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ELECTRIFICATION (J LOGAN, SECTION EDITOR)

Electrification of Industry: Potential, Challenges and Outlook

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Abstract

Purpose of the Review Industry is one of the most difficult sectors to decarbonize. With the rapidly falling cost of solar PV, wind power, and battery storage, industry electrification coupled with renewable electricity supply has the potential to be a key pathway to achieve industry decarbonization. This paper summarizes the latest research on the possibility of electrification of the industry sector.

Recent Findings The transition to industry electrification would entail major changes in the energy system: large scale increases in renewable electricity or nuclear power supplies, the expansion of electricity transmission and distribution networks, completely different end-use technologies for process heating, and new infrastructure for distributing and dispensing hydrogen. Thus, aggressive and sustained supportive policies and much wider research, development, demonstration, and deployment activities are required to meet net zero carbon emissions goals in the industrial sector.

Summary Existing economically competitive electrified industrial processes (such as electric arc furnaces for secondary steelmaking from scrap steel), coupled with zero-carbon electricity sources can sharply reduce greenhouse gas emissions (GHG) compared to manufacturing processes that rely on fossil fuels. Fuel switching in industry from fossil fuel–based process heating to electrified heat can offer many product and productivity benefits, but operating costs in general are much higher than fossil fuel-based heating. Either much lower costs of electricity and energy storage are required and/or new, cost-competitive electric-technology applications are needed to enable further electrification of industry. Indirect electrification i.e., hydrogen production via water electrolysis is another complimentary technology reliant on electricity. Hydrogen can be used as an energy carrier, industrial feedstock for products and fuels, or for long-duration energy storage, and thus can also play a key role in industry decarbonization when the hydrogen is produced from zero-carbon electricity and/or with carbon capture and storage. As with direct electrification, cost is the key barrier for the deployment of hydrogen resources.

Keywords Industry electrification · Indirect electrification · Industry decarbonization · Hydrogen · Water electrolysis · Synthetic natural gas · Renewable heating · Electro-winning

Introduction

The costs of variable renewable electricity and solar photovoltaics (PV) in particular have fallen sharply over the last 10 years. The electrification of an economy coupled with greater supplies of low- to zero-carbon electricity sources can sharply reduce greenhouse gas emissions and has been an increasing area of focus for technology research, development, demonstrations, and deployment (RDD&D) and supporting policies in many regions of the world.

Industry accounts for more than a third of the global energy use [1] and is the most challenging sector to electrify due to a combination of factors: heterogeneous end-uses, cost sensitivity, high-temperature, and continuous process requirements. In China industry contributes to over 70% of energy-related greenhouse gas (GHG) emissions [2] and industrial emissions are projected to grow from 45 to 60% in India by 2050 [3]. High to very high temperatures (> 500 °C) account for over half of industrial heat demand and very high temperature (> 1000 °C) are 33% of demand [4]. It is technically possible to electrify high temperature process heating [5]; however, replacing current fossil fuel-based heating with electricity is generally not cost-effective with the current price spread between fossil fuels and electricity. Other barriers to electrification are discussed below.

This article is part of the Topical Collection on *Electrification*

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Many studies indicate that the decarbonization of industry will be difficult with any single technology approach or strategy. Full decarbonization or near zero emissions will most likely require a set of approaches including demand reduction through material use reduction and/or designs for material reuse; energy efficiency; fuel switching to low or zero carbon fuels (i.e., from natural gas to renewable natural gas); carbon capture; storage and use (CCUS); and electrification.

We begin this chapter with a description of global energy trends, followed by brief discussions of direct and indirect electrification technologies, benefits of electrification, key challenges and barriers, the interaction of electrification with renewable electricity and grid integration, some competing approaches for industry decarbonization, and finally some outlook statements and suggested areas for future research and policy development.

Global Trends in Industrial Energy Use

Globally, industrial final energy consumption represents 37% of total final energy consumption. While in most other sectors of the economy, end-use electricity consumption is increasing rapidly, industry still relies heavily on direct fossil fuel combustion, representing 60% in 2016 [1]. Industry's share of electricity was only 27% in 2016, surpassed by coal (30% in 2016), driven by industrialization in China and India [6]. The industry sector is considered the most difficult to electrify due to the need of high heat for transforming raw materials into more refined materials. The share of electricity within industry varies widely, from the lowest share of 14% in non-metallic minerals (mostly cement, glass, and ceramics industries) to the highest share of 65% in non-ferrous metals, composed mostly of primary aluminum production that uses electrolysis to reduce aluminum from aluminum oxide (Fig. 1).

Electricity is mostly used for machine drives, to provide electrical control of industrial processes, and for refrigeration and process cooling. Only a small share is used for process heat. For example, in the US, machine drives, which are primarily electric motors, pumps, and fans, account for about half of the manufacturing sector's delivered electricity, and process heat represents only 14.4% of electricity consumption in the sector [7].

The basic metal sector (steel industry), chemicals and petrochemicals, and the non-metallic mineral sector (cement and glass industry) require a significant portion of high temperature heat. These requirements are difficult to replace with electrified heating. Lower temperature heat often provided by steam or direct firing can be substituted with commercialized electric technologies (e.g., electric boilers and heat pumps).

Direct Electrification in Industry

Similar to electrification in residential and commercial buildings, industrial electrification primarily involves substituting heat generated from combustion for heat generated from an electrical source. Unlike the buildings sectors, however, industry has a much wider range of required temperatures and possible technologies. Industrial electric technologies can be grouped by the method that they generate heat [8]. Electromagnetic induction technologies, such as induction furnaces used in the fabricated metal products and primary metals industries, use a changing magnetic field to heat electrically-conductive materials. Dielectric heating technologies, such as microwave heating and radio frequency heating used in the food and beverage and plastics and rubber industries, use high frequency electromagnetic radiation to heat materials. Resistive heating technologies provide heat using either a heating element or the resistance of the material to be heated, as in the case of certain types of glass production. Still

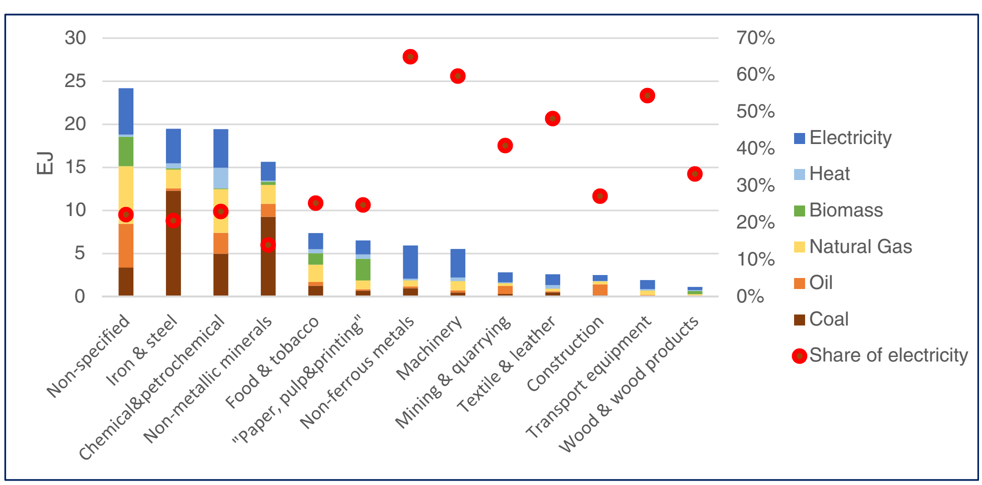

Fig. 1. Global industry final energy use per sub-sector in 2016. Source: [1]

other means of electric heating include electric arc, infrared radiation, electron beam, and plasma heating.

Other industrial electric technologies may use electricity as an alternative to directly provide heat. For example, electric technologies may use mechanical work, as in mechanical vapor recompression heat pumps, or to separate materials using selectively permeable membranes. Other means of material separation use electric potential gradients (e.g., electrodialysis) or electrolysis (e.g., electrolytic refining of alumina and copper).

Indirect Electrification - Hydrogen Produced by Electrolysis

Hydrogen is a highly flexible element that can be used as an energy carrier, an industrial feedstock, and for energy storage, and it can span across different energy sectors (electricity, transportation, industry). Hydrogen is most commonly produced from the steam methane reforming (SMR) which produces CO_2 emissions. Carbon capture can also be employed in the SMR process to sequester or utilize the co-generated CO_2. Alternatively, hydrogen production from water electrolysis using renewable electricity such as solar PV and wind (renewable hydrogen) or nuclear power does not produce GHG emissions. This is an example of what is commonly called power-to-gas (PtG), or more generically, power-to-x (PtX).

Similarly, combustion of H_2 or chemical conversion of H_2 and O_2 (e.g., from air) in a fuel cell system to produce electricity does not produce any CO_2 and has very low NOx emissions and negligible SOx emissions. Thus, H_2 has the potential of zero GHG from production to end-use application assuming zero-carbon electricity is used for its production as well as any electricity required for storage, distribution, and dispensing (e.g., compression pumps and refrigeration cooling systems).

H_2 can be injected to natural gas pipeline directly at low volumetric fractions (typically less than 10–15%) or combined with CO_2 to form synthetic natural gas (SNG) in a process called methanation [9]. Currently, there are 63 PtG projects in operation in Europe [10]. Renewable H_2 can also be used as a feedstock or input for chemical synthesis (e.g., ammonia), petroleum refining (e.g. hydrogenation), and for the direct reduction of iron ore [11•]. The advantage of a PtG system producing synthetic natural gas is that the currently existing natural gas grid could be utilized and that end-use equipment using natural gas as a combustion fuel for process heating or steam systems can be used. The net CO_2 impact of synthetic fuels such as SNG depends on the source of CO_2. For example, CO_2 from biogas/biofuels production or from direct air capture would be most beneficial for near-full decarbonization [12•].

Pure H_2 could also be delivered in an H_2 pipeline but the existing natural gas pipelines would either have to be upgraded to be compatible with H_2 or a parallel pipeline system would have to be built, and end-uses would need modification for H_2 combustion.

In general, the use of renewable H_2 is limited by the high cost for hydrogen production and the infrastructure required to generate, compress, store, and distribute and dispense hydrogen. The cost of SNG produced from renewable hydrogen is four to twenty times more expensive than conventional natural gas [9] and will be more economically competitive with much lower cost electrolysis systems (e.g., less than $250/kW) and low costs of input electricity (e.g. less than $30/MWh) at high capacity factors [13].

Benefits and Challenges of Electrification

Overall benefits of electrification in industry can include the provision of grid support and ancillary services; improving electric load factors and potentially lowering costs per delivered kWh; flexibility for integration of variable electric resources; and synergies with solar PV, electric vehicles, and storage [14].

Electrification benefits for industrial processing can include non-energy benefits, such as product quality, product yield, process time, process controllability, process flexibility, and safety. For example, non-energy benefits in induction heating include higher yield, faster startup, better product quality, enhanced flexibility, compact installation with no space required for fuel storage and handling, and a better working environment for workers with no combustion emissions and less waste heat [15]. Note that these benefits are process- and product-specific and need more extensive quantification.

Challenges and barriers to industry electrification are similar in a sense to those that face the adoption of deep energy efficiency measures but are compounded for direct electrification because of the need for new process heating equipment for end-use applications such as drying, curing, calcining, and melting. These challenges [14] include the following:

1. Fuel and other operating costs: "own-use" fuel[1] and low natural gas costs are hard to overcome with direct electrification often having higher operating costs
2. Capital costs of fuel-switching
3. Existing regulations and policies that may favor one fuel over another
4. Electric delivery infrastructure costs and constraints
5. Risk aversion in industry

[1] "Own-use" fuel refers to fuel that is produced during an industrial process and subsequently used as a fuel or as a feedstock. For example, blast furnace gas produced during the combustion of coke in the iron and steel industry is typically recovered and used as a fuel within the plant. Similarly, refinery fuel gas (a complex combination of light gases including nitrogen, hydrogen, and hydrocarbons) is produced from a refinery catalytic cracker unit and can be used for refinery own-use.

6. Availability of electric process equipment in industry and lack of engineering knowledge or capacity to redesign manufacturing process lines and/or process integration[2]
7. Heterogeneity of industrial sectors
8. High temperature processes due to their higher energy costs relative to industries with lower process temperatures and are often found in low-margin sectors (e.g., cement, iron and steel, and glass)
9. If intermittent renewable electricity is used, then low cost power may only be available for some hours of the year during times of overproduction or very low overall demand, and process equipment capacity factors will be low. This will drive up the cost of production and require more flexible modes of operation and potentially modified equipment designs.

As an example of some of the above challenges facing electrification even for moderate process temperatures, Campbell's Soup Company reports that for tomato processing, electrification of steam generation would require major investments in electrical infrastructure and electricity costs that are much lower than what they are currently to be competitive.[3]

General supportive policies include levying a price on carbon, either through carbon taxes or cap and trade policies and developing sectoral policies. One policy of note is the Buy Clean California Act (AB 262), enacted in 2018. This statue sets procurement standards for low-carbon construction materials (e.g., steel rebar, structural steel, flat glass, etc.) used for state infrastructure projects and could incentivize suppliers of these products to reduce the carbon intensity of their products [16].

Note that even if all the above barriers are overcome in a region such as California, a critical additional barrier for regional industry decarbonization is the competitiveness disadvantage of moving to potentially higher cost production methods for materials or products which are served by a global market. Thus, additional support and policies for this transition to insulate domestic manufacturers from international competition may be needed [12•].

Distributed Energy and Grid Integration Considerations

As the price of solar PV decreases, industrial electrification via distributed generation is an emerging area of analysis. Pérez-Aparicio et al. [17] and Meyers et al. [18•] developed methodologies to compare the costs of solar thermal technologies with PV resistance heating (resistance heating in combination with a heat pump in the case of Pérez-Aparicio et al.) The methodology developed by Meyers et al. [18•] was adapted to the comparison of solar thermal technologies and grid-powered heat pumps [19]. The authors assume the process heating demands do not exceed temperatures of 200 °C in each of these three examples.

Electrification of industry provides opportunities to change the way the sector interacts with the electric grid, particularly with an increasing penetration of variable renewable energy. The ability of industry to implement and benefit from a more dynamic or "smart" interaction with the grid and provide grid services is in part determined by its production processes and their tolerance for interruption. Shoreh et al. [20] survey applications of demand response in industry and focus on aluminum, steel, cement, and refrigeration. Dorreen et al. [21] describe the ability to control heat loss from aluminum reduction cells, which increases amperage flexibility of smelting operations by controlling heat loss from aluminum reduction cells. Regulation services may be provided by variable frequency drives, induction furnaces, and electrolysis processes; non-spinning reserves can be provided by electrolysis, electric arc furnaces, mechanical pulp production, and cement milling [20].

Smart manufacturing systems with dynamic production scheduling are another approach for industry to adapt to electrification. Sharma et al. [22] develop a scheduling model for simultaneously optimizing the energy cost and greenhouse gas emissions under a time-varying electricity price and find that the benefits of optimization are dependent on production output.

Survey of Recent Literature Related to Industry Electrification and Decarbonization

Table 1 presents a summary of recent industry electrification and decarbonization studies. Industrial electrification may play a significant role in decarbonization strategies. The United States Mid-Century Strategy Report for reducing GHG emissions identifies roughly half of the 14 quadrillion BTUs of manufacturing energy use in 2050 to be low-carbon electricity [23]. No specific industries or technologies are discussed, however. Conversely, the European Union examined electrification technologies by industry (e.g., electrolysis of iron ore, electric boilers in chemicals manufacturing, electric kilns in cement manufacturing) in supporting analysis for its 2050 decarbonization strategy [24, 25].

Two national electrification potential studies have been published since the United States Mid-Century Strategy Report and both indicate relatively small potentials for the industrial sector, although neither was conducted in the context of achieving near-zero GHG emissions. In Mai et al. [28] the electricity share of final industry energy demand in 2050

[2] Note for some industrial processes, fossil fuel is used as both a fuel and as a material input, e.g., in extracting iron from iron ore using a blast furnace, coke is produced by heating coal in the absence of air and provides both the reducing agent for the reaction and also the heat source.
[3] Accessed from https://ww3.arb.ca.gov/cc/scopingplan/meetings/070819/panel2-2_campbellssoup.pdf, August 2, 2019.

Table 1 Key recent studies on industry electrification

Reference	Title	Key results
EPRI 2018 [26]	U.S. National Electrification Assessment	Estimates industry electrification potential for 2050 in the U.S. The most aggressive scenario shows the electricity share of industry final energy demand increasing to about 45% in 2050 from the reference scenario of about 27%.
Lechtenböhmer et al. 2016 [27••]	Decarbonising the energy intensive basic materials industry through electrification–implications for future EU electricity demand	Assuming electro-thermal technologies for heating and electrolysis for material separations replace all energy requirements for eight energy intensive industries in the European Union, a four-fold increase in electricity demand is estimated, from 125 to 512 TWh in 2050. Estimates are also provided for the electricity required to produce hydrocarbons from H_2, CO_2, and syngas for fuels and feedstocks (demand increases to 1201 TWh).
Mai et al. 2018 [28]	Electrification Futures Study: scenarios of Electric Technology Adoption and Power Consumption for the United States	Estimates industry electrification potential for 2050 in the U.S. For the most aggressive scenario, industry increases its electricity share of final energy demand to 27% in 2050 compared to the reference scenario of 23%.
Deason et al. 2017 [14]	Electrification of buildings and industry in the United States. Drivers, barriers, prospects, and policy approaches	This study reviews the possible benefits and barriers to greater electrification in industry and buildings, the technical potential for electrification, and policy and programmatic approaches for regions that want to encourage a more rapid transition to beneficial electrification.
Material Economics 2019 [29]	Industrial Transformation 2050 Pathways to Net-zero emissions from EU heavy industry	Several pathways are described to reach net zero emissions including new production processes (e.g., electrification), increased material efficiency, material recirculation and carbon capture, storage and use. Average cost estimated at 75–91 EUR per ton of CO_2.
Philibert 2019 [12•]	Direct and indirect electrification of industry and beyond	Summarizes trends in renewable energy and hydrogen resources, electrification approaches in basic materials, and policy considerations for international markets and competitiveness.

increases from 23% in the reference case to 27% in the most aggressive scenario. The most aggressive scenario in EPRI [26] shows the electricity share of industry final energy demand increasing to about 45% in 2050 from the reference scenario of about 27%.

The EPRI study highlights the proprietary and integrated nature of industrial processes are among the barriers to change; that industrial electrification is driven by improved productivity, lower cost, lower emissions, worker safety, and many other non-energy benefits; that the move to electricity fuel switching will be driven by energy and environmental policies; and that industry electrification could provide opportunities for closer integration and optimization of the US energy system.

Khanna et al. [30] found that maximizing electrification using commercially available technologies in industries including steel, food and beverages, glass, and pulp and paper could increase the share of electrification of China's industry sector from 31% under business-as-usual assumptions to nearly 40% by 2050, from the current level of 20%.

Completely electrifying the industrial sector would require significant new electricity generation, even when electric technologies provide improved energy efficiency. Assuming electro-thermal technologies for heating and electrolysis for material separations replace all energy requirements of eight energy intensive industries in the European Union, Lechtenböhmer et al. [27••] estimate a 4-fold increase in electricity demand by 2050. Replacement of petroleum-derived fuels and feedstocks with H_2, CO_2, and syngas involves nearly ten times more electricity by 2050. The carbon required to produce replacement hydrocarbons is assumed to be either captured CO_2 from power plants, from the CO_2/CO portion of syngas ($CO_2/CO + H_2$), or from direct air-capture. The study assumes that high temperature processes in cement and glass can be fully electrified, but does not provide details regarding the transition, timing, implementation, process equipment, or economic costs of the transition.

The implications of electrolytic production of non-fossil feedstocks were analyzed in more detail by Palm, Nilsson, & Åhman [31•]. The authors estimate that switching the entire

European Union production of ethylene and propylene to electrolytic processes by 2050 would require roughly the equivalent of one-fourth the gross EU electricity production in 2012. Transitioning all EU plastics to electrolytic production would require between 1400 and 1900 TWh and could increase production costs by two to three times current costs.

VoltaChem—a consortium of European Union chemicals manufacturers—has begun technology road mapping and identifying RD&D activities in four key areas of electrification for the chemicals industry: producing or upgrading heat, producing hydrogen, synthesis of specialty chemicals, and synthesis of commodity chemicals [32]. The consortium envisions industrial scale heat pumps for electrochemical synthesis and decentralized facilities powered by distributed electricity generation.

The electrification of iron and steel production has several possible routes. The first route is to increase the circularity of the product flow in the economy by increasing recycling rates and use of secondary steel, which is produced in electric arc furnaces. Steel retains an extremely high overall recycling rate, which in 2014, stood at 86% [33]. However, the proportion of steel scrap used in crude steel production was only 35.5% worldwide last year as demand exceeded world scrap availability [34].

Direct electrification of primary steel is possible through electrolysis of iron ore (electro-winning). Several metals are produced via electrolysis, such as aluminum, nickel, and zinc [35]. However, electrolysis of iron ore has only been demonstrated at the laboratory scale [36, 37]. SIDERWIN is a project funded by a consortium of industries in the EU with the objective to validate the iron electrolysis technology with a fully integrated pilot [38]. Modeling scenarios show that electrolysis could become a dominant technology by 2035 if electricity prices are on the order of 43€/MWh [39]. In the United States the first industrial-scale use of molten oxide electrolysis (MOE) technology for the production of ferroalloys was recently funded [40].

Indirect electrification corresponds to using hydrogen as a reducing agent and energy carrier in direct reduction of iron ore instead of natural gas. Natural gas-based direct reduced iron (DRI) is a proven technology that represents about 5% of iron production globally [41]. In this process, natural gas is reformed into hydrogen (H_2) and carbon monoxide (CO) content, which are then used as reductant agent to produce iron. A study from Vogl et al. [42•] shows that steelmaking using hydrogen based DRI needs 3.48 MWh of electricity per tonne of liquid steel, mainly for the electrolyzer hydrogen production and becomes cost competitive with a carbon price of 34–68 €/tCO_2 and electricity price of 40 €/MWh. Bench-scale testing showed that reduction with hydrogen at temperatures of 1300 °C is feasible [43].

Several hydrogen-based pilot plants are being developed [44, 45]. A flash ironmaking technology, which converts iron ore directly into metallic iron in a flash-type furnace similar to that used in the copper industry, has also been developed [46]. These developments based on hydrogen have the benefits to be carbon free if hydrogen is produced with zero-carbon electricity. Either direct electrification through electro-winning or indirect electrification though hydrogen as a reducing agent will require large volumes of inexpensive electricity.

Competing Technologies

Industrial electric technologies face competition from other heating technologies, several of which are mentioned here. Solar thermal technologies can provide thermal energy for process at low temperatures (e.g., two recent reviews are [47, 48]). The reviews identify solar thermal technologies in use across a variety of industries, including automotive, food and beverage, chemical, textile, paper, and mining. What most of these applications have in common are processes (e.g., washing, cleaning, preheating, and drying) that occur at temperatures below 140 °C. Processes that require much higher temperatures, such as calcining limestone, can be matched to concentrating solar technologies (e.g., parabolic dish and power tower/heliostat field technologies). Although solar thermal could provide 50% of industrial heat demand only 567 megawatts thermal (MW_{th}) total capacity was in operation by the end of 2018 [49]. Barriers to increased deployment include process integration difficulties, customization requirements for small-scale systems, high capital costs, and a lack of adequate policy and regulatory support [48].

Examples of low- to zero-carbon fuels include biomass and biomass-derived liquid and gaseous fuels [9], e.g., renewable natural gas (RNG) produced by biomass gasification and biogas-derived methane from landfills, wastewater units, and dairies. In some cases, the production pathway can be net carbon negative if the CO_2 from biomass-derived fuel production is captured and stored. Some disadvantages of biomass-derived pathways are potential land use and biomass competition issues, and bio-derived fuels are still combusted which can produce other air pollutants. A key concern for conventional natural gas substitutes is that methane leakage can still occur during the production and distribution phases, and costs are still much higher than conventional natural gas [13].

Another high energy density carrier is ammonia. Ammonia contains 1.7 times more H_2 per cubic meter than liquefied H_2 and is much cheaper to transport and store than hydrogen. However, producing ammonia and converting it back to hydrogen imposes a 14–33% energy penalty of the energy contained in H_2 [11•].

Analysis, Modeling, and Research, Development, Demonstration, and Deployment Needs

Industrial electrification could be promoted by addressing current gaps in modeling and analysis capabilities, as well as by supporting efforts in the RDD&D of industrial electric technologies. Existing electrification studies for the United States have not applied the same level of analytical detail in the industrial sector as the other end-use sectors. Additionally, modeling and analysis could benefit from a better characterization of the possible interactions between the industrial sector and other end-use sectors. Analysis improvements would not only assist with evaluating electrification potential, but could complement the planning and design of technology demonstrations. Specific modeling and analysis needs include the following:

- Further process-level analysis and modeling to identify which sectors or processes to prioritize for electrification. This includes modeling capability to characterize output material characteristics and quality as a function of input material composition and thermal and/or thermochemical process.
- New national-level modeling capabilities that account for material and energy flows within the industrial sector and between other end-use sectors. One of the most significant and understudied electrification implications for industry are the effects of transportation electrification on the petroleum refining and petrochemicals industries, which are among the largest GHG emitters and energy users [50]. The industries' response to transportation electrification is largely a function of whether their products are exported. For instance, Yang et al. [51] estimate petroleum consumption decreases by less than 50% from 2010 to 2050 and out-of-state consumption accounts for about 83% of the remaining amount.
- Better quantification of costs and benefits of direct and indirect (i.e., via hydrogen production) electrification. In addition, there is a need for a more comprehensive treatment of the total costs of electrification and competing pathways such as synthetic natural gas production from biomass and renewable hydrogen.

Many of the challenges and barriers to widespread industrial electrification (e.g., commercialization of novel industrial electric technologies—especially for high-temperature processes, high capital costs of commercialized electric technologies, and risk aversion of industries) could be addressed by RDD&D efforts. These include the following:

- Improved performance and lower costs in industrial electric technologies, especially for high temperature processes, solar PV, and energy storage technologies.
- Pilot and demonstration projects to assess the electrification impacts to process performance, cost, and output. These projects could support technology development and risk mitigation for industries.
- Thermal storage at high temperatures is an understudied and developed area and could play a larger role in smoothing out the supply of variable renewable electricity sources (e.g., [52]).
- Demonstrations of electrolysis-generated hydrogen production and integration as a feedstock replacement, fuel carrier, renewable fuel, or storage carrier for reconversion back to electricity.

Renewable heating targets, policies and incentives exist in many countries but are primarily focused in the building sector [53]. Policies that support low carbon or renewable heating in industry could also be helpful for industry decarbonization and industry electrification efforts.

Conclusion

Deep reductions in GHG emissions in the industrial sector require reductions in basic material demand, material re-use, new processes such as direct electrification and renewable hydrogen production using electrolysis, and carbon capture, utilization, and storage (e.g., [29]). Much lower electricity costs could alter the economics and outlook for electrified heating. In particular, sharply falling solar PV and battery prices (e.g., at or below \$50/MWh for solar and electrical storage) could make electrified process heating and steam systems more cost competitive. Some industrial end-uses that may be more readily electrified from a technology-readiness standpoint include boiler systems, drying, and reheating metals. However, electrification costs can be challenging in many cases. Industries in areas with high electricity prices relative to combustion fuel prices currently have little financial incentive to electrify. The move to electricity will be highly influenced by energy and environmental policies.

Compliance with Ethical Standards

Conflict of Interest Max Wei, Colin A. McMillan, and Stephane de la Rue du Can declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with humans or animal subjects performed by any of the authors.

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