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US industrial sector decoupling of energy use and greenhouse gas emissions under COVID: durability and decarbonization

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Abstract

The 2020 response to the coronavirus pandemic has had a profound and rapid effect on social behavior, the economy, and consumption. Associated declines in greenhouse gas (GHG) emissions have prompted calls to action to use the pandemic experience to accelerate decarbonization. Such action depends on understanding how GHG emissions reductions were achieved and whether they can be sustained. In this work, we focus on the industrial sector by comparing United States (US) industrial energy consumption, CO2 emissions, and key materials production between the first two quarters (Q1 and Q2) of 2020, when pandemic response became active, relative to 2019. We show a striking decoupling between energy use and GHG emissions in the US industrial sector between Q2 2020 and Q2 2019, yet pandemic decarbonization in the industrial sector is unlikely to be durable. Observations suggest three major takeaways for US industrial decarbonization: (1) efforts to decarbonize transportation will contribute to industrial decarbonization due to the large impacts of petroleum refining; (2) increasing demands for materials that use energy resources as feedstocks (e.g., plastics) can result in an apparent decoupling in energy demand and GHG emissions that is not indicative of a durable pathway for reducing GHG emissions; and (3) temporary reduction in demand for industrial infrastructure materials would have resulted in greater reductions of GHG emissions than the relative change in fuels used during this period. Cumulatively, while shifts that would lower GHG emissions occurred, no substantial structural changes to industrial activity were observed. As such, society still requires systemic change to interdependencies on other sectors and the methods we use to produce and deploy our industrial materials.

1. Introduction

The coronavirus pandemic and 2020 response profoundly altered people’s lives and relationships with infrastructure. In an era where rapid decarbonization is critical for limiting global impacts of climate change, evidence that some pandemic-induced behavior changes led to lower greenhouse gas (GHG) emissions from fossil fuel use [1, 2] has prompted interest in leveraging the pandemic to meet climate goals [3]. As such, analysis must be performed to understand if pandemic-driven shifts in the consumer economy have initiated reform in material and energy demands that could facilitate future movement towards sustainable consumption [4] and spur reduced use (or even retirements) of older, less efficient production facilities.

Although drivers of reduced individual household energy use have been relatively straightforward (e.g., reduced commuting during stay-at-home orders), the impact of societal-scale behavior change on other sectors has been less clear. One major observation from United States (US) data is that the industrial sector specifically exhibited a dramatic decoupling between energy use and GHG emissions during the early months of the pandemic response: energy consumption for June 2020 dropped by 9% versus June 2019, but energy-derived CO2 emissions dropped by 17% (supplementary information, SI; available online at stacks.iop.org/ERC/3/...
This observed pandemic-driven decoupling between US industrial sector energy consumption and GHG emissions is of interest partly because the industrial sector is often considered ‘difficult to decarbonize’ [6] due to reliance on energy-intensive manufacturing methods; high levels of consumption; and GHG emissions not only from fossil fuel combustion but from chemical reactions inherently tied to production pathways—particularly notable for production of cement and steel [6, 7]. Furthermore, breakthroughs in industrial manufacture have proven difficult for key products: in addition to lock-in associated with capital intensive production facilities [8], common long-lived infrastructure materials like concrete and steel are susceptible to lock-in effects from initial building material decisions [9, 10]. For example, a new lane added to a concrete highway would be made from concrete rather than some other material. As such, evaluating whether the drivers of the observed 2020 decoupling between energy consumption and GHG emissions in the US industrial sector represent durable, replicable actions for decarbonization is of particular interest. For example, if the economic downturn contributed to the permanent closure of especially high emission, low profit facilities, this might inform policies focused on targeted accelerated retirements.

Here we investigate how the COVID-19 pandemic affected industrial energy and material resource consumption in the US, with a focus on characterizing the mechanisms leading to the decoupled energy consumption and GHG emissions observed in the US industrial sector in the first half of 2020 and their expected durability in leading to continued GHG emissions reductions. Namely, we assess the effects of initial societal reaction to the pandemic on several large sources of GHG emissions in the industrial sector: energy resource utilization and the production of cement and steel, both materials that are known to be difficult to decarbonize.

2. Materials and methods

This work investigates changes in CO₂ emissions from the US industrial sector (as defined by EIA [5]) for the first and second quarters (Q1 and Q2; January–June) of 2020 relative to 2019. Data sources are primarily US federal data on energy production [11–13] and consumption [14], as well as for energy-derived CO₂ emissions [14]. Note that refining is part of the industrial sector (although its products are primarily used in transportation), but electricity generation for retail sales is not. These data are used to assess the impact of pandemic-induced societal behaviors on industrial decarbonization via comparison between no-pandemic and pandemic conditions. This time period is chosen both because of data availability as of this writing (December 2020) and because stay-at-home or equivalent orders related to the coronavirus pandemic, expected to correlate with coordinated societal behavioral changes, were a common mechanism used at the beginning of Q2 2020, as illustrated by data on which states were under such orders by April 6 [15]. Data and calculations are available in the SI.

Given specific interest in decarbonization pathways associated with industrial production of certain infrastructure materials, and due to their status as the two largest industrial sector emitters of GHGs beyond fossil fuel combustion [16], this work places an additional focus on cement/concrete and iron/steel production material flows. While these material flows were not anticipated to experience as radical of a change as common consumer-driven flows (e.g., personal-vehicle transportation fuels), cement and steel are industrial materials with known high emissions from production. One potential outcome of the pandemic-related economic downturn could be that high emissions facilities are permanently shut down, as has been observed in the electricity industry [17]. As such, we investigate indicators of whether observed industrial system shifts are due to similarly durable changes, particularly for cement and steel production that, unlike petroleum refining for transportation fuels, will continue to be needed even after energy sector decarbonization. The demand changes for these material flows are assessed primarily via non-energy resource industrial material demand (cement-based materials [18] and infrastructure metals [18, 19]).

The predominant use of concrete is in infrastructure systems, with approximately 90% used in buildings, roadways, and public works in the US [20]. Concrete is composed of several constituents including cement, a powder that reacts with water to create hydration products that can bind together granular rocks (aggregates). In typical cement systems, clinker (a kilned and quenched material) is interground with gypsum, as well as potentially other mineral admixtures. As such, to examine flows associated with concrete demands, this work tracks data for cement, gypsum, sand and gravel, and crushed stone. Hydraulic cement, blended cement, and masonry cement were considered cumulatively based on production statistics from the US Geological Survey (USGS) [18].
For metals production, this work focuses on iron/steel manufacture, with secondary attention to zinc and aluminum due to their use in civil infrastructure. While not the sole driver of iron/steel production, construction accounts for over 25% of US steel demand \[^{21} \] The majority of iron ore produced in the US is used to support the steel market, with 87% of the ore being used to make pellets or direct shipping ore used in steel manufacture \[^{22} \]. Zinc production is similarly tied to the steel market, with 88% of zinc produced used for galvanization, commonly applied for galvanized steel in automobiles and construction \[^{23} \]. While less tied to infrastructure, 12% of the aluminum in the US is used for building and construction, the third largest market for the material after packaging and transportation \[^{24} \].

3. Results and discussion

We do not find evidence that the relatively large decoupling between industrial energy consumption and industrial energy-derived CO₂ emissions observed during Q2 2020 represents a durable industrial decarbonization pathway without further intervention (figure 1). Given that the majority of the US was under stay-at-home orders for at least part of the quarter \[^{15} \], this observation suggests that behavioral change alone has limited impact on industrial CO₂ emissions.

Rather, we note that observations from the COVID-19 societal behavior shift suggest several pathways forward for reducing US industrial GHG emissions. Here, we suggest that observations from the COVID response indicate that (1) a transition away from petroleum-based fuels for transportation has synergistic industrial decarbonization effects given the use of high-CO₂ emitting fuels for refining; (2) demand for certain materials shifted in response to COVID-19, with a relative increase in plastics production, leading to an increased fraction of hydrocarbons used as a material feedstock rather than as combusted fuel; and (3) reduced demand for materials with high production-related emissions, e.g., iron/steel, would have led to associated reductions in GHG emissions. We note that potential medium-term responses to the COVID-19 pandemic motivate special attention to infrastructure-related GHG emissions due to possible shifts in preferences for more GHG intensive infrastructure systems. We describe why our observations do not indicate durable decoupling, then discuss these observations in turn.

3.1. Industrial decarbonization via transportation fuel switching

Much of the observed decoupling between US industrial energy consumption and energy-related CO₂ emissions is due to COVID-19-related impacts on bulk chemical production and petroleum refining, which accounted for 29% and 18% of 2019 US industrial energy resource consumption, respectively \[^{25} \]. The pandemic has increased demand for certain plastics \[^{26} \], while consumption of transportation fuels from refineries dropped dramatically during the initial stay-at-home period. Shifts in demands for transportation fuels would have
driven change in the fuels used by the industrial sector. The majority of petroleum refineries focus on producing transportation fuels, such as gasoline [27]. Petroleum refining tends to use low quality fractions of crude oil (essentially, the often carbon-intensive components of crude oil that are not financially viable to upgrade to diesel, gasoline, and other liquid fuels) for refinery steam and electricity needs. Such fuel resources tend to have higher CO₂ emissions per MJ of energy [28]. However, declines in demand for transportation fuels, and the associated refining, would have altered the degree to which these higher emitting fuels were used.

At the same time, based on seasonally adjusted indices reflecting the US industrial sector, the manufacturing of plastic materials and resins, agricultural chemicals, and basic chemicals that typically rely on fossil hydrocarbons became larger fractions of the industrial market in Q2 2020. The manufacturing of these compounds experienced net reductions in production of 2%, 3%, and 6%, respectively, during Q2 2020 from 2019, while total industrial production reflected a reduction of 14% (with production of glass, primary metals, and mining all experiencing declines between 10%–30%) [29–35]. As a result, there were relatively more embodied energy resources in commodities like plastics and reduced use of high emitting fuels at refineries (figure 1). Notably, bulk chemical production uses substantial quantities of fossil energy resources as feedstocks that are not completely oxidized to CO₂ (e.g., for plastics), lowering GHG intensity per unit of energy resource consumption (though we note that plastics production is still a high GHG emitter [36], particularly when considering upstream methane emissions [37]).

In Q2 2020, petroleum energy consumption (e.g., as feedstocks and refinery fuels) fell by about 17% versus Q2 2019, while CO₂ emissions from petroleum fell by 30%, accounting for 41% of the energy consumption and 65% of the CO₂ emissions declines observed in the industrial sector as defined by EIA (SI, Sheet 2). The discrepancy is largely because of a greater decline in petroleum as a fuel (at refineries) versus as a feedstock (e.g., for plastics). Electricity emissions also fell faster than consumption (81% and 89%), versus 2019, as expected given ongoing grid decarbonization [14], accounting for an additional 28% of energy consumption and 20% of CO₂ emissions declines. For natural gas, both industrial energy consumption and CO₂ emissions fell by about 5%. For coal and biomass, CO₂ emissions actually declined less than energy consumption, possibly indicating less efficient operations, e.g., more starts and stops associated with pandemic-related demand and labor schedule adjustment. Thus, changes in the CO₂ intensity of industrial petroleum consumption are the primary driver of energy-emissions decoupling, likely due to reduced consumption of liquid fuels and stable or increased demand for petroleum as a feedstock. In future work, exploration of the specific commodities that drive change in demand for petroleum as feedstock relative to a fuel resource could be examined. Notably, transportation energy consumption has largely returned to normal as the pandemic has progressed, suggesting the decoupling identified is not durable without fuel switching for transportation. We do not otherwise find evidence of increased industrial GHG efficiency, as we might expect from durable structural changes (e.g., plant closures).

For example, as of July 2020, a survey of chief executives by the Portland Cement Association reported only two plant shutdowns out of about 100 in the United States, with many more executives reporting more reversible changes like layoffs and reduced hours [38].

As discussed above, petroleum refining both uses a particularly GHG intensive fuel source [25] and is unlikely to engage in fuel switching because the fuel is a nondiscretionary process byproduct (that is, refineries use a low-value byproduct of refining as fuel). Transitioning the transportation sector away from petroleum-based fuels (e.g., to electricity, which continues to decline in GHG intensity) will also reduce industrial sector energy-derived GHG intensity and absolute emissions, even though the industrial sector is not the target. Eliminating refining as a result of transportation fuel switching thus has large implications for industrial sector GHG emissions.

Specifically, we note that the pronounced change in transportation fuel consumption from societal reaction to COVID-19 is among the largest drivers in GHG emissions reductions found in early 2020. In the past four years, high levels of fluctuation in residential and commercial energy consumption have been recorded, attributable to varying reasons (such as hotter weather and increased use of cooling systems); while trends in energy consumption are apparent in those sectors in response to COVID, they are in fact within fluctuations of prior years. However, variation for the transportation and industrial sectors in recent years has been far less pronounced, typically ranging by less than ±5%. In Q2 2020, there was a ~9-fold drop in energy consumption for the transportation sector and a ~2-fold drop in the industrial sector. While there was no significant decoupling of CO₂ emissions from the transportation sector (the decrease in energy consumption was paired with a commensurate decrease in CO₂ emissions), the industrial sector, responsible for fuel refining, saw a pronounced decoupling, with much higher CO₂ emissions reductions than decreases in energy consumption.

Longer term trends, particularly if the pandemic continues to suppress US GDP, could have impacts not detected here. In the Great Recession (2007–2009), the US per capita GDP hit a low in 2009 [39]. Data from that period and the preceding 25 years indicate the per capita production of cement and steel exhibited their greatest declines in production in the same year as the drop in per capita GDP [39, 40]. However, the production of these materials did not recover as quickly as the US GDP, likely reflecting shifts in government procurement and the
nature of the recession, which was linked to a prior housing and construction boom. While drivers for the
changes in the economy differ from the COVID-19 pandemic, it could be anticipated that there may be
prolonged effects from the COVID-19 related economic shifts.

3.2. Industrial decarbonization via reduced material demand
Increasing material efficiency, in which material services are provided with less material production and
processing, is a commonly discussed route towards mitigation of GHG emissions [41–43]. Demand reduction is
a viable pathway to lowering GHG emissions for industrial infrastructure materials, like cement/concrete and
iron/steel. Due to lock-in effects of long-lived equipment and the need to support existing infrastructure
systems with ongoing use of broadly similar materials, findings here act as real-time example of the effects of
material efficiency as a lever for industrial decarbonization even if reductions in GHG intensity per unit of
material are difficult to achieve. That is, total emissions from an industrial sector can be lowered by reducing
material demand as well as by reducing the emissions intensity of materials. Although fuel switching has a major
role to play in industrial decarbonization, providing similar or better infrastructure services with less material
can have a major impact on overall sector emissions, and potentially faster. From the example provided by the
COVID-19 pandemic, applying the same general shifts in industrial fuel resources noted in 2020 Q2 fuel use to
US cement production would result in a <5% change in emissions per kg of cement, but at peak initial response
to the pandemic, the drop in cement demand for states like Washington and New York would have resulted in
approximately a 50% reduction in GHG emissions from cement production relative to the same time in the
prior year.

Substantially increasing material efficiency will require concerted design effort, building on a lesson from the
COVID-19 experience: namely, even the highly disruptive economic slowdown from the pandemic had
strikingly limited impact on demand for infrastructure materials (figure 2). This result was likely related to many
construction activities not being subject to similar shutdowns as other activities [44]; yet shifts were still
apparent.

As figure 2 shows, the commodities with the greatest loss in production during the first few months of the
pandemic were the ones already on downward trajectories: coal and iron/steel. However, declines became
exacerbated in Q2 2020 (over a 30% decline in coal production—a 10% larger decrease than any quarter since
2015 [11] and an over 30% decline in steel production—a 20% larger decrease than any quarter since 2015 [45]).
These commodities had already exhibited declining economic viability prior to the pandemic, with facilities
closing around the US. However, for materials like cement and the associated minerals used in the production of
cement-based products, like concrete, such downwards trajectories were not uniformly prevalent prior to the
pandemic. While there was a slight downturn in national cement production in April and May (by ~5%), the
depression was short-lived, with production in June 2020 production exceeding that of June in 2019 by over
10%. The seasonal reduction of these materials that occurs each winter, when it is harder to place concrete, was
more prominent than the shifts from societal response to the virus.
The spread of the virus and political actions taken had various implications on societal behavior. By the end of Q2, 2020, every state in the U.S. was reporting response to the coronavirus pandemic. Each state was reporting infections and deaths, and most states were using strategies to slow virus transmission (figure 3). Relative to the changes in the prior year, there were notable shifts in material demand (figure 3(b); here using cement due to available and pertinent data reflecting shifts in material demand). Historical data shows a greater than 0.9 correlation between cement production and GDP over long periods, and there were weak correlations between cement production and each infections, deaths, and policy interventions. However, there were pronounced changes in the demand for this difficult to decarbonize material during the early response to the COVID-19 pandemic.

Figure 3. Effects of COVID, Governmental Response to the Pandemic, and Cement Production by State. This figure shows panels of (a) the number of infections as well as the number of deaths from COVID-19 as percentages of state population as of June 30th (the end of 2020, Q2—data from the COVID Tracking Project [46] and 2019 state population statistics from the U.S. Census [47]), governmental interventions of stay-at-home or equivalent orders by April 6th (data from [15]) and state mask-mandates issued by October 30 (data from [48]), and (b) the percent change in cement demand by state in the month of April between 2017 and 2018, between 2018 and 2019, and between 2019 and 2020. Note: only data for the continental U.S. are shown; all data can be found in the supporting information.
While there was nearly no change in cement demand for the US as a whole immediately after pandemic response began, individual states saw dramatic shifts in production. In April 2020, half of the states in the US reported reduced cement demand compared to their demand in 2019; 11 of which reported reductions over 20%. Many of these states were in regions hit hard early-on by the COVID-19 pandemic, such as the North East and Washington state. In comparison for April 2019, only 7 states reported reduced consumption versus 2018, with none exceeding 20% reduction; in 2018, 16 states reported reductions relative to the prior year with only 4 noting over 20% reductions. For large cement consuming states, like California, New York, and Florida, there were reductions of cement demand of 23%, 54%, and 8%, respectively, in April 2020 relative to April 2019. Yet, over the full Q2 of 2020, each of these three states reported less dramatic drops in cement demand: 7%, 21%, and 4% for California, New York, and Florida, respectively. Notably, some states, such as Montana and the large cement consuming state of Texas, reported increases in cement demand in the same periods. In certain cases, the states exhibiting increased production had low impact from the COVID-19 pandemic at the time; while others, such as Texas and South Dakota, had relatively high rates of infections and deaths for the country. Such findings indicate social response to COVID-19 did not result in uniform behavior with regard to demand for high emitting materials and overall, evidence for durable material demand reductions from the pandemic is low.

The pronounced depression in steel production, an almost 10% reduction in production for March, and over 30% reduction throughout Q2, may be reflective of the more disperse markets in which steel is used. Beyond application in infrastructure systems, steel has large markets in manufacture of vehicles and mechanical equipment, which may have seen a more pronounced decline as a result of society’s reaction to the virus [49]. For example, US car sales dropped dramatically as potential purchasers stopped commuting and lost income [50]. The GHG impacts of this demand reduction emphasizes that reducing demand (either via lower consumption or via material efficiency) can substantially reduce GHG emissions. While limited shifts in GHG emissions would be projected based on fuel resource use in the steel industry, the lower demand for steel resulting from conservative spending would correspond to approximately a 30% reduction in GHG emissions, with all other production methods held constant. If this mechanism can be achieved through material efficiency rather than as a temporary response to the pandemic, there could be prolonged benefits in meeting GHG emissions goals.

Although full decarbonization depends on structural changes like fuel switching, application of carbon capture and storage or utilization (CCS / CCU), and major changes to material production methods, findings reinforce past work showing that designing for lower materials intensity—that is, altering the robust relationship between demand and indicators like GDP [39]—can provide durable GHG benefits reductions starting immediately without relying on overhauling US industry [51, 52]. Despite changes in average fuel resources noted during the first US response to COVID-19, material demand changes would have had a greater effect on CO₂ emissions for the high emitting materials, such as cement. This opportunity exists both at the individual project level (e.g., a building) and at the system level (e.g., densification leading to lower roadway intensity or investment in transportation modes like bicycles that require less roadway material).

While not directly shown in these data due to their reflecting very early reactions to the COVID-19 pandemic, there are indicators that social response is driving desires for larger, more disperse dwellings. Pandemics have a history of changing how we interact with the built environment, including shifts in housing density, public spaces, outdoor spaces within dwellings (e.g., balconies), and urban planning (e.g., roadway organization) [53]. Anticipated factors changing infrastructure material demand from COVID-19 include increased value on private outdoor space and uncrowded dwellings (potentially achievable through greater indoor square-footage) [54]. Remote working conditions, mortgage rates, and other drivers resulting from the pandemic has led to a decreased desire to live in rentals in urban areas [55] and an increased desire to purchase larger homes [56]. The new value of these built-environmental attributes can have effects on the construction, water, and energy services needed for those spaces, leading to increased associated resource consumption [57]. Demand for low-density housing and socially distant travel in particular could lead to long-term commitments to difficult-to-decarbonize materials for roads and vehicles. Factors such as these could drive de-densification of urban areas, which is known to increase land use and resource consumption [41]. The timing of the pandemic is particularly challenging in this regard, with the possibility that shifts in preferences for more socially distant transportation modes, like private cars over public transit, could contribute to a COVID-19-related lock-in of long-lived petroleum-dependent vehicles. This trend could result from current limited availability of alternative fuel (e.g., electric) vehicles coupled with households purchasing new cars earlier than they otherwise would have or that they might not otherwise have purchased. However, it is possible that new needs for social distancing, easy to clean surfaces, and appropriate indoor air quality controls could be used as a catalyst for improving social and environmental sustainability in the built environment [53, 58], particularly in the context of stimulus investments.
4. Conclusions

In this work, we show that the initial social response to the COVID-19 pandemic revealed several key aspects towards measures that can support decarbonization of the industrial sector as well as decoupling of energy resource consumption and GHG emissions. Our findings indicate that lowered petroleum demand and relative increases in products that use energy resources as material feedstocks were strong contributors to a decoupling of energy resource consumption and GHG emissions present in the US during the initial response. Despite some changes in fuel resources used in the industrial sector during this period, the decline in demand for materials known to have high emissions from production (e.g., cement, steel) would have contributed to greater GHG emission reductions. However, such alterations are not durable means to reduce GHG emissions from the industrial sector.

Without systemic change to interdependencies on other sectors and the methods we use to produce and deploy our industrial materials, societal behavior in response to the virus will not unilaterally be enough to change GHG emissions from the industrial sector. As noted previously, economic parameters could lead to lowering of procurement of construction materials. However, efforts to recover the economy through infrastructure investment could exacerbate some of these environmental concerns. Namely, investment in conventional infrastructure projects as an economic recovery could lead to increased GHG emissions from the production of infrastructure materials as near-term investment in shovel-ready projects are likely to use materials the way we have in the past. Without active intervention toward greener manufacturing and low material intensity design, there is no reason to assume near-term, long-lived projects will be less GHG intensive than past. Active steps to promote decarbonization, including an emphasis on the efficient use of energy and material resources—as has been highlighted in roadmaps prior to the pandemic—will likely be critical for success.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Associated content

An Excel file is supplied as Supporting Information. It contains supplementary data Tables.

Notes

The authors declare no competing financial interest.

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