CLEAN HEAT PATHWAYS FOR INDUSTRIAL DECARBONIZATION

C2ES CLIMATE INNOVATION 2050

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Achieving net-zero emissions will require large scale change across all sectors of the economy, and efforts to drive this transition are intensifying. Over the past several years, through the Climate Innovation 2050 initiative, the Center for Climate and Energy Solutions (C2ES) has engaged closely with leading companies across diverse sectors to examine challenges and solutions to decarbonizing the U.S. economy by 2050. As we laid out in *Getting to Zero: A U.S. Climate Agenda*, reaching net-zero will require this large-scale change, but it will also require us to address a number of discrete and urgent challenges. To inform policymakers considering these near- and long-term questions, C2ES launched a series of "*Closer Look*" briefs to investigate important facets of the decarbonization challenge, focusing on key technologies, critical policy instruments, and cross-sectoral challenges. These briefs will explore policy implications and outline key steps needed to reach net-zero by mid-century.

EXECUTIVE SUMMARY

Most heat energy industry uses today comes from fossil fuel combustion, accounting for about 10 percent of global carbon dioxide emissions. In the United States, the industries using the most heat include petroleum refining, paper, chemicals, cement, and steel. Unless industries change course, U.S. industrial emissions are expected to rise significantly by mid-century. Identifying and deploying clean heat solutions will be essential.

As with combustion emissions in any sector, the options for reducing heat-related emissions from industry involve either shifting to cleaner fuels, capturing emissions, or minimizing the amount of energy needed. Cleaner fuels could potentially include electricity, biomass and biofuels, hydrogen, renewable and synthetic natural gas, nuclear, solar, and geothermal. The addition of carbon capture and storage could capture emissions from industrial facilities. Energy demand reduction measures could include energy efficiency, process changes, recycling and reuse, and product or material substitution. There are pros and cons related to all of these options, including with respect to heat characteristics (e.g., the ability to reach

the temperature levels needed in different industries) and commercial readiness (e.g., cost, availability, necessary infrastructure).

Policy interventions are needed to drive faster development and adoption of clean heat technologies. Necessary policies include:

- **Innovation:** additional investment in research, development, and demonstration of clean heat technologies (particularly ones that could be used in the highest-emitting sectors), as well as expanded pilot programs and improved access for businesses to the technical expertise in the national labs
- **Deployment:** tax incentives and technical assistance to overcome cost-competitiveness challenges and perceived risks in deploying less established technologies
- **Carbon pricing:** a price signal to the market that would make clean heat technologies more cost-competitive, while giving industries the flexibility and time to find opportunities to innovate
- **Standards and regulations:** measures to drive or require the industrial sector to produce a certain amount of its heat from clean energy sources
- **Competitiveness:** measures, such as border carbon adjustments, to protect the global competitiveness of American industries adopting clean heat technologies.

To-date, industrial decarbonization has been largely overlooked by policymakers. Instead, the focus has been on electric power and transportation, driving the deployment and adoption of technologies that are enabling significant emission reductions in those sectors. As policymakers turn their attention to industry, reducing thermal-related emissions offers an important opportunity to not only decarbonize the sector, but also to drive innovation and boost economic competitiveness.

INTRODUCTION

Industry needs heat energy to produce a vast array of products—from ordinary household goods to the steel that goes into buildings and cars. 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.[1] 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.[2] These high temperatures are required for the production of certain materials (e.g., metals, cement, glass) and can exceed 1,100 degrees C (2,000 degrees F).

Worldwide, heat represents roughly three-quarters of industry's energy demand, and industrial heat accounts for more than one-fifth of total (all sectors) global energy consumption (**Figure 1**).[3] Roughly 10 percent of total global carbon dioxide emissions comes from industrial heat production.[4] In the United States, about 43 percent of total industrial emissions (direct and indirect) comes from burning fossil fuels to produce heat or steam.[5]

In order to fully decarbonize the economy by mid-century and potentially avert dangerous impacts from climate change, it is necessary to find ways to reduce heating-related emissions from the industrial sector.[6] However, doing so presents many challenges. Many industrial processes require levels of heat that are physically and/or economically difficult to generate without burning fossil fuels. Some energy-intensive industries are also vulnerable to competition from other countries, making it difficult to impose regulations on them without driving the industries, and the jobs associated with them, abroad.[7] Still, there are a number of technologies with the potential to dramatically reduce emissions produced by industrial heat production, including: switching to lower-carbon fuels; capturing emissions through carbon capture, utilization, and storage (CCUS); transforming industrial processes; and making industrial processes more energy efficient.

This brief first provides an overview of the current status of industrial heat in a range of sectors. It then lays out the key criteria for evaluating or characterizing clean heat technologies and describes some of the challenges and opportunities presented by clean heat technology options. The brief concludes with recommendations for a suite of policies that can provide a pathway to reducing emissions from industrial heat.

CURRENT STATUS OF INDUSTRIAL HEAT IN KEY SECTORS

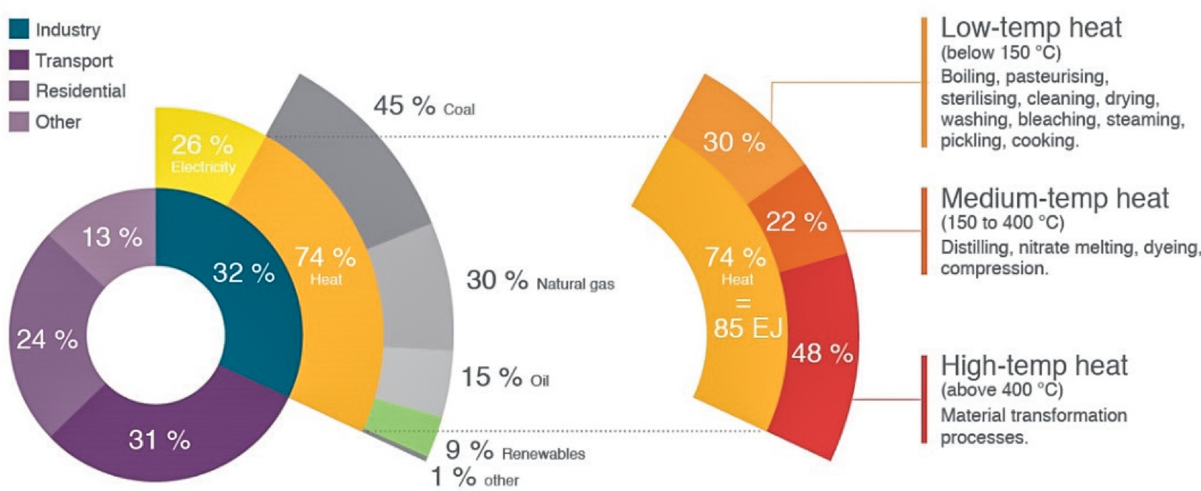
According to data compiled by the National Renewable Energy Laboratory (NREL), the industries using the most heat in the United States include petroleum refining, paper, chemicals, cement, and steel (**Table 1**).[8]

In 2019, the industrial sector consumed 26.3 quadrillion Btu (quads), or 35 percent of total U.S. energy consumption.[9] Under a business-as-usual scenario, industrial energy consumption is projected to grow to 35.7 quads by mid-century, however this growth is not equal across subsectors.[10] The fastest-growing industrial subsector in the United States through 2050 is expected to be bulk chemicals.[11] Energy consumption in the paper industry is also expected to increase 11 percent by 2050, while energy consumption in the iron and steel industry is expected to decrease by 19 percent, and cement and lime emissions are expected to remain flat.[12]

Importantly, there are differences in how each industrial subsector produces and uses heat. For example, petroleum refineries heat crude oil using still gas, petroleum coke, and natural gas to separate it into a range of hydrocarbon products, such as gasoline, diesel, and aviation fuel.[13] The cement industry most commonly uses coal to achieve the required temperatures (around 1,400 degrees C) to heat calcium carbonate in cement kilns.[14] The paper industry typically burns natural gas and black liquor to generate heat for its production processes.[15] The majority of iron ore-based steel is produced with basic oxygen furnaces, using coking coal to produce heat, while electric arc furnaces, which generate temperatures up to 1,600 degrees C by running an electrical charge through electrodes, are used to produce new steel from scrap metal.[16] The bulk chemicals industry—which, unlike many other industries, produces a wide variety of materials and products using different methods—uses numerous fuels for heat, including natural gas and other hydrocarbons.[17]

All told, around 90 percent of direct energy consumed by the U.S. industrial sector comes from fossil fuels—a number that has changed little over the past 40 years.[18] In spite of increasing U.S. consumption of natural gas (up 34 percent since 2005) and decreasing use of coal (falling from 10 percent to 5 percent share) and petroleum (down nearly 7 percent), emissions have remained relatively flat in the sector. While carbon intensity has fallen, total primary energy consumption by the industrial sector has increased 8 percent since 2005. A business-as-usual scenario therefore will not lead to sector decarbonization; indeed, emissions are expected to rise 15 percent by mid-century.[19]

FIGURE 1: Share and Breakdown of Global Industrial Heat



Total global energy consumption (all sectors) is depicted in the circle on the left-hand side. Global industry energy consumption is 26 percent electricity and 74 percent heat.

Source: Renewable Energy for Industry, International Energy Agency

TABLE 1: Industrial Sub-Sector Emissions and Heat Use

INDUSTRY SUB-SECTOR	REPORTED CO_2 EMISSIONS [$MMTCO_2E$/YR]	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
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 Steam/drying	50 177	8.06
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

*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.[1]

Source: U.S. EPA GHG Reporting Program, National Renewable Energy Laboratory (NREL)Highlighted industry actions

CRITERIA FOR EVALUATING CLEAN HEAT TECHNOLOGIES

Identifying clean heat solutions is critical to reducing emissions from industry and the entire U.S. economy by mid-century. In assessing clean heat technologies, it is important to consider at least four criteria: (1) heat characteristics; (2) commercial readiness; (3) emission reduction potential; and (4) applicability across sectors. Some of these criteria are of particular relevance to companies or industries looking for solutions, while others are more relevant to governments looking to incentivize or support research and development of solutions.

- **Heat characteristics:** Perhaps the most obvious characteristic in considering potential clean heat sources is whether they can reach the temperatures needed in any given subsector. The industries listed in **Table 2** have varying heat requirements, ranging from very low to extremely high (see also **Table 1** above).[20] Different energy sources can reach different levels of heat (**Figure 2**). In addition to attaining specific temperatures to create a variety of products, the temperatures must be maintained consistently over time. As heat is consumed in an industrial process, temperature reduction occurs, so additional energy must be continuously added to maintain a constant temperature. Furthermore, for economic purposes, most facilities operate both around the clock and throughout the year, which means energy sources have to be available at all times and through all seasons.
- **Commercial readiness:** Clean heat solutions already exist for low- and medium-temperature applications. In general, for high-temperature heat, fewer clean technology pathways exist and they are further away from commercial readiness. Some clean heat solutions (e.g., renewable natural gas and solar thermal) are technologically ready to deploy now (at least in some applications), while others are still in development. Technology challenges include producing and transporting sufficient commercial quantities to where they will be consumed. Solutions also vary in how cost-effective they are—and thus how economically ready they are to be deployed. Solutions that are technologically and economically ready to deploy now will be of the greatest value; after all, it is important not just to get to net-zero emissions by mid-century, but to limit the total amount of emissions between today and 2050.
- **Emission reduction potential:** It will be impossible to get industrial emissions to zero without commercially ready clean heat solutions for all temperature applications. Overall, there are fewer industries (and far fewer total facilities) that require high temperature process heat. But, implementing clean heat technology solutions that reduce or eliminate emissions from the highest-emitting facilities (typically, but not always high-temperature industries, see **Table 2**) will have a high impact (i.e., greater emission reduction potential) in advancing decarbonization. Still, two-thirds of process heat used in U.S. industry is for applications below 300 degrees C (572 degrees F).[21] Though, globally it is around 50 percent (**Figure 1**). There are more industries (point sources) that have

low- and medium-temperature heat requirements. And, though there are commercial readiness challenges, there are more technologies capable of providing clean low- and medium temperature heat. Implementing lower temperature, smaller facility individual solutions have a lower emission reduction potential than higher temperature, large facility clean heat solutions.

- **Applicability across sectors:** Generally, the more widely a technology can be utilized across sectors—also known as sector coupling—the greater its value in advancing decarbonization. For example, hydrogen can be used in mobile fuel cells for vehicles and in stationary fuel cells for distributed electricity and heat, combusted in combined cycle power plants for electricity and heat, and directly combusted for cooking and industrial heat.

CLEAN HEAT PATHWAYS AND ENERGY DEMAND REDUCTION MEASURES

As with sources of combustion emissions in any sector, industrial heat emissions can be reduced either by shifting to cleaner fuel alternatives, capturing emissions, or minimizing energy demand. Clean heat alternatives could include electricity, biomass and biofuels, hydrogen, renewable and synthetic natural gas, nuclear, solar, geothermal, and fossil fuels with CCUS. While energy demand reduction measures could include energy efficiency, process changes, recycling and reuse, and product or material substitution.

ELECTRICAL HEATING

Electrification is the process of introducing electricity (to power or heat) in the first instance or as a substitute for other technologies. The U.S. electric power sector has become significantly cleaner since 2005; as a result, the level of indirect emissions attributable to the industrial sector—the result of electricity generated offsite and transported to and consumed by industry—has fallen 39 percent.[22] As the electricity mix is expected to continue decarbonizing, finding ways to increase the amount of electricity used to produce industrial heat is a logical pathway to reducing heating-related emissions.

Opportunities

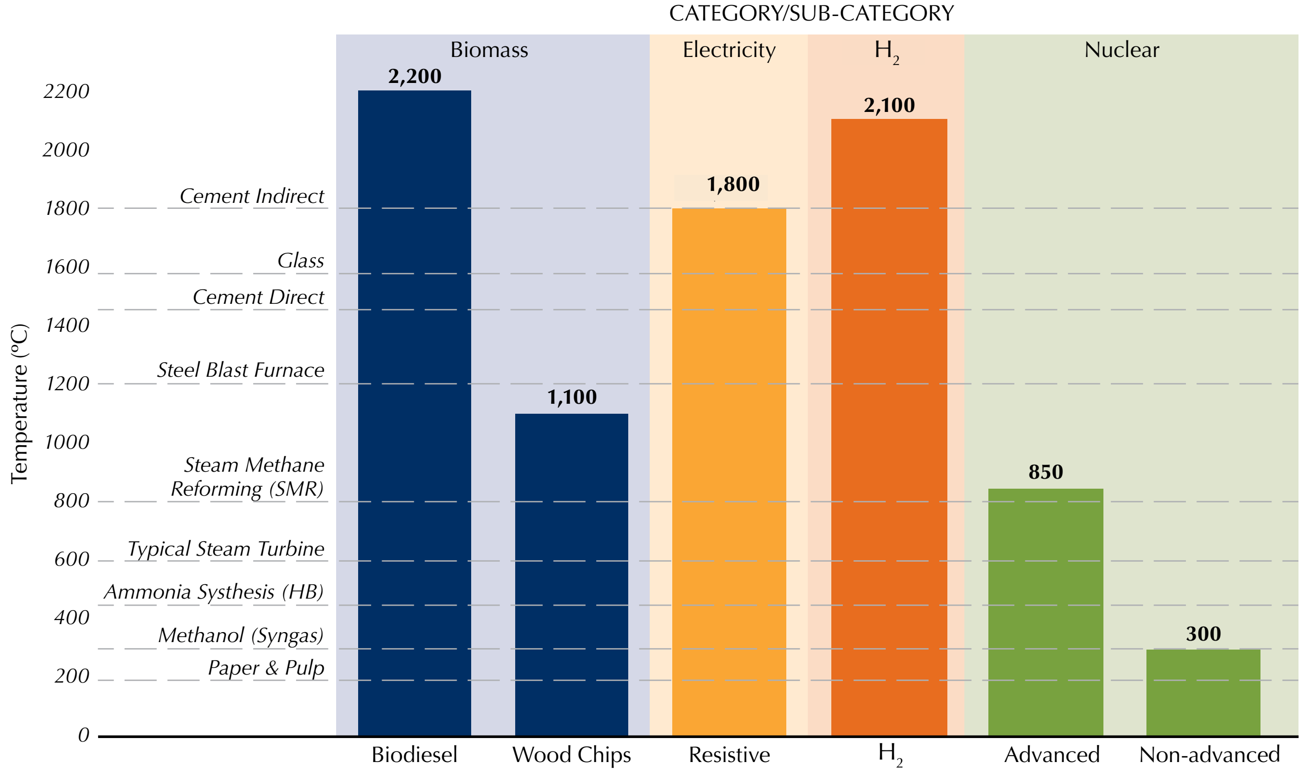
Electric arc furnaces, which have been used in the steel industry for decades, can reach very high temperatures. There are also a number of nascent technologies emerging as potential ways to electrify industrial processes, including resistance heating, infrared heating, microwaves, and induction. Electric resistive heating is capable of reaching temperatures of 1,800 degrees C (as shown in **Figure 2**). A key advantage of electrical heating systems is their greater ability to control precise

TABLE 2: Heat Temperature Levels for Making Industrial Products

LOW-TEMPERATURE HEAT PROCESSES (BELOW 150 C)	MEDIUM-TEMPERATURE HEAT PROCESSES (150–400 C)	HIGH-TEMPERATURE HEAT PROCESSES (ABOVE 400 C)
Food and beverages	Food and beverages	Steel
Paper	Paper	Cement
Textiles	Chemicals	Glass
Agro-industry	Plastics	Refining
Pharmaceuticals	Mining	Chemicals
Plastics	Pulp (paper)	Fertilizer
Chemicals	Ethyl alcohol	
Mining		

Sources: International Energy Agency (2017), German Energy Agency (2016), Columbia Center on Global Energy Policy (2019), National Renewable Energy Laboratory (2016)

FIGURE 2: Temperature Requirement for Select Industry Processes and Temperature Capability of Clean Heat Alternatives



Note that "advanced" refers to new nuclear (e.g., molten salt reactors) and "non-advanced" refers to the current generation of light-water reactors.

Source: ICEF 2019 Roadmap: Industrial Heat Decarbonization

temperature levels compared to traditional, combustion-based process heating techniques.[23] When the electricity is generated by clean energy sources, it can provide a fundamentally clean source of heat.[24] 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;[25] if clean electricity prices drop below those of fossil fuels, electrification could actually save industries money in the long term, across sectors.[26]

Challenges

A substantial increase in electricity consumption from industry and other sectors (e.g., transportation, buildings) will require a significant build-out of power sector infrastructure and put heavy demands on the electricity grid.[27] Additionally, while electrification powered by clean electricity sources can provide clean heat, most electricity generation is not yet clean; the carbon footprint of industrial electrification depends on the actual fuel sources used.[28] Daily and seasonal variations in renewable energy resource availability present additional challenges to electrification in the absence of sufficient energy storage and other sources of firm capacity that can ensure electricity availability across times and seasons.[29] Furthermore, some geographies naturally have more favorable conditions for renewable energy generation than others, so widespread deployment of these technologies will require greater power transmission.[30] There will be social resistance (e.g., NIMBYism) and lengthy environmental reviews for new generation and transmission projects. The use of electricity as a heating source can also be expensive, and the costs of electrification could be prohibitively high in some regions relative to fossil fuel combustion without some form of policy intervention.[31]

BIOMASS AND BIOFUEL COMBUSTION

Biomass is wood, waste, and other organic material (e.g., wood chips) that is burned to produce heat and/or electricity.[32] Biofuels like ethanol and biodiesel are produced from biomass materials and can be blended with traditional fuels or combusted on their own.[33]

Opportunities

Biofuels have the ability to produce temperatures up to 2,200 degrees C when burned, more than enough for most industrial processes, and biomass can reach temperatures up to 1,100 degrees C (**Figure 2**).[34] Unlike many other potential clean heat technologies, the biomass industry is already mature, with a market capable of transporting biomass over long distances.[35] As a liquid, biofuels can also be transported easily via truck, rail, or pipeline without upgrades to traditional equipment that currently ships liquid fossil fuels. While burning biomass does produce carbon emissions, it can potentially be a carbon-neutral source because the feedstocks remove carbon dioxide from the atmosphere as they are grown, meaning that the carbon dioxide released in combustion was already in the natural carbon cycle, in contrast to fossil fuels dug up from underground geological formations.[36] While the carbon neutrality of biomass depends on the right feedstocks and a host of other variables, the potential for some biomass to be a carbon-neutral energy source also creates the potential for it to become carbon-negative through the use of CCUS technology.[37]

Challenges

The emission reduction potential of biomass and biofuels is a matter of contention. Similar to fossil fuels, biomass releases carbon dioxide when burned—in fact, more carbon dioxide than coal per unit of energy produced—and the feedstocks for biomass and biofuels have the potential to result in greenhouse gas emissions if their production causes changes in land use.[38] For example, crops grown for biomass can compete for land with food crops, resulting in an indirect increase in net emissions if additional land clearing (e.g., deforestation) occurs.[39] Depending on the feedstocks and the net greenhouse gases emitted across the entire life cycle, the biomass conversion process may be considered carbon neutral, carbon negative, or carbon positive. In addition, combustion of biomass creates air pollution (e.g., particulate matter), impacting human health.[40]

HYDROGEN COMBUSTION

Hydrogen is a naturally plentiful resource and a clean (i.e., producing only heat and water), combustible gas capable of reducing industrial heat-related emissions.[41]

Opportunities

Hydrogen is capable of producing extremely high temperatures (up to 2,800 degrees C), enough for any industrial process.[42] While most hydrogen today is produced by extracting it from natural gas through a carbon-intensive process called steam methane reforming, there are ways to produce zero- or low-carbon hydrogen, the most promising of which are "blue" hydrogen and "green" hydrogen.[43] Blue hydrogen refers to hydrogen produced by steam reforming of natural gas, combined with CCUS. Green hydrogen is produced using electrolysis powered by clean sources of electricity, such as wind, solar, hydro, and nuclear, to extract hydrogen from water.[44] If excess clean electricity, or curtailed production of renewable or nuclear power, is used to power electrolysis, the hydrogen would effectively be storing clean energy that would otherwise have been wasted. To begin reducing emissions from the current natural gas system, hydrogen can be safely blended with natural gas and transported in existing natural gas pipelines at low concentrations (i.e., less than 5 to 15 percent by volume).[45] There are some estimates that nearly 20 percent of existing U.S. natural gas pipelines can already transport hydrogen with minimal modifications.[46] Hydrogen also can be utilized across numerous sectors; for example, it can be used in mobile fuel cells for vehicles and in stationary fuel cells for distributed electricity and heat, combusted in combined cycle power plants for electricity and heat, and directly combusted for cooking and industrial heat. In the steel industry, some companies are working to use hydrogen reduction, rather than coking coal, to produce zero-carbon steel.[47]

Challenges

Hydrogen is abundant and burns clean, but current methods of hydrogen production are very carbon-intensive, meaning that only hydrogen produced with CCUS or by using electricity from clean sources can be useful for decarbonization.[48] Blue and green hydrogen are currently more expensive than regular hydrogen, and 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 of its low molecular weight (i.e., it is small and light) and its chemical properties (i.e., colorless, odorless, and burns invisibily), leakage can be a problem and leak detection difficult.[49] Hydrogen is also highly combustible and can present a safety risk: it readily reacts with materials, including metals, causing embrittlement and cracking. Therefore, systems (e.g., pipelines, storage containers) need to be specifically designed for high concentrations of hydrogen; an extensive pipeline network will be needed to deliver the gas to industrial (and other) consumers. Furthermore, conversion of industrial facilities to use hydrogen will require new equipment and burners by end-use consumers. In particular, utilizing hydrogen for steel and cement production would require redesigning plants that were constructed with the use of fossil fuels in mind.[50] Finally, hydrogen is an indirect greenhouse gas with a global warming potential of 5.8 over a 100-year timeframe; therefore, if hydrogen consumption should increase, care must be taken to avoid hydrogen leakage during greater production and distribution, as it would have a non-trivial impact on global warming.[51]

RENEWABLE AND SYNTHETIC NATURAL GAS

Increasingly, industry is utilizing natural gas not only as a feedstock but also for electricity and heat production to reduce carbon intensity; combustion of natural gas emits about half as much carbon dioxide as coal and 30 percent less carbon dioxide than oil per unit of energy produced. Renewable natural gas (RNG), also known as biogas or biomethane, and synthetic natural gas (syngas) are potential alternatives to traditional natural gas. RNG can be captured from agricultural waste, landfills, wastewater treatment plants, and other sources, after which it is processed and then used as a fuel. For example, through the process of anaerobic digestion, microbes break down organic waste, releasing both biogas and fertilizer. The biogas generated can then be used as an alternative fuel, displacing more polluting forms of energy.[52] Synthetic natural gas can be created through a process known as Power-to-Gas, or P2G, which uses electrolysis to produce hydrogen that is then combined with CO_2 to produce methane (CH_4).[53]

Opportunities

As another form of natural gas, RNG and syngas have the same heat characteristics as natural gas. Given that 30 percent of industrial process heat is generated using natural gas, utilizing alternative natural gas could be important in the industrial sector.[54] RNG and synthetic natural gas can be used in existing pipeline infrastructure and can be used directly for heating purposes like traditional natural gas. RNG provides a way to simultaneously displace fossil natural gas and capture methane emissions from landfills, agricultural operations, and other sources, while syngas provides a means of using renewable power that cannot easily be transported over long distances. [55]

Challenges

The emissions reduction potential of alternative natural gas options is dependent on many factors, including the counterfactual of how the methane emissions would have been managed otherwise, the feedstocks generating the gas, and how much methane escapes between production and end-use.[56] In order to realize the potential benefits from alternative natural gas options, it is essential to minimize leaks of methane wherever they occur; although methane's atmospheric lifetime is only 12 years, its global warming potential is 25, meaning that the radiative effect of each unit of methane over 100 years is 25 times that of carbon dioxide.[57] Another challenge to the scaling of biogas is the geographic limits to its deployment, as it is dependent on very localized sources such as landfills and wastewater treatment plants.[58] There are also limits to the quantities of RNG available. Biogas and biomethane production in 2018 was around 35 million metric tons of oil equivalent (Mtoe), only a fraction of the estimated overall potential, which is 730 Mtoe for biomethane and 570 Mtoe for biogas—but even the full potential would only cover about a fifth of current global gas demand.[59] P2G technology, meanwhile, is still relatively immature and remains expensive and inefficient.[60]

NUCLEAR HEAT PRODUCTION

Nuclear power is responsible for the second largest amount of low-carbon electricity (after hydropower) produced in the world today. Currently, the United States is the largest producer of nuclear power, producing 31 percent of the world's total nuclear electricity.[61]

Opportunities

Some countries are already utilizing nuclear energy for their industrial processes. For example, in Russia and Ukraine there is limited use of heat from the production of nuclear electricity for desalination, district heating, and industrial process heating.[62] If nuclear plants could be co-located with industrial facilities, they could provide enough heat for certain industrial processes, including desalination, refining, synthetic and unconventional oil production, biomass-based ethanol production, and hydrogen production.[63] Existing light-water nuclear plants can generate heat at about 300 degrees C, but small modular reactors have the potential to generate temperatures up to 850 degrees C, creating opportunities for nuclear power to be used for all medium- and some high-temperature processes.[64] Some advanced reactor designs could produce even higher temperature heat. Newer reactor designs are also inherently safer and create far less waste than the current generation of nuclear plants.[65]

Challenges

Heat generated by conventional nuclear reactors cannot achieve temperatures high enough for many industrial processes. While future advanced nuclear technologies will be able to generate heat at much higher temperatures,[66] these plants are largely in the early stages of development, years away from deployment. Critics of nuclear technologies contend that even new reactors do not adequately address safety and waste storage issues.[67] Existing nuclear facilities are also struggling to remain operational due to declining energy market revenue, driven by persistently low natural gas prices and declining costs of renewables.[68]

SOLAR THERMAL

Currently, the only solar thermal technology capable of producing temperatures high enough for industrial processes is concentrated solar power (CSP).[69] 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 generate electricity—by heating water, producing steam, and turning a turbine—or to provide heat directly for industrial processes.[70]

Opportunities

While solar power has typically been unable to generate heat at the temperature levels required for the most energy-intensive industrial processes, companies, such as HelioGen, have introduced new CSP approaches, capable of achieving temperatures up to 1,000 degrees C—high enough for most industrial processes. Low operating and fuel costs could make CSP more economically viable than other heat generation options.[71]

Challenges

In addition to very large land requirements, CSP has very specific climatic requirements for its use, which 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.[72] In addition, like other solar power technologies, CSP must rely on energy storage to ensure reliable delivery of energy during periods when the sun is not shining. CSP uses molten salt to store thermal energy, but even with the use of this technology, CSP's energy output would still be subject to a degree of seasonal variability (e.g., shorter daylight hours in the winter months). Molten salt storage also is only able to hold temperatures up to 560 degrees C, making it unsuitable for use in higher-temperature processes.[73]

GEOTHERMAL ENERGY

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.[74] In the United States today, geothermal provides 2.5 GW of capacity and is used primarily for electricity.[75]

Opportunities

Typically, geothermal power plants make use of dry steam or hot water wells between 150 degrees C and 370 degrees C, which is hot enough for most low- and medium-temperature industrial processes. Geothermal is a highly reliable source of energy, as it is not affected by seasonal or weather variability. It requires no fossil fuels and, depending on the plant type, produces either no emissions or only one-sixth of the carbon dioxide produced by a natural gas power plant; the carbon dioxide does not come from combustion, rather it is naturally present in all geothermal reservoirs.[76] The current level of geothermal energy use remains far below the technical potential worldwide; a recent U.S. Department of Energy (DOE) report found that geothermal energy capacity could increase by as much as 26 times by 2050.[77] Furthermore, advanced drilling technologies developed for the oil and gas sector can be applied to help bring down the costs and expand the geographic range of geothermal.

Challenges

While cleaner than many other forms of energy production, geothermal energy is not entirely free of environmental consequences. As mentioned above, geothermal energy also results in carbon dioxide emissions, albeit at a significantly lower level than fossil fuels. It also results in low-level emissions of other gases, such as sulfur dioxide and hydrogen sulfide, which can create an odor issue for nearby residents.[78]

Geothermal energy faces obstacles to becoming 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.[79] Geology and geography are also constraints on where geothermal energy can be economically deployed. Tectonic hot spots are the only locations where high-temperature heat can be easily extracted (though 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).[80] In addition, removing steam from reservoirs and returning water from geothermal power plants has, in some cases, caused tectonic instability, resulting in earthquakes.[81]

CARBON CAPTURE, UTILIZATION, AND STORAGE (CCUS)

CCUS can be used to capture carbon dioxide from industrial processes and fossil fuel combustion, which can then either be permanently stored or used to produce carbon-based products.

Opportunities

CCUS is a promising technology for reducing industrial emissions because it allows for decarbonization without altering underlying fuels or industrial processes. CCUS is also ready for wide-scale deployment today.[82] As of 2020, there were already 26 commercial carbon capture facilities operating globally.[83] 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.[84] In addition, CCUS can be utilized across sectors, including in industry, power, fuels production, and direct air capture; carbon capture projects in the power sector have demonstrated the ability to reduce up to 90 percent of emissions, with future plants are forcasted to capture 99 percent or more of emissions.[85] Furthermore, when used with certain forms of bioenergy, CCUS has the ability to generate net-negative emissions on a life-cycle basis.[86]

Challenges

CCUS technologies are energy-intensive, which means a plant or facility has to siphon or supplement energy to run them. Because electricity inputs are required for carbon capture to operate, 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. Creating a network of pipelines connecting sources of carbon dioxide to locations where the carbon dioxide will be utilized or stored will cost hundreds of millions of dollars to appraise, build, and develop, and public concerns about the safety, efficacy, and value of carbon dioxide transport and storage could generate opposition to projects.[87] Emission reductions also currently have little to no value in most markets. Furthermore, although CCUS technologies are well established, there is often a perceived risk due to the limited application of the technologies in most industries, which can limit investment in CCUS projects.

ENERGY EFFICIENCY

Improving industrial energy efficiency can reduce demand for heat energy, thereby reducing emissions. There are opportunities to improve energy efficiency in every industrial subsector. For example, the cement sector has the potential to improve its efficiency by 10 percent, and both steel and plastics have the potential for improvements of 15 to 20 percent.[88]

Opportunities

One pathway for improving industrial energy efficiency is through digitalization and the Internet of Things; by connecting industrial machinery with digital technologies, processes can be automated to optimize levels of energy use.[89] Additionally, combined heat and power (CHP) can improve energy efficiency in the industrial sector by utilizing heat produced as a byproduct of electricity generation for industrial processes.[90] When electricity generation and heat production are separate, their combined efficiency is roughly 45 percent; however, with CHP systems, overall energy efficiency can be increased to more than 80 percent.[91]

Challenges

CHP cannot achieve full decarbonization alone if the heat source is powered by fossil fuel combustion, and it may not be cost-effective to deploy CCUS on a small CHP unit. CHP deployment has also been hindered by high capital costs, high stand-by rates, and policy uncertainty.[92] Many other potential energy efficiency improvements for industry likewise involve high capital costs (with longer payback periods), making them difficult to adopt without policy incentives.[93]

PROCESS CHANGES

For many major industrial products and materials, energy demand and emissions intensity can be reduced by altering processes that require significant amounts of heat.[94]

Opportunities

Some industrial subsectors have the potential to achieve significant emissions reductions by shifting from fossil fuel-intensive production processes to those that require less energy or cleaner sources. In the cement industry, for example, fly ash from coal-fired power plants or other materials can be substituted for clinker—which requires high heat to produce—and there are a number of companies working on novel cement production approaches that eliminate the need for Portland clinker entirely.[95] Clean energy sources with relatively low upper bounds on achievable temperatures can also be used to provide “pre-heat” for industrial processes, helping to displace some of the fossil fuels that would otherwise be used to achieve the necessary temperature for a process.[96]

BOX 1: Highlighted Industry Actions

Steel

ArcelorMittal is exploring a number of approaches for reducing the carbon emissions from producing steel through iron ore reduction.[2] It is conducting a pilot project in Hamburg, Germany, that is experimenting with the use of electrolysis and hydrogen for industrial steelmaking. It also has a demonstration project in Ghent, Belgium, that is converting waste wood into biocoal and testing CCUS technology.[3]

Cement

LafargeHolcim is taking steps to reduce the emissions it generates from cement production. These include sourcing 20 percent of its energy from alternative fuels, including low-carbon fuels and biomass. It has increased use of replacements for clinker in cement to 29 percent, among the highest levels in the industry, and is working with partners on 5 CCUS projects in 4 countries.[4]

Chemicals

BASF has a Carbon Management Research and Development Program through which it is developing technologies that focus on decarbonizing base chemical production, which accounts for 70 percent of the emissions of the chemical industry.[5] These solutions include producing hydrogen and developing the first-ever electric heating concept for steam cracking.[6] If steam cracking could be powered with electricity from renewable sources rather than natural gas, the CO_2 emissions from the process could be reduced by 90 percent.[7]

Challenges

Large industrial equipment tends to have a very long lifetime, and facilities operate on razor-thin margins, making it difficult to radically alter the processes once built.[97] Novel methods of producing materials also face barriers (e.g., stranded costs, perceived product quality) to becoming cost-competitive with current approaches. Furthermore, some of these methods may have narrower applications than materials produced via traditional means.[98] For example, cement made from new materials and/or under a new process may have limited applications until testing and certification can expand its uses.

CIRCULAR ECONOMY

Another way to reduce industrial heat demand is to increase recycling and reuse, thereby reducing the amount of new industrial products manufactured.

Opportunities

Achieving a more circular economy has the potential to reduce emissions from key industrial sectors (e.g., aluminum, plastics, steel, cement) by 40 percent globally by 2050.[99] Increasing the recycling rate of steel from 85 percent to 95 percent could reduce the demand for virgin steel by two-thirds; designing products to facilitate end-of-life recycling could shift more steel production from ore-based to scrap-based.[100] In the cement industry, recycling un-hydrated cement found in used concrete, or reusing concrete itself, presents opportunities for more efficient use of resources.[101]

Manufacturing scrap-based recycled steel with electric arc furnaces is up to 90 percent less carbon-intensive (i.e., significantly reducing heat-related emissions) than the basic oxygen furnace route from raw iron ore.[102] And, electricity-based production pathways can be completely decarbonized with the use of zero-emission electricity sources. As to the process of recovering un-hydrated cement in order to reduce demand for more energy-intensive virgin cement (i.e., more heat-related emissions), a careful examination of the full product lifecycle is essential to determine whether it makes sense.

Challenges

While the majority of steel produced today is already recycled, there are still challenges in getting to 95 or 100 percent recycling. Some steel structures are simply abandoned without efforts to recover and reuse the material. Furthermore, 4-5 percent of steel is lost in the recycling process, and the mixing of other alloys with steel during the process can degrade the quality of the recycled product, which limits the applicability of recycled steel for products requiring high-quality steels.[103] Furthermore, with a growing global market for steel, scrap-metal is insufficient to meet demand, and there is still a need to create new ore-based steel. Plastic recycling suffers from the same “downcycling” problem, as recycled plastic cannot always be used to produce the same products.[104] The cement industry faces even greater challenges in recycling materials, as cement is impossible to recycle once hydrated.[105]

PRODUCT OR MATERIAL SUBSTITUTION

It may also be possible to reduce demand for industrial heat through product or material substitution—replacing less carbon-intensive goods for more carbon-intensive goods (and, presumably, lower-heat goods for higher-heat goods) in end-uses. For example, cross-laminated timber is gaining acceptance as a substitute for steel in a range of building projects.[106]

COMMON BARRIERS ACROSS CLEAN HEAT TECHNOLOGIES

Many of the potential clean heat solutions described above would increase industries’ production costs, making them unlikely to be adopted without strong incentives.[107] Colocation of infrastructure is one way for industries to reduce costs from heat production. However, there may be geographic constraints that could prevent colocation from being a viable option.[108] For example, a facility may not be located in a region with a viable year-round solar resource. Another issue stems from the fact that industrial facilities also often have long lifetimes and can cost hundreds of millions of dollars to build, and the slow turnover of capital stock can be a barrier to the adoption of newer, more efficient, and cleaner equipment.[109] Without government intervention, it could be costly for an industry to retrofit its facilities with new, cleaner technologies.

RECOMMENDED POLICIES

Decarbonizing the industrial sector will require deploying many of the technologies mentioned above, but several of them are still in the early stages of development and may not be cost-competitive in the near future.[110] Policy interventions will need to drive faster progress and adoption of clean heat technologies. These policies generally fall into four categories: (1) innovation; (2) technology-specific deployment incentives; (3) carbon pricing; and (4) standards. It is important that these policies include safeguards to protect the competitiveness of U.S. industries—particularly energy-intensive, trade-exposed industries—and prevent carbon leakage to other countries.

INNOVATION

As many potential clean heat technologies are not market-ready, they could benefit from additional resources dedicated to research, development, and demonstration (RD&D). Investment in RD&D also offers the potential to discover novel technologies for generating clean heat, which could have advantages over current options. Bipartisan legislation has been introduced in both the House and the Senate that would establish an interagency RD&D program, led by the U.S. Department of Energy (DOE), to encourage the development of technologies that would reduce emissions from the industrial sector.[111]

The federal government should also encourage pilot programs and expand businesses' access to technical assistance from the national labs. This assistance can help companies overcome technology and commercialization challenges and bring new clean energy technologies to market more quickly. DOE's Advanced Manufacturing Office can help coordinate and prioritize public-private pilot programs in conjunction with DOE's Loan Programs Office, which provides project finance to accelerate the deployment of new, high-impact technologies.

TECHNOLOGY-SPECIFIC DEPLOYMENT INCENTIVES

Some cleaner heat technologies that are technologically ready are not being widely deployed because of cost-competitiveness challenges and perceived risks in deploying less established technologies. Deployment incentives—particularly tax incentives—can help overcome these hurdles. For example, the federal government is supporting the deployment of CHP through tax credits. The investment tax credit for CHP is set to expire in 2022, but legislation has been introduced to extend the tax credit through 2027.[112] Likewise, the 45Q tax credit for CCUS provides incentives for capturing and storing carbon in geologic formations, as well as using carbon dioxide as a feedstock for other products.[113] These incentives are a good start for encouraging the commercial adoption of CCUS technologies, but more needs to be done to encourage broader adoption. The deadline for the tax credit—which currently only applies to projects that begin construction before January 1, 2026—could be extended.[114] The amount of money offered as an incentive could also be increased, and the incentive could be reformed to allow a "direct pay" option.[115] Deployment incentives could also be used to help ramp up production of low- or zero-carbon fuels, such as biofuels, renewable natural gas, and hydrogen.

Technology-specific government support for deployment goes beyond tax incentives. For example, DOE's CHP Technical Assistance Partnership Program promotes and assists in transforming the market and reducing barriers for CHP, waste heat to power, and district energy technologies throughout the United States. Such partnerships could also support increasing electrification, such as using clean electricity for resistance heating, microwaves, induction and electric arc furnaces. Electrification of certain industrial processes will be a vital part of decarbonizing industry. However, in order for this to be possible, it will be necessary to address barriers facing electrification, including the challenges of grid integration and energy storage. The House Select Committee on the Climate Crisis recommends that Congress fund DOE to support RD&D for industrial electrification and energy storage.[116] Additionally, bipartisan legislation has been introduced in both the House and the Senate that would establish new DOE programs for research, development, and commercialization of CCUS technologies.[117]

CARBON PRICING

A carbon price at the federal level in the United States could be a powerful tool for reducing emissions across all sectors, including industry. With few exceptions, entities that burn fossil fuels currently pay no costs for the climate damage their pollution causes. Carbon pricing policies such as a carbon tax, cap-and-trade, or baseline-and-credit system would send an important price signal to the market that would make clean heat technologies more cost-competitive, while giving industries the flexibility and time to find opportunities to innovate.

A carbon price could be implemented via a carbon tax, which would be a charge for each ton of carbon dioxide (and other greenhouse gases) emitted. Cap-and-trade, which some states are implementing (e.g. RGGI), could also be used to reduce emissions across all sectors. This system sets an overall limit on emissions, requires businesses to hold sufficient allowances (which may be auctioned) to cover their emissions, and lets businesses comply by reducing emissions at their facilities and/or by buying additional emission allowances (or credits) from the government or from other businesses that have reduced emissions below the amount of allowances they hold. This leads to a price on greenhouse gas emissions. Similarly, under a baseline-and-credit system, industrial emission-reducing overachievers could earn credits (measured in tons of carbon dioxide) by outperforming a sub-industry or facility-specific performance standard that ratchets down over time, with the credits being tradable between sectors.

STANDARDS

Standards are another policy intervention that could drive adoption of clean heat technologies. These could take the form of agency regulations (e.g., DOE equipment efficiency standards, Environmental Protection Agency carbon standards), executive orders, legislation passed at the federal or state level, or voluntary agreements by companies. An analogue would be the state renewable portfolio standards that have helped broaden the adoption of renewable sources of electricity by requiring a minimum percentage of electricity generated by renewable energy sources. Congress (or states) could pass a similar policy that would require the industrial sector to produce a certain amount of its process heat from clean energy sources; costs could be minimized and flexibility provided via trading of clean thermal energy credits.

COMPETITIVENESS

One roadblock to implementing policies that would limit emissions from industry or put a price on carbon is the expected impact that such an action could have on the global competitiveness of industries. Critics argue that these policies would put domestic industries that are energy-intensive and trade-exposed (such as steel, cement, and chemicals) at a disadvantage by making their products more expensive. Firms in these industries could potentially lose market share to firms in other countries that do not have the same kinds of restrictions on emissions. This would be a lose-lose situation for the United States, as it could lead to job losses while also failing to lower global emissions, as the emissions would just be displaced to another country.[118]

A border carbon adjustment could help address some of these concerns. It would impose a carbon tariff on imports of emissions-intensive goods, ensuring that domestic manufacturers would not be disadvantaged in domestic markets by competition from other countries that do not impose carbon restrictions.[119] Other countries are exploring border carbon adjustments as well, which could put American industries at a disadvantage in those markets if they are not operating under a carbon price. The use of border carbon adjustments or other policy measures must be part of the solution to foster industry decarbonization.

CONCLUSION

Deep cuts to global emissions across sectors must be made over the next several years in order to have any hope of averting the worst impacts of climate change.[120] The discussion around how to make these cuts has been centered around the electricity sector and, increasingly, the transportation sector, as the options for decarbonizing those sectors are more readily available. However, with roughly 10 percent of total global carbon dioxide emissions coming from industrial heat production, strong policy and action are needed to develop and deploy clean heat solutions and industrial energy demand reduction measures, as well.

Other Climate Innovation 2050 Resources:

Getting to Zero: A U.S. Climate Agenda
https://www.c2es.org/document/getting-to-zero-a-u-s-climate-agenda/

Pathways to 2050: Scenarios for Decarbonizing the U.S. Economy
https://www.c2es.org/document/pathways-to-2050-scenarios-for-decarbonizing-the-u-s-economy/

Restoring the Economy with Climate Solutions: Recommendations to Congress
https://www.c2es.org/document/restoring-the-economy-with-climate-solutions-recommendations-to-congress/

Climate Policy Priorities for the New Administration and Congress
https://www.c2es.org/document/climate-policy-priorities-for-the-new-administration-and-congress/

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FIGURES/TABLES/BOX HIGHLIGHT

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