An Evaluation of the Potential to Decarbonize the U.S. Manufacturing Sector by 2050

Gale Boyd, Duke University
Elizabeth Dutrow, U.S. Environmental Protection Agency
Josh Smith, ICF
Ernst Worrell, Utrecht University

ABSTRACT

The United States Environmental Protection Agency (US EPA) estimated the potential for reducing carbon dioxide (CO_2) emissions from U.S. manufacturing by 2050. The starting point is a Reference Case based on the U.S. Energy Information Administration's 2019 Annual Energy Outlook (AEO2019). The analysis is founded on a detailed accounting exercise that relies on estimates of emission reduction potential from other reputable studies and applies those potentials to the manufacturing sector using a bottom-up approach. The actions are grouped into four "pillars" that support deep decarbonization of manufacturing (DDM): Energy Efficiency, Material Efficiency, Industry-Specific Technologies, and Power Grid Synergies. Based on this bottom-up approach, the analysis shows that an 86% reduction in carbon dioxide emissions from the Reference Case is feasible, while no single pillar dominates DDM. An approach incorporating a broad set of elements from each pillar is more likely to be successful and robust for effectively impacting emissions from the manufacturing sector than reliance on any single action or technology. The implication of this analysis is that, ceteris paribus, if some actions are not as successful as estimated, then others will need to achieve higher emission reductions, or the potential will not be attained by 2050. Additionally, to realize the full extent of potential savings in the U.S. manufacturing sector, action would need to begin immediately to take advantage of industry's natural capital stock investment cycle to avoid both higher emissions and costs.

Introduction

Manufacturing, the foundation of the global economy, consumes large amounts of fossil energy and is a large source of U.S. carbon dioxide emissions (EPA 2020). The sector has had a long, successful history of improving both energy and associated emissions intensity. U.S. industrial gross domestic product (GDP) grew 52% from 1985 to 2007, and delivered energy intensity (adjusted for structural changes) declined ~18%. Structural shift, the changing composition of U.S. industry, contributed another 10% to the decline in aggregate energy intensity (Belzer 2014). Taken together, this resulted in lower energy-related CO_2 emissions than otherwise would have occurred, but still produced a net increase in emissions over that time period. Lowering the energy intensity of U.S. industry is a necessity but will be insufficient alone for lowering greenhouse gas (GHG) emissions to levels required to reach the Paris Accord target which restricts global temperature rise to less than 2 degrees Celsius above pre-industrial levels by 2100. Additional means of reducing emissions will be necessary.

Recent studies have provided information on specific technologies or policies that could be used to create a "pathway" or "roadmap" for DDM but have not quantified the potential, overall carbon reduction. These studies offer a menu of opportunities to enable change for manufacturing's carbon emissions. DDM likely will be the result of an "all of the above" approach, utilizing the full menu. This evaluation uses the U.S. Energy Information Administration's (EIA) Annual Energy Outlook (AEO) as its Reference Case forecast of industrial activity, energy use, and CO_2 emissions, and combines it with a review of extant literature on industrial GHG emissions technologies and practices to address the question: "How much can industry reduce GHG emissions by 2050?" The question is answered via a set of quantified CO_2 emission reduction estimates for U.S. manufacturing. The cumulative potential of combinations of various technologies and changes to deeply reduce CO_2 emissions in industry by 2050 is examined, and insights for long-term decarbonization of the manufacturing sector are offered. The evaluation focuses on the potential for industrial transformation at an aggregate level and concentrates on the seven, most carbon- and energy-intensive industries. An assessment is also made for the less energy-intensive manufacturing industries, labelled "light industry" in contrast to the energy-intensive, "heavy" industries.

Industries in Focus

Within the U.S. manufacturing sector, most carbon emissions are concentrated in a few carbon- and energy-intensive industries identified by the North American Industry Classification System (NAICS). These include NAICS 322: Paper Manufacturing; 324: Petroleum and Coal Products Manufacturing; 325: Chemical Manufacturing; 327: Nonmetallic Mineral Product Manufacturing; 331: Primary Metal Manufacturing; and a few industries in 311: Food Manufacturing and 313: Textile Mills. The nature of these industries' processes (e.g., high temperature, high energy intensity) presents challenges in the search for new, low carbon technologies. For other industries, more benign operating conditions allow easier conversion to low-carbon processes or technologies. Yet, deep decarbonization of industry will require significant technological changes and innovation within a relatively short window of opportunity.

Approach

This evaluation is based on a detailed set of DDM potentials from industry-specific actions informed by other studies that examine how specific technologies might influence future industrial emissions broadly, or in specific industries. From this body of literature, consensus point estimates of the potential percentage reduction in energy and GHG emissions for specific technologies and activities on individual industries were proposed. These estimates were then applied in an accounting exercise, building from EIA's AEO as a Reference Case forecast (U.S. Energy Information Administration 2019). This study focuses only on energy-related CO_2 emissions from manufacturing, except for process CO_2 emissions from cement and lime manufacturing, which are the single largest component of industrial process CO_2 emissions.

While some studies analyze specific energy or GHG policies, this exercise is based on the presumption that policies and changes in public behavior occur to incentivize these emission reductions. DDM will have major implications for energy markets specifically and for the structure of the future economy more generally. In particular, DDM will likely result in lower demand for fossil fuels and place downward pressure on those prices. Under DDM, the roles of different portions of the economy will change. This exercise does not estimate the partial equilibrium impact on energy prices or general equilibrium interactions between segments of the economy. The evaluation may be viewed as a thought experiment; a quantification of the logical outcome of individual GHG emission reduction actions determined to be feasible in other published studies. The question posed above is answered by building up from a detailed set of assumptions regarding estimates of potential emission reductions and assuming that, if these potential emission reductions are feasible with the right incentives, then there is a logical outcome in terms of GHG emission reductions.

A 30-year forecast is a relatively long time horizon over which to model the changing world, but a relatively short time frame given the scope of decarbonizing the manufacturing sector. This study presents a set of transparent assumptions about actions that can feasibly reduce GHG emissions while not picking "winners and losers," but suggesting an all of the above, inclusive approach. Care is taken to avoid double counting, since there are synergies between the various opportunities that may be taken to reduce GHG emissions. The thought experiment laid out in this study can be also interpreted as a pathway or roadmap to DDM in the sense that, if one or more of these actions are not undertaken, then emissions will be higher or other actions will have to be implemented to a greater degree to achieve the same level of DDM.

The wide range of technologies and actions embodied in the studies that were reviewed are grouped into four categories, or pillars, that support DDM. The studies provide evidence of the feasibility of reducing emissions in a variety of ways and were publicly available at the beginning of 2019. The emission reduction pillars include:

- Pillar One—Energy Efficiency: Energy efficiency offers large potential in the industrial sector as new technologies will continue to be developed to enable further reductions. Several technologies or strategies include the use of expanded energy management driven by advanced data analytics ("Industry 4.0"), artificial intelligence, additive manufacturing, efficient process designs, advanced process integration, and new process innovations (e.g., electro-chemistry, bio-based feedstocks, selective catalysts, separation technologies). Also, there is still considerable potential for energy savings by implementing well-known technologies and practices such as combined heat and power (CHP), waste heat recovery, efficient motor systems, and good management practices. Since some energy efficiency is included in the Reference Case, this pillar includes additional efficiency improvements beyond the Reference Case.
- Pillar Two—Material Efficiency: Industry faces pressure as it seeks to access a finite amount of critical raw materials. Further, the increasing problem of waste management (e.g., landfilling, incineration, litter, and the proliferation of plastic) is in the news regularly. Industry must restructure to ensure that resources and materials are used efficiently and not lost. Recycling and related measures are critical. In a "circular economy," products and materials are reused and recycled to retain the highest value for the economy. Reuse and recycling will lead to reduced production of primary materials and is often less energy intensive. The largest impact on industry will likely be for the energy-intensive material production industries, as these produce primary materials. However, this will also affect fabrication and other functions if society moves from product ownership to leased products or shared-use products, a model anticipated for automobiles and other manufactured goods. While the transportation sector is not modeled in this study, it is likely that factors driving material efficiency would also have a major impact on the demand for transportation fuels, considering the movement toward electric mobility which will impact the demand for oil products and emissions from oil

refineries. For this reason, impacts on oil refining are included under the material efficiency pillar but are identified separately in the results.

- Pillar Three—Industry-Specific Technologies: There are several DDM opportunities that are likely to be effective in specific industries, including:

  - Renewables: This evaluation generally assumes that off-site electricity generation in the power sector increasingly will come from renewable energy toward 2050. However, renewables may also offer potential for on-site use at manufacturing plants. On-site renewable energy uses include installed solar energy for drying or heat generation, the use of self-generated biomass residues as fuel, or on-site generated power. In the evaluation, on-site use of renewable energy sources is included under Pillar Three while renewable energy in the power grid is assessed under Pillar Four.
  - Hydrogen or renewable gases: Hydrogen or other generated renewable gases (e.g., methane from renewable sources) can be used in energy-intensive process industries (high temperature) to replace use of fossil fuels. Hydrogen production can be semi-centralized or local, as is already done in some industrial complexes (e.g., in chemical production). Hydrogen or local/pipelined biogas could provide a source of non-fossil carbon fuel with sufficient energy value to reduce greenhouse gas emissions from the energy-intensive industries. This offers the potential for deep reductions in on-site emissions if the gases are produced at net-zero GHG emissions. Low- or zero-carbon hydrogen can be produced through the combination of natural gas steam reforming with carbon capture and storage ("blue hydrogen") or through electrolysis of water using renewable power sources ("green hydrogen"). Note that production of zero-CO_2 hydrogen will involve energy losses in the supply chain (e.g., transmission losses in the grid). Further, if hydrogen production relies on a route from natural gas, consumption of blue hydrogen would be associated with emissions of methane or CO_2 in the supply chain.
  - Carbon capture and storage (CCS): CCS and carbon capture and utilization (CCU) offer the opportunity to convert fossil fuels to low-carbon energy carriers (e.g., hydrogen), or reduce energy- and process-related emissions in specific industries such as chemicals and cement. The captured CO_2 can be stored underground (e.g., in depleted oil or gas reservoirs or aquifers) or can be recycled as fossil carbon into feedstocks or chemical products. If the feedstocks are used to produce materials that store the carbon outside the atmosphere long term, CCU can contribute to emission reductions so long as the emissions are captured at the end of the product's life.

- Pillar Four—Power Grid Synergies: Decarbonizing commercial power production in combination with electrification of manufacturing operations can offer much for DDM. The manufacturing sector may actively participate in grid decarbonization via on-site renewable generation or through power procurement practices. The role of manufacturing companies to assist grid decarbonization goes further by providing load balancing, either with dispatchable demand side management or on-site energy storage. With a zero-carbon grid, there are further opportunities for decarbonization through substitution of electricity for fuel. While there are generic electrification opportunities (e.g., electric boilers, electric heaters), many energy-intensive industries will require specific technologies. Some will need new technology development. Other electrification opportunities offer simultaneous energy savings and may already be cost effective or applied in current markets (e.g., heat pumps, mechanical vapor recompression). Note that developments in power generation, energy markets, and energy pricing will affect the realization of the potential offered by electrification.

DDM Relative to the Reference Case

The DDM question is inherently about deep emission reductions, so it is necessary to ask, "Reductions from what level?" This study measures emissions reductions against the EIA's AEO Reference Case forecast. The long, public history of EIA producing the AEO forecasts has made it a reliable public source for an outlook for the U.S. energy sector. The AEO forecasts assume current laws and regulations affecting the energy sector, including sunset dates for laws that have them, are unchanged throughout a projection. The projections assume trend improvement in known technologies, along with economic and demographic trends drawn from other forecasts.

When this study was initiated, the most recent AEO forecast was AEO2019; thus, the AEO2019 Reference Case[1] (hereafter the Reference Case) is used here as the forecast underlying the DDM estimates. The AEO is a product of the National Energy Modeling System (NEMS), a partial equilibrium model of the U.S. energy system. NEMS forecasts the U.S. energy sector to 2050. The NEMS Industrial Demand Module (IDM) provides production forecasts for each manufacturing industry and energy consumption for individual fuels and electricity. This detail is needed, since DDM actions are industry- and energy-specific. While the AEO is an annual forecast through 2050, this study only uses the AEO base year, 2018, and the terminal year, 2050. Timing of DDM actions is not assessed.

Building upon the Reference Case, this study develops two sets of DDM estimates. These estimates are synergistic in terms of emission reductions and are accounted for in sequence to minimize double counting. These DDM estimates are conceptualized in this thought experiment to capture the source of the various DDM actions. The first is industry direct action, and the second is industry/grid interaction. The numbering is not intended to suggest a sequence of events. The first estimate is composed of the first three pillars and is primarily the result of actions that must be taken by industry. The second estimate is the indirect emission reductions in the fourth pillar that arise from industrial electric power consumption from zero-carbon sources, complemented by beneficial electrification. In other words, industry decarbonizes when it uses power from utilities that rely on renewable energy and when it replaces fuel-powered equipment with electrified equipment.

In the Reference Case, energy prices, technical change, government policy, and capital stock turnover provide businesses a foundation for improvements in manufacturing energy efficiency. Moving beyond the Reference Case, this thought experiment provides a plausible view of the future where it is assumed that the policy and socio-economic drivers are further aligned to make mitigation of climate change a top priority. Then, businesses and households will reduce energy-intensive materials consumption, obviating or significantly reducing the need

[1] AEO produces several "side cases" that have different assumptions regarding resource availability and other factors that might impact energy prices. While EIA is clear that it does not believe that the Reference Case is "the most likely" projection, it does tend to represent the central tendency of the AEO forecasts.

for some of those energy-consuming processes. At the same time, manufacturing activities will be done in a more energy-efficient manner than in the past. When practical, biomass energy will be substituted for direct fossil fuels, even while the overall consumption of fossil fuels falls. In some “hard to abate” manufacturing activities, hydrogen will also be substituted for fossil fuels, and CCS will make inroads in sectors where CO_2-rich sources make it most cost effective. These types of changes are the basis for the first estimate of DDM via industry direct action.

These policy and socio-economic drivers will have a parallel impact on the electric grid. Manufacturing companies may install on-site zero-carbon sources or proactively engage in procurement of zero-carbon sources of electricity via power purchase agreements (PPA) or virtual PPAs. Companies also can engage in production scheduling and other activities that enable grid balancing that is beneficial to the intermittent forms of low-carbon power, like photovoltaics (PV) and wind. Since the overall demand for electricity is lower than it otherwise would have been, manufacturing can more easily satisfy all of this reduced electricity demand from zero-carbon sources. The success of a partial or complete grid decarbonization allows for many remaining sources of fossil fuel demand to switch over to low- or zero-carbon electricity, sometimes with efficiency benefits. These types of changes are the basis for the second estimate of DDM via industry/grid interaction.

For purposes of estimating the potential for U.S. manufacturing to reduce its emissions, three sets of estimates are produced. The first is the Reference Case produced independently by EIA. The second and third sets of estimates are the results of the approach detailed below.

- Reference Case: This forecast estimates energy and emissions based on well-established modeling by EIA and includes penetration of energy efficiency and low-carbon technologies based on current policy combined with forecasts of energy prices and economic activity to 2050.
- Industry Direct Action: This forecast quantifies direct industry actions attributable to a response to enhanced industrial policies and captures the impacts of changes in the industries. It assumes that factors will directly lower energy-intensive activities, increase energy efficiency, shift fuel use to renewable sources, and employ hydrogen and CCS in the “hard to abate” industries where it would be most cost effective. For purposes of quantifying emissions, the emissions from electric power generation from the grid and the direct fossil fuel mix will be as forecast in the Reference Case. Industry direct action includes the first three pillars: Energy Efficiency, Material Efficiency, and Industry-Specific Technologies (including Renewable Energy, Hydrogen, and CCS).
- Industry/Grid Interaction: This forecast quantifies how indirect emission from industry electricity use would change from the supply-side decarbonization of the electric power grid from enhanced grid policy. It assumes that electricity used by the manufacturing sector would come entirely from zero-CO_2 sources by 2050. The role of manufacturing companies in enabling grid decarbonization may be from directly installing or purchasing zero-carbon electricity, or enabling grid decarbonization via load balancing, etc. Additional emissions reductions will arise from industry’s decision to replace direct fossil fuel use with electricity use from a net-zero-CO_2 emissions power grid (i.e., electrification of select industrial operations). Industry/grid interaction captures the fourth pillar: Power Grid Synergies.

Combining estimates for industry direct action and industry/grid interaction represents the lower bound for emission reductions in this study's results. These estimates are constructed to provide an internally consistent aggregation of the impacts of each pillar for 2050. The assumptions regarding emission-reducing activities that are derived from studies reviewed for this evaluation are applied on a manufacturing industry-by-industry basis (discussed in more detail below). These actions are synergistic in nature.

1. First, energy efficiency improvement embodied in the Reference Case is considered to account for energy efficiency enabled by current technologies and business behavior in Pillar 1.
2. Second, material efficiency changes are examined as these will affect the structural composition of manufacturing activities compared to what was forecast in the Reference Case for 2050.
3. Third, the further potential for Pillar 1's additional energy efficiency improvement is assessed. To avoid double counting, energy efficiency that may be incremental to the efficiency that is implicit in the Reference Case is computed in this step. The incremental contribution of this pillar is estimated by comparing the Reference Case energy use to a counter-factual "frozen efficiency" energy use, calculated by multiplying the assumed 2050 industry-level production by the industry-level energy intensity in the base year of the Reference Case.[2] The difference between the two values gives an indication of the energy efficiency improvement potentials implicit in the Reference Case.
4. Fourth, fuel demand and site emissions that can be further reduced are included in the Pillar 3 industry-specific technologies, e.g. the on-site generation of renewable energy (including self-generated biomass-wastes), hydrogen, or CCS.
5. Finally, the potential for industry/grid interactions from Pillar 4 is estimated (i.e., the potential emissions reduction from existing electricity demand and from on-site fuel use that can switch to electricity-based technology with electricity obtained from carbon-free generation sources). Note that improving electricity efficiency is an important enabler of this pillar.

The combined results of each pillar for the individual manufacturing industries are aggregated to calculate the impact of changes within manufacturing and changes due to generation of power.

Nature of the Reference Case

Since the analysis of DDM is an estimate of reductions in future CO_2 emissions, a Reference Case is required. Sometimes a Reference Case is called the "business as usual" (BAU) scenario. This type of language can lead to a misinterpretation of the Reference Case for this study, as the reader could take the mindset of "If we do nothing." The correct way to think about this study's Reference Case is "If we continue to do all the things we have been doing, this is one possible outcome." The Reference Case embodies all the existing policies and programs that impact CO_2 emissions; ongoing adoption of newer, more efficient production technologies; and the behavior of manufacturing firms in response to markets and other incentives.

[2] The "frozen efficiency" or "frozen technology" approach is so named because it freezes the efficiency rates at the base year level.

For this study, the Reference Case is adjusted to account for the evaluation criteria to create the two estimates described above through 2050. While the AEO provides an annual time path of industrial production and energy use, this study presents the results based on the average annual growth rate or cumulative percentage change over the study period, defined as 2018–2050. The annual time path is not used in this study to project the timing of the actions that generate DDM. During the 30-year forecast horizon, the Reference Case assumes a near 100% turnover of the energy-using capital stock based on currently available technology.

Findings

Employing a full menu of options from the above approach for all four pillars would reduce the Reference Case carbon emission level from manufacturing from 1,282 mmtCO_2 to 184 mmtCO_2 in 2050, a reduction of 1,098 mmtCO_2 and an 86% reduction relative to the Reference Case. The reduction is produced by summing the bottom-up estimates of feasible DDM actions for a total of possible reductions. Figure 1 shows the relative contribution of the associated component parts of each pillar to DDM. The shares in the overall contributions from each pillar include the following:

- Pillar 1, Energy Efficiency, contributes 34%;
- Pillar 2, Material Efficiency, contributes 22%;
- Pillar 3, Industry-Specific Technologies, contributes 14%; and,
- Pillar 4, Power Grid Synergies, contributes 30%.

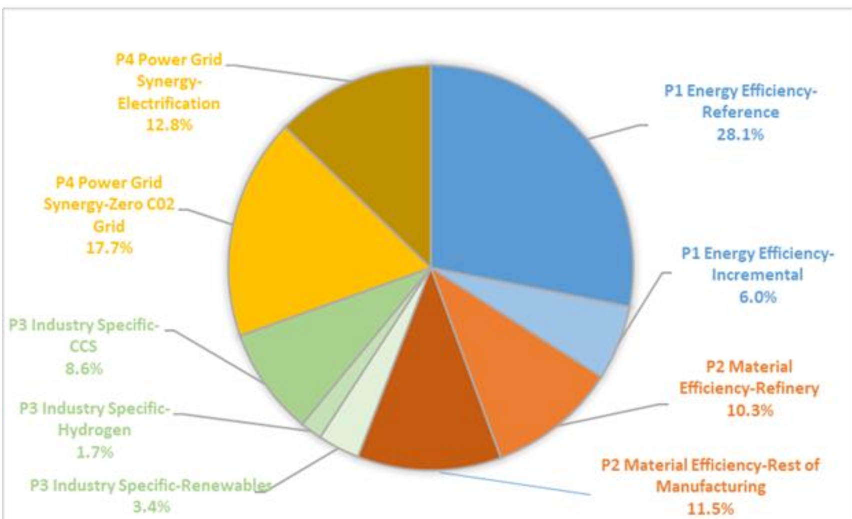

Figure 1. Relative Contributions of the Four Pillars of DDM, with Detailed Components

Error! Reference source not found.2 summarizes the quantified estimates of DDM by each pillar relative to the base year of 2018 and potential emissions in 2050.[3] Emissions

[3] Recall that potential emissions are defined as Reference Case emissions plus the avoided emissions from energy efficiency included in the Reference Case.

estimates are in grey, and reductions, by pillar, are in color. The DDM estimates are grouped by *industry direct action* (Pillars 1–3) and *industry/grid interaction* (Pillar 4) and are cumulative.

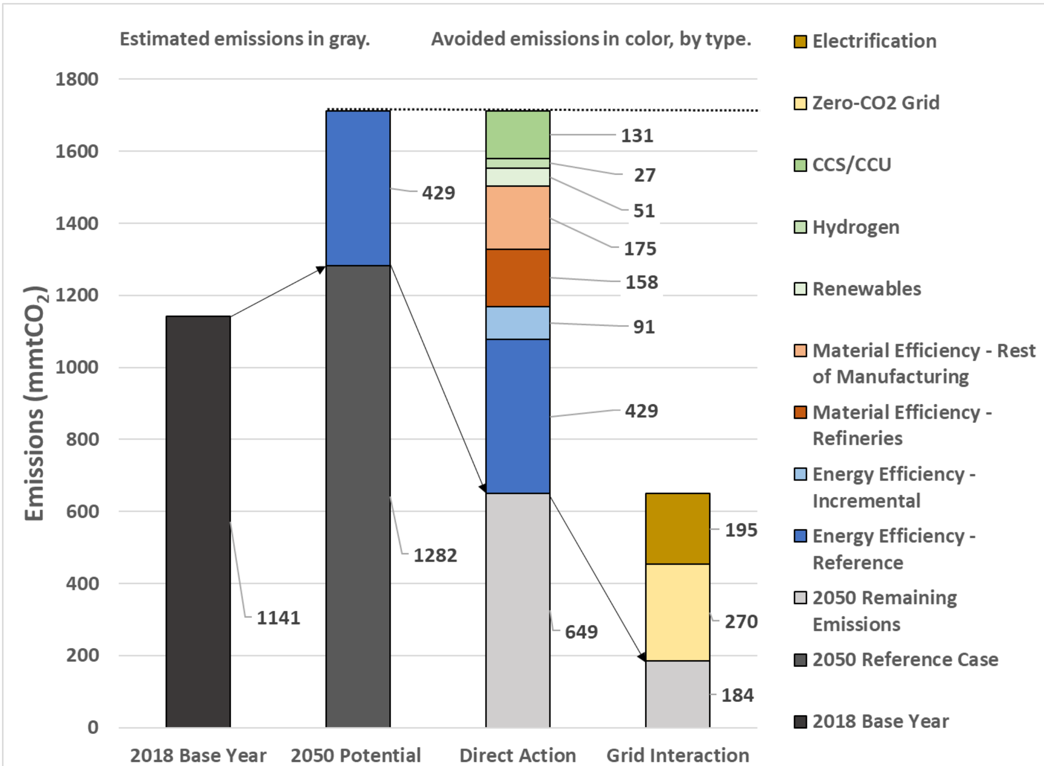

Figure 2. Summary of DDM Estimates by Pillar and Component

The study design also enables a view of industry-specific contributions to DDM. Figure 3 shows the industries' composition of the DDM reduction. Light industry is 39% of DDM emission reductions, followed by bulk chemicals (24%) and refining (14%). The other energy-intensive industries contribute the remaining 24%. Within industries, both light industry and aluminum and glass derive about one-half of the emission reductions from industry/grid interaction. Cement and refining reductions come primarily from industry direct action since electricity is less important in their carbon footprint. The remaining industries' reductions are more influenced by industry direct action than industry/grid interaction, but both play a significant role.

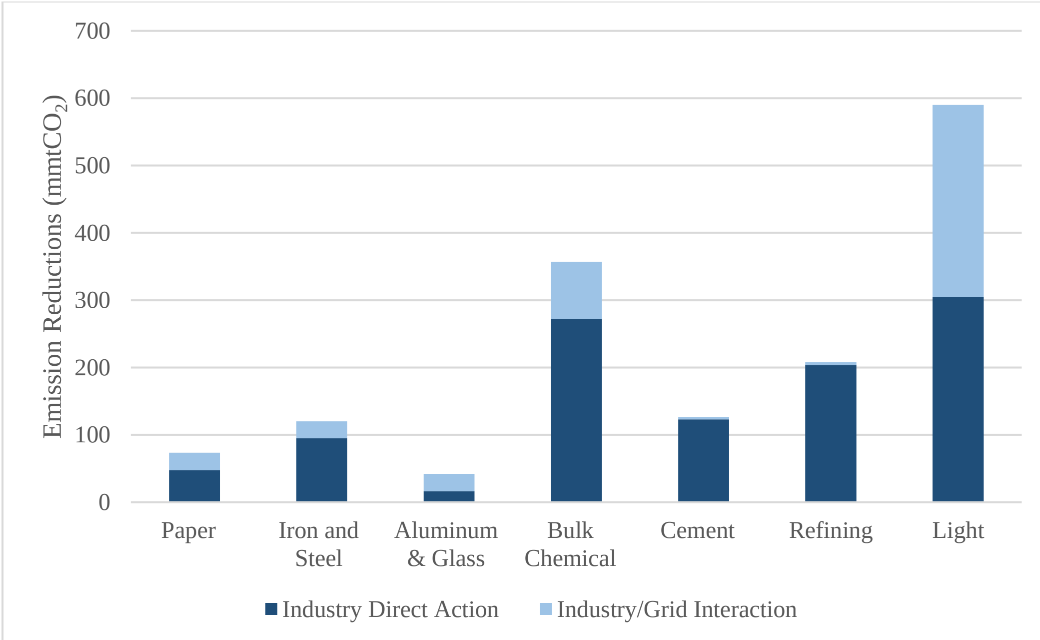

Figure 3. Industry-Specific Relative Contributions to DDM, by Type of Industry Action

Table 3 provides a view of the estimated potential for the pillars of DDM in reducing emissions from the manufacturing sectors. Table 3's final row includes the total estimated percent reduction in emissions for each sector in 2050 from the Reference Case if all activities are deployed.

Table 3. Estimated potential for DDM pillars in reducing emissions from manufacturing sectors

DDM Opportunity	Bulk Chemicals	Cement, Lime	Light Industry	Oil Refining	Pulp & Paper	Steel	Aluminum, Glass
Energy Efficiency	Medium	High	High	High	High	High	High
Material Efficiency	Medium	Medium	Medium	Medium	High	High	Medium
Industry-Specific: Renewables	Medium	Medium-high	High	Low	High	Low	n/a
Industry-Specific: Hydrogen	Medium	Low	Low	Medium	Low	Medium	n/a
Industry-Specific: CCS	Medium	Medium	Low	Low-medium	Low	Medium	n/a

Grid Interaction: Electrification	Medium	Low	High	Low-medium	Medium	High	High
Grid Interaction: Balancing	Low	Medium	Medium	Low	Medium	Low	Medium
Total Reduction from Reference Case	76%	90%	95%	93%	100%	93%	97%

The paper does not prescribe a "silver bullet" for DDM, but rather illustrates what is achievable if the individual opportunities supported by the studies reviewed are indeed feasible. When viewed as a roadmap, the study provides one possible path to DDM. If any of the actions described in the study falls short of its potential, then others must accomplish more, or resulting emissions will be higher. The thought experiment leverages the 30-year time horizon which would substantially, or completely, result in the turnover of the energy-using capital stock in manufacturing. This implies, ceteris paribus, that delay in implementation will result in higher emissions.

DDM will only occur if reducing GHG emissions to avoid climate change is a priority. Given the inclusive nature of the DDM estimates presented in this paper, an all of the above approach will also be required to motivate change and lower barriers to implementation. A variety of approaches will be necessary to achieve the full potential of DDM as this paper envisions.

References

Belzer, D. 2014. A Comprehensive System of Energy Intensity Indicators for the U.S.: Methods, Data and Key Trends. Richland, WA, Pacific Northwest National Laboratory: 1-215.

U.S. Energy Information Administration. 2019b. *EIA Today in Energy, March 20, 2019.* www.eia.gov/todayinenergy/detail.php?id=38773#. Washington DC: U.S. Energy Information Administration, U.S. Department of Energy.

U.S. Environmental Protection Agency (2020). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2018. Washington DC.

Acknowledgments

The research described in this paper has been funded wholly or in part by the United States Environmental Protection Agency (U.S. EPA), Office of Atmospheric Programs, Climate Protection Partnerships Division, ENERGY STAR for Industry through contract 68HE0H18A0003 to ICF Incorporated, L.L.C. (Elizabeth Dutrow, EPA Contracting Officer's Representative; Joshua Smith, ICF Task Manager). The views expressed in this paper are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency or of ICF Incorporated, L.L.C. It has not been subject to the Agency's official review. This paper is a synopsis of a more detailed paper, "Bottom-up Estimates of Deep

Decarbonization of U.S. Manufacturing in 2050," under revision for the Journal of Cleaner Production. That paper includes a detailed discussion of the industry-specific underlying assumptions and includes references to all the studies used to develop these estimates. Copies of that paper are available from the authors by request.