THE INDUSTRIAL ZERO EMISSIONS CALCULATOR

Assessing Options and Resource Requirements on the Road to Clean Industry

Jeffrey Rissman and Nik Sawe

August 2024

EXECUTIVE SUMMARY[i,ii]

Production of the raw materials and finished products that support our global society comes at an immense energy cost, with the industrial sector consuming 43 percent of the world's energy in 2020 and generating about a third of global greenhouse gas emissions in the process. The increasingly ambitious climate goals of many nations require industry to transition to low- or zero-emission processes.

Eliminating greenhouse gas emissions from industry will require energy and carbon management resources, such as zero-carbon electricity, green or blue hydrogen, sustainable bioenergy, and capacity to capture and store carbon dioxide (CO_2) underground. Different approaches to decarbonizing the industrial sector would involve different mixes of these resources. Policymakers need a way to assess the resource demands of different industrial zero-emissions strategies (including heating and non-heating energy requirements, chemical feedstocks, and methods of green primary steel production) with a transparent, customizable, easy-to-use tool.

The Industrial Zero Emissions Calculator (IZEC) has been developed to let stakeholders test different decarbonization pathways and visualize their resource requirements. Built in Excel, the IZEC incorporates publicly available data to model five regions: the United States, China, the European Union, India, and the world. Users can choose the energy sources used for industrial heat and power, specify energy and material efficiency improvements, determine methods of forming chemical feedstocks, and more. They can also compare built-in scenarios that focus on particular decarbonization strategies such as direct electrification, green hydrogen, bioenergy, or fossil fuel use with carbon capture and storage (CCS), as well as a mixed scenario. Outputs include non-feedstock and feedstock energy usage, electricity demand, hydrogen demand and electrolyzer capacity, bioenergy land use requirements, industrial CO_2 emissions, CO_2 stored underground via CCS, and the required capacity of zero-carbon electricity sources.

This report discusses the built-in scenario results for the U.S. (While the magnitude of the resource demands differs across regions, the performance of the scenarios relative to each other is often similar across regions.)

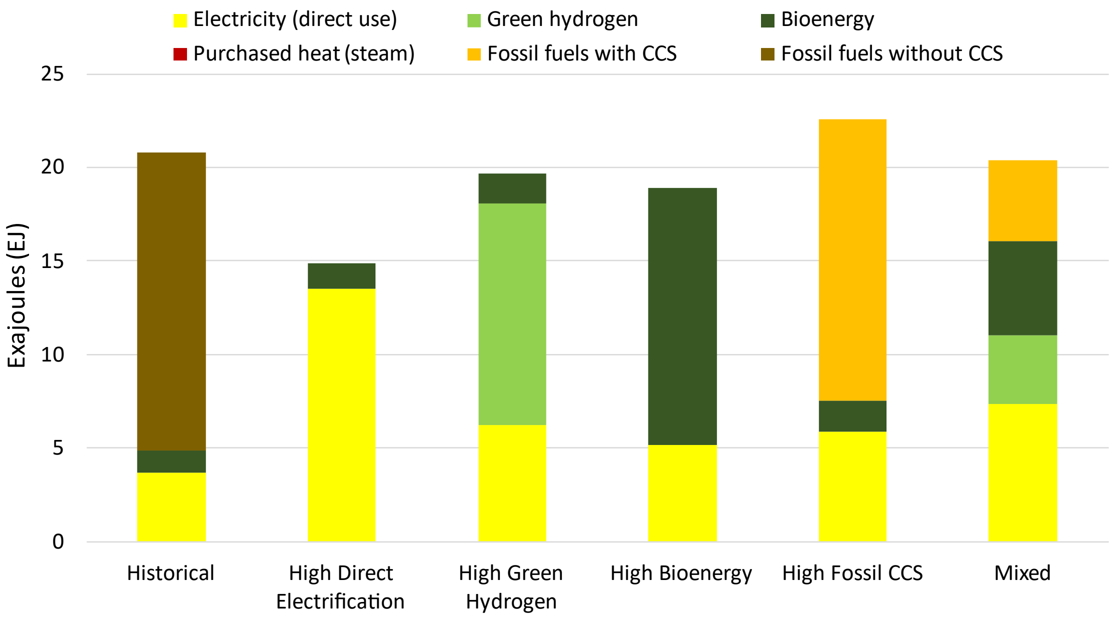
Several key findings emerge:

- Direct electrification is the most efficient way to provide energy for industrial processes, but industry is a large energy consumer (and feedstocks cannot be directly electrified), so electric utilities will need to plan for demand growth. The High Direct Electrification scenario would increase annual electricity demand

---

[i] This research is accessible under the CC BY 4.0 license. Users are free to copy, distribute, transform, and build upon the material as long as they credit Energy Innovation Policy & Technology LLC® for the original creation and indicate if changes were made.
[ii] Cover image credit: piqsels, public domain, https://www.piqsels.com/en/public-domain-photo-fovii/.

Figure ES1. Industry sector non-feedstock energy use in the U.S. (historical data and built-in scenarios)



by almost 4 petawatt-hours (PWh), equivalent to a 2.4 percent annual growth rate, to fully decarbonize all U.S. industrial energy and feedstock use in 30 years. With moderate 25 percent energy efficiency and 15 percent material efficiency improvements, demand growth would be limited to 2.5 PWh, a 1.7 percent annual growth rate. This is lower than annual growth rates of U.S. electricity demand in all but six years between 1950 and 2000.

- Meeting industrial heat demand by forming and burning green hydrogen would increase electricity demand by 7.8 PWh, almost twice as much as in the scenario relying heavily on direct electrification, equivalent to a 3.7 percent annual growth rate over 30 years.
- A scenario that relies heavily on bioenergy for heat and feedstocks would have low electricity demand but prohibitively high land use needs, requiring the U.S. to devote more than 21 percent of its agricultural land (farmland, pastures, and rangelands) to bioenergy crop production. The required area would be 25 percent larger than the state of Texas.
- A scenario that relies heavily on fossil fuel combustion with carbon capture would have moderate electricity and land use requirements but would involve storing a massive amount of CO_2 underground every year, necessitating more than $3 trillion in capital investment (even excluding the cost of energy to power the CCS process).

- A mixed scenario would balance resource requirements across the four resource types (clean electricity, clean hydrogen, bioenergy, and fossil CCS capacity). Nonetheless, it is not necessarily preferable to a heavier reliance on direct electrification since it achieves only a moderate reduction in electricity needs while introducing demands for green hydrogen, bioenergy, and CCS that could pose feasibility challenges.
- Energy and material efficiency dramatically cut the resource demands of clean industry, making any of the decarbonization scenarios faster and cheaper.

Direct electrification is the most energy-efficient industrial heat source. Hydrogen is an inefficient heat source due to the energy required to create the hydrogen and energy losses in hot exhaust gases and formed water vapor, so it should be reserved for the highest-value uses—such as chemical feedstocks and primary steelmaking—where it is injected into the chemical process, not burned. In addition to being a very inefficient way to produce heat, burning hydrogen creates high emissions of nitrogen oxide (NO_x), a local air pollutant that can harm public health.

Modest growth in bioenergy use (particularly for feedstocks) can help to ease the pressure on other resource types but must be done carefully to ensure the produced bioenergy is truly sustainable. (For instance, it must not cause unfavorable land use change, either domestically or by increasing demand for internationally traded bioenergy, which could drive deforestation in regions with weak land use protections.) CCS is currently expensive compared to the other options analyzed here, and it does not address upstream emissions associated with the production, processing, and transport of fossil fuels. Nonetheless, it may yet be among the best options for certain types of emissions, such as CO_2 from calcination of limestone in cement-making and process (non-energy) CO_2 from the chemicals industry. And no matter the mix of energy sources chosen, energy efficiency and material efficiency improvements are important in enabling a successful clean energy transition.

The additional clean electricity needed to supply decarbonized industrial processes need not all come from the grid. It may be more economical to directly power industrial facilities with low-cost, off-grid renewable energy where feasible. Technological solutions such as industrial thermal batteries can help mitigate the variability of these off-grid renewable sources, allowing facilities to procure electricity at one-half to one-third the cost of buying it from the grid.[1]

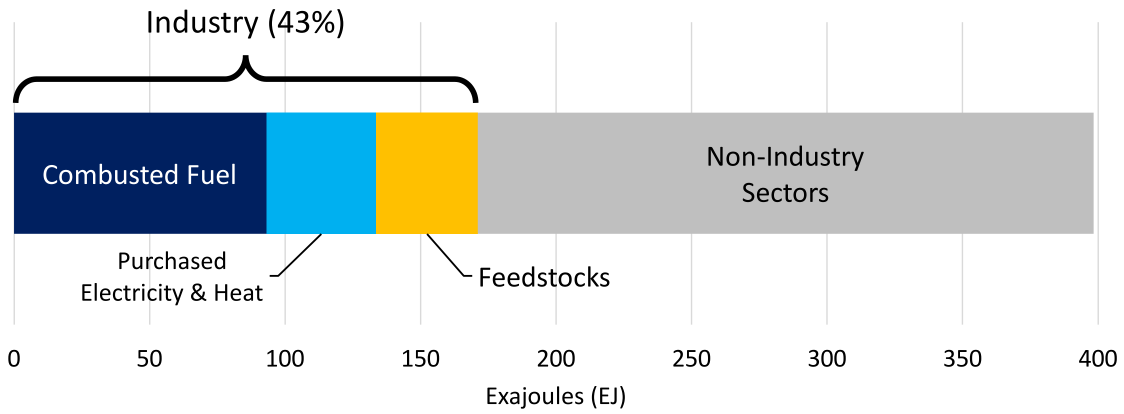
The IZEC is an accessible and intuitive tool that conveys the scale of the resources needed to decarbonize the industrial sector and helps stakeholders identify the best pathways to do so. Reducing industrial sector emissions is necessary if countries are to meet their net-zero targets, and following a set of strategies that are pragmatic and scalable in the long term is crucial to successfully attaining those goals.

TABLE OF CONTENTS

INDUSTRIAL ENERGY DEMAND

Industrial firms produce all the materials and products we rely on every day, ranging from raw steel and cement to finished buildings, vehicles, and consumer goods. In doing so, the industrial sector consumes a prodigious amount of energy. In 2020, industry was responsible for 43 percent of the world's final energy consumption (or 37 percent, if excluding feedstocks) (Figure 1).

Figure 1. Global final energy use in 2020[2]



Industrial energy use is split between three types of energy:

Combusted fuels include fossil fuels (such as coal, oil, and natural gas), biomass, and waste. They are burned within industrial facilities to generate energy, most commonly heat, needed by industrial processes.

Purchased electricity and heat refers to electricity or hot steam purchased by an industrial facility from the electric grid or from district heat plants. It does not include any electricity or steam generated onsite by the industrial facility itself.

Feedstocks are fuels that are not burned for energy. Rather, they are chemically transformed to form part of the output products. The most common feedstocks are fossil fuels that go into making ammonia and petrochemicals, which in turn are used to make products such as plastics and synthetic fertilizer.

DECARBONIZING INDUSTRIAL FUEL USE

To transition to zero-emission industry, it is necessary to address emissions from each of the ways industry consumes energy. Emissions from combustible fuels can be avoided by burning zero-carbon fuels (such as clean hydrogen and sustainable bioenergy), by capturing and storing CO_2 underground (CCS), or by avoiding combustion entirely and switching to direct use of electricity.

Emissions from purchased electricity are avoided if the electric grid switches to zero-emission resources such as wind, solar, hydroelectric, geothermal, or nuclear power. This requires supporting technologies to address renewables' variability, such as demand response programs, interlinking larger balancing areas with transmission, distributed generation (such as rooftop solar), energy efficiency, and energy storage (pumped hydro, batteries, etc.). Purchased heat, which supplies a very small share of industrial energy use, can be replaced with either electricity or clean fuel combustion.

Even though feedstocks are not combusted, it is nonetheless necessary to decarbonize them to achieve true zero-carbon industry. This is because feedstocks can generate greenhouse gas emissions in three ways:

- Feedstocks have upstream emissions (in the production and transport of fossil fuels), such as methane leaked from oil and gas infrastructure or coal mines, as well as emissions from processing steps (e.g., at natural gas processing plants and petroleum refineries).
- Feedstocks often emit "process" CO_2 when they are chemically transformed, i.e., in cases where only some of the carbon in the feedstocks is incorporated into the output products. This process CO_2 is substantial. For example, in 2019, the global chemicals and petrochemicals industry emitted 518 million metric tons (MMT) of process CO_2, representing 40 percent of that industry's direct CO_2 emissions. (The remaining 60 percent was from fossil fuel combustion.)[3]
- Finally, the finished products themselves may not be reliable long-term stores of carbon. For instance, some products release their carbon as CO_2 soon after use, such as urea-based fertilizers. Other products are burned or decay at end of life.

Feedstocks cannot be directly replaced with electricity, but it is possible to substitute clean alternatives (such as biomass or hydrogen with captured carbon) for fossil fuels.

LIMITATIONS OF PAST STUDIES ON ASSESSING INDUSTRIAL DECARBONIZATION REQUIREMENTS

Some prior studies have not considered the full scope of clean energy demand that would be required to decarbonize industry. For example, in the National Renewable Energy Laboratory's 2018 *Electricity Futures Study*, even the "high" electrification scenario in 2050 still relies on fossil fuel combustion to provide more than 70 percent of the energy used by boilers and other industrial process heating, and it makes no attempt to decarbonize feedstocks.[4] More recent studies often cover more industrial energy use but still fall short of full decarbonization. For instance, the International Energy Agency's *World Energy Outlook 2023* "Net Zero Emissions by 2050" scenario sees unabated (i.e., without CCS) oil, gas, and coal making up 19 percent of industrial fuel use in 2050 (about 80 percent of which consists of feedstocks and 20 percent fuels burned for energy).[5] Another example is the International Renewable Energy Agency's

World Energy Transitions Outlook: 1.5°C Pathway, which includes about 40 EJ of coal, oil, and gas use by industry in 2050 (a 23 percent share), inclusive of feedstocks.[6] (Net-zero scenarios that include unabated fossil fuel use typically compensate for those emissions through negative-emissions technologies elsewhere in the economy and may ignore some emissions associated with feedstocks.)

The other key limitation of many past scenarios is the availability and ease of running the computer models used to generate the scenarios. Published scenarios, such as the examples above, have fixed parameters that cannot be altered by policymakers without re-running computer models that are technically complex, may require hours or days of computation to produce results and, in many cases, are not publicly available. This affects the scenarios' ability to help policymakers dynamically explore decarbonization pathways, test their assumptions, and discover key insights about the best way forward. There is a need for a publicly available, easy-to-use tool that allows a user to understand the resource requirements entailed by a complete decarbonization of industrial energy use—including the most challenging aspects, such as chemical feedstocks and the smelting of iron ore to make primary steel.

THE INDUSTRIAL ZERO EMISSIONS CALCULATOR

A range of methods exist by which industrial fuel use can be decarbonized that involve using direct electrification, hydrogen, bioenergy, and CCS to varying degrees. However, not all methods are equally efficient or practical. Due to the large scale at which industry uses fossil fuels, it can be difficult to envision the resources required by any particular strategy, and over-reliance on any one route can encounter physical or economic constraints.

A new tool, the Industrial Zero Emissions Calculator (IZEC), lets stakeholders test decarbonization pathways and visualize the associated resource requirements, such as the amount of clean electricity, hydrogen production, sustainable bioenergy, or CCS that would be needed. Understanding these resource requirements is crucial when setting today's policies to ensure that the technologies and approaches we invest in are compatible with a desirable, longer-term vision of how industry will shift to clean processes.

The IZEC is a free and open-source tool built in Excel, with a supplementary data explorer available on the web that shows key findings for the preconstructed scenarios but lacks the full customizability of the Excel version. The IZEC comes pre-loaded with datasets for five regions: the U.S. (which represents 7 percent of global industrial emissions[7]), China (45 percent), the European Union (6 percent), India (8 percent), and the world (100 percent). It provides users the following options for how to decarbonize industry in the chosen region:

- Method of supplying energy for today's non-heat uses of thermal fuels (such as diesel engines)
- Method of supplying energy for low-temperature heat
- Method of supplying energy for medium- and high-temperature heat
- Method of forming chemical feedstocks (energy source and, where applicable, how to obtain carbon to form carbon-containing feedstocks)
- Method of decarbonizing primary iron and steel production (i.e., considering iron-specific technological pathways)

The tool also lets users set a few configuration parameters:

- What is the expected extent of improvements in energy efficiency and material efficiency?
- Should non-manufacturing industries (e.g., mining/drilling, construction, agriculture) be included in the industry sector?
- Should the calculator seek to displace existing use of bioenergy or let bioenergy use remain?
- Should the calculator seek to displace existing use of purchased heat (steam) with zero-carbon alternatives?
- What mix of electricity sources should be used to supply electricity to industry?

The calculator uses publicly available data from more than 50 sources, including the U.S. Energy Information Administration, the International Energy Agency, China's Energy Statistical Yearbook, and the World Bank. Each source is carefully documented and cited in the tool.

The calculator takes a historical year (the most recent year for which data are available, varying by region) and illustrates the consequences of decarbonizing that historical level of industrial production via the user-selected strategy. The calculator does not have a time dimension, as it does not predict how fast industries could implement the user-selected strategy. Rather, its goal is to illustrate the endpoint, to help users identify the most desirable ultimate composition for the industrial sector, and hence, which strategies to pursue today.[iii]

[iii] For analysts who desire more detail about transition timelines, all of the capabilities in the IZEC will be included in a future release of the Energy Policy Simulator—a powerful, open-source computer model that includes a time dimension as well as many other features, such as the ability to estimate impacts on jobs, GDP, public health, etc.[8]

LIMITATIONS AND ASSUMPTIONS

Assumptions and simplifications are inherent in developing any computer simulation that is less complex than the real world, particularly in a tool that aims to be easy to use. Some notable assumptions follow:

Feedstocks: The energy in fossil feedstocks (coal, natural gas, and petroleum) is replaced with hydrogen or bioenergy on an energy-equivalent basis. This assumes that the efficiency of turning fossil feedstocks into each petrochemical is roughly similar to the efficiency of turning bioenergy or hydrogen into each petrochemical. A more detailed analysis would need to consider production quantities of each specific petrochemical and the relative efficiencies of making each petrochemical from traditional fossil feedstocks versus hydrogen versus bioenergy, which is beyond the scope of this simplified calculator.

Metallurgical coal: For some regions, data on metallurgical or coking coal consumption are not available. Coke consumption is used instead. This slightly understates energy use, as it disregards energy consumed by coking ovens to produce the coke.

Lower heating values, not higher heating values: Heating values are a measure of the energy content of combustible fuels. The calculator uses only lower heating values, which exclude the latent energy in formed water vapor. Recovering this energy involves condensing the water vapor in the combustion exhaust, and the recovered energy is small in quantity and at a low temperature (i.e., up to 100°C), so it is not useful for most industrial processes. The calculator uses lower heating values in hydrogen formation for consistency.

RESULTS OF BUILT-IN SCENARIOS

In addition to allowing users to define their own scenarios from scratch, the IZEC includes five built-in scenarios that aim to illustrate specific findings, particularly around resource requirements to achieve zero-carbon industry. These scenarios are High Direct Electrification, High Green Hydrogen, High Bioenergy, High Fossil CCS, and a Mixed case.

SCENARIO DEFINITIONS

The approaches of each of the five scenarios are summarized here. Specific numerical settings for each scenario are provided in Table 1.

The **High Direct Electrification** scenario relies on direct use of electricity to the greatest practical extent. All fuels burned for non-thermal energy and for low-temperature heat are replaced with electrified equipment, particularly electric motors and heat pumps, respectively. All medium-and high-temperature heat is also supplied directly by electricity using technologies such as electric resistance, electromagnetic induction, electric arcs, and dielectric heating. Feedstocks cannot be directly electrified and are supplied via a mix of 55 percent “green” hydrogen (hydrogen produced by splitting water using renewable electricity) and 45 percent bioenergy. Primary steel is made mostly through two direct iron ore electrolysis routes, which have low technological maturity today.

The **High Green Hydrogen** scenario still relies on electricity for non-thermal uses of fuels, but it splits low-temperature heat between electricity (67 percent) and hydrogen combustion (33 percent). Medium- and high-temperature heat is provided entirely by green hydrogen combustion. Feedstocks are provided exclusively by green hydrogen. Primary steel is produced exclusively via green hydrogen–direct reduced iron.

The **High Bioenergy** scenario splits low-temperature heat evenly between electricity and bioenergy, uses bioenergy combustion entirely for medium- and high-temperature heat, and relies on bioenergy to form chemical feedstocks.

The **High Fossil CCS** scenario splits low-temperature heat evenly between electrification and fossil fuel combustion with CCS. Medium- and high-temperature heat is supplied entirely by fossil fuel combustion with CCS. Feedstocks are provided by “blue” hydrogen (hydrogen produced from fossil fuels with CCS).[iv]

Finally, the **Mixed** scenario aims to provide a pathway to zero-carbon industry that is balanced across all the available approaches (see Table 1).

A NOTE ON EFFICIENCY IMPROVEMENTS

Users can introduce both energy efficiency and material efficiency improvements across all scenarios. Due to the large scale of industrial energy demand, it is difficult to supply so much zero-emission energy without efficiency improvements. Users are encouraged to try different values to see the beneficial impacts of pursuing moderate efficiency gains alongside efforts to shift to clean energy sources.

Energy efficiency is often thought of in terms of specific pieces of industrial equipment, such as improving the efficiency of a motor or a furnace. In fact, significant efficiency opportunities also exist at the scale of facilities (such as right-sizing equipment and material flows or employing waste heat recovery) and in decisions made beyond the factory (such as optimizing product design and the supply chain to improve energy efficiency). As a sample value, a 25 percent improvement in industrial energy efficiency is aligned with the improvement from 2020 to 2030 in the International Energy Agency’s Net Zero scenario.[9] However, the IZEC models a fully decarbonized industry

---

[iv] In the IZEC, blue hydrogen is only used for feedstocks, not burned for energy. Converting fossil fuels to hydrogen involves energy losses, which may be acceptable if a facility needs hydrogen as a feedstock (e.g., to form ammonia and petrochemicals or to chemically reduce iron ore). However, if a facility simply needs heat, it is more efficient to burn the fossil fuels directly with CCS than to first convert them to hydrogen with CCS and then burn the hydrogen.

sector, which would require significantly more than 10 years to achieve. This would allow more time for technological improvements in energy efficiency, so users may consider testing improvements greater than 25 percent.

Table 1. Settings used in built-in scenarios in the IZEC

	High Direct Electrification	**High Green Hydrogen**	**High Bioenergy**	**High Fossil CCS**	**Mixed**
Method of Supplying Non-Heat Uses of Thermal Fuels					
percent electrified	100%	100%	100%	100%	100%
Method of Supplying Low-Temperature Heat					
percent electrified	100%	67%	50%	50%	25%
percent shifted to green hydrogen combustion	0%	33%	0%	0%	25%
percent handled via fossil fuel combustion with CCS	0%	0%	0%	50%	25%
percent handled via bioenergy combustion	0%	0%	50%	0%	25%
Method of Supplying Medium- and High-Temperature Heat					
percent electrified	100%	0%	0%	0%	25%
percent shifted to green hydrogen combustion	0%	100%	0%	0%	25%
percent handled via fossil fuel combustion with CCS	0%	0%	0%	100%	25 %
percent handled via bioenergy combustion	0%	0%	100%	0%	25%
Method of Forming Chemical Feedstocks					
bioenergy (direct use)	45%	0%	100%	0%	34%
green hydrogen + captured carbon	55%	100%	0%	0%	33%
blue hydrogen + captured carbon	0%	0%	0%	100%	33%
Method of Obtaining Carbon to Form Chemical Feedstocks					
percent from bioenergy combustion with carbon capture	50%	50%	100%	50%	50%
percent from direct air capture	50%	50%	0%	50%	50%
Method of Decarbonizing Primary Iron and Steel					
green hydrogen–direct reduced iron (H_2–DRI)	0%	100%	80%	0%	34%
molten oxide electrolysis	50%	0%	10%	0%	33%
aqueous electrolysis	50%	0%	10%	0%	33%
percent using fossil fuels	0%	0%	0%	100%	0%
Method of Addressing Remaining Process (Non-Energy) CO_2 Emissions					
percent handled via carbon capture	100%	100%	100%	100%	100%

Material efficiency involves using smart design and production processes to make products that deliver equal- or better-quality services while using less material. Researchers Allwood and Cullen found that “we could use 30 percent less metal than we do at present, with no change in the level of material service provided, simply by optimizing product design and controlling the loads that they experience before and during use.”[10] The potential is similar for other materials, such as concrete. Users may wish to experiment with material efficiencies between 15 percent and 30 percent, depending on how conservative they wish their estimates to be.

The five built-in scenarios each fully decarbonize the industry sector, except for any residual emissions that result from using CCS, since CCS typically captures only up to 90-95 percent of the CO_2 in an exhaust gas stream. However, in custom user-created scenarios, the IZEC allows users to decarbonize only a portion of each industrial end use or only specific end uses. Therefore, it is possible to identify the resource requirements to, for example, decarbonize only non-feedstock energy use, decarbonize only low-temperature heat, decarbonize 50 percent of medium- and high-temperature heat, etc.

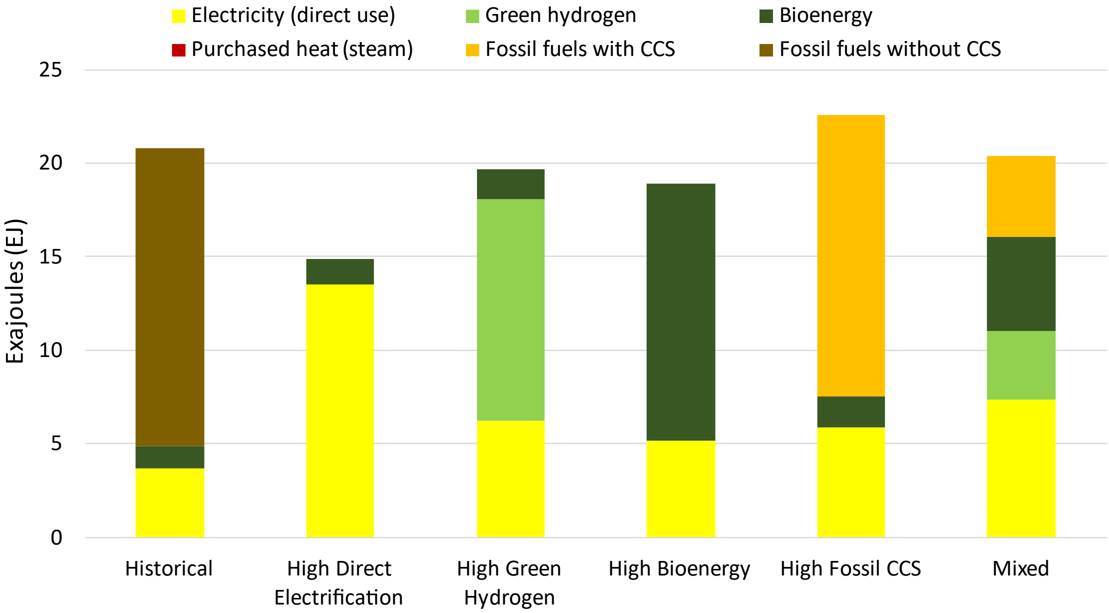
SCENARIO RESULTS

With five built-in scenarios for each of five regions, there are 25 sets of outputs—more than can be discussed in this report. Therefore, this report will focus on sharing U.S. results across scenarios, but corresponding results are available from the IZEC for the other regions. While scenarios’ decarbonization settings differ (as shown in Table 1), each scenario is presented with the same set of configuration options: non-manufacturing industries are included in the definition of the industry sector, existing bioenergy use is not displaced, purchased heat (steam) use is displaced, and the same illustrative mix of power plant types is used to supply zero-carbon electricity. Figures 2 through 12 depict the built-in scenarios with no energy or material efficiency improvements to aid in comparing the scenario results to the historical data. Figure 13 illustrates the effects of 25 percent energy efficiency and 15 percent material efficiency improvements, and users of the Excel tool can test other efficiency settings to understand how efficiency impacts resource requirements. All of the built-in scenarios are shown in Figures 2 through 12, but for each graph, we discuss only the most prominent takeaways, highlighting those that differ most from the historical case.

INDUSTRY SECTOR NON-FEEDSTOCK ENERGY USE

Historically, most industrial sector energy use relies on fossil fuel combustion. The various scenarios rely instead primarily on their respective energy sources, eliminating non-CCS fossil fuel combustion (Figure 2).

Figure 2. U.S. industrial sector energy use for non-feedstock applications

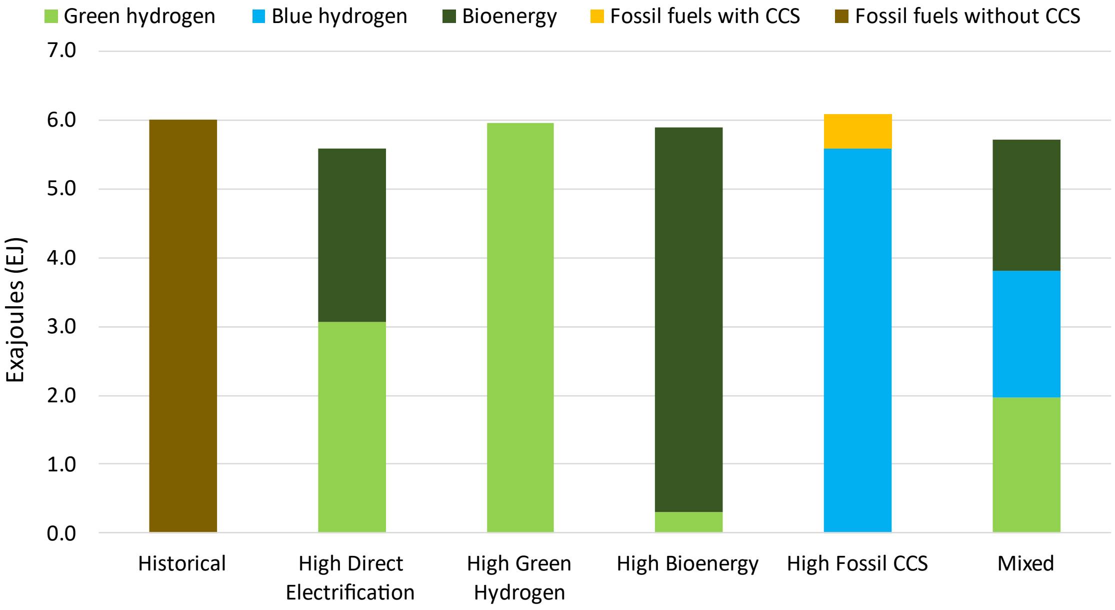


Electricity is used more efficiently than combustible fuels for creating useful heat and conveying that heat to processed parts and materials. For instance, there are no energy losses in hot exhaust gases or formed water vapor. As a result, total energy use declines in all scenarios except the one focusing on fossil fuel combustion with CCS for heat. Historical bioenergy use is retained in all alternative scenarios in its original applications, primarily the pulp and paper and the wood and wood products industries, while bioenergy use expands in the High Bioenergy and Mixed scenarios. The most efficient strategy is High Direct Electrification, which reduces non-feedstock energy use by 28 percent.

INDUSTRY SECTOR FEEDSTOCK ENERGY USE

Today, feedstocks are derived from fossil fuels. Ammonia is primarily produced by steam methane reforming, and petrochemicals such as methanol, olefins, and aromatics are produced from petroleum and natural gas, either in chemicals plants or refineries. Metallurgical coal or coke consumption is considered a feedstock in the IZEC and is included in this graph. This is why CCS can apply to feedstocks. The energy demands for feedstocks across scenarios in the U.S., regardless of the mix of bioenergy and green or blue hydrogen, are roughly comparable to that of historical fossil fuel usage (Figure 3), unless the scenario incorporates material efficiency improvements.

Figure 3. U.S. industrial sector energy usage for feedstock production

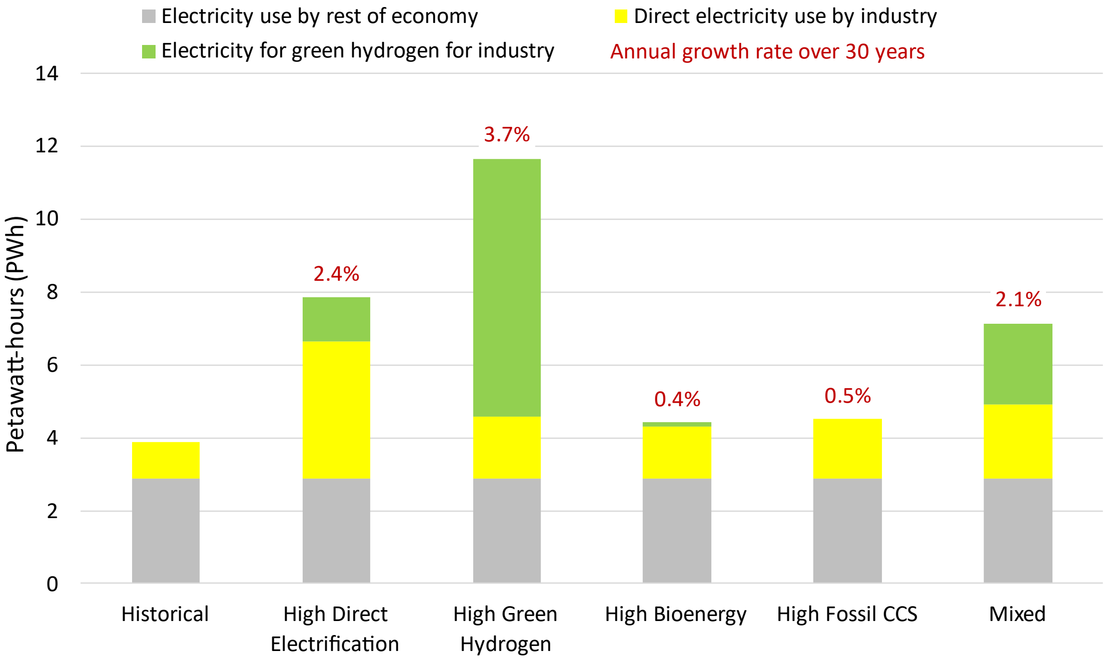


ELECTRICITY DEMAND

U.S. industrial electricity demand increases in all scenarios from the historical baseline. For instance, in the High Green Hydrogen scenario, total U.S. electricity demand is tripled (Figure 4). This is akin to building two more United States' worth of electricity supply just to serve industry, all of which must come from zero-emission sources. These energy demands illustrate the need to reserve hydrogen for high-value applications rather than treating it as a panacea. While the High Bioenergy and High Fossil CCS scenarios only modestly increase electricity demand, the costs of these strategies in other regards (the required agricultural land and the costs of storing CO_2 underground, respectively, discussed later) pose the greatest challenges to their adoption. The Mixed scenario only modestly reduces electricity consumption relative to the High Direct Electrification scenario because its limited use of bioenergy and fossil CCS for heat (which reduce electricity demand) is partially offset by its limited use of green hydrogen combustion (which increases electricity demand).

It will take several decades to achieve zero-emission industry, so it is helpful to view electricity demand increases in terms of annual growth rates over the next 30 years. For instance, the High Direct Electrification scenario would require an annual growth rate of 2.4 percent. Between 1950 and 2023, the average growth rate of U.S. demand was 3.9 percent, and 40 out of the 50 years between 1950 and 2000 experienced growth greater than 2.4 percent.[11] While growth has slowed somewhat in recent years, 2.4 percent is still not unusual, with 2018 and 2022 exceeding 3 percent growth.

Figure 4. U.S. electricity demand for industry and for the rest of the economy



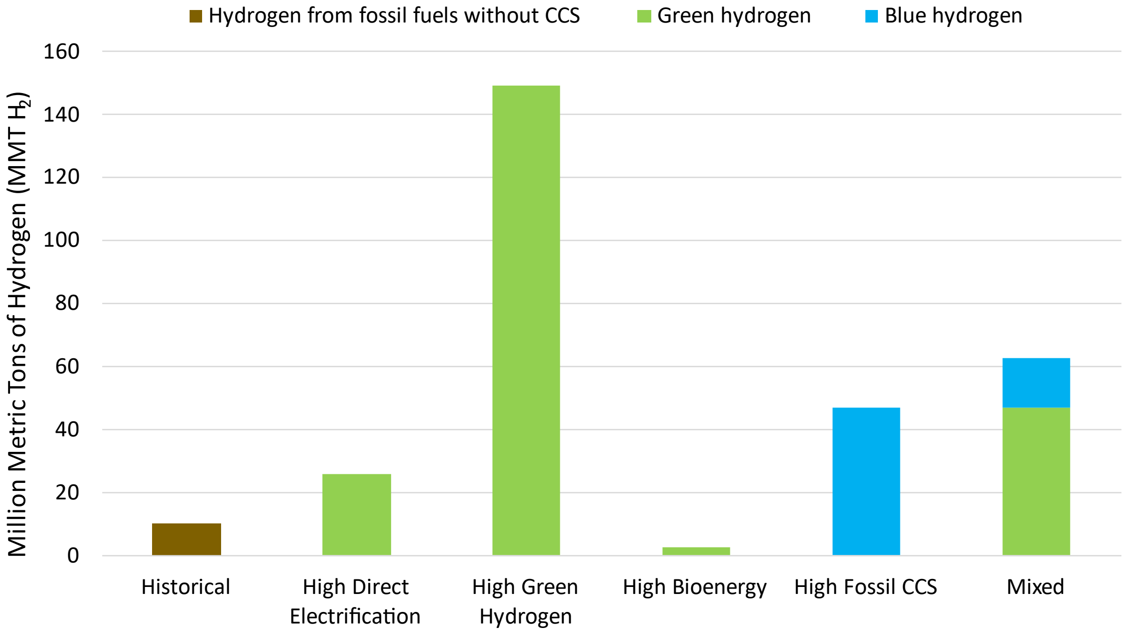
HYDROGEN DEMAND AND ELECTROLYZER CAPACITY

Annual hydrogen demand in the High Direct Electrification scenario grows from 10 MMT of hydrogen use today[v] to just over 25 MMT in a decarbonized industry sector (Figure 5). Though this increase is large in percentage terms, the current scale of dedicated hydrogen production is not that large, and scaling to 25 MMT is attainable. In this scenario, hydrogen supports 55 percent of the feedstock production, but no hydrogen is burned for energy. In the High Green Hydrogen scenario, where green hydrogen is relied upon heavily for all uses, the industrial sector would need nearly 150 MMT.

---

[v] This includes only dedicated hydrogen production (from steam methane reforming in the U.S., coal gasification in China, etc.). It excludes byproduct hydrogen that is part of a gas mixture, such as in blast furnace gas, which is a mixture of nitrogen, carbon dioxide, carbon monoxide, and hydrogen.

Figure 5. Hydrogen demand for U.S. industry



Blue hydrogen is produced from fossil fuels coupled with CCS, so it accounts for all of the hydrogen in the High Fossil CCS scenario. (Blue hydrogen supplies 100 percent of feedstocks in that scenario, but blue hydrogen is not burned for energy because it is more efficient to burn fossil fuels directly with CCS without first converting them to blue hydrogen.) Roughly 50 MMT per year is required—a scale that may be difficult to achieve. Creating this amount of blue hydrogen would require nearly 10 billion GJs of natural gas (nearly a third of total U.S. natural gas consumption) and 1.5 km^3 of fresh water, and would occupy 125 km^2 of land.[12] Large-scale blue hydrogen production would require a confluence of these resources at geographic sites that also have geological reservoirs and transportation infrastructure for carbon storage.[12] Deployment is currently lagging far behind the estimated required capacity, with many announced North American projects not yet at a final investment decision.[12] Additionally, as with other forms of fossil CCS, blue hydrogen does not address upstream emissions from extracting and processing natural gas, which can be very significant depending on methane leakage rate.[13,vi]

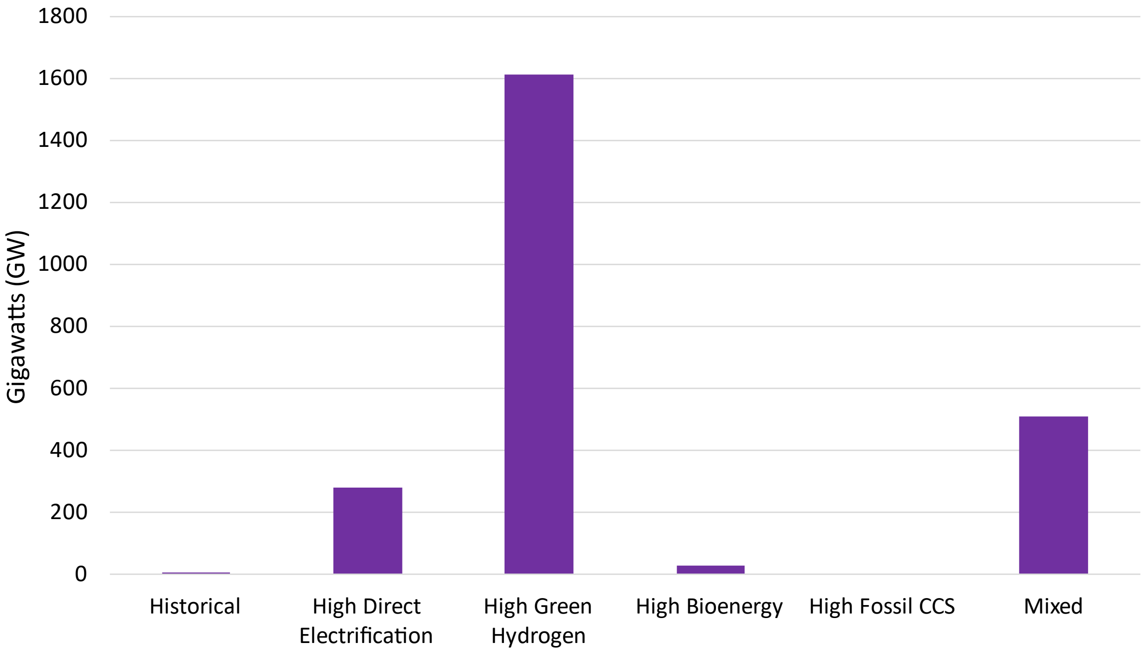
The IZEC estimates the electrolyzer capacity that would be necessary to meet each scenario's green hydrogen demand (Figure 6). (Electrolyzer capacities are measured in watts, referring to the rate of input electricity they can accept.) Almost all dedicated

---

[vi] The IZEC does not include "white hydrogen," or hydrogen extracted from naturally occurring underground H_2 reservoirs. While geologic hydrogen reservoirs are an emerging resource of interest, it has not yet proved to be cost-effective or available at scale. Most of the supply is likely to be inaccessible at competitive cost or in locales far from where it is needed; currently, geologic hydrogen supplies less energy than a single wind turbine.[14]

hydrogen production today is from fossil fuels, so existing hydrogen electrolyzer capacity is near zero. Modeled electrolyzer capacity is based on a usage rate of 50 percent, a rate that the International Energy Agency found to be optimal for minimizing the cost per unit of hydrogen produced.[15] (Usage rates significantly lower than 50 percent are more costly because capital equipment fixed costs are spread among fewer units of hydrogen produced. Usage rates significantly higher than 50 percent are more costly because electricity must be purchased even in hours when it is expensive, instead of operating the electrolyzer only during the hours when electricity is cheapest. This is also why electrolyzers with a 50 percent usage rate may help to balance the grid, whereas a 100 percent usage rate would add stress to the grid at its most difficult times.)

Figure 6. Electrolyzer capacity required for hydrogen production for use in the U.S. industrial sector



Even though electrolytic hydrogen in the High Direct Electrification scenario provides a little over half of U.S. industrial feedstocks and none is combusted for heat, the required electrolyzer capacity is 279 GW. To give a sense of scale, total U.S. electricity generation capacity is around 1,100 GW (excluding distributed generation like rooftop solar), so if all these electrolyzers were operating at once, they could absorb a quarter of the power from the U.S. electric grid. In the High Green Hydrogen scenario, the scale of needed capacity is an astronomical 1,613 GW—around 146 percent of current U.S. generation capacity—all of which would need to consist of new zero-carbon energy sources. Using green hydrogen for industrial energy uses such as process heating is substantially less efficient than direct electrification and imposes an unnecessary burden on the electricity system when the same goal can be met via direct electrification.

BIOENERGY LAND USE REQUIREMENTS FOR INDUSTRY

The IZEC estimates the amount of agricultural land that would be required to produce the bioenergy used by industry.[vii] The IZEC provides this estimate in two formats: in millions of hectares (Figure 7) and as a percentage of the agricultural land in the modeled region (Figure 8). (Agricultural land includes all land used for growing crops, animal pasture and rangelands, meadows, and fallow land. It excludes non-orchard forests, mountains, deserts, water bodies, etc.) Currently, around 4.3 percent of agricultural land is used for bioenergy demands, such as growing corn to make ethanol transportation fuel. Increasing the usage of bioenergy modestly, as in the High Direct Electrification scenario—which relies on bioenergy for 45 percent of feedstock production—would require 6.8 percent of the U.S.'s agricultural land. In the High Bioenergy scenario, the land use requirements become daunting, necessitating 21.5 percent of U.S. agricultural land (around 87 million hectares, about 25 percent larger than the state of Texas). These figures are only attainable with dramatic changes to today's food demand (particularly substituting more plant products for animal products, thereby freeing up acreage without reducing calorie/protein supply), irrigation and fertilizer to turn some pasture and rangeland into cropland, and investment in capital equipment to turn the crops into usable fuels and feedstocks. Such large-scale changes to U.S. land use and the U.S. food system seem unlikely, so encouraging growth in bioenergy use is risky, as the real-world effect may be to increase bioenergy imports and drive deforestation in countries supplying that bioenergy.[16]

[vii] Today's bioenergy use by industry largely consists of byproducts of the pulp and paper and the wood and wood products industries. These byproducts come from forest or timber lands, not agricultural lands (and much of the harvested material from those lands went into paper and wood products, rather than serving as bioenergy). In contrast, it is assumed that expanded bioenergy production to meet industrial energy or feedstock needs would be derived from dedicated bioenergy crops (sugar beet, sugarcane, or maize) on agricultural lands, which offers benefits such as rapid growth, ease of harvesting, ease of processing, and high energy density. Therefore, per hectare, the land area involved in *existing* bioenergy production may not resemble the land involved in *expanded* bioenergy production. For simplicity and comparability, the calculator expresses bioenergy demand in terms of the hectares that would be required if all bioenergy had been produced via dedicated bioenergy crops on agricultural lands.

Figure 7. Bioenergy land requirements for the U.S. industrial sector in hectares

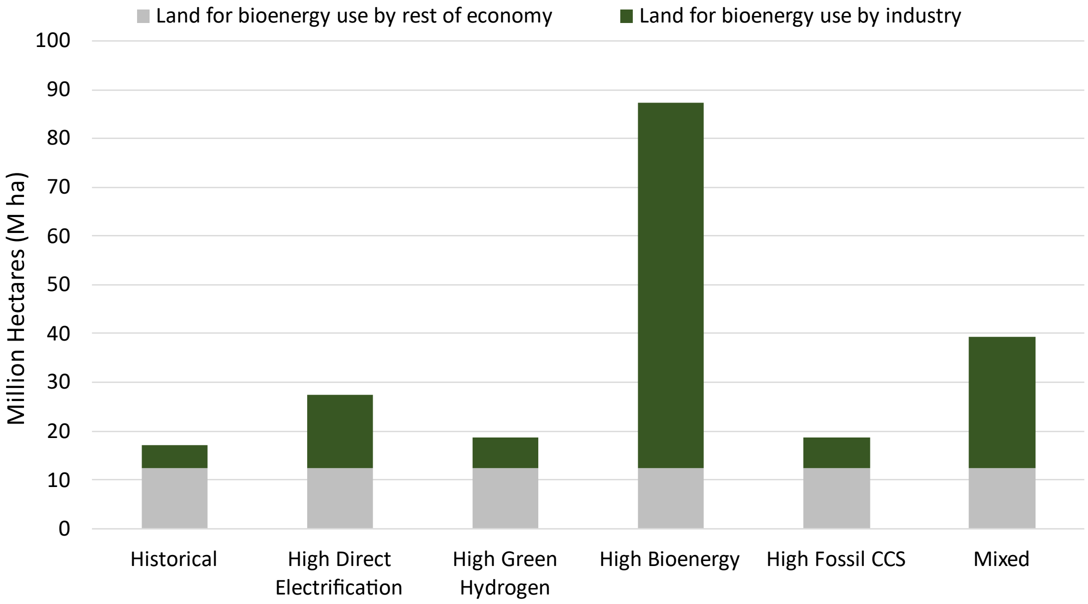
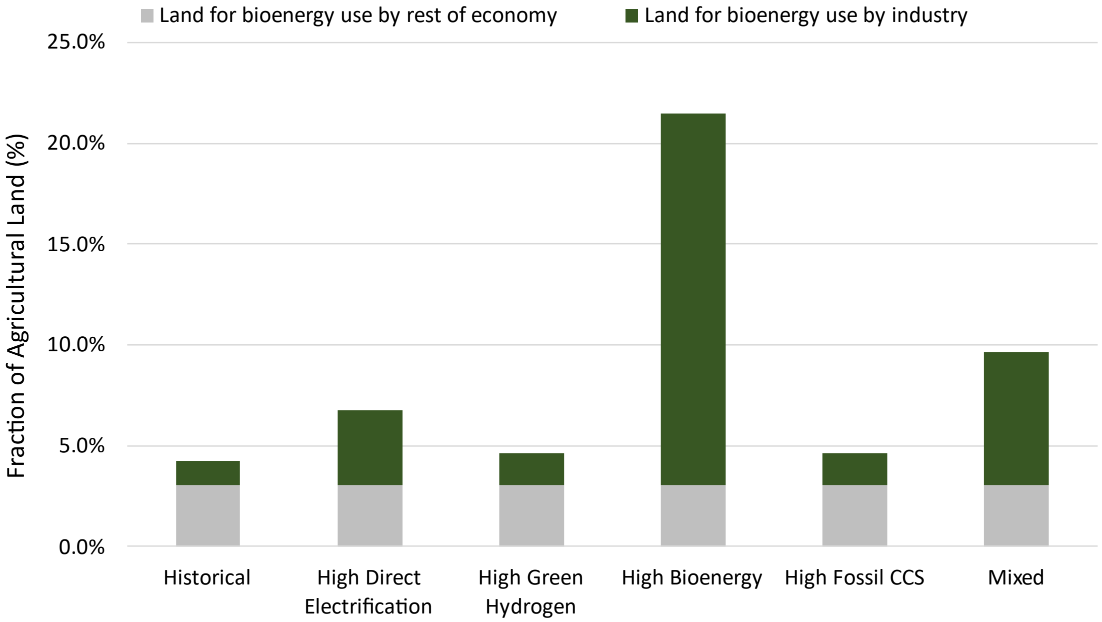


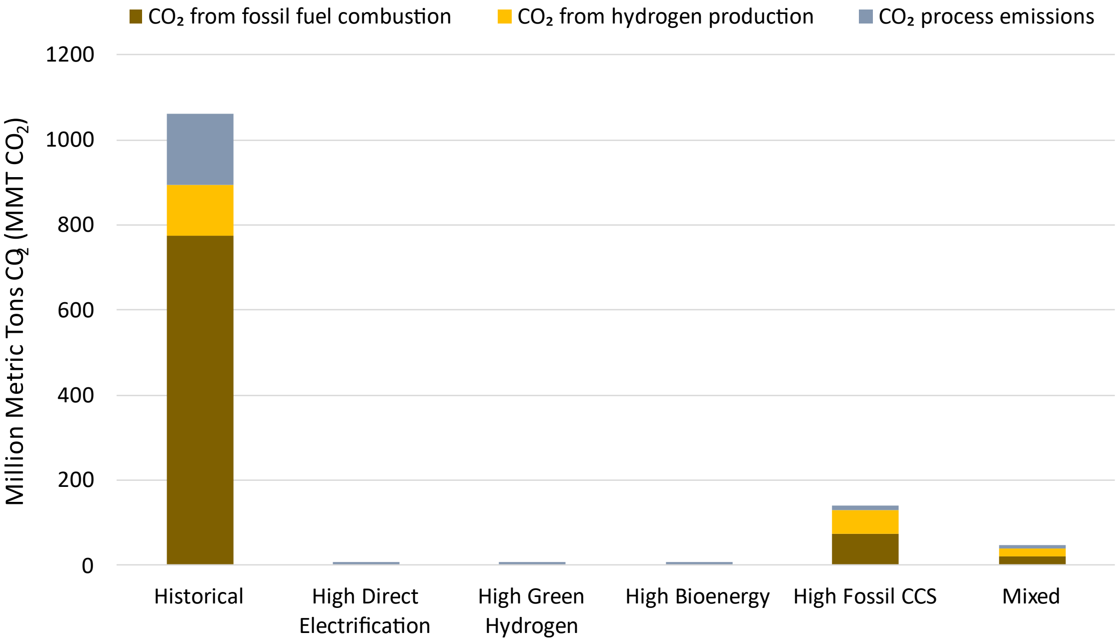
Figure 8. Bioenergy land requirements for the U.S. industrial sector as a share of agricultural land



CO_2 EMISSIONS FROM INDUSTRY

The IZEC calculates industrial CO_2 emissions (Figure 9). None of the built-in scenarios include any unabated fossil fuel use, so the only CO_2 emissions are from CCS, which is assumed to capture 90 percent of the CO_2 in an exhaust stream (the upper end of the performance range of today's commercial technology).[17] Naturally, this pushes emissions higher in the High Fossil CCS scenario, though they are still only 13.2 percent of the U.S. industrial sector's historical emissions.

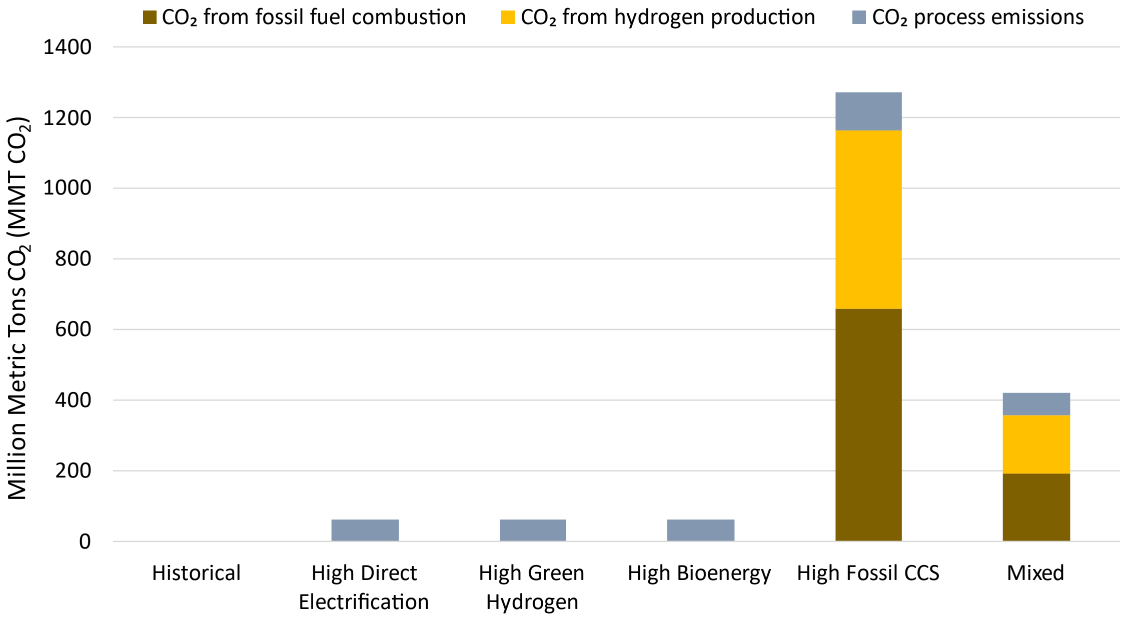
Figure 9. CO_2 emissions for the U.S. industrial sector



CO_2 STORED UNDERGROUND FROM INDUSTRIAL CCS

The IZEC calculates the amount of captured CO_2 that needs to be stored underground in millions of metric tons (Figure 10). However, reporting a large quantity of CO_2 in mass units does not provide an intuitive sense of the expense or difficulty of storing this quantity of CO_2 annually. Therefore, the IZEC calculates the volume that CO_2 would occupy after being pressurized for injection into underground storage and compares this with the volume of oil produced by the global oil industry (Figure 11). The comparison with the global oil industry facilitates a rough estimate of the capital cost involved in deploying CCS equipment and infrastructure.

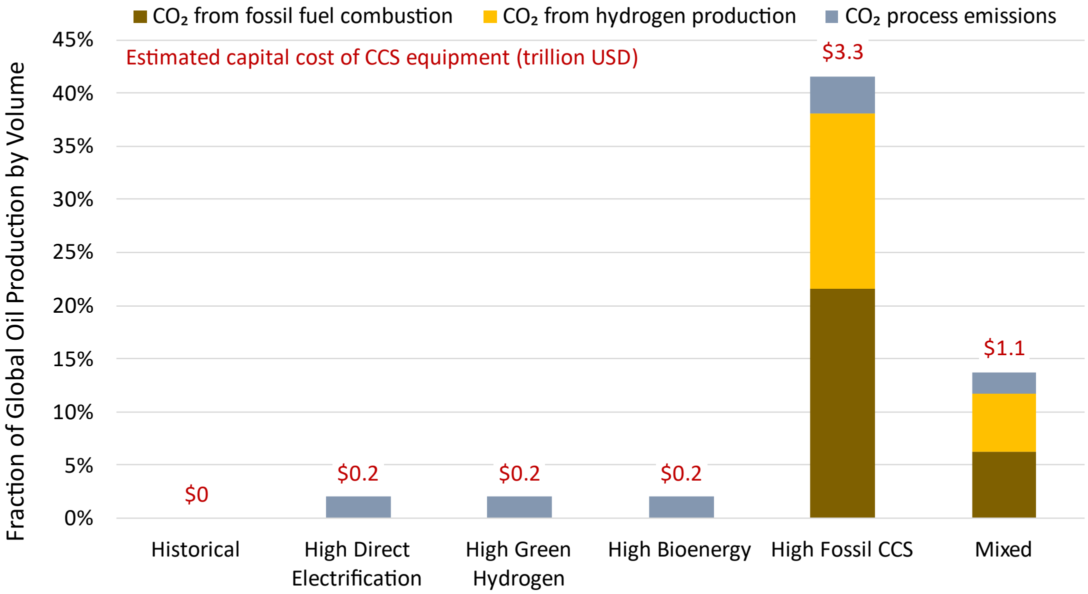
Figure 10. Mass of CO_2 stored underground from CCS in the U.S. industrial sector



The capital investment of the global oil industry (pipelines, tankers, wells, etc.) from 2010 to 2022 was $8 trillion. This excludes the cost of any pre-2010 assets still in use (and excludes natural gas-related assets).[18] Storing the equivalent amount of fluid underground is like running all these pipelines, tankers, platforms, and wellheads backwards to take CO_2 from the point of combustion and put it back into geological formations. Unlike oil production, CO_2 storage does not produce a salable product in the end, so there is no built-in economic incentive to do this. This scenario suggests the U.S. would need to make trillions of dollars in capital investments to capture, compress, transport, and inject CO_2, with ongoing capital expenses similar to a proportionate share of the oil industry's ongoing expenses to replace worn equipment and develop new geological formations. (The cost of energy to power the carbon capture, transport, and storage process would be additional.)

In the High Fossil CCS scenario, industry sector CO_2 stored by the U.S. represents 40 percent of the volume of *global* oil industry production, with estimated capital investment needs of $3.3 trillion. (The equivalent figure for China is 100 percent of the global oil industry, and the "World" region is more than 250 percent of the global oil industry.) Even the Mixed scenario with its balanced approach relies on enough CCS to carry capital costs of $1.1 trillion (Figure 11). The likely cost in the U.S. High Direct Electrification scenario is $0.2 trillion, on par with focused green hydrogen and bioenergy strategies but without their pitfalls.

Figure 11. Volume of CO_2 stored underground from CCS in the U.S. industrial sector, as a fraction of global oil production and estimated associated capital expenses



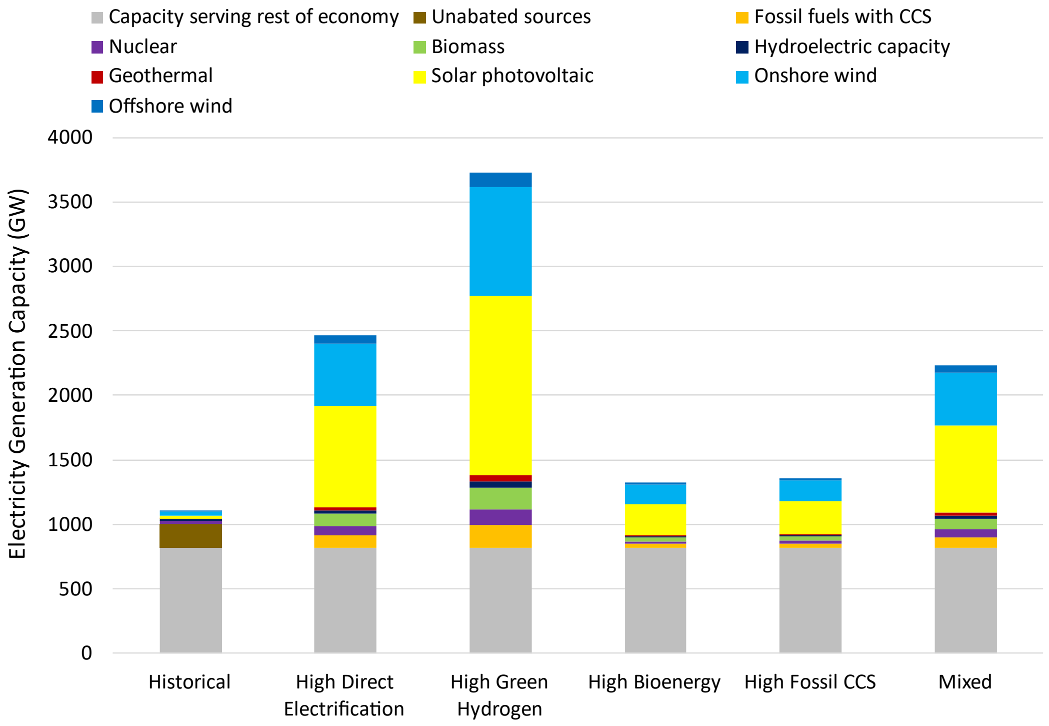
REQUIRED ELECTRICITY CAPACITY

The IZEC displays the power plant capacity required to supply electricity to the modeled region (Figure 12). The types of plants used to meet demand are based on user-specified configuration settings and are not endogenously determined by the model.[viii,ix] The percentage increase in required power plant capacity can be higher or lower than the percentage increase in electricity demand depending on whether the average capacity factor (the fraction of the time a power plant is generating electricity) of the user-selected power plant mix is higher or lower than the average capacity factor of the plant mix in the historical year. Solar and wind tend to have lower capacity factors than other plant types due to the variability of sunlight and wind, so mixes that rely heavily on wind and solar tend to have higher capacity requirements than configurations that rely more heavily on other energy sources. Note that the simulator accounts for a system reserve margin, the amount of extra capacity utilities seek to have available to ensure reliability.

[viii] The settings used here are 30 percent onshore wind, 5 percent offshore wind, 30 percent solar photovoltaic, 3 percent geothermal, 2 percent hydroelectric, 10 percent biomass, 10 percent nuclear, and 10 percent fossil fuels with CCS.

[ix] Unlike the IZEC, the Energy Policy Simulator (see footnote iii) endogenously determines which power plants to construct to meet economic, environmental, and reliability criteria. That model can be used if this capability is needed.

Figure 12. U.S. electricity capacity required by the industrial sector (and rest of the economy in gray)

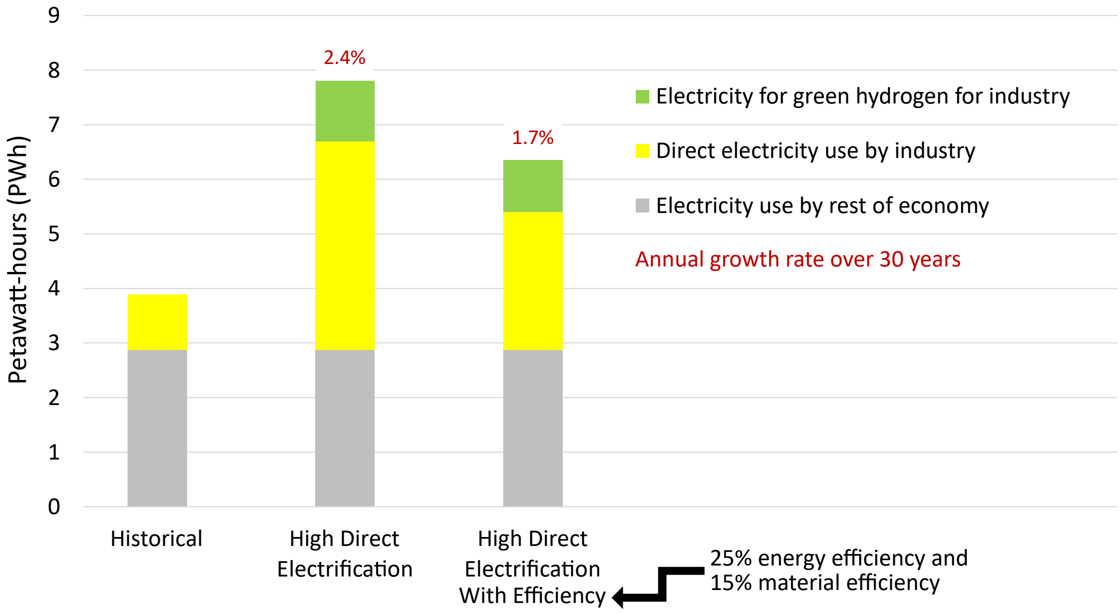


Ending fossil fuel use by the industrial sector is likely to require a significant increase in generation capacity. These requirements can be reduced through energy efficiency and material efficiency improvements, discussed in the next section.

EFFECT OF EFFICIENCY

The figures above depict the built-in scenarios with no energy or material efficiency improvements applied, to aid in comparing the scenario results to the historical data. However, energy and material efficiency are powerful measures that can make the transition to clean industry faster and cheaper. Efficiency reduces the need for all resource types (clean electricity, hydrogen, bioenergy, and CCS capacity). As an example, Figure 13 shows how a 25 percent energy efficiency improvement and a 15 percent material efficiency improvement affect electricity demand for the High Direct Electrification scenario. These efficiency improvements lower the growth in electricity demand to 64 percent, down from a 102 percent increase without efficiency improvements. Notably, this is less electricity demand than the Mixed scenario without efficiency improvements (see Figure 4). Over the next 30 years, this equates to just a 1.7 percent annual growth rate of delivered electricity to fully decarbonize all industrial energy and feedstock use.

Figure 13. The effect of energy efficiency and material efficiency on electricity demand



This example shows the High Direct Electrification scenario with and without a 25 percent energy efficiency and a 15 percent material efficiency improvement.

No matter which energy sources are chosen to supply industrial heat and feedstocks, energy efficiency and material efficiency are critical aspects of a rapid and cost-effective transition to clean industry.

INSIGHTS AND PATHWAY RECOMMENDATIONS

Comparing the scenarios outlined above offers several lessons. First, green hydrogen should be reserved for only the highest-priority use cases, such as forming ammonia and petrochemicals or chemically reducing iron ore. Burning hydrogen for energy or heat produces local air pollution and is inefficient, which results in problematically large resource requirements for clean electricity generation. Similarly, bioenergy and CCS become unrealistic solutions with prohibitive resource requirements when either is relied upon too heavily.

Second, direct electrification should be the main source of industrial heat. Electrical technologies are capable of producing heat at any temperature required by industry[19] and are especially efficient at low temperatures, where industrial heat pumps can be used. While the High Direct Electrification scenario still requires a large amount of clean electricity, this can be accommodated by growing the grid with renewable sources to meet demand at an annual growth rate that falls well below the average growth rate in the 20th century. Industrial facilities may in fact be able to help the grid integrate more renewables by serving as flexible loads (i.e., by buying electricity when it is cheap and not buying electricity, or even selling it to the grid, when electricity is expensive). Additionally, some industrial facilities may develop dedicated, off-grid wind and solar resources with thermal storage to buffer variability, putting less demand on the grid. Using thermal batteries to support direct industrial electrification with renewables can make economic sense, and detailed studies have shown the technology's viability in both the U.S.[1] and China.[20]

Third, energy and material efficiency are essential to make the transition to clean industry faster and cheaper. The IZEC shows that even moderate efficiency gains can transform formerly daunting resource requirements into feasible targets, creating new possibilities for industrial decarbonization. These approaches help society to avoid running into resource constraints (such as the rate at which clean electricity can be deployed, sustainable bioenergy can be grown, or CCS equipment can be purchased and installed). Efficiency is also effective at reducing energy bills and—until the industrial energy system is decarbonized—reducing CO_2 emissions. There remains significant technical headroom to improve efficiency technologies.[9,10]

FUTURE DIRECTIONS

The IZEC provides an intuitive yet detailed look at the resource requirements for decarbonizing the industrial sector across many key regions. Future modeling efforts could build upon this framework. For instance, the IZEC uses the best available information for today's technologies (e.g., electrolyzers) but makes no assumptions or projections about future improvements. Emerging but nascent energy resource approaches like enhanced geothermal systems (i.e., using geothermal heat directly in an industrial process) could provide additional avenues for industrial decarbonization and could be incorporated into the IZEC when they reach commercial viability. Building in more detailed forecasting and adding a time dimension to the model would better capture technological change and enable users to explore scenarios where technologies grow at different rates, or where one technology grows for a time before being displaced by a different technology. Another key improvement would be to capture changes in demand for industrial products. The IZEC only considers the resource requirements to decarbonize the industrial sector at a historical level of activity. However, in countries that are growing and industrializing, demand for industrial products may increase, which could increase the resource requirements for industrial decarbonization. A third potential improvement would allow users to customize energy use and efficiency settings individually for specific industries (such as the cement industry or the chemicals industry) rather than apply these settings to the industrial sector as a whole.

CONCLUSION

Realistic pathways exist to decarbonize industry in the main industrial regions and globally. However, the sheer magnitude of industrial energy demand can be surprising, and if a decarbonization pathway is chosen without awareness of its implied resource requirements, society may encounter resource constraints that hamper the transition to clean industry. The IZEC makes the process of testing industrial decarbonization pathways and estimating resource requirements simple and efficient, helping policymakers and other stakeholders understand key trade-offs. An approach that prioritizes energy and material efficiency, emphasizes direct electrification for most industrial heating (with a small role for bioenergy and/or fossil CCS in some regions), and employs a mix of hydrogen and bioenergy to form chemical feedstocks can be an effective way to navigate these trade-offs and avoid resource constraints.

ACKNOWLEDGEMENTS

We wish to thank the reviewers of the IZEC: Al Armendariz, Emily Bruns, Kathleen Yip, Megan Raisle, Radhika Lalit, Anna Johnson, Dan Esposito, Eric Gimon, Jack Conness, Sara Baldwin, Ali Hasanbeigi, Anand Gopal, and Sonia Aggarwal.

REFERENCES

1. Jeffrey Rissman and Eric Gimon, *Industrial Thermal Batteries: Decarbonizing U.S. Industry While Supporting a High-Renewables Grid* (Energy Innovation LLC, July 2023), https://energyinnovation.org/wp-content/uploads/2023/07/2023-07-13-Industrial-Thermal-Batteries-Report-v133.pdf.
2. International Energy Agency, "World Energy Balances Data Service," July 29, 2021, https://www.iea.org/data-and-statistics/data-product/world-energy-balances.
3. Jeffrey Rissman, *Zero-Carbon Industry: Transformative Technologies and Policies to Achieve Sustainable Prosperity*, (New York: Columbia University Press, 2024), https://zerocarbonindustry.com/.
4. Trieu Mai et al., *Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States* (National Renewable Energy Laboratory, June 2018), https://www.nrel.gov/docs/fy18osti/71500.pdf.
5. International Energy Agency, *World Energy Outlook 2023,* October 2023, https://iea.blob.core.windows.net/assets/614bb748-dc5e-440b-966a-adae9ea022fe/WorldEnergyOutlook2023.pdf.
6. International Renewable Energy Agency, *World Energy Transitions Outlook: 1.5°C Pathway*, 2021, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_World_Energy_Transitions_Outlook_2021.pdf?rev=71105a4b8682418297cd220c007da1b9&hash=4EC5B011E599B28CE4A5301451D225A9.

7. World Resources Institute, "Climate Watch," 2022, https://www.climatewatchdata.org.
8. Energy Innovation LLC, "The Energy Policy Simulator," https://energypolicy.solutions/.
9. International Energy Agency, *Energy Efficiency 2022*, 2022, https://iea.blob.core.windows.net/assets/7741739e-8e7f-4afa-a77f-49dadd51cb52/EnergyEfficiency2022.pdf.
10. Julian M. Allwood and Jonathan M. Cullen, *Sustainable Materials Without the Hot Air* (Cambridge, England: UIT Cambridge Ltd., 2015).
11. U.S. Energy Information Administration, "April 2024 Monthly Energy Review, Table 7.1," April 2024, https://www.eia.gov/totalenergy/data/monthly/.
12. Wanying Wu, "Technological Evolution of Large-Scale Blue Hydrogen Production toward the U.S. Hydrogen Energy Earthshot," *Nature Communications* 15 (2024).
13. Robert W. Howarth and Mark Z. Jacobson, "How Green Is Blue Hydrogen?," *Energy Science & Engineering* (August 12, 2021), https://doi.org/10.1002/ese3.956.
14. Sam Meredith, "A Global Gold Rush for Buried Hydrogen Is Underway — as Hype Builds over Its Clean Energy Potential," *CNBC*, March 26, 2024, https://www.cnbc.com/2024/03/26/natural-hydrogen-a-new-gold-rush-for-a-potential-clean-energy-source.html.
15. International Energy Agency, *The Future of Hydrogen*, June 14, 2019, https://www.iea.org/topics/hydrogen/.
16. Yan Gao, Margaret Skutsch, Omar Masera, and Pablo Pacheco, *A Global Analysis of Deforestation Due to Biofuel Development* (Center for International Forestry Research, 2011), https://www.cifor-icraf.org/publications/pdf_files/WPapers/WP68Pacheco.pdf.
17. International Energy Agency, *CCUS in Clean Energy Transitions,* 2020, https://www.iea.org/reports/ccus-in-clean-energy-transitions.
18. International Energy Agency, *World Energy Investment 2023*, May 2023, https://iea.blob.core.windows.net/assets/8834d3af-af60-4df0-9643-72e2684f7221/WorldEnergyInvestment2023.pdf.
19. Silvia Madeddu et al., "The CO2 Reduction Potential for the European Industry via Direct Electrification of Heat Supply (Power-to-Heat)," *Environmental Research Letters* 15, no. 12 (November 2020): 124004, https://doi.org/10.1088/1748-9326/abbd02.
20. Nikhil Sawe, Hongyou Yu, Jeff Rissman, Zhiyu Tian, and Nan Zhou, C*lean Industry in China: A Techno-Economic Comparison of Electrified Heat Technologies, Barriers, and Policy Options* (Lawrence Berkeley National Laboratory, 2024), https://escholarship.org/uc/item/7tg4x3n3.