are limited, and costs are high relative to fossil fuels. Finding new ways to produce these fuels, increasing production and distribution, reducing costs, and providing incentives to consume them can help to reduce heat-related emissions. Similarly, expanding use of clean heat sources like solar thermal, geothermal, and nuclear can help. These clean heat sources face challenges too, but they need similar support to expand the options available for reducing industrial emissions.

Clean thermal pathways exist for high-temperature processes, but greater investment is needed to lower costs and make them accessible. High-temperature processes are responsible for one-third to one-half of industrial heat-related emissions and they must be fully addressed in order to mitigate the effects of climate change. Hydrogen, and CCUS are very promising, and nuclear and geothermal power could be significant too.

Companies have an important role to play in helping to decarbonize the global economy. With regard to heat, it is clear that companies need more options and tools. Expanding the available clean heat pathways can encourage companies to adopt clean thermal emission targets. Policy at all levels is necessary as well, incentivizing companies to become cleaner sooner. And, policies must be designed to anticipate competitiveness and carbon leakage issues. Policies should be inclusive, supporting the advancement of all promising clean heat technologies. Policies that can support clean industrial heat technologies are investigated in more details in a companion policy-focused paper that presents recommendations for the needed regulatory and financial support for clean heat.[89]

Taking a portfolio-based, technology-inclusive approach will reduce the risk of not having viable, affordable, and accessible clean heat solutions available. For some industrial sub-sectors, CCUS may offer the best pathway to decarbonize heat-related (and process) emissions. Additionally, while renewable energy will play a substantial role in deploying clean thermal heat, it will not be able to provide solutions at all temperatures and in all global geographies. A timely transition away from uncontrolled fossil fuel combustion for industrial heat is required. A technology-inclusive approach is likely to provide the quickest, most economical solution to help avoid the worst effects of climate change.

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