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Manufacturing a Stable Climate: Drivers of Industrial Sector Greenhouse Gas Mitigation

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Manufacturing a Stable Climate: Drivers of Industrial Sector Greenhouse Gas Mitigation

By

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Professor Daniel M. Kammen, Co-Chair

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Professor Reed Walker

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Abstract

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As the primary means for growth and development over the past two centuries, industry has played a central role in generating our current Anthropocene. The increasing impacts of climate change bring industry to the fore as the largest global emitter of greenhouse gases and as a potential manufacturer of transformational technologies and infrastructure. While energy efficiency improvements are driving industrial sector emissions and cost reductions, additional switching away from fossil fuels and capture of carbon emissions is needed for climate stabilization.

The decline of U.S. industrial sector carbon dioxide emissions by one-fifth between 2000 and 2015 was driven by multiple economic and technological transitions. Five megatrends that contributed to the reduction of U.S. industrial and manufacturing sector emissions include: structural shift from goods to services, energy transition to electricity, natural gas, and renewables, increased trade and globalization, introduction of new technologies, and changing norms, regulations, and policies. These interrelated megatrends provide context for decomposition and facility-level analysis of U.S. manufacturing GHG emissions.

Achieving the Paris climate goal of limiting warming to well-below two degrees will require substantial greenhouse gas (GHG) emissions reductions and economic transformation. A growing group of countries are moving toward the Paris goal by reducing GHG emissions while continuing to grow their economies. However, existing metrics such as carbon emissions intensity of gross domestic product (GDP) do not capture dynamic country contributions to economic transformation and global emissions reductions. This dissertation develops an index of GHG-GDP divergence (ICGGD) to characterize country performance and explore the role of

industry and trade in low-carbon economic transformation between 2000 and 2015. In addition to assessing historical drivers, the index is also used to identify factors that can enable a growing group of countries to delink their GHG emissions and GDP growth. One unexpected finding of the ICGGD empirical research is that larger growth in merchandise imports is correlated with lower levels of country-level emissions performance. This appears to contravene the "leakage" theory that countries have reduced local production-based emissions via import growth; it is one of several topics addressed in this dissertation that could benefit from further research.

Finally, the global political swing towards populism in 2016 was largely resultant from real and perceived changes to industry and manufacturing employment. The global redistribution of industrial activity and jobs between 1990 and 2015 undermined the previous social contract whereby government legitimacy rested on provision of economic growth and opportunity for all. Rather than attempting to turn back the clock with nostalgic shibboleths about fossil-fueled manufacturing greatness, a new social contract is needed based on inclusive, climate-focused industrial policy. The fourth chapter assesses the role of industrial policy mechanisms in achieving inclusive low-carbon transformation.

dedicated to Ansel and the Jacksons

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Working full-time while pursuing a PhD is not a recipe for carefree relaxation. I am very grateful for the patient support of the ERG community and especially Kay Burns. The dissertation would not have been possible without my committee members Daniel Kammen, Arpad Horvath, Meredith Fowlie, Christine Rosen, and Reed Walker. Finally I am happy to acknowledge the role of my family and friends in keeping me inspired. Here's to creating useful new knowledge.

Chapter 1. Necessary but Not Sufficient: The Role of Energy Efficiency in Industrial Sector Low-Carbon Transformation

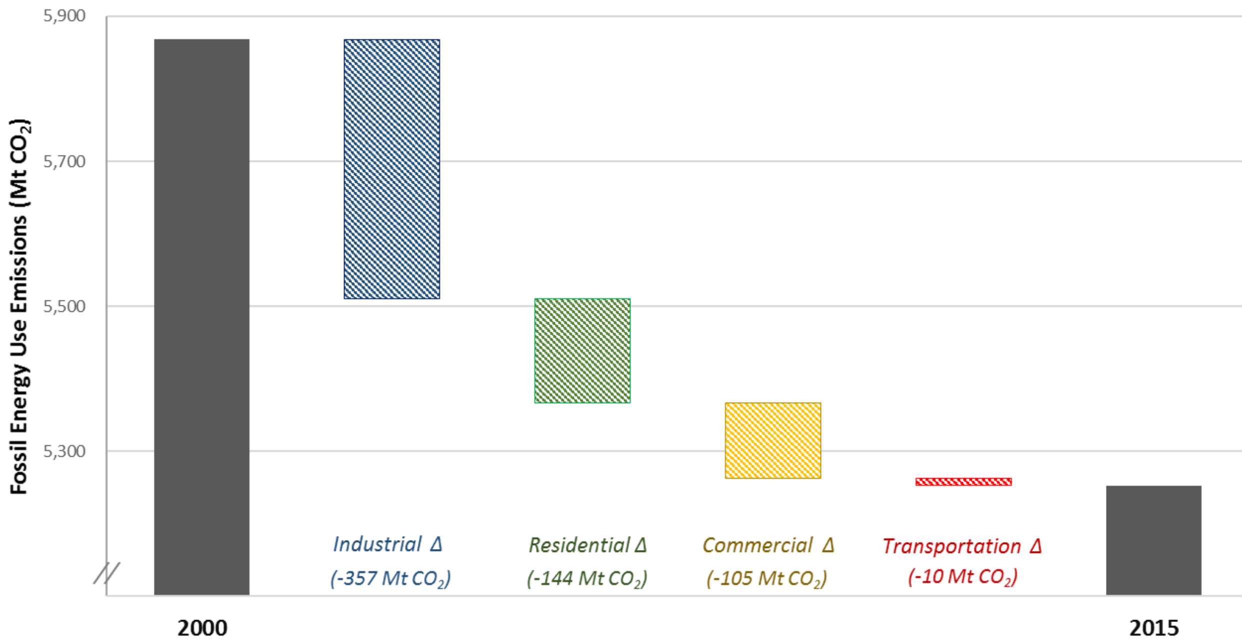
As the primary means for growth and development over the past two centuries, industry has played a central role in generating our current Anthropocene. The increasing impacts of climate change bring industry to the fore as the largest emitter of greenhouse gases and as a potential manufacturer of transformational technologies and infrastructure. While energy efficiency improvements are driving industrial sector emissions and cost reductions, additional switching away from fossil fuels and capture of carbon emissions is needed for climate stabilization.

Introduction

Since the advent of textile mills with power looms, steam engines, and iron making in blast furnaces during the late 1700's, industrial production has driven economic growth and greenhouse gas emissions. On a global scale, the industrial sector accounts for one third of total greenhouse gas (GHG) emissions—more than residential, commercial, or transportation sectors.[1] The shift of the economy toward services has not reduced the central influence of the industrial sector on global climate. Within the United States, for example, the industrial sector led the reduction of energy-related emissions between 2000 and 2015, as illustrated in Figure 1 below.

[1] Fischedick, et al. (2014). The IPCC calculated the industrial share of total global emissions between 30 and 40 percent depending on sector definition and boundaries. Regardless of boundary assumptions, the IPCC consistently reported with high confidence that industry is the largest end-use sector source of GHGs (i.e., allocating electricity and heat production-related emissions to consuming sectors).

Figure 1: Total U.S. Fossil Energy-Related CO_2 Emissions with 15-year Changes by End-use Sector (2000-2015)



Source: EIA, Monthly Energy Review, 2016.

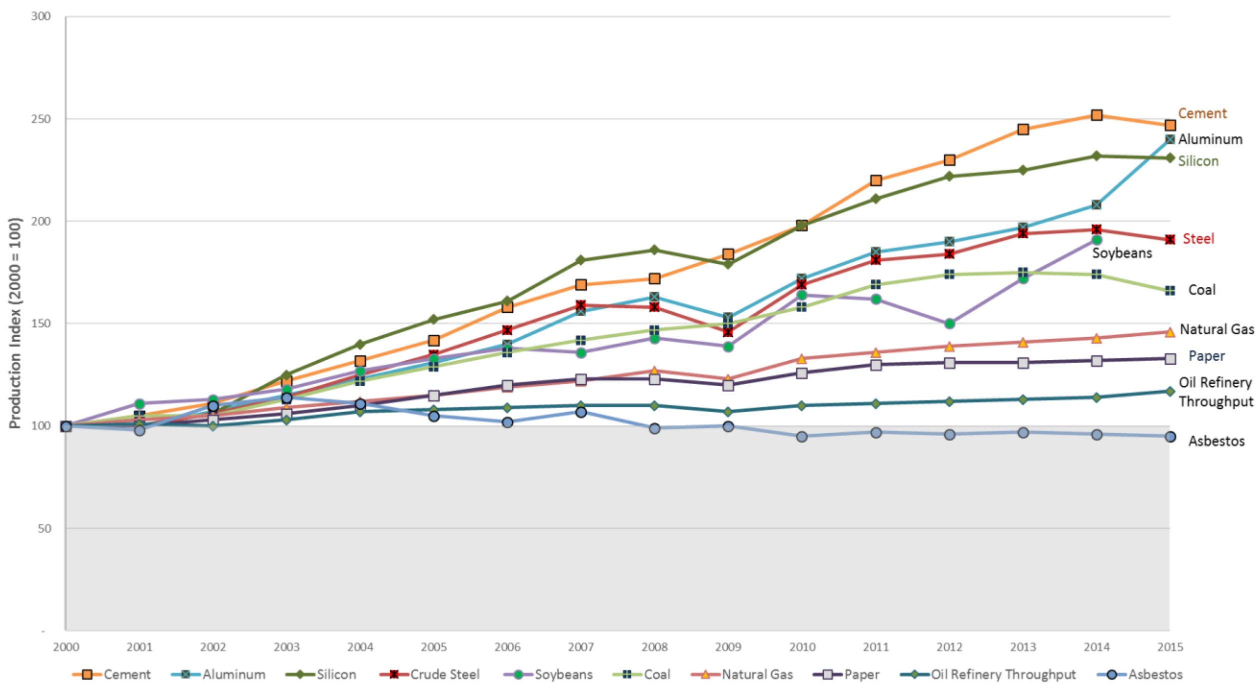
Over the first fifteen years of this century, total U.S. energy-related carbon dioxide emissions dropped by 10 percent (615 million metric tons CO_2). This lead 2015 carbon emissions to be lower than any point since the early 1990's, with continued declines in 2016. Figure 1 shows the industrial sector's leading role in reducing total energy-related CO_2 emissions. During the 2000-2015 period, U.S. industrial sector carbon emissions dropped by a greater share than any point since the 1979-1983 period.

Industrial transformation is a central component of the emerging low-carbon economy and society of the 21st century. This dissertation assesses the impacts and drivers of industrial transformation, the changing role of industry in economic development, and options for addressing adverse outcomes. The first chapter provides an overview of the metrics of industry globally and in the United States, as well as industrial sector pathways and programs for limiting average warming to 2-degrees Celsius above pre-industrial levels this century. Chapter two uses subsector decomposition and facility-level analysis to examine production and GHG emissions dynamics of U.S. manufacturing. Chapter three investigates the role of the industrial sector in country-level divergence of GDP and GHG emissions. Chapter four discusses policies and other options for guiding industrial transformation and addressing distributive impacts, as well as concluding thoughts and suggestions for further research.

Metrics of Industry

During the 21st century, the global industrial sector has been characterized by demand growth, new production capacity, supply chain fragmentation, and increased trade. Global demand has been largely driven by urbanization, exports, and infrastructure construction in China. An example of high demand growth is the cement sector, where China came to account for half of global production by 2009. Between 2000 and 2014 more cement was produced globally than during the entire 20th century.[2] Figure 2 illustrates annual changes in physical production over ten indicative industrial subsectors.

Figure 2: Indicators of Global Industrial Sector Annual Production (2000-2015)



Sources: Matos, 2015; WSA, 2015; BP, 2016; FAO, 2016. Note: All root production data are in physical terms.

Cement production increased by more than two and a half times over this period while annual steel production nearly doubled. At the same time, global population was 20 percent larger in 2015 than it had been in 2000 and real value added of industry was 47 percent larger.[3] Coal production grew at an average 4 percent rate per year until 2013, when global coal mining and production began to decline.[4] Beyond relative growth rates, the diverse subsectors included in Figure 2 reflect the broad boundaries of industry. The outline and definition of industry varies by country and organization regarding inclusion of agriculture, construction, and utilities—

[2] Global cement production records commence in 1926; if the 1926 global rate of cement production (62 million tonnes per year) is extended prior to that year then global cumulative production would be equal over the periods of 1869-1999 and 2000-2014. Source: Matos, 2015.
[3] Real value added of industry was $20 trillion out of $73 trillion global GDP (constant 2010 dollars) in 2014, up from $14 trillion in 2000. World Bank, World Development Indicators, 2016.
[4] See BP (2017) for coal production data; although global coal production has consistently declined since 2013, 2016 global coal production remained 58 percent higher than year 2000 levels.

mining and manufacturing are usually included. Among the subsectors in Figure 1, the decline of asbestos production reflects the impact of public health policy interventions on global industrial production.[5] Since 2000, global industry experienced rapid growth to 2008, when demand dropped and rebounded in 2011, followed by slower growth through 2015.

Changes in the economy, and particularly globalization and fragmentation of supply chains, have shifted the geography of industrial production during the 21st century. The predominant geographical trend in industry between 2000 and 2015 was increased concentration of production in China. For example, while China was already the largest producer of cement and steel in 2000, its share jumped from 36 to 60 percent and 15 to 49 percent of global production respectively between 2000 and 2014.[6] Increased geographic concentration was accelerated by the decline of physical production in many high income countries. The United States was the world's largest primary aluminum producer in 2000, at which point it accounted for 15 percent of global production. The 57 percent decline of U.S. production between 2000 and 2015 brought the U.S. down to the fourth largest aluminum producer, behind China, with 55 percent of global production in 2015, and Russia and Canada. The geographic concentration of industrial production has been mirrored by expansion of international manufactured goods trade, which grew by 151 percent in value-added terms between 2000 and 2015.[7]

On a global level, production growth has been accompanied by increased industrial sector employment, value added, and greenhouse gas emissions. The changing sector share of total employment reflects urbanization and the transition away from agriculture that has accelerated in many countries during the 21st century. Between 2000 and 2010, the agricultural share of total global employment declined from 36 to 20 percent, while the industrial share of total employment grew from 20 to 29 percent over the same period.[8] Total industrial sector employment expanded from 531 million employed persons in 2000 to 886 million employed persons in 2010. As with production, global growth masks divergent country-level employment changes in industry. While China added more than 200 million industrial sector jobs between 2000 and 2010, more than 8 million U.S. industrial sector jobs disappeared over the same period, reducing U.S. industrial sector employment by 25 percent. Between 2000 and 2014 the real value added of global manufacturing increased by 33 percent.[9] Meanwhile, global direct carbon dioxide emissions from manufacturing grew by 59% between 2000 and 2013. This relatively high growth drove up the CO_2 intensity of global manufacturing real value-added by nearly a quarter between 2000 and 2013. Given the widespread intra-country reductions of carbon intensity of real manufacturing value added over this period, including in China, the

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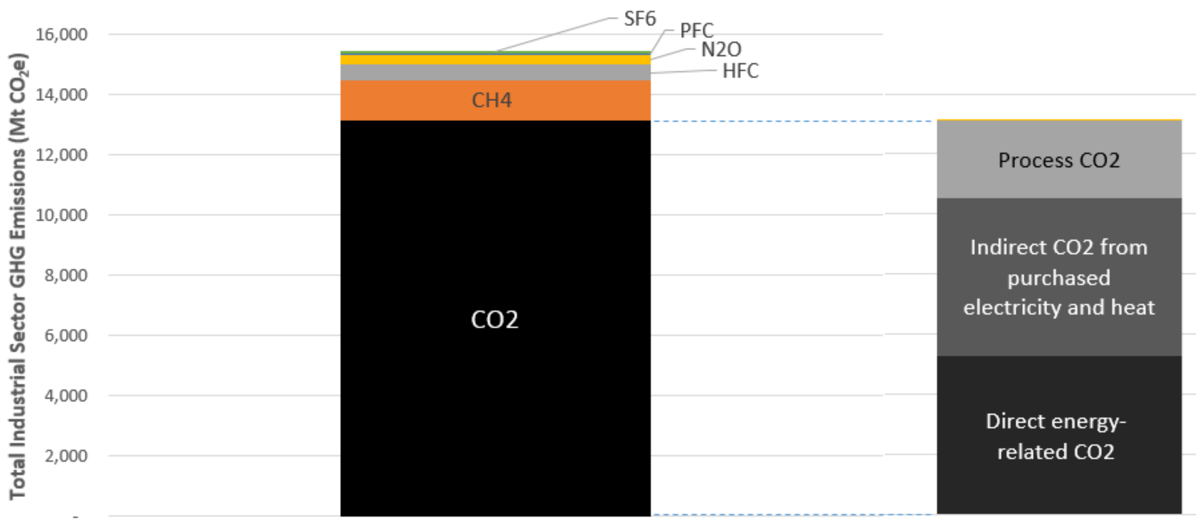
[5] UNEP, 2013.
[6] Matos, 2015.
[7] World Bank, World Development Indicators, 2016.
[8] Note that 2010 is the latest available year for global employment data; World Bank, World Development Indicators, 2016.
[9] Global manufacturing value-added data are in chained 2010 dollar terms. Global industrial value-added data are not available. World Bank, World Development Indicators, 2016.

global increase reflects geographic relocation of production as well as structural shift of manufacturing toward more emissions-intensive products and subsectors.

Based on current technologies and the structure of the global economy, industry is the largest sector source of greenhouse gas (GHG) emissions, accounting for a third of total global GHGs in 2010. Most industrial sector GHG emissions result from direct fossil fuel combustion and the production of purchased electricity and heat. Figure 3 illustrates the composition of total global industrial sector GHG emissions by gas, and by source for carbon dioxide.

Figure 3: Total Global Industrial Sector Greenhouse Gas Emissions (2010)



Sources: IEA (2012); JRC/PBL (2013) via Fischedick, et al. (2014).

Carbon dioxide accounts for 85 percent of global industrial sector greenhouse gas emissions, followed by methane, which makes up 9 percent. Global industrial sector carbon dioxide in turn comprises 40 percent direct emissions from on-site fossil fuel combustion, 40 percent indirect emissions from purchased electricity and heat, and 20 percent carbon dioxide emissions from industrial production processes such as cement calcination, chemicals and lime production, and coke ovens. More than half of global industrial process emissions in 2010 were from cement production.[10] GHG emissions are often divided into three scopes, particularly for company- and facility-level accounting. Scope 1 refers to all direct GHG emissions, i.e. from fossil fuel combustion or manufacturing process emissions. Scope 2 includes indirect GHG emissions related to production of purchased electricity, heat or steam. Scope 3 covers other indirect emissions, such as the extraction and production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, electricity-related

[10] The IPCC Fifth Assessment Report, Industry Chapter details process emissions by source and gas; 2010 global cement process emissions from clinker calcination amounted to 1.4 billion tonnes CO_2e (Fischedick, et al. 2014).

activities (e.g. T&D losses) not covered in scope 2, outsourced activities, waste disposal, etc.[11] This analysis is focused on scope 1 and 2 industrial sector emissions.

Since the start of the industrial revolution, global industrial GHG emissions have moved in tandem with total GHG emissions (including transport and buildings) and the global economy.[12] As atmospheric concentrations of greenhouse gases continue to rise and climate impacts become more evident, stakeholders have coalesced around the goal of limiting warming this century to less than 2 degrees Celsius above pre-industrial levels.[13] The challenge for limiting average global warming to 2 degrees Celsius is to break the linkage between industrial sector GHG emissions and the economic activity required to fulfill human needs.

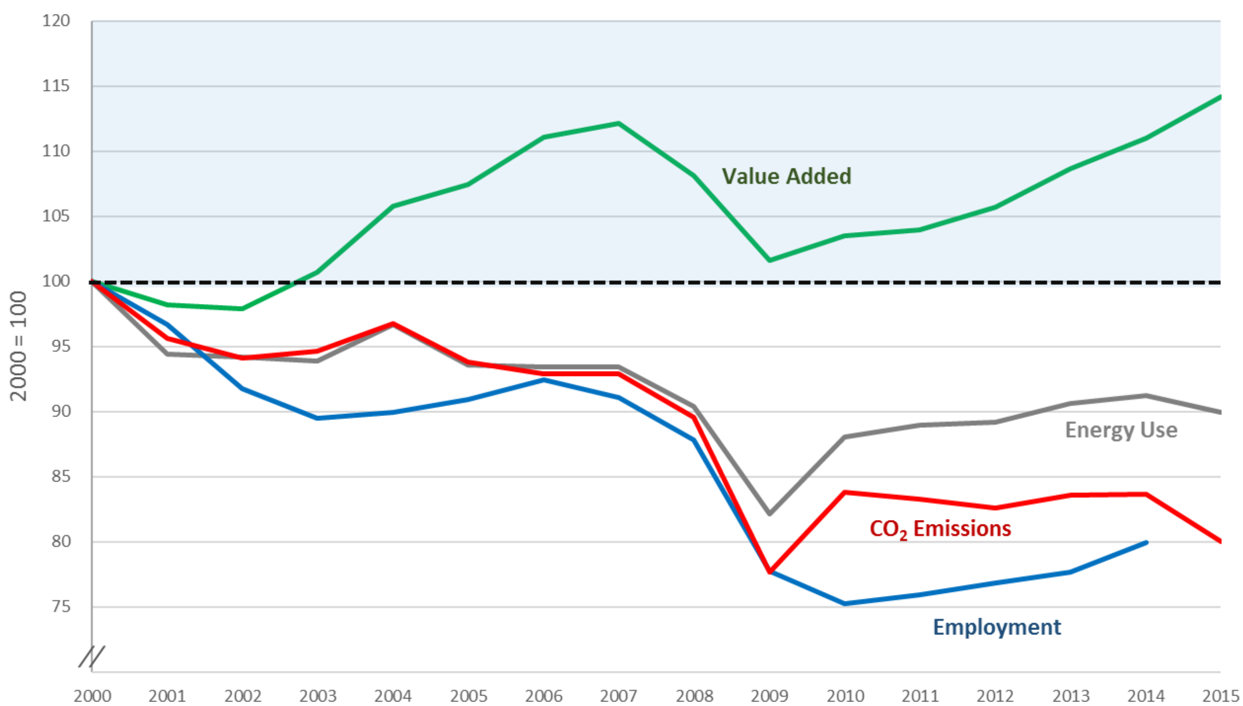
Industry is more GHG-intensive than buildings, transport, and power sectors. As such, the industrial sector will play a central role in the Nationally-Determined Contributions (NDCs) presented by countries in the 2015 Paris Agreement. In contrast with previous top-down approaches to international climate policy, the NDCs represent country offers largely based on bottom-up assessments. NDCs cut across multiple levels of climate engagement: country, sector, company, and facility. The NDC framework provides a new structure for coordinating the global 2-degree goal with national climate and energy policies and investments. If countries achieve their published NDC goals, average warming this century is likely to reach 2.7 degrees Celsius above pre-industrial levels, thereby surpassing the agreed Paris target.[14] Industrial, sector-based approaches can help companies and other stakeholders to bridge the gap between country NDC actions and the global 2-degree pathway.

U.S. Industrial Sector Metrics

Within the United States, the industrial sector experienced more contraction and low-carbon growth than its global counterparts since 2000. While U.S. industrial sector real value added increased by 14 percent between 2000 and 2015, physical indicators of industrial subsector activity (e.g., tonnes of crude steel produced per year) declined. Total U.S. employment, energy use, and carbon dioxide emissions also declined over this period. Figure 4 details the annual changes in four aspects of industrial sector activity from a year-2000 baseline to 2015.

[11] Additional information about GHG accounting is available in WBCSD (2013).
[12] Meanwhile, over the past 15 years more than 30 countries have de-linked their GHG emissions and GDP. While GHG-GDP divergence is becoming increasingly prevalent, the larger challenge of decarbonizing industry still stands.
[13] Nordhaus (1977) was the first published reference to the 2-degree goal, which has been repeatedly affirmed, most recently in ratification of the 2015 Paris Agreement. The 2-degree goal persists in spite of numerous critiques (e.g., Victor & Kennel, 2014).
[14] The 2.7-degree estimate is from IEA (2016b).

Figure 4: U.S. Industrial Sector Trends, 2000-2015



Sources: EIA MER, EPA GHG Inventory Report, BEA, BLS. Note: value-added data are in chained 2009 dollars.

The real value added of industry has grown at an average annual rate of 2 percent since its financial crisis nadir of 2009, bringing 2015 total industrial sector real value added to 14 percent above its 2000 value.[15] Within industry, manufacturing real value added experienced 19 percent growth between 2000 and 2015, while agriculture and mining grew by 54 and 79 percent respectively, and construction value added contracted by 19 percent. In reflection of the importance of new technology in the 21st century economy, 'computer and electronic products' was the U.S. manufacturing subsector with by far the largest growth of real value added, more than doubling from $91 billion (chained 2009 dollars) in 2000 to $211 billion (chained 2009 dollars) in 2015. Several, predominantly traditional, manufacturing subsectors lost value over this period, notably fabricated metal products, textiles, apparel, and paper. The overall value-added growth of U.S. industry stands in stark contrast with industrial employment, energy-use, carbon-dioxide-emissions, and physical-production declines over this period.

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[15] Industrial sector value-added data are calculated as the sum of 'Agriculture, forestry, fishing, and hunting', 'Mining', 'Construction', and 'Manufacturing' subsector data from the U.S. Bureau of Economic Analysis. Chained 2009 data indicate that total industrial sector real value added reached its highest level in 2015. Real U.S. industry and manufacturing value-added data from the World Bank exhibit similar trends with slightly different values.

Employment in U.S. industry peaked in 1979, when the sector had more than 27 million full and part-time employees.[16] Each of the four U.S. industry sectors exhibited independent long-term employment trends: agriculture steadily decreased; mining jobs experienced a sharp peak in the early 1980's and have grown since 2000, though yet to reach the earlier peak; construction jobs grew for decades, reaching a pre-financial crisis high in 2007; manufacturing employment intermittently declined since its peak in 1979. Manufacturing drove U.S. industrial sector employment losses of 5.8 million jobs (20 percent) between 2000 and 2014.[17] Construction and agriculture sector employment contracted by 9 and 10 percent respectively, while more than 300,000 mining jobs were created during this period, amounting to a 62 percent expansion over year-2000 levels. As with value added, some manufacturing subsectors added jobs, notably 'other food manufacturing', while the vast majority contracted. The large scale of industrial sector job losses has undermined numerous communities and accelerated U.S. income inequality as unemployed manufacturing workers struggle to find similarly paid work.

After shedding a quarter of jobs between 2000 and 2010, industrial sector employment grew continuously through 2014 (the latest year of available data). Comparison of industrial subsector employment numbers over the pre- and post-2010 periods shows that some sectors shed and re-gain jobs in line with overall GDP while other sectors are on more sustained pathways of contraction or growth. Construction, for example, shed 1.3 million jobs between 2000 and 2010 and then re-gained 520,000 in the following four years. The manufacturing rebound was significantly smaller, regaining 630,000 of the 5.8 million jobs lost between 2000 and 2010. Many sectors, particularly in industry, are highly cyclical and have been for decades. The sector-level impact of growth and contraction cycles depends on the extent to which certain (e.g., more labor-intensive) facilities permanently close during downturns, as opposed to being mothballed and restarted when demand returns.

U.S. industrial sector total energy use peaked at 35 Quads (37 EJ) in 1997.[18] Industrial energy use experienced a sharp bounce around the financial crisis, dropping by 9 percent in 2009 and then rebounding by 7 percent in 2010. The drop was precipitated by demand reductions and energy and commodity price spikes, and it marks a relatively discrete event in the longer-term trend of declining industrial energy use. U.S. industrial sector energy use declined in 9 of the 15 years between 2000 and 2015, resulting in a total reduction of 10 percent over this period. Energy efficiency improvements, structural change, substitution of domestic production with

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[16] BEA (2006) "GDPbyInd_VA_NAICS_47to97R.xls" via http://www.bea.gov/industry/NAICSemployment_datarelease.htm.

[17] Charles et al. (2016) have found that the secular decline of manufacturing employment after 2000 was initially masked by absorption of less-educated workers by the construction sector, which made for a more debilitating collapse in 2007-9.

[18] Note that 1997 industrial sector energy use was a subtle peak that only exceeded the previous 1979 high by 4 percent. Data from EIA (2016).

imports, and final demand reductions all contribute to reductions of U.S. industrial sector energy use.

As with employment, fossil energy-related carbon dioxide emissions from the U.S. industrial sector peaked in 1979.[19] While there was gradual growth from the mid-1980's to mid-1990's, industrial sector energy-related CO_2 declined with a sustained trend since 2000. These emissions were reduced over 10 of the years between 2000 and 2015. The financial crisis marked a more pronounced bounce of energy-related emissions than occurred with total energy use—emissions dropped by 13 percent in 2009 and rebounded by 8 percent in 2010. The overall decline led to 2015 U.S. industrial sector energy-related CO_2 emissions 20 percent below their 2000 levels (1.4 billion tonnes CO_2). The higher level of emissions reductions than energy use reductions indicates that U.S. industrial sector companies switched to less-emissions-intensive energy sources during this period. In fact, the carbon dioxide intensity of U.S. industrial sector energy use (g CO_2/Btu) declined by 11 percent between 2000 and 2015. Declining carbon intensity of energy use combined with energy efficiency improvements to reduce the CO_2 intensity of U.S. industrial sector value added by 30 percent over the same period.[20]

Cleaner energy use and energy efficiency improvements are central components of the transition to a low-carbon economy. Additional determinants of the emissions impact of the industrial sector come from structural change, i.e., the shift of industrial activity among subsectors, and fluctuations of physical demand levels. Physical production measures correspond more closely with energy and environmental aspects of industrial production than economic metrics such as value added; however, the diversity of industrial production prevents consistent physical aggregation across subsectors.[21] Figure 5 shows ten indicators of U.S. industrial subsector physical production (e.g., BCM of natural gas, bushels of corn, as opposed to economic measures of production such as value added) between 2000 and 2015.

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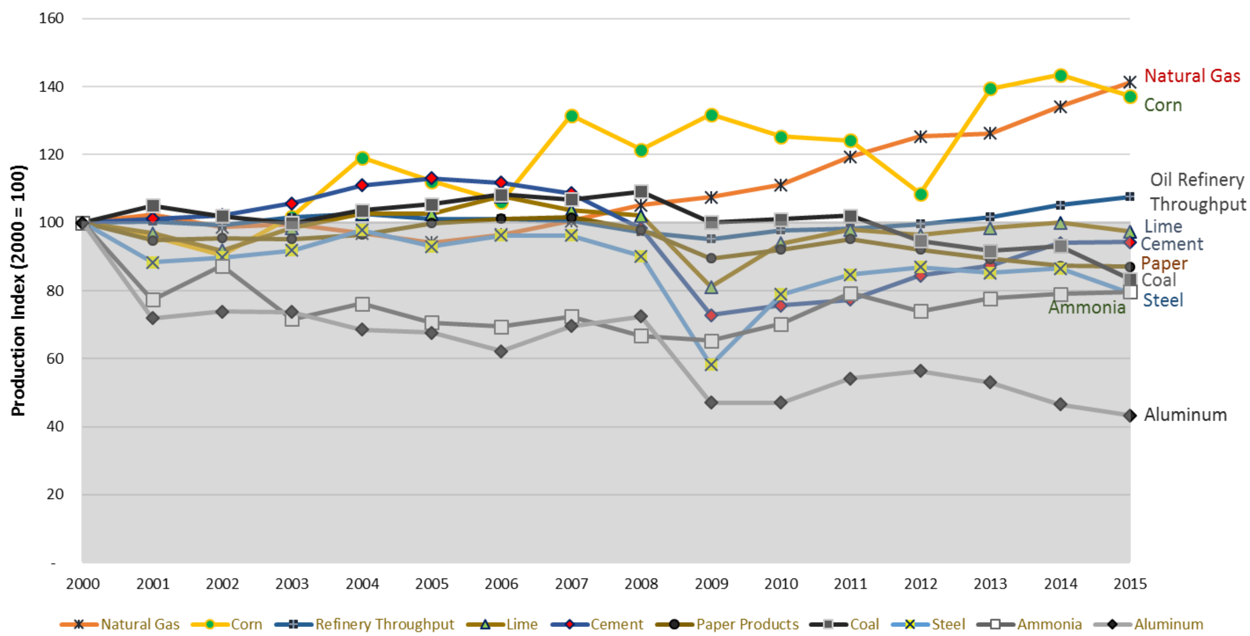
[19] The energy-related CO_2 peak was more definitive than industrial energy use peaks. For example, the subsequent high point in 1997 was still 6 percent below the 1979 value. Data from EIA (2016).
[20] EIA (2016), BEA (2016).
[21] Physical indicators are commonly used to assess activity in relatively homogenous subsectors. For paper and steel subsector examples see Farla et al. (1997) and Worrell et al. (1997); for physical data incorporation into aggregate industry analysis, see Ang and Xu (2013).

Figure 5: Indicators of U.S. Industrial Production (2000-2015)



Sources: USGS, BP, USDA. Note: All root production data are in physical terms.

In contrast to global physical production and U.S. industrial sector value added, most U.S. industrial subsectors reduced physical production between 2000 and 2015. Numerous subsectors gradually reduced total physical production with an additional drop related to the financial crisis. Whereas global primary aluminum production grew by nearly two and a half times between 2000 and 2015, U.S. domestic primary aluminum production contracted by 57 percent. As mentioned above, the U.S. was the largest primary aluminum producing country in 2000, but was subsequently surpassed by China, which increased its annual aluminum production more than ten-fold between 2000 and 2015. Two factors that contributed to the decline of U.S. aluminum production are increased imports, which grew from 3.3 to 4.7 million tonnes (43 percent), and reduced apparent consumption, which dropped by 22 percent.[22] The decline of U.S. aluminum production, however, is not exclusively a story of import displacement and demand destruction. U.S. aluminum exports grew by a larger portion (72 percent) than imports between 2000 and 2015. Over the same period U.S. secondary production of aluminum from old scrap increased by 20 percent, thereby exceeding U.S. primary aluminum production. Given the large stocks of produced metals in the U.S. economy, a shift from primary to secondary production makes sense from cost and environmental perspectives.[23]

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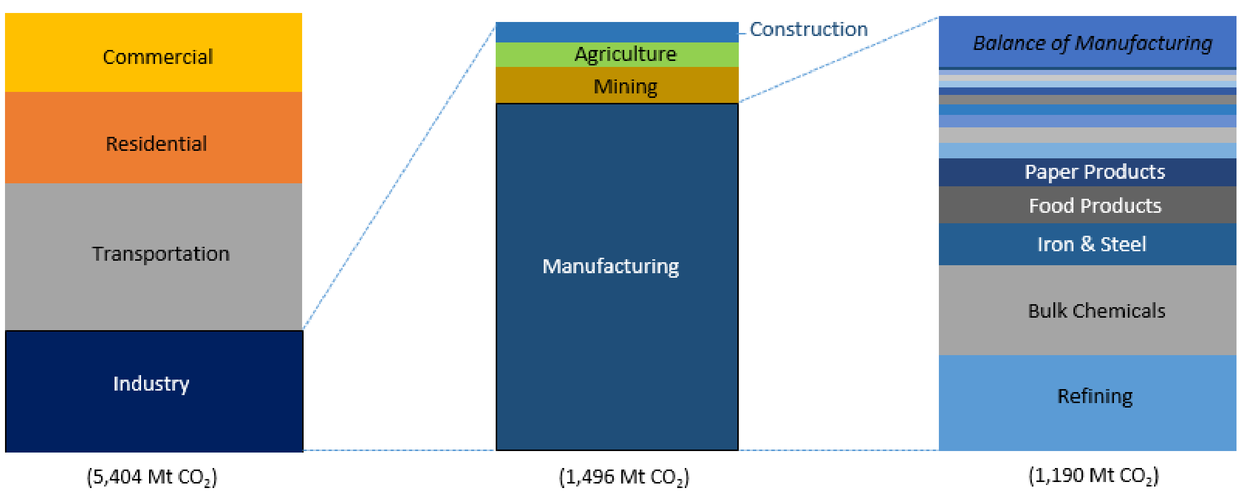
[22] Apparent consumption of aluminum is defined as domestic primary metal production + recovery from old aluminum scrap + net imports; excludes imported scrap. Data from USGS (2016).

[23] Researchers in the field of industrial ecology have identified steel saturation effects via material flow analysis; see Cullen et al. (2012), Pauliuk et al. (2013), and Fishman et al. (2016).

Steel and cement also experienced declining U.S. production and growing global production over the 2000-2015 period. Cement, steel, and aluminum subsectors all reduced apparent consumption between 2000 and 2015. While steel and aluminum imports increased over this period, U.S. cement imports dropped by 60 percent. These changes are reflected in the subsectors' net import reliance as a percentage of apparent consumption, which grew from 17 to 25 percent for steel, and 33 to 40 percent for aluminum, while it dropped from 20 to 10 percent for cement between 2000 and 2015.[24] On the other end of the spectrum, U.S. natural gas, corn, and refinery production increased between 2000 and 2015. Based on new fracking and other shale technologies, U.S. natural gas production grew by 40 percent between 2007 and 2015. The growth of U.S. oil and gas production is also reflected in the rise of oil refinery throughput by 8 percent between 2012 and 2015. Among the dozens of subsectors that comprise industry, each one has specific factors that explain its production, energy use, emissions, and employment dynamics. To identify the most salient sectors for mitigation purposes, Figure 6 maps industry, manufacturing, and subsector energy-related CO_2 emissions in 2014.

Figure 6: Energy-related CO_2 emissions from U.S. industry, manufacturing, and subsectors (2014)



Sources: EIA, Monthly Energy Review; EIA, Annual Energy Outlook 2016.

The ongoing decline of U.S. industrial sector emissions has relegated industry to the second-largest emitting U.S. sector behind transportation.[25] In 2014, the industrial sector accounted for 28 percent of total U.S. energy-related carbon dioxide emissions and transportation accounted for 34 percent. Within industry, manufacturing accounted for 81 percent of energy-related CO_2 emissions in 2014. Sixteen subsectors comprise U.S. manufacturing, of which the top five accounted for 67 percent of total manufacturing energy-related carbon dioxide emissions in

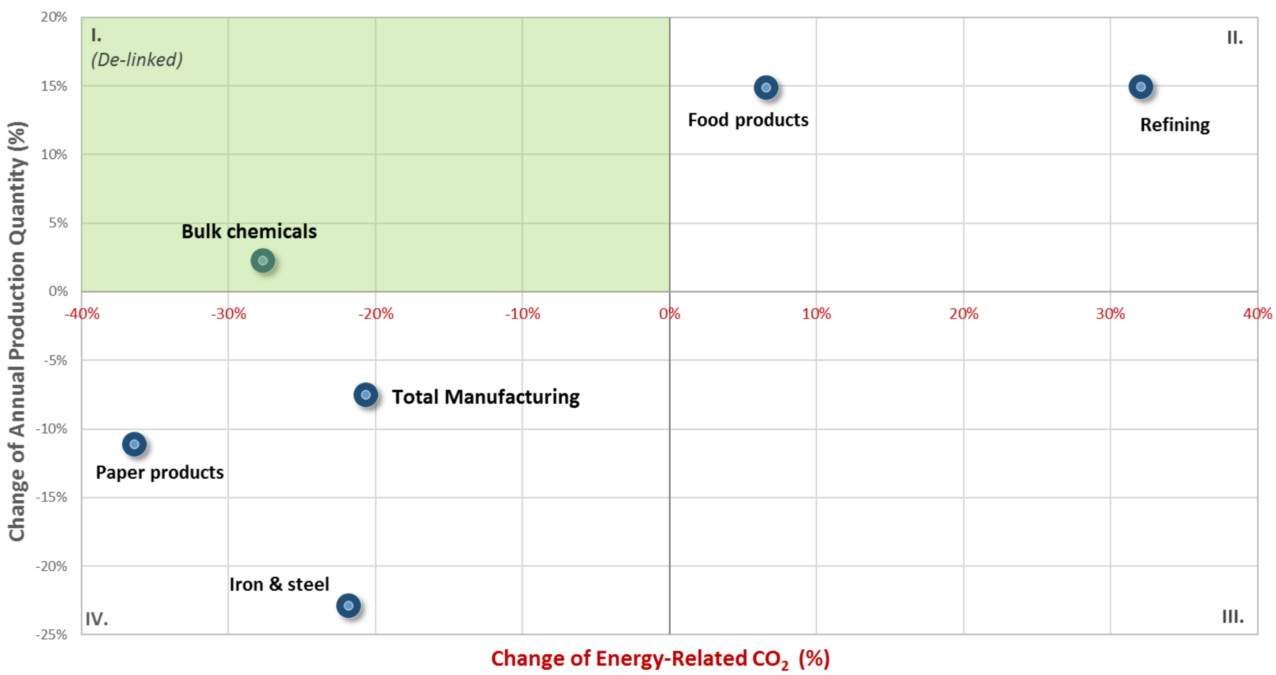
[24] Net import reliance is calculated as: $\frac{(imports - exports - net\ stock\ change)}{(apparent\ consumption)}$. Data source: USGS (2016).

[25] These data include emissions from fossil energy use and electricity consumption.

2014.[26] Refining and bulk chemicals production are the dominant manufacturing subsectors, accounting for 22 and 21 percent of total manufacturing energy-related CO_2 emissions respectively. Given the transitions in U.S. industry after the year 2000, the distribution of manufacturing subsector emissions remained remarkably stable. Bulk chemical production was the largest emitting manufacturing subsector in 2000 followed by refining. Fabricated metal products dropped out of the top-five group and was replaced by food products, but the top-five subsector share of total manufacturing energy-related CO_2 remained steady at two-thirds.

Manufacturing subsectors have played different roles in the reduction of U.S. industrial sector emissions. Two metrics for understanding the roles and impacts of manufacturing subsectors are changes in annual emissions and value added. Figure 7 presents a scatter plot of total manufacturing and top-five subsector change in energy-related CO_2 versus change in indexed quantity of production between 2000 and 2015.

Figure 7: Scatterplot of U.S. Manufacturing Subsector Change of Energy-Related CO_2 vs Production Quantities (2000-2015)



Sources: BEA; AEO. Note: Y-axis production data are based on chain-type quantity indexes for Gross Output.

The four quadrants in Figure 7 capture the range of manufacturing subsector trajectories with regard to production and emissions. The first, upper left quadrant is labeled *De-linked* because

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[26] The 16 manufacturing subsectors (in order of 2014 emissions): Refining, Bulk Chemicals, Iron and Steel, Food, Products, Paper Products, Aluminum, Transportation Equipment, Plastics, Fabricated Metal Products, Cement and Lime, Machinery, Computers and Electronics, Glass, Wood Products, Electrical Equipment, (Balance of Manufacturing).

this subsector, bulk chemicals, increased its quantity of production between 2000 and 2015 with simultaneous energy-related CO_2 reductions. The bulk chemicals subsector increased production quantities by 2 percent while reducing CO_2 by 28 percent between 2000 and 2015. The heterogeneity of bulk chemicals production means that some of this divergence was a result of product-mix shifting to less emissions-intensive products.[27] Divergence is a win-win outcome in the sense that production growth continues with its related benefits while GHGs are reduced and the challenges of climate change are partially mitigated. In economic terms, the U.S. manufacturing sector achieved aggregate divergence between 2000 and 2014 with 18 percent growth of real value added (from $1.6 to $1.9 trillion 2009 dollars) and a commensurate 17 percent reduction of energy-related carbon dioxide emissions (from 1.4 to 1.2 billion metric tons CO_2), but as shown in Figure 7 above it did not achieve delinking in production-quantity terms. The version of the Figure 7 scatterplot based on value-added y-axis data moves iron and steel and total manufacturing into the de-linked quadrant along with basic chemicals. The difference between economic and physical metrics of manufacturing activity is significant and reflects price effects as well as broadening business models among subsectors.

The second quadrant, in the upper right, signifies increases in both energy-related CO_2 and production quantities. This 'linked' growth was standard for U.S. manufacturing subsectors during the 20th century, and is still the standard production-emissions relationship for most global manufacturing. Between 2000 and 2015 food products and refining followed this path with 15 percent increases in production quantities and 7 and 32 percent growth of energy-related CO_2, respectively.

The third, lower right, quadrant is a lose-lose case in the sense that production is declining at the same time that energy-related emissions are increasing. Fortunately, no major U.S. manufacturing subsectors fell into this quadrant in quantity terms between 2000 and 2015. Price effects can drop subsectors into this situation in periods of rising input costs, particularly when combined with global overcapacity.[28]

The fourth, lower left, quadrant can be characterized as 'linked decline' in the sense that there is simultaneous reduction of energy-related CO_2 emissions and production quantities. Insofar as social and political systems are predicated on continual growth, the linked decline mitigation pathway is problematic. It would come as no surprise to U.S. steel and paper mill workers to know that their sectors are in this fourth quadrant. The paper subsector followed a coupled decline pathway with 36 percent reduction of energy-related emissions and 11 percent reduction of production quantities between 2000 and 2015. Antiquated capital equipment, failure to invest in energy efficiency improvements, and weak demand combined to create a

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[27] This chapter uses the terms "divergence" and "de-linking" to describe reduction of GHG emissions with contemporaneous GDP growth instead of 'decoupling' to avoid confusion with the regulatory term that describes disassociation of an electric utility's profits from its sales of an energy commodity. The divergence described here is equivalent to "absolute decoupling" in its general use.

[28] For example, see OECD (2015) for discussion of impacts of overcapacity in global steel production.

challenging situation for the U.S. paper subsector and the rural communities that depended on those dwindling jobs.[29]

Given the need to reduce GHG emissions from the manufacturing sector and other portions of the economy, the challenge for companies, policymakers, and other stakeholders is how to move as many subsectors as possible into the upper left, de-linked quadrant. Ex post assessment of U.S. manufacturing emissions reductions can help to identify mitigation mechanisms, priority subsectors, and opportunities for new approaches. Historical assessment can also be combined with climate modeling to inform forward-looking pathways for competitive and sustainable low-carbon manufacturing.

Pathways for Stabilizing Climate this Century

The IPCC's Fifth Assessment Report (AR5) provided a comprehensive picture of the relationship between GHG emissions and climate impacts based on an ensemble of climate models. One approach adopted in AR5 is to use cumulative carbon dioxide emissions budgets as an indicator of expected warming and other climate impacts. The AR5 scenario with the highest likelihood of limiting warming to less than 2 degrees yields a cumulative economy-wide 2011 to 2100 emissions budget of 630 to 1,180 Gt CO_2. To reach this level, total GHG emissions in 2050 must drop 49% to 72% below 2010 levels.[30] If 2014 rates of global emissions are maintained, the cumulative budget for this century will be exceeded at some point between 2030 and 2050.[31] Subsequent analysis of non-carbon dioxide emissions impacts has found that the cumulative budget for avoiding 2-degree warming is significantly lower than previous exceedance-based estimates.[32] While the long-term picture indicates that aggregate emissions should drop to a net-zero level to limit climate impacts[33], cumulative and sector-level budget estimates are useful for guiding subsector and company mitigation actions.

Industrial Sector Emissions Budget Estimates

While there is broad global consensus on the need to limit warming this century to less than 2 degrees, there is not a single cumulative budget or pathway associated with that target. Beyond climate uncertainty, the budgets and pathways vary depending on their reliance on emissions removal technologies. All scenarios that achieve the 2-degree target also include net negative emissions, at least in the second half of the century. Although negative emissions will be costly,

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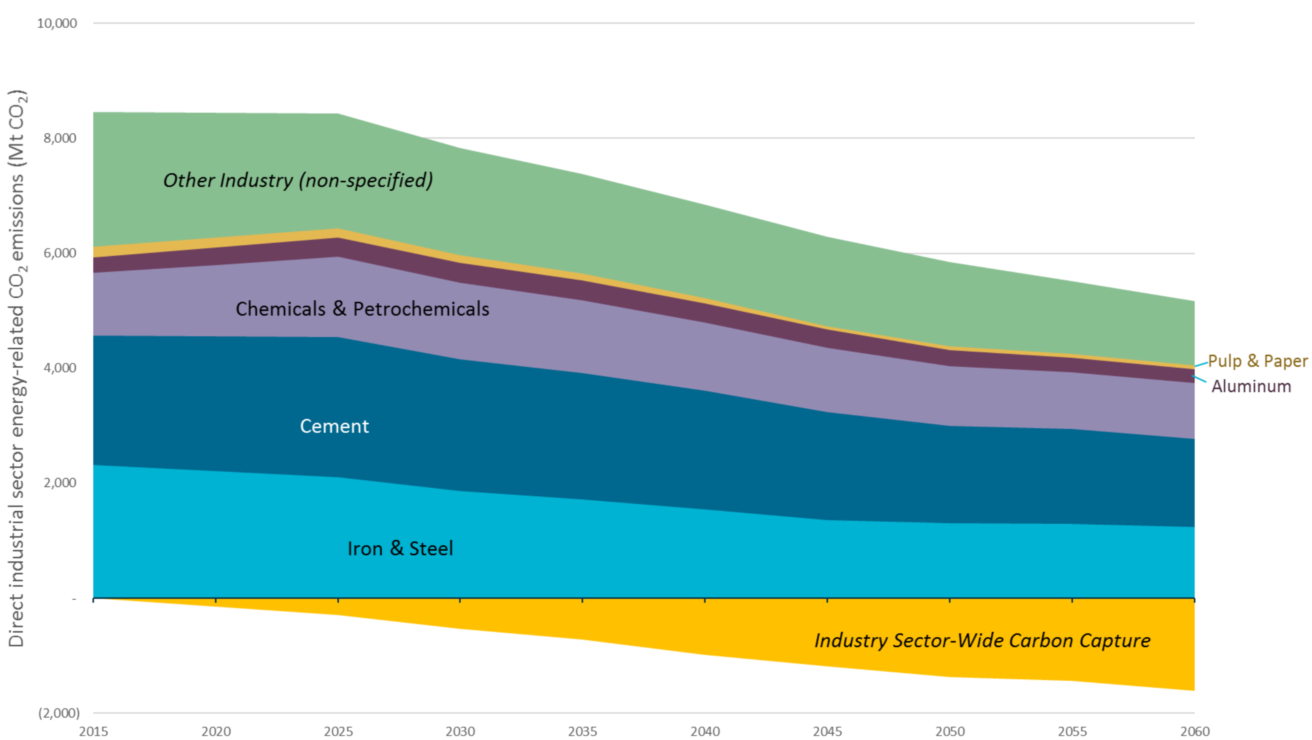
[29] For additional information and analysis of the U.S. pulp and paper sector, see Aden, et al. 2013.
[30] Clarke, et al. (2014). These numbers are based on scenarios with minimal overshoot (< 0.4 W/m^2), i.e., less reliance on carbon removal technology deployment to achieve negative emissions in the second half of the century.
[31] Le Quéré, et al. (2015) estimate 2014 total global emissions of 36 Gt CO_2, and ~141 Gt CO_2 cumulative emissions from 2011 to 2014.
[32] Rogelj, et al. (2016) present a broad range of budgets based on varying assumptions.
[33] Geden (2016) argues that a net zero emissions target is more actionable than 2-degree budgets. However, some existing industrial companies and stakeholders find net zero targets to be unrealistic and detrimental to current efforts.

the ensemble of scenarios included in AR5, the IEA's publications, and academic articles include negative emissions technologies' deployment for cumulative emissions budget reduction.

Just as there is a range of aggregate global emissions budgets among models and scenarios, multiple approaches have been developed for calculating corresponding global industrial sector emissions budgets for limiting warming this century to 2 degrees. A simplistic equal-mitigation approach would suggest that industrial sector carbon dioxide emissions must be reduced by at least 49%, from 5.3 Gt direct CO_2 (13 Gt CO_2 direct and indirect) in 2010 to 2.7 Gt direct CO_2 (6.7 Gt CO_2 direct and indirect) in 2050; linear interpolation over this period yields an upper limit cumulative industrial sector budget of 163 Gt direct CO_2 (407 Gt CO_2 direct and indirect). Application of a constant (3%) annual reduction rate over the 40-year period with 2050 emissions 72% below 2010 levels yields a more conservative cumulative budget of 123 Gt direct CO_2 (306 Gt CO_2 direct and indirect). Extending the 2010 rate of global industrial sector carbon dioxide emissions exceeds these simple cumulative 2-degree budgets at a point between 2033 and 2041. These 2050 interpolation-based approaches can be characterized as 'absolute contraction' methods based on the assumption that sectors move in tandem.

The IEA also models 2-degree emissions and energy-use pathways in its *Energy Technology Perspectives* (ETP) series of reports and datasets. The ETP model uses technology data to calculate least-cost emissions budgets within and among sectors. Figure 8 illustrates global annual Scope 1 CO_2 emissions among industrial subsectors per the ETP's 2-degree scenario.

Figure 8: Annual Global Industrial Subsector CO_2 Emissions under a 2-Degree Scenario (2015-2060)



Source: IEA, 2017. Note that 2015 data are interpolated from published 2014 and 2025 data; negative emissions are only specified at the industry sector level.

The ETP scenario yields a cumulative direct (Scope 1) gross emissions budget of 270 Gt CO_2 between 2015 and 2050.[34] The ETP 2-degree emissions pathways are the basis of the Sector Decarbonization Approach (SDA) for guiding company emissions reduction targets.[35] Whereas absolute contraction methods assume immediate emissions reductions equally apportioned among all sectors and companies, the SDA uses a peak-and-decline pathway that gradually reduces emissions among sectors according to modelled production technologies, demand, and mitigation costs. To accord with global 2-degree emissions budgets, the ETP scenario includes 6 percent annual growth of industrial sector carbon capture, to the point where global industry captures a quarter of gross annual carbon dioxide emissions in 2050.

Subsector Pathways and Related Initiatives

Based on projected demand, technology trends, and abatement costs, this section describes the ETP 2017 emissions budgets and pathways for industrial subsectors to align with the global 2-degree pathway. These data reflect gross Scope 1 emissions. Industry-wide carbon capture begins in 2020 under the 2-degree scenario and amounts to 24 billion tonnes carbon dioxide between 2015 and 2050.

Iron and steel

The cumulative 2015-2050 ETP17 emissions budget for the global iron and steel subsector is 65 billion tonnes carbon dioxide. The 2-degree pathway reduces gross steel subsector emissions in 2050 to 44% below 2015 levels. At continued 2015 rates of emissions, the total cumulative budget would be exceeded by 2043. Existing international initiatives that could coordinate with this budget information include World Steel, the Eurofer Low Carbon Steel Roadmap 2050, the China Iron and Steel Research Institute (CISRI), and the Steel Institute VDEh in Germany.

Cement

The cumulative 2015-2050 emissions budget for the global cement subsector is 78 billion tonnes carbon dioxide. The 2-degree pathway reduces gross cement subsector emissions in 2050 to 25% below 2015 levels. Existing international initiatives that could coordinate with this budget information include the Cement Sustainability Initiative (CSI), the Portland Cement Association (PCA), and the European Cement Association (CEMBUREAU).

Chemicals and petrochemicals

Chemicals and petrochemicals is the largest industrial subsector in terms of projected demand growth. The cumulative 2015-2050 emissions budget for the global chemicals and

[34] In the 2-degree pathway the industrial sector captures 24 billion tonnes carbon dioxide between 2015 and 2050.
[35] Krabbe, et al. (2015) describe the assumptions used to translate emissions pathways into intensity targets for company reference.

petrochemicals subsector is 44 billion tonnes carbon dioxide. The 2-degree pathway decreases gross chemicals and petrochemicals subsector emissions in 2050 to 5% below 2015 levels. Existing international initiatives that could coordinate with this budget information include the International Council of Chemical Associations (ICCA) and the European Chemical Industry Council (CEFIC) Roadmap.

Aluminum

The cumulative 2015-2050 emissions budget for the global aluminum subsector is 11 billion tonnes carbon dioxide. The 2-degree pathway increases gross aluminum subsector emissions in 2050 to a level 8% above 2015 levels. Existing international initiatives that could coordinate with this budget information include the International Aluminum Institute (IAI) and the Aluminum Stewardship Initiative.

Pulp and paper

The cumulative 2015-2050 emissions budget for the global pulp and paper subsector is 4.5 billion tonnes carbon dioxide. The 2-degree pathway reduces gross cement subsector emissions in 2050 to 70% below 2015 levels. At continued 2015 rates of emissions, the total cumulative budget would be exceeded by 2038.

Science-based targets for companies

The Science Based Targets (SBT) initiative was cofounded by the World Resources Institute (WRI), CDP (formerly the Carbon Disclosure Project), the World Wildlife Fund (WWF), and the United Nations Global Compact in 2014. The purpose of the SBT initiative is to increase corporate ambition on climate action by changing the conversation on GHG emissions reduction target setting and creating an expectation that companies will set targets consistent with the level of decarbonization required to limit warming to less than 2°C compared to pre-industrial temperatures. To move SBTs toward standard business practice, the initiative set a goal of recruiting at least 300 leading companies to publicly commit to reduction targets in line with climate science by 2018. Recruitment of these companies will also serve to demonstrate to policymakers the scale of ambition achievable among leading companies, and begin to bridge the remaining gap between countries' announced Nationally-Determined Contributions (NDCs) and the 2-degree target.[36]

While the SBT initiative is not exclusively focused on industrial sector emissions, its methods cover industry and key sectors. In its compilation of new and previous related work, the SBT initiative identified the seven methods described in the table below for companies to align their emission reduction targets with a 2-degree pathway.

[36] Fawcett, et al (2015) found that announced NDCs have a greater than 50% likelihood of 2 or 3-degree temperature rise this century and an 8% chance of limiting warming to less than 2 degrees.

Table 1: Methods for Aligning Company and Sector Targets with a 2-Degree Pathway

Method	Geographic Scope	Sector Scope	Metric
Absolute Contraction	Global	Total economy; parallel sectors	Absolute annual reductions or cumulative budgets
Corporate Finance Approach to Climate-Stabilizing Targets (C-FACT)	Developed versus developing countries	Company-specific forecast of contribution to GDP	Absolute annual target based on carbon-GDP intensity reduction rate
Climate Stabilization Index (CSI)	Developed versus developing countries	Company-specific based on contribution to GDP	Economic intensity (g CO_2e/$ value added)
Centre for Sustainable Organizations (CSO)	Developed versus developing countries	Company-specific based on contribution to GDP.	Context-based assessment score based on emissions per dollar of contribution to GDP.
Greenhouse gas emissions per unit of value added (GEVA)	Global	Total economy; sector; company	Economic intensity (g CO_2e/$ value added)
Sectoral Decarbonization Approach (SDA)	Global	Subsector-specific	Physical intensity (g CO_2e/tonne product)
3% Solution	U.S.	Subsector-specific	Absolute annual target (2020)

As discussed above, the simplest method for science-based target setting is to allocate equal and parallel reductions to all existing sources such that 2050 emissions are reduced at least 49% below 2010 levels. If all companies and other emissions sources cut emissions at this rate warming this century would likely remain below 2 degrees. While the absolute contraction method is simple and transparent, it is neither cost-efficient nor fair. Marginal abatement costs vary significantly across sectors and countries.[37] The political and equity implications of the

[37] McKinsey (2009) quantified 2020 expected costs per sector and technology in their series of reports.

absolute contraction approach are untenable due to the limitation of growth opportunities for low-income countries.

The GEVA approach targets the same level of emissions reduction (commensurate with a 2-degree pathway) in combination with continuous economic growth. Assuming aggregate global GDP growth of 3.5% per year, the GEVA method provides a simple target of 5% annual reduction of company greenhouse gas emissions per unit value added. Insofar as GEVA treats all sectors similarly, it is not cost-efficient. However, the linkage of emissions with economic growth rates allows for flexibility and a shift of emissions from declining to growing industries/countries.[38] The C-FACT, CSI, and CSO methods are variations on GEVA's GDP-centric approach with nuances regarding geographic scope, growth assumptions, and output metrics.

The 3 Percent Solution and the SDA are more recent methods developed by SBT initiative partners to identify cost-efficient options for limiting warming to 2 degrees. Both methods incorporate varying demand projections and abatement options to calculate subsector-specific least-cost emissions reductions. Whereas the 3% Solution is focused on U.S. industries to 2020, the SDA is a global method with results to 2050. The IEA's 2-degree scenarios in its Energy Technology Perspectives (ETP) series of reports and modelling results is the basis for SDA sector pathways and allocations.[39] For sectors with granular ETP data, the SDA provides physical emissions intensity or annual absolute emissions targets at the company level. However, the SDA's sector-specific nuance also sometimes functions as a weakness by providing aggregated median performance indicators that are less relevant for leading companies with unique production processes. For example, the SDA provides steel subsector 2-degree pathway information in terms of kg CO_2/tonne crude steel. This type of aggregated physical intensity information is not particularly useful for steel companies that produce secondary steel in electric arc furnaces, especially if they are using advanced technologies.

The reason that there are seven methods described here is that there is not a single SBT method that's best in all sectors and company situations. Companies' emissions intensiveness, mitigation options, and demand growth affect the ambition of targets generated by the different methods. Moreover, many companies develop their own target-setting approach that may be related to one or more of the reference methods described above.

The lack of universal, comprehensive methods is not preventing companies from setting science-based targets. The SBT initiative has issued a call to action for companies to set targets according to the following five criteria:

1. Boundary: The target must cover company-wide Scope 1 and Scope 2 emissions and all relevant GHGs as required in the GHG Protocol Corporate Standard.

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[38] Randers (2012) describes the assumptions, benefits, and shortcomings of the GEVA approach.
[39] Krabbe et al. (2015) describe the background, assumptions, and results of the SDA in detail.

2. Timeframe: The target must cover a minimum of 5 years and a maximum of 15 years from the date of announcement of the target.
3. Level of ambition: At a minimum, the target will be consistent with the level of decarbonization required to keep global temperature increase to 2°C compared to pre-industrial temperatures, though companies are encouraged to pursue greater efforts towards a 1.5° C trajectory.
4. Scope 3: An ambitious and measureable Scope 3 target with a clear time-frame is required when Scope 3 emissions cover a significant portion (greater than 40% of total scope 1, 2 and 3 emissions) of a company's overall emissions. The target boundary must include the majority of value chain emissions as defined by the GHG Protocol Corporate Value Chain (Scope 3) Accounting and Reporting Standard (e.g. top 3 categories, or 2/3 of total scope 3 emissions).
5. Reporting: The company will disclose company-wide absolute GHG emissions inventory on an annual basis.

As of August 2017, more than 290 companies have publicly committed to setting SBTs and 60 companies have published targets that meet the eligibility criteria described above. Participating companies have headquarters in more than 30 countries and approved SBTs cover sectors ranging from food and beverage manufacturing to energy companies, pharmaceuticals, and technology equipment manufacturing. Company motivations include competitive advantage (e.g., more efficient industrial producers), risk mitigation (e.g., supply chains affected by climate impacts), regulatory hedging, reputational risk/stakeholder pressure, and moral conviction. Growing uptake indicates that SBTs are well on their way to becoming standard practice for leading companies.

The SBT initiative provides reference information, company guidance, and recognition of company leadership. Companies are left to determine how they will implement their SBTs and the public reporting requirement provides a mechanism for maintaining accountability. By organizing a critical mass of companies across sectors, the SBT initiative also demonstrates the feasibility of low emissions transformation for policymakers and investors.

Options for Reducing Industrial Sector Emissions

Industrial sector GHG emissions are byproducts of numerous decisions along product value chains. Five categories capture the range of industrial sector GHG mitigation options along value chains:

1. Energy efficiency- best practice technologies can help reduce process energy requirements
2. Emissions efficiency- fuel switching away from coal and other fossil fuels toward clean electricity, or using CCS to remove energy-related emissions
3. Material efficiency- either in production via reduced yield losses, recycling, re-use of old materials or in product design through light-weighting and other material substitutions

4. More intensive product use- for example via extended lifespans or new business models that foster dematerialization
5. Reducing demand through behavior change, structural change, or saturation effects.

Energy efficiency improvements play a foundational role in industrial sector GHG emissions mitigation. Whereas demand reduction and some types of material efficiency can conflict with company business models by reducing revenue, efficiency improvements fit in the strategies of incumbent companies by simultaneously reducing costs and emissions.[40] Numerous studies have found that efficiency improvements are not sufficient to achieve required emissions reduction singlehandedly. The IEA for example found that implementation of end-use fuel efficiency could achieve 40%, fuel and feedstock switching can achieve 21%, recycling and energy recovery can achieve 9%, and CCS can bridge 30% of the gap between a 6-degree pathway and a 2-degree pathway.[41] In their study of global steel, cement, plastic, paper, and aluminum production, Allwood et al. (2010) found that ambitious technical efficiency improvements only reduced 2050 emissions by 14% below 2010 levels—well short of their 50% target.[42] Beyond fuel switching, an industry-specific GHG mitigation challenge is process emissions, such as CO_2 emissions from calcination of limestone to make clinker, that are not effectively reduced through efficiency improvements. Although energy efficiency improvements are not sufficient for companies to achieve GHG reduction targets aligned with a global 2-degree pathway, they serve as an essential first mitigation option for existing industrial companies.

Leading Horses to Water: the role of voluntary programs

A growing number of companies are voluntarily tracking their GHG emissions and reporting them publicly every year. In fact, there was a 20-fold increase in companies that disclosed through CDP from 2003 to 2014, resulting in 1,825 companies reporting to the climate change questionnaire in 2014 alone. Alongside tracking emissions, 75% of these companies have also set GHG emissions reduction targets.[43] However, a study conducted by We Mean Business, a coalition of international organizations,[44] points out that most companies are not setting targets in line a global 2-degree pathway and few companies have set public targets that reach beyond 2020.[45] This is confirmed by academic research that found little compelling evidence

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[40] Material efficiency can in some cases be more profitable for a company than energy efficiency, as material costs often make up for much higher shares than energy cost. Industrial symbiosis can also be a very attractive alternative, where possible.
[41] IEA (2009).
[42] Allwood, et al (2010) present alternate CCS, recycling, demand reduction, and innovation scenarios that achieve more emissions mitigation.
[43] Does not include separate energy-based targets
[44] BSR, The B Team, CDP, Ceres, The Climate Group, The Prince of Wales's Corporate Leaders Group and WBCSD
[45] We Mean Business. The Climate Has Changed, 2014 (p 13).

that carbon management practices resulted in reduced emissions.[46] The Science Based Targets (SBT) initiative attempts to fill this gap by providing guidance for companies to align their mitigation targets with a global 2-degree pathway.

The SBT initiative builds on academic research findings that voluntary environmental programs can achieve improvements at low cost when serving as a complement to mandatory minimum-performance regulations.[47] The idea is that leading companies are defining new best practices that public recognition can turn into sector norms. A longer-term outcome of voluntary programs such as the SBT initiative is that they influence subsequent sector and technology-related regulatory policies.

Horizontal Integration: Sectoral Approaches to Industrial Low-carbon Transformation

This chapter has provided an overview of GHG emissions impacts of industrial production in the United States and globally for the period from 2000 to 2015. Industry has been central to global greenhouse gas emissions growth, but its role varies among countries, for example leading overall GHG reductions in the U.S. The production revolution that is transforming industry is driven by a confluence of technologies that are also generating social and political instability via employment churn and re-distribution of incomes. Mitigation imperatives, social concerns about accelerating disruption, and increasingly instantaneous global communication all point to the potentially beneficial rise of sectoral institutions and programs that bridge national and regional differences.

Sectoral approaches can accelerate GHG mitigation by disseminating best practices, for example through company science-based targets, guiding NDC implementation, and leveraging local resource availability. The idea of sectoral approaches has been discussed, especially in Europe, for decades.[48] However, competitiveness concerns, nostalgia for 20th century socioeconomic norms, and vested interests prevented earlier adoption of broad sectoral institutions. In combination with the lack of consensus on how to address equity and cost challenges, these barriers indicate that sectoral approaches may be most likely to be develop from the ground-up, i.e., on a voluntary basis. Networked, transparent programs such as the Science Based Targets initiative have the potential to generate new institutions for rising challenges. Moreover, bottom-up sectoral approaches can help companies and other sector stakeholders to understand the role of energy efficiency improvements versus fuel switching and other mitigation activities in achieving low-carbon transformation. While existing industry associations are limited by anti-trust and competitiveness rules, new bottom-up sectoral approaches could be well-positioned to address political concerns as well as the emissions uncertainty related to intensity targets.[49] As countries begin to implement their NDCs, Korea's

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[46] Doda, et al (2015)

[47] Borck and Coglianese (2009) develop a typology of voluntary environmental programs to assess the factors that lead to maximum effectiveness.

[48] See, for example Groenenberg, et al (2001).

[49] Akimoto et al. (2008) discuss the emissions unpredictability of sectoral intensity schemes.

top-down "Roadmap to Achieve National GHG Reduction Goals" exemplifies the near-term potential informational benefit of company-SBT-integrated sectoral approaches. While most countries have less structured NDCs, such as the United States' 26-28% reduction from 2005 to 2025, sectoral approaches can also guide implementation, NDC updating for 2020, and long-term low-carbon strategy development.

Agenda for Future Research

Development and popularization of sectoral pathways can accelerate company-led low-carbon transition. Sector pathway guidance can provide a global, cross-sector mechanism to define new best practices, mobilize investment capital, and stimulate the development of new institutions to coordinate mitigation action. Seven areas of further research are suggested here to advance sector 2-degree pathways and the larger low-carbon transformation of the industrial sector.

Is carbon intensity a more relevant and useful summary metric than energy efficiency? How can decomposition analysis elucidate the role of efficiency improvements, fuel switching, demand abatement, structural change, and leakage in emissions reductions?

What data, modelling approaches, and institutional structures are needed to assemble a single integrated company 2-degree-pathway emissions assessment method to consistently and equitably cover all sectors and companies? Given the transformation needed to limit warming this century to 2 degrees, what's the role of existing company improvement/adaptation versus closures and sector churn?

Can energy efficiency improvements facilitate the deployment of negative emissions technologies in industry? How can circular economy frameworks and cross-sector planning reduce the costs of carbon removal?

Between 2000 and 2015, 30 countries have de-linked of GHG emissions and GDP growth. Meanwhile, many countries are reducing industrial activity before reaching previously observed income and saturation levels.[50] What's the role of industrial sector productivity gains, deindustrialization (i.e., the reduction of industrial activity), and leakage/trade in observed and prospective delinking? Should deindustrialization be incorporated into NDCs and new climate transition institutions?

What types of policy approaches are most cost-effective for achieving industrial sector emissions mitigation? CDP research[51] found that companies with lower emissions performance earned higher returns on investment—can industrial subsectors grow into low-carbon transformation or do they need a regulatory push?

[50] Rodrik (2016)
[51] CDP (2014)

How can company-level voluntary initiatives best address the equity and distributional challenges of common but differentiated responsibilities? Are simplifying global convergence assumptions (such as that used in the SDA) adequate and fair?

Company and facility level GHG performance data are becoming increasingly available. Given the dispersion of GHG emissions intensities and capacity utilization rates within and among manufacturing subsectors[52], how much could emissions be reduced via production re-allocation to the highest-performing facilities? On a more general level, what are the drivers of GHG performance (regulatory policy, exposure to trade/competition, vintage of equipment, fuel/resource availability)?

Emissions-intensive industrial activity has put enough greenhouse gases in the atmosphere that climate impacts are becoming increasingly evident. Radical transformation of industry is needed to achieve the global target of limiting warming to 2 degrees this century. Indeed, the industrial sector will determine if and when the 2-degree threshold is surpassed. To communicate high-level climate targets, emissions budgets are useful metrics for the industrial sector and emissions-intensive subsectors. These budgets and the move toward company science-based targets present new norms for private sector leadership and support of NDC implementation. Additional research is needed to understand the opportunities and risks inherent in the low-carbon transformation of the industrial sector. As the need to reduce GHG emissions becomes more clear, emissions intensity may become a more prevalent industrial performance metric than energy efficiency.

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[52] Akimoto, et al. 2008, Boyd, et al. 2011, Fugii, et al. 2015.

Chapter 2. Efficiency, decarbonization, structural churn, and trade: Untangling the drivers of U.S. manufacturing emissions reductions

As a matter of fact, capitalist economy is not and cannot be stationary. Nor is it merely expanding in a steady manner. It is incessantly being revolutionized from within by new enterprise, i.e., by the intrusion of new commodities or new methods of production or new commercial opportunities into the industrial structure as it exists at any moment. (Joseph Schumpeter, 1942).

Introduction

The decline of U.S. industrial sector carbon dioxide emissions by one-fifth between 2000 and 2015 was driven by multiple economic and technological transitions. Five megatrends that contributed to the reduction of U.S. industrial and manufacturing sector emissions include: structural shift from goods to services, energy transition to electricity, natural gas, and renewables, increased trade and globalization, introduction of new technologies, and changing norms, regulations, and policies. These interrelated megatrends provide context for decomposition and facility analysis of U.S. manufacturing GHG emissions.

The ongoing, multi-century structural shift from goods-producing industry to services is reflected in jobs and GDP. Manufacturing share of total U.S. employment peaked at 33 percent during World War II, in 1943, and declined to a record low of 7.5 percent in 2015. The services share of jobs rose from a low of 49 percent in 1943 to 75 percent in 2015. Likewise, the manufacturing share of GDP dropped from 28 percent in 1953 to 12 percent in 2015, matched by the rise of services from 46 percent of GDP in the early 1950’s to a record high of 68 percent in 2015. Between 2000 and 2015, the shift became more gradual in GDP terms and more abrupt in employment terms, with steep reductions from 2000 to 2010 followed by moderate manufacturing job growth from 2011 through 2015.[53] Within manufacturing, the move toward services augmented the share of value-added generated independently of physical production and the rise of circular business models that look beyond maximizing one-time sales revenue.

Energy systems in the U.S. and globally have also been shifting for decades, with accelerated transformation after the year 2000. U.S. energy use tripled between 1950 and 2015 and primary energy use shifted from fossil fuels to nuclear and renewable energy sources over the same period. Within U.S. industry, the coal share of total final energy use dropped from 37 percent in 1949 to 4 percent in 2015, with a corresponding growth of renewable energy use, natural gas, and purchased electricity. In 2015 the U.S. added more new renewable electricity generation capacity than natural gas or other fossil-fired electricity generation capacity for the

[53] U.S. manufacturing shed 5.7 million jobs between 2000 and 2010 and then added 790,000 jobs between 2010 and 2015. Employment data from BLS (2016) and GDP data from BEA (2016).

first time.[54] Declining costs for renewable generation and storage technologies are likely to further decarbonize electricity—an open question is the extent to which the decarbonization benefits from energy transformation will spill over into emissions-intensive manufacturing processes such as coking, petroleum refining, chemicals production, and calcination. The U.S. Department of Energy's Advanced Manufacturing Office is an example of programs seeking to extend energy technology innovations such as high efficiency electric motors into manufacturing facilities.

U.S. trade in goods and services has grown steadily since 1960, when it accounted for 9 percent of GDP, to 2015, when trade accounted for 28 percent of GDP.[55] Three quarters of 2015 U.S. trade was in goods rather than services, down from 80 percent in 2000. The U.S. has incurred annual goods trade deficits every year since 1973; services trade has seen a surplus of U.S. exports since the 1960's. China's accession to the World Trade Organization, and normalization of trade relations with the U.S., in December 2001 marked the start of a period of high annual U.S. goods trade deficits. Between 2000 and 2015, the nominal value of U.S. gross trade grew at an average rate of 5 percent per year. Trade growth has been accompanied by globalization of many sectors and increasingly fragmented supply chains, particularly in manufacturing.[56]

A fourth megatrend is the introduction of new manufacturing and cross-cutting technologies. While innovations in computing and data storage helped to streamline manufacturing processes during the 20th century, emerging 3-D printing, automation, and ubiquitous sensor technology have the potential to reconfigure manufacturing processes from energy, social, and environmental perspectives. The manufacturing sector is also bringing together and producing new technologies such as solar panels, LED bulbs, wind turbines, and efficient building materials that support the transition to a low-carbon economy.

Finally, U.S. manufacturing emissions are being reduced by growing awareness, changing norms, and new regulations and policies. It has become standard practice for large companies to report their GHG emissions in annual sustainability reports, as well as stakeholder programs such as CDP's questionnaires.[57] In the U.S., facilities with sources that in general emit 25,000 metric tons or more of carbon dioxide equivalent per year are required to publicly participate in the EPA's Greenhouse Gas Reporting Program (GHGRP).[58] Beyond reporting emissions, a growing number of jurisdictions such as California, China, and the EU have introduced policies

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[54] Source: EIA, Today in Energy (March 23, 2016); https://www.eia.gov/todayinenergy/detail.php?id=25492.

[55] The 2015 trade portion of GDP was down slightly from its high in 2011, when trade accounted for 31 percent of GDP.

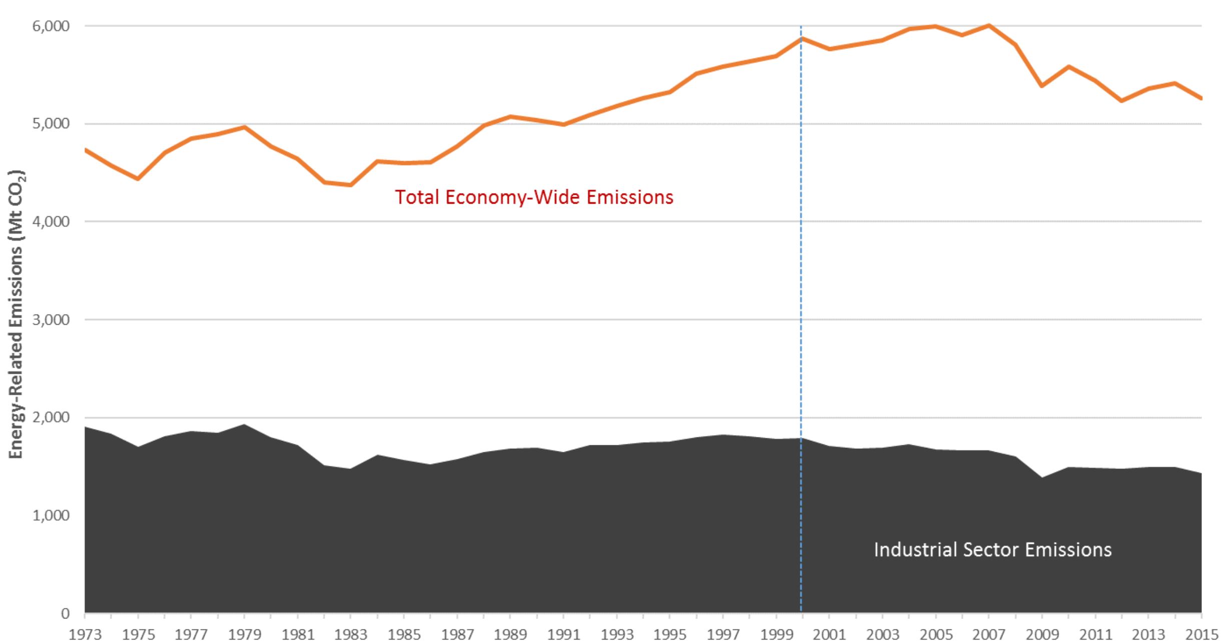
[56] Baldwin and Lopez-Gonzalez (2015) find that "supply-chain trade has revolutionized global economic relations and the revolution is still in full swing."

[57] In 2016 CDP had more than 5,000 company respondents globally; for more information, see https://www.cdp.net/en-US/Pages/About-Us.aspx.

[58] The EPA published its mandatory reporting rule in 2009: http://www.ecfr.gov/cgi-bin/text-idx?c=ecfr&tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl. The rule, Title 40, is in part based on Clean Air Act language that precludes emissions data from being treated as confidential.

that require industry or manufacturing sector GHG mitigation. At the national level, five policies have accelerated U.S. manufacturing sector mitigation. The Clean Air Act Amendments of 1990 placed limits on process emissions, emissions from hazardous or toxic substances, and criteria pollutants including SO_2, a tropospheric greenhouse gas.[59] The Energy Policy Act of 1992 accelerated mitigation with efficiency standards for boilers, furnaces, and electric motors. The Energy Independence and Security Act of 2007 included updated minimum efficiency standards for electric motors. The next year, the Energy Improvement and Extension Act of 2008 introduced an investment tax credit for new combined heat and power (CHP) capacity, which reduces overall emissions by utilizing waste heat. Finally, the Boiler Maximum Achievable Control Technology (MACT) rule, which was finalized in 2012, further stimulated efficiency improvements through new limits on hazardous air pollutants.[60] Many rules grandfather in all but the most egregious existing facilities and establish more stringent standards for new investment. These five megatrends have all contributed to the reduction of U.S. industrial and manufacturing sector emissions, particularly since 2000. Figure 9 shows total and industrial sector energy-related CO2 emissions from 1973 to 2015.

Figure 9: Annual U.S. Energy-Related Carbon Dioxide Emissions (1973-2015)



[59] While SO_2 limits were stipulated by the CAA Amendments, they were not enacted as U.S. sulfur dioxide emissions independently declined with sulfurous coal use.

[60] Most U.S. policies toward industry do not specifically target GHG mitigation, but achieve reductions as a "co-benefit" while reducing other hazardous air pollutants. See Aden (2012) for discussion of U.S. industry co-benefits and http://www.wri.org/blog/2012/12/holiday-gift-epa-new-rules-will-cut-toxic-air-pollution-american-boilers for discussion of the Boiler MACT rule.

Source: EIA, MER (2016). Note this industrial series includes CO_2 from production of purchased electricity, as well as direct industrial sector fossil fuel consumption.

To understand which trends and divers had the largest influence on U.S. manufacturing emissions between 2000 and 2015, this chapter analyzes aggregated and facility-level data. Current data and methods can provide some insight on historical mitigation dynamics, as well as the outlines of upcoming U.S. manufacturing scenarios and the role of manufacturing in low-carbon transformation more broadly. Finally, the chapter closes with discussion of implications and suggestions for new manufacturing mitigation metrics.

Data and Methods

The profusion of low-cost sensors, information storage, and computing power, and the corresponding move towards greater transparency have increased the amount of data available on manufacturing sector energy use and emissions. At the industrial sector level, the U.S. Energy Information Administration (EIA) publishes its Monthly Energy Report with energy-related carbon dioxide emissions numbers dating back to 1973. This is complemented by industry, manufacturing, and subsector-level data from the Bureau of Economic Analysis (BEA), Bureau of Labor Statistics (BLS), World Bank, International Energy Agency (IEA), U.S. Department of Energy Manufacturing Energy Consumption Survey (MECS), Annual Survey of Manufactures (ASM), and Economic Census (EC).[61] The U.S. Department of Energy, Census Bureau, and Internal Revenue Service collect facility-level data; however, these are only publicly available in the aggregated formats listed above. The newest source of industry, manufacturing, and subsector data is the U.S. Environmental Protection Agency (EPA), which publishes aggregated data in its annual emissions inventories and facility-level data in its Greenhouse Gas Reporting Program, Facility Level Information on GHGs Tool (FLIGHT) database. Additional company-level GHG and performance information is also published by non-governmental organizations such as CDP. Table 2 summarizes data sources for U.S. GHG emissions, energy use, activity at the aggregated national total, industry, manufacturing, and subsector level, as well as for facilities.

Table 2: Data sources for U.S. Industry and Manufacturing

	Emissions		Energy Use		Activity	
	GHGs	CO_2	Total	Electricity	Physical	Economic
National Total	Annual CO_2e,	Annual energy-CO_2	Annual use by fuel	Annual use 1949-2015		GDP, value added,

[61] The MECS and EC provide the most comprehensive and granular data including energy use by fuel, number of companies, number of establishments, number of employees, value added, etc. up to the NAICS 6-digit level—i.e., for particular products within subsectors. However, these datasets are only published periodically (2010 is the most recent year available for MECS data and 2012 is the current most recent year available for EC data), and neither dataset includes carbon or other GHG emissions.

	Emissions		Energy Use		Activity	
	GHGs	CO_2	Total	Electricity	Physical	Economic
	1990-2014 (EPA Inventory)	1949-2016 (EIA, MER; BP; IEA; ORNL; World Bank)	1949-2015 (EIA, MER; BP; IEA; World Bank; ASM; EC)	(EIA, MER; BP; IEA)		gross output (BEA, World Bank)
Industry level	Annual CO_2e, 1990-2014 (EPA Inventory)	Annual energy-CO_2 1973-2015 (EIA, MER; IEA)	Annual use by fuel 1949-2015 (EIA, MER; BP; IEA; World Bank; ASM; EC)	Annual use 1949-2015 (EIA, MER; BP; IEA)	Gross output quantity index (BEA)	GDP, value added, gross output (BEA, World Bank)
Manufacturing		Annual energy-CO_2 2000-2015 (EIA, AEO)	Annual use by fuel 2000-2015 (EIA, MECS; EIA, AEO; ASM; EC)	Annual use 2000-2015 (EIA, MECS; EIA, AEO; ASM; EC)	Gross output quantity index (BEA)	GDP, value added, gross output (BEA; ASM; EC; World Bank)
Subsector	[annual process emissions data (EPA Inventory)]	Annual energy-CO_2 2004-2015 (EIA, AEO; [industry associations])	Annual use by fuel 2004-2015 (EIA, MECS; EIA, AEO; ASM; EC)	Annual use by fuel 2004-2015 (EIA, MECS; EIA, AEO; ASM; EC)	Gross output quantity, physical production (BEA; USGS)	GDP, value added, gross output (BEA; ASM; EC)
Facility	Annual CO_2e, 2010-2015 (EPA FLIGHT)	[derivable from confidential Census data]	[fuel use expenditures reported in confidential	[electricity expenditures reported in confidential	[derivable from confidential Census data]	[value added reported in confidenti

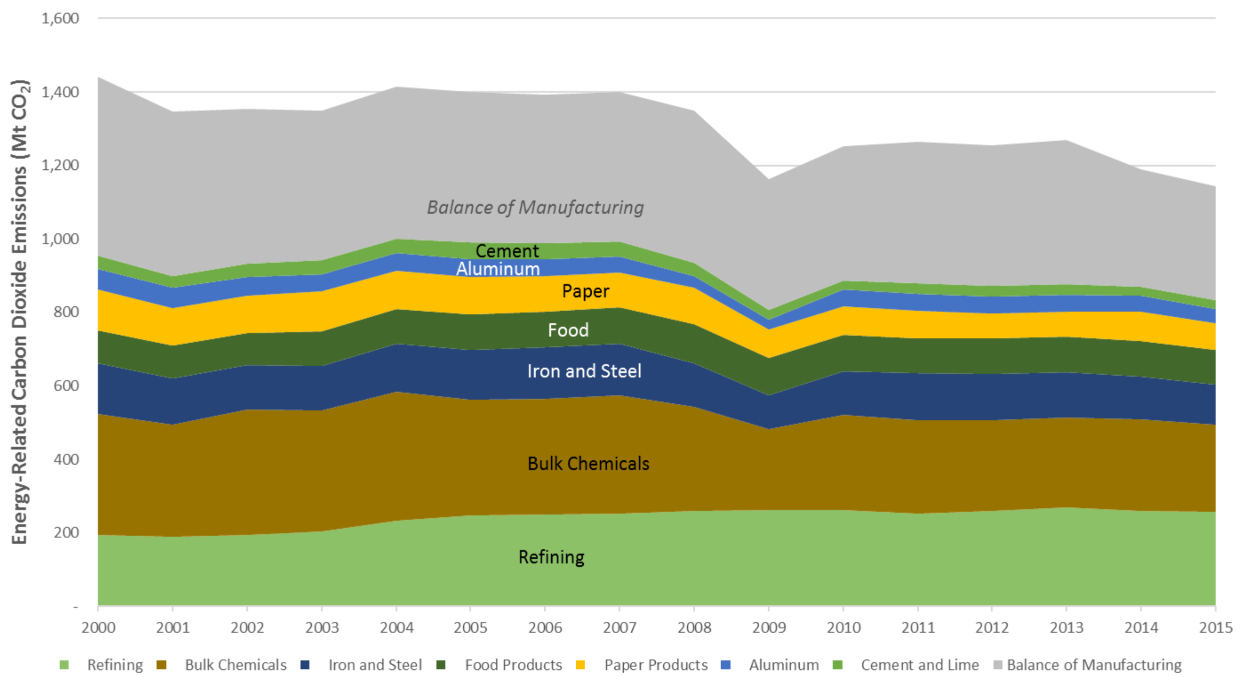
Emissions		Energy Use		Activity	
GHGs	CO_2	Total	Electricity	Physical	Economic
		Census data]	Census data]		al Census data]

Note: this table is not comprehensive; it identifies top primary data sources.

Manufacturing GHG emissions data are becoming more available, but they are still not comprehensive or as widely tracked as energy efficiency indicators. As illustrated in Table 2, U.S. manufacturing and subsector GHG emissions time series data beyond fossil-fuel-related carbon dioxide emissions are not publicly available. Three of the limitations of tracking fossil-related CO_2 rather than total GHGs are that these emissions don't reflect emissions associated with imported goods, they exclude significant methane emissions related to natural gas production, and they also do not include process emissions from manufacturing processes such as cement calcination. These are reasons to expand U.S. manufacturing GHG emissions accounting. In the meantime, this study utilizes publicly-available fossil-fuel-related CO_2 data to track U.S. manufacturing and subsector emissions.

The two basic sets of U.S. manufacturing data are aggregated at the subsector and above level and at the facility level. As discussed in chapter 1, numerous metrics are available at the subsector level including emissions, employment, energy use by fuel, activity, and number of facilities. The dependent variable in this first analysis is subsector-level emissions. Figure 10 shows annual U.S. manufacturing subsector energy-related CO_2 emissions, the dependent variable, between 2000 and 2015.

Figure 10: U.S. Manufacturing Subsector Energy-Related CO_2 Emissions (2000-2014)



Source: EIA, AEO (2001-2016).

The energy crisis of the late 1970's initiated numerous departments and programs, as well as a new research method called index decomposition analysis for understanding changes in electricity consumption in industry.[62] The two most prevalent decomposition techniques are index decomposition analysis (IDA) and structural decomposition analysis, which is based on input-output (I-O) table data. Based on the time lag, periodicity, and limited availability of I-O tables, IDA methods have become more common and have subsequently been used in numerous studies to quantify the drivers of aggregated metrics such as energy use or emissions. If *V* is the aggregated value with *n* contributing factors and *i* subcategories, then the general IDA identity is given by Equation 1:

$$V = \sum_{\mathrm{i}}^{n} V_i = \sum_{i} x_{1,i}, x_{2,i} \dots x_{n,i}$$

Aggregate changes are calculated from $V^0 = \sum_i (x_{1,i}^0, x_{2,i}^0 \dots x_{n,i}^0)$ in period 0 to $V^T = \sum_i (x_{1,i}^T, x_{2,i}^T \dots x_{n,i}^T)$ in period *T*. Index decomposition analysis can be expressed in additive or multiplicative forms. In additive terms, the difference is simply quantified as $\Delta V_{tot} = V^T - V^0 = \Delta V_{x1} + \Delta V_{x2} + \cdots + \Delta V_{xn}$. The subscript *tot* represents total or overall change and the

[62] The index theory foundations of IDA stretch back at least to the 1930's; see Montgomery (1937), Vartia (1976), and Su and Ang (2012).

terms on the right-hand side give the effects associated with the respective factors in Equation 1 above.[63]

Within IDA the three principal groups of methods are linked to the Laspeyres index, the Divisia index, and the Mean Rate of Change Index (also associated with the Stuvel index). While the Laspeyres and related Paasche and Fisher Ideal indexes have been described as more intuitive discrete approximations of the continuous Divisia index, they also include residual terms that undermine interpretation.[64] The Divisia methods include the Arithmetic-Mean Divisia Index (AMDI), the Log-Mean Divisia Index I (LMDI I), and the Log-Mean Divisia Index II (LMDI II). The principles of the Divisia methods were first suggested by Boyd et al. in 1988 to substitute for the Laspeyres linked indexes and eliminate the residual term and inconsistency in aggregation of the multiplicative functional forms. Divisia indexes are generally defined with a weighted average of the relative growth rate.

The Log Mean Divisia Index (LMDI I) method of IDA has become prevalent on account of its straight-forward formulation and communication of results. Beyond the absence of the unexplained residual term that originally plagued IDA, LMDI has the benefits of factor reversibility (i.e., all change is fully accounted for by factors investigated), satisfaction of time-reversal test, and effective approximation of zero values (i.e., with replacement by small numbers). Beyond academic publications, institutions such as the U.S. Department of Energy use LMDI to track energy efficiency trends over time.[65] For LMDI decomposition of energy-related CO_2 emissions from manufacturing, the general identity is given by Equation 2:

$$C = \sum_{ij} C_{ij} = \sum_{ij} Q \frac{Q_i}{Q} \frac{E_i}{Q_i} \frac{C_{ij}}{E_i} = \sum_{ij} Q S_i I_i F_i$$

C represents total CO_2 emissions and C_{ij} is the CO_2 from use of fuel *j* in subsector *i*. In the middle term of the equation, Q represents the total (manufacturing) activity level and E is energy consumption. The right-hand side of the equation represents the four analytical factors for manufacturing sector carbon dioxide emissions. The first factor, Q, quantifies the impact of overall industrial activity changes and is known as the production or activity effect. The second factor, S_i (= Q_i/Q) represents the industry activity mix which is also referred to as the structural effect. The third factor, I_i (= E_i/Q_i) is subsector *i* energy intensity, also known as the intensity effect. Energy intensity is often used as an indicator of energy efficiency though distortions can occur from multi-process and product aggregation and fixed energy overhead effects.[66] The fourth factor, F_i (= C_{ij}/E_i) represents the carbon dioxide intensity of energy use for subsector *i* given its fuel mix *j*. Carbon intensity changes can be traced to efficiency of energy production

[63] For additional discussion of IDA methods, options, and background, see Ang (2005) and Su and Ang (2012).
[64] See Diewert (1976) and Park (1992).
[65] See Belzer (2014) for the Department of Energy's comprehensive report of LMDI energy indicators for the U.S.
[66] In their decomposition of UK manufacturing emissions, Hammond and Norman (2012) note that "decreasing intensity can occur with no efficiency improvement at the process level".

(e.g., using less coal or natural gas to generate a kWh) and/or fuel switching (i.e., generating steam from natural gas instead of coal).

The LMDI change scheme for additive decomposition of manufacturing emissions is expressed in Equation 3:

$$\Delta C_{tot} = C^T - C^0 = \Delta C_{act} + \Delta C_{str} + \Delta C_{int_E} + \Delta C_{int_C}$$

Where

$$\Delta C_{act} = \sum\nolimits_{ij} \left(\frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \right) \ln \left(\frac{Q^T}{Q^0} \right)$$

$$\Delta C_{str} = \sum\nolimits_{ij} \left(\frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \right) \ln \left(\frac{S_i^T}{S_i^0} \right)$$

$$\Delta C_{int_E} = \sum\nolimits_{ij} \left(\frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \right) \ln \left(\frac{I_i^T}{I_i^0} \right)$$

$$\Delta C_{int_C} = \sum\nolimits_{ij} \left(\frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \right) \ln \left(\frac{F_i^T}{F_i^0} \right)$$

The activity, structural, energy intensity, and carbon intensity effects are indicators used here to assess the drivers of U.S. manufacturing sector and subsector CO_2 emissions between 2000 and 2015. While LMDI studies have been published on numerous sectors and countries, this is the first study of U.S. manufacturing subsector CO_2 in the post-2000 period.[67] The LMDI method provides a point of reference for understanding changes in aggregated emissions, but it is not comprehensive.

Limitations of LMDI are associated with its structure and reliance on available subject data. As mentioned above, intensity effects, particularly in manufacturing, are not necessarily conclusive with regard to efficiency, structure, and intra-sector dynamics. Current IDA methods do not address trade substitution effects that affect some manufacturing sectors deeply, or the deployment of combined heat and power (CHP) and carbon capture and sequestration (CCS) technologies, the latter of which is expected to capture 25 percent of total global industrial sector CO_2 emissions by 2050 to keep warming this century to less than 2 degrees Celsius above pre-industrial levels.[68] IDA methods also fail to capture company and facility churn, which is a central mitigation mechanism as manufacturing subsectors prevail over competition, idle, or close in the midst of cyclical expansion and contraction of demand.

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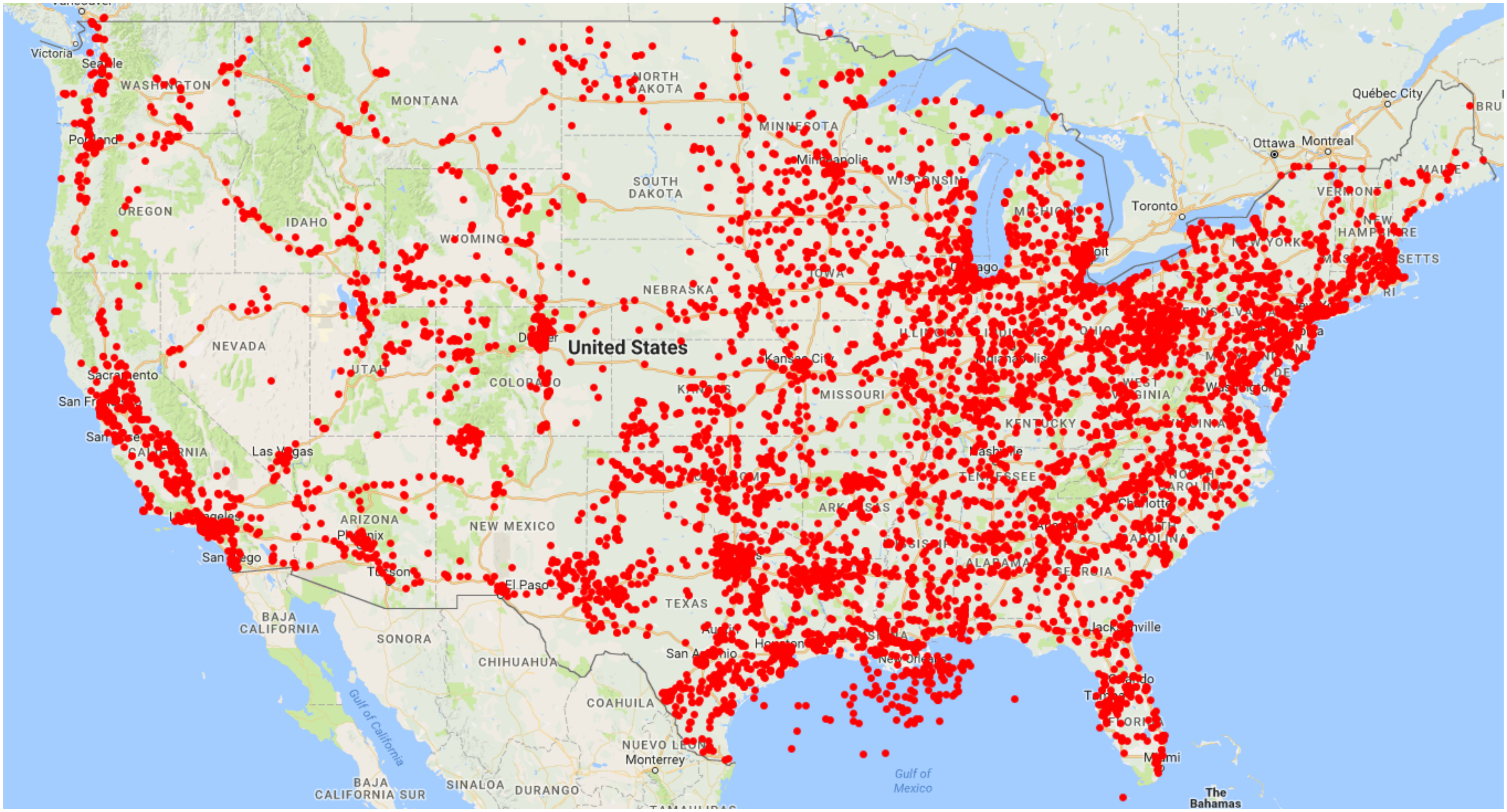
[67] See Xu and Ang (2013) for a comprehensive review of CO_2 IDA studies and Ang and Xu (2013) for a review of industrial sector IDA analyses.
[68] See IEA (2016) for details of industrial sector carbon capture scenarios.

These limitations lead to the supplemental aggregate manufacturing subsector emissions assessment and the facility-level assessment. Two supplemental aggregate factors are trade impacts on domestic production, which is implicitly included in the LMDI activity effect, and the impact of cleaner and more efficient electricity generation, which again is implicitly included in the LMDI carbon intensity effect, along with carbon intensity of fuel use. The question with trade is whether and to what extent increased imports are replacing domestic production and thereby reducing manufacturing sector emissions. The question with electricity is to what extent apparent manufacturing mitigation has occurred as a result of generator efficiency improvements and fuel switching outside and independently of the manufacturing facility.

Transparent and public manufacturing facility-level data represent the next frontier of energy and emissions analysis. While facilities can produce multiple product types with varying processes, this level of data generally has much higher precision and granularity than aggregate data. Furthermore, sensor technology is making it likely that real-time process-specific data become increasingly available, opening the door for more accurate and actionable analysis.

The EPA GHGRP FLIGHT data are a relatively new resource that has not yet been extensively studied in academic publications. An estimated 85-90 percent of the total U.S. GHG emissions from over 8,000 facilities are covered by the FLIGHT data. Smaller sources and certain sectors such as the agricultural sector and land use changes are not included in the Greenhouse Gas Reporting Program. To ensure data quality, the GHGRP provides electronic verification of annual reports. Prior to submission, there are multiple checks built into data reporting tool that provide data validation for reporters. After submission, EPA electronically verifies the data through the use of statistical, algorithm, range, and other verification checks. When needed, EPA conducts direct follow-up with facilities concerning potential data quality issues. Beyond location, the FLIGHT data include company name, NAICS code, sector subpart, annual emissions, and additional information such as fuel type and activity for suppliers. Map 1 illustrates the locations of the direct emitters that reported emissions between 2011 and 2015.

Map 1: Location of U.S. Direct Emissions Sources (2011-2015)



Source: EPA, FLIGHT tool (2016).

The facility-level analysis to be conducted can use EPA FLIGHT data to explore three questions regarding U.S. manufacturing emissions:

- How has facility churn affected subsector-level GHG emissions pathways?
- Is there evidence of spatial clustering effects whereby manufacturing facilities are benefiting from knowledge spillovers, increasing specialization, or otherwise competing in ways that correlate with emissions performance?
- Has the emissions performance of facilities in California varied significantly from the rest of the U.S. since implementation of AB 32?

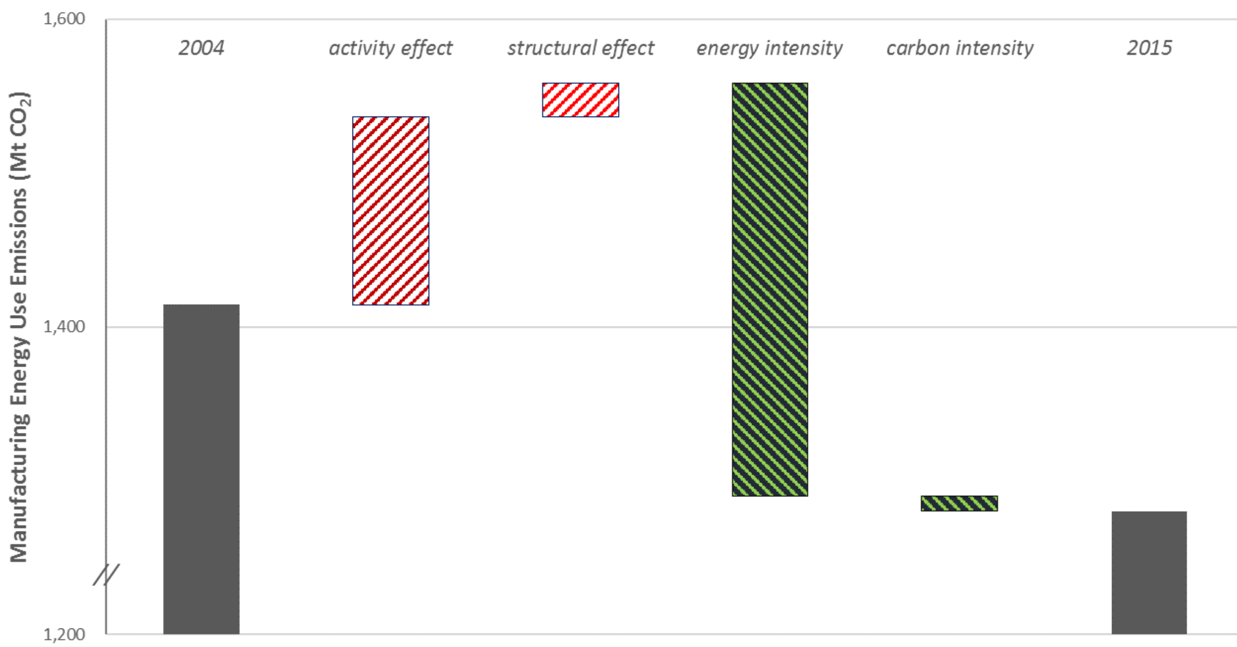
These questions can supplement the aggregate LMDI assessment described above and identify key aspects of the low-GHG transition for manufacturing.

Facility-level analysis can provide an interdisciplinary, empirical foundation for creating a new, inclusive industrial policy focused on green growth. Geographical analysis of clustering effects, quantification of the impact of permanent closure versus moth-balling during cyclical demand reductions, and state-level regulatory effects can help to resolve ongoing policy debates and guide institutional development. New knowledge is often built on a 3-legged stool of data, theory, and narrative. Additional facility-level research on U.S. industrial GHG mitigation can also help to add narrative framing to low-carbon transformation.

Results

LMDI analysis of U.S. manufacturing between 2004 and 2015 shows that energy intensity reductions had the largest impacts on total changes in energy-related CO_2 emissions. As illustrated in Figure 11, the activity and structural effects had a net positive impact on U.S. manufacturing emissions—i.e., growth of value added and shifts to more intensive production acted to increased CO_2. These effects were more than outweighed by the energy intensity effect, which overwhelmed all the other effects. Carbon intensity improvement also helped to reduce U.S. manufacturing, though at a smaller scale than the other modeled LMDI effects during this period.

Figure 11: U.S. Manufacturing Additive Decomposition Results by Modeled Effect



Implications

The reduction of manufacturing emissions was the central mechanism for decoupling U.S. GDP growth and total GHG emissions between 2000 and 2015. Since the U.S. produced large quantities of industrial goods for many decades, it is not surprising that saturation effects would slow demand growth and help to initiate the low-carbon transformation of U.S. manufacturing. As the need to reduce global emissions grows with climate impacts, a central question is whether the 2000-2015 reduction of manufacturing emissions and related divergence of GDP and GHG emissions can be replicated in other countries.

Questions for Further Research

Three questions for further research on U.S. industrial sector emissions:

What's the role of productivity improvements in further reducing industrial sector GHG emissions?

How has trade impacted industrial subsectors' and facilities GHG emissions performance?

What facility-level best practice information is most effective for guiding economically-competitive GHG mitigation?

Chapter 3. Divergence of Country-Level GDP and Carbon Emissions: The Role of Industry and Trade

"Two roads diverged in a wood, and I -- I took the one less traveled by, and that has made all the difference." (Robert Frost)

Abstract

Achieving the Paris climate goal of limiting warming to well-below two degrees will require substantial greenhouse gas (GHG) emissions reductions and economic transformation. A growing group of countries are moving toward the Paris goal by reducing GHG emissions while continuing to grow their economies. However, existing metrics such as carbon emissions intensity of gross domestic product (GDP) do not capture dynamic country contributions to economic transformation and global emissions reductions. This chapter develops an index of GHG-GDP divergence to characterize country performance and explore the role of industry and trade in low-carbon economic transformation between 2000 and 2015.

Introduction

The IPCC's Fifth Assessment Report (AR5) provides a comprehensive picture of the relationship between GHG emissions and climate impacts based on an ensemble of climate models. The AR5 scenario with the highest likelihood of limiting warming to less than 2 degrees requires total 2050 GHG emissions to drop 49% to 72% below 2010 levels.[69] If 2015 rates of global emissions are maintained, the cumulative budget for this century will be exceeded at some point between 2030 and 2050.[70] Subsequent analysis of non-carbon dioxide emissions impacts has found that the cumulative budget for avoiding 2-degree warming is significantly lower than previous exceedance-based estimates.[71] The long-term picture indicates that aggregate emissions should drop to a net-zero level to stabilize climate impacts.[72] Global emissions reductions—not to mention reductions to net-zero emissions—will require a reversal of historical global trends and metamorphosis of economies.

Industrial production has been synonymous with economic growth and greenhouse gas emissions for the past two centuries. Since the publication of Thomas Robert Malthus's "Essay on the Principle of Population" in 1798, people have debated the relationship between resources, economic development, and environment. Malthus's concern about the availability

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[69] Clarke, et al. (2014). These numbers are based on RCP2.6 scenarios with minimal overshoot (< 0.4 W/m^2), i.e., less reliance on carbon removal technology deployment to achieve negative emissions in the second half of the century. For more information on RCP2.6, see Vuuren D, et al (2011).

[70] Le Quéré, et al. (2015) estimate 2015 total global emissions of 36 Gt CO_2, an increase of 7 percent above 2010 levels.

[71] Rogelj, et al. (2016) present a broad range of budgets based on varying assumptions.

[72] Geden (2016) argues that a net zero emissions target is more actionable than 2-degree budgets. However, some existing industrial companies and stakeholders find net zero targets to be unrealistic and detrimental to current efforts.

of sufficient resources to support growth of population and the economy has been a periodic theme of environmental, and now climate, discussions for decades. Two related, contemporary ideas are the concept of planetary boundaries and 'degrowth'—i.e., that economic contraction is necessary to avoid environmental and climate calamity, and is perhaps inevitable.[73] While debates continue, historical data illustrate longstanding links between carbon emissions and economic growth.[74]

Combustion of fossil fuels has served as a central engine of economic growth since the nineteenth century. Figure 12 illustrates the linked explosion of global carbon dioxide emissions and GDP between 1820 and 2015. Over this period global carbon emissions increased 700-fold (from 50 million tonnes to nearly 40 billion tonnes) while global economic activity increased 80-fold (from $700 billion to $60 trillion 1990 international Geary-Khamis dollars).[75] The high emissions-intensiveness of economic growth over this period explains how global atmospheric concentrations of carbon dioxide climbed to historic highs over 400 parts per million.[76]

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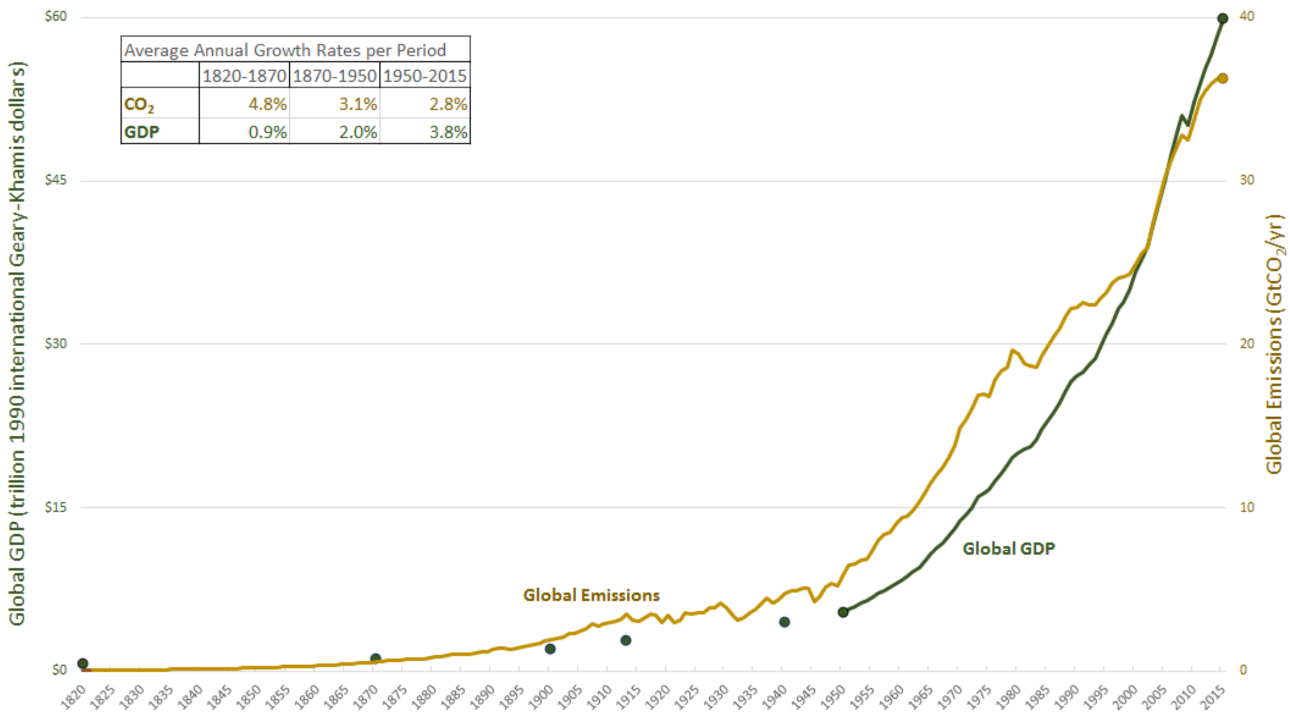
[73] See for example Rockström et al. (2009) on planetary boundaries and Sekulova et al. (2013) on degrowth.

[74] Carbon dioxide accounts for 90 percent of greenhouse gas emissions and is the most widely-tracked GHG data point. To maximize country data coverage and timeframes, this chapter focuses on carbon dioxide as an indicator of total GHG emissions.

[75] The Geary–Khamis dollar, more commonly known as the international dollar, is a hypothetical unit of currency that has the same purchasing power parity that the U.S. dollar had in the United States at a given point in time. See Madison (2003) for historical GDP data and estimation methods.

[76] These levels are higher than any point in at least the last 10,000 years. Global data on atmospheric concentrations of carbon dioxide are available via Ed Dlugokencky and Pieter Tans, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/). For more information on long-term concentrations of atmospheric carbon, see Indermühle et al. (1999).

Figure 12: Global GDP and Carbon Dioxide Emissions from Fossil Fuels and Cement (1820-2015)



Source: Boden et al. (2016), Maddison A (2007), and World Bank (2017).

The relationship between GHG emissions and economic growth is changing, and recent international developments indicate that previous linkages that persisted since Malthus are breaking. The inset table in Figure 12 shows the long-run global decline of carbon emissions annual growth rates while GDP growth accelerated. These crossing trends have driven a sustained reduction in the carbon emissions intensity of global GDP. What is new in recent years, and hinted at with the global slowing of emissions after 2010, is that a growing number of countries are reducing annual carbon emissions while continuing to increase GDP.[77] The GHG-GDP divergence trend suggests a potential win-win pathway where economic growth continues within planetary boundaries and avoids the dire predictions of Malthus and de-growth theorists.[78]

This chapter is focused on two research questions. First, what is driving the growing divergence of country-level GDP and carbon emissions? An index is developed to empirically assess the roles of de-industrialization and import growth in country divergence. The second question

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[77] Between 2000 and 2015, 30 countries reduced CO_2 emissions while growing real GDP. During the previous period from 1990-2000, 19 countries achieved GHG-GDP divergence.

[78] This chapter uses the terms "divergence" and "de-linking" to describe countries' reduction of GHG emissions with contemporaneous GDP growth instead of 'decoupling' to avoid confusion with the regulatory term that describes disassociation of an electric utility's profits from its sales of an energy commodity. The divergence described here is equivalent to "absolute decoupling" in its general use.

looks forward to ask whether the GHG-GDP divergence trend can be scaled up to include an ever-larger group of countries. To establish a foundation for answering these questions, the next section describes country pathways, metrics of divergence, and how post-2000 developments differ from the long-run dynamics illustrated in Figure 12. The third section presents results from industry and trade analysis, as well as a look at the role of household consumption and clean energy technology deployment in scaling up country divergence. The final section presents conclusions, initial policy implications, and questions for further research.

New Country Pathways and Metrics of Divergence

Given the historical link between greenhouse gases and economic activity, emissions mitigation presents a fundamental challenge to governments that predicate their legitimacy on continued GDP growth and provision of economic opportunity to all citizens. This challenge is compounded by the global atmospheric distribution of GHGs with delayed impacts well beyond emitting countries. Equity concerns stymied previous top-down attempts at global climate policy and led to the bottom-up, nationally-determined-contribution structure of the 2015 Paris agreement. In this context, the divergence of 30 countries' GHG emissions and GDP growth between 2000 and 2015 presents a beacon of hope for reconciling climate and development imperatives.

Since 1950, there have been three periods with global carbon emissions reductions and concurrent real GDP growth: 1974-1975, 1979-1983, and 1991-1992. These periods were related to oil supply shocks and their aftermaths—the OPEC embargo, the Iranian revolution, and the U.S.-Iraq Gulf War. During the longest period, from 1979 to 1983, global carbon emissions dropped by 5 percent while real GDP increased by 7 percent. This 4-year achievement was driven by a group of 40 divergent countries, but the trend reversed once surplus oil supply resumed in the mid-1980's. Three key differences between these earlier periods and post-2000 divergence are energy technology, the structure of the global economy, and the number of divergent countries. The rapid reduction of solar, wind, and other renewable energy technologies is creating economically-motivated fuel switching and decarbonization.[79] The second large difference is the redistribution of economic activity accompanying the global value chain revolution that began in 1990.[80] Thirdly, and largely due to the first two factors, the group of divergent countries is growing. While 40 countries experienced GHG-GDP divergence from 1979-1983, the divergent country group surged to 51 during the 2012 to 2015 period.[81] To concentrate on more robust and long-term developments, this chapter is primarily focused on GHG-GDP divergence over the 2000-2015 period.

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[79] See Hosenuzzaman, et al (2015) for discussion of global impacts of solar electricity generation.
[80] Baldwin (2016) provides an incisive assessment of the value chain revolution with his "three-cascading-constraints view of globalization".
[81] See Appendix for country-specific data.

The group of 2000-2015 divergent countries is diverse. It spans four continents and 2015 per-capita GDP from $2,100 in Ukraine to $ 81,000 in Switzerland.[82] The group is also diverse in terms of population, ranging from 65,000 people in Bermuda to more than 320 million in the United States. The range of country circumstances indicates that multiple factors are driving the divergence of GDP and carbon emissions.

The simplest measure to describe diverse country pathways between 2000 and 2015 is each country's aggregate change in emissions and economic activity. Figure 13 presents a scatter plot of 179 countries' changes in annual carbon dioxide emissions on the X-axis and changes in real GDP on the Y-axis for the 2000-2015 period.[83] The four quadrants of the scatter plot correspond with the relationship between each country's changes in CO_2 and GDP. The first quadrant, in the upper left, includes the 30 divergent countries that reduced annual emissions while increasing real GDP. The largest country in this quadrant is the United States, which is labelled in the figure and reduced carbon emissions by 10 percent (from 6 billion tonnes carbon dioxide to 5.4 billion tonnes) while GDP grew by 31 percent (from $13 trillion to $17 trillion constant 2010 US$) over the 2000-2015 period.[84] Within this positively delinked quadrant, the largest proportional emissions mitigation was achieved by Denmark: a 36 percent reduction, while real GDP grew by 14 percent. The highest proportional GDP growth in the group was achieved by Uzbekistan, which reduced annual carbon emissions by 10 percent while nearly tripling GDP.

The second quadrant represents the linked GHG-GDP growth that was prevalent through the twentieth century. The largest country in this quadrant is China, which nearly tripled emissions while quadrupling GDP over the 2000-2015 period. The diagonal line through the positively linked quadrant indicates the balance between carbon growth and GDP growth. Half of countries were in the linked quadrant (II) and above the equal growth line during this period, including China and India, indicating that their GDP grew by a larger portion than they expanded their carbon emissions. This group achieved a reduction in emissions intensity of GDP which is also known as "relative decoupling". The positively-linked quadrant also includes the *World Total* point, which shows that global carbon emissions increased by 46 percent while GDP grew by 51 percent.

The third and fourth quadrants reflect difficult circumstances insofar as these countries reduced GDP over this period. The two countries in the third quadrant (Zimbabwe and the Central African Republic) experienced the worst-case pathway of negatively de-lined growth:

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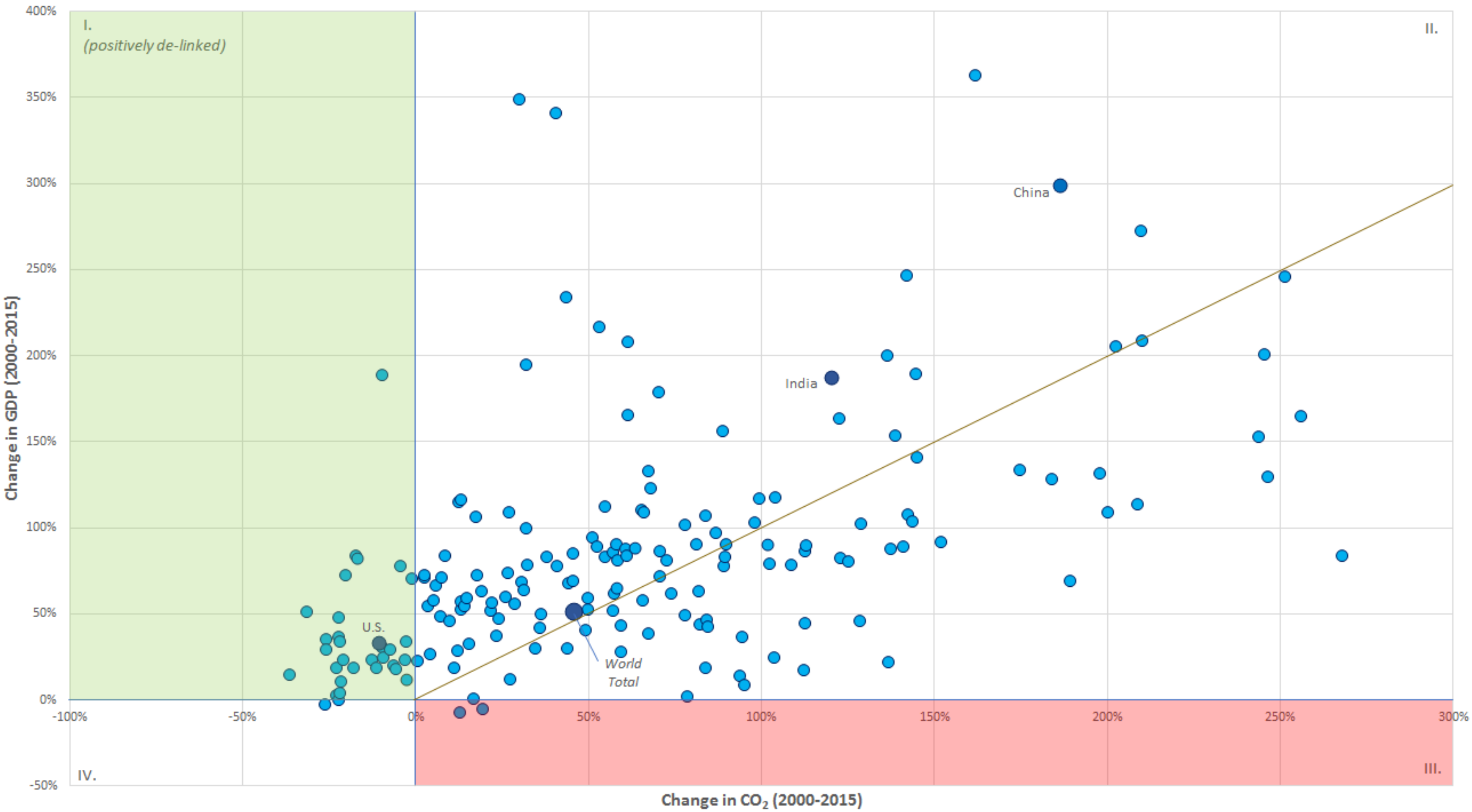
[82] Continents still lacking divergent countries are Africa, Antarctica, and Australia. Per-capita GDP data are in nominal terms, sourced from the World Bank, World Development Indicators (2017).
[83] Data for other countries are incomplete or unavailable. Also, note that 3 outlier countries (Tanzania, Mongolia, and Equatorial Guinea) are not displayed due to emissions growth greater than 300% over this period.
[84] China surpassed the U.S. as the largest GHG-emitting country around 2005; preliminary 2017 BP data indicate that China reduced carbon emissions in 2015 and 2016.

their carbon emissions increased while their economies contracted. The two countries in the fourth quadrant (Italy and Greece) experienced linked decline of both CO_2 and GDP.

The four quadrants in Figure 13 provide a visual summary of countries' progress toward low-carbon transformation over the 2000-2015 period. Countries in the positively delinked first quadrant are making the most progress toward the 2-degree pathway described in the Paris Agreement. However, the distinction between quadrants can exaggerate the differences between country performance. For example, Poland is in the delinked group with 1 percent emissions reduction and 71 percent GDP growth, while Latvia is in the linked quadrant with 3 percent increase in emissions and 73 percent GDP growth between 2000 and 2015. While countries will need to reduce emissions to align with a global 2-degree pathway, low-carbon transformation is a process for most countries with multiple stages prior to divergence.

Figure 13: Scatterplot of 179 Country Changes in GDP versus CO_2 Emissions (2000-2015)



Sources: UNFCCC (2016), Boden et al. (2016), World Bank. Note that carbon dioxide emissions data cover fossil fuel combustion and cement-related emissions from production activities; GDP data are based on market prices (constant 2010 US$). Six countries display other period information due to missing 2015 data; 3 outlier countries are not displayed (Tanzania, Mongolia, Equatorial Guinea); see Appendix for individual country data and details.

The 30 countries represented in the positively de-linked quadrant of the figure are Andorra, Belgium, Bermuda, Canada, Croatia, Cyprus, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Jamaica, Japan, Macedonia, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Suriname, Sweden, Switzerland, Ukraine, United Kingdom, USA, and Uzbekistan.

The distribution of countries shown in Figure 13 and the appendix raises two questions: first, what is driving the growing divergence of country-level GDP and carbon emissions? And second, can the GHG-GDP divergence trend be scaled up to include an ever-larger group of countries? The primary existing metric used to approach these questions is carbon intensity of GDP (and its converse carbon productivity). [85] While carbon intensity metrics describe the structural impact of countries' economies, their static nature limits their utility for answering these research questions.

Introducing the index of country GHG-GDP divergence (ICGGD)

To describe the continuity of dynamic country GHG-GDP performance and establish a quantitative foundation for hypothesis testing, I have developed an index of country GHG-GDP divergence (ICGGD).

The index of country GHG-GDP divergence is expressed in Equation 1:

$$ICGGD = (1 - \Delta CO2_i)(1 + \Delta GDP_i) - \Delta CO2_i + \Delta GDP_i$$

Benefits of ICGGD: continuous, comprehensive, balances mitigation and economic growth imperatives, simple, transparent. Drawbacks: doesn't differentiate negatively linked countries, allows for significant emissions growth, country-based (not emissions- or GDP-weighted), novel and unknown.

Discussion of ICGGD: higher scores indicate more divergence (beneficial); production-emissions basis; comparison with CO2-intensity of GDP; comparability and consistency.

The ICGGD values are based on production-based emissions data because they are more widely available and use agreed-upon accounting approaches. However, consumption-based data are available for many countries and do present a slightly different picture. Figure 14 illustrates the differences in production- versus consumption-based emissions for China and the U.S. Full country-level data are available in the appendix.

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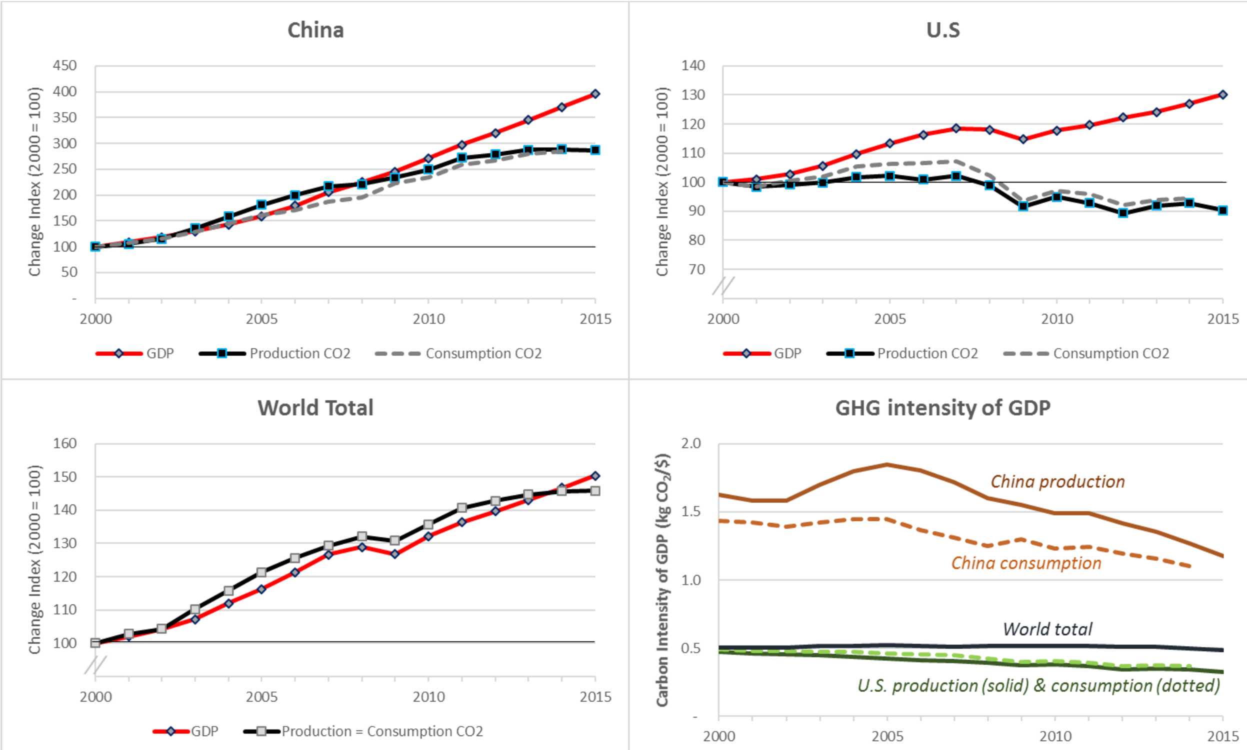
[85] See for example OECD (2017) for discussion of selected countries' carbon productivity as measured in $ per kg CO_2.

Figure 14: Changes in CO_2 Emissions and GDP for China, the U.S., and the World Total (2000-2015)



Sources: UNFCCC (2016), Boden et al. (2016), World Bank. Note that carbon dioxide emissions data cover fossil fuel combustion and cement production-related emissions; GDP data are based on market prices (constant 2010 US$). Consumption emissions are computed as in Peters et al. (2011), using Boden et al. (2016) as reference.

Table 3: Metrics of 30 GHG-GDP Divergent Countries (2000-2015)

	Country Name	ΔCO_2 2000-2015 (Production)	ΔCO_2 2000-2014 (Consumption)	ΔGDP 2000-2015	**Index of Country GHG-GDP Divergence**	CO_2 Intensity of GDP (kg CO_2/$ 2015 GDP)	Industry Share of GDP (2015)	Δ Industry Share of GDP (2000-2015)	Trade Share of GDP (2015)	Δ Trade Share of GDP (2000-2015)
1	Denmark	-36%	-16%	14%	2.07	0.10	23%	-16%	103%	24%
2	Macedonia	-32%		51%	2.81	0.78	27%	5%	114%	42%
3	Ukraine	-26%	7%	35%	2.31	1.66	26%	-29%	107%	-11%
4	United Kingdom	-26%	-13%	29%	2.17	0.16	19%	-23%	57%	10%
5	Finland	-23%	-8%	18%	1.87	0.18	27%	-26%	74%	-1%
6	Portugal	-23%	-31%	3%	1.52	0.22	22%	-20%	80%	19%
7	Sweden	-22%	-12%	36%	2.25	0.08	26%	-13%	86%	5%
8	Czech Republic	-22%	-14%	48%	2.51	0.43	38%	2%	160%	62%
9	Bermuda	-22%		4%	1.53	0.07	6%	-49%	77%	
10	Hungary	-22%	-11%	34%	2.19	0.32	32%	1%	173%	26%
11	Jamaica	-21%	11%	10%	1.66	0.59	23%	-9%	75%	-8%
12	Belgium	-21%	-7%	23%	1.93	0.20	22%	-20%	164%	16%
13	Romania	-20%	-10%	72%	2.99	0.40	34%	0.5%	83%	17%
14	France	-18%	-14%	18%	1.75	0.12	20%	-16%	61%	11%
15	Ireland	-17%	-21%	84%	3.17	0.12	42%	18%	216%	23%
16	Slovakia	-17%	3%	82%	3.13	0.34	35%	-3%	185%	67%
17	Spain	-13%	-12%	23%	1.74	0.19	24%	-23%	64%	6%
18	Germany	-11%	-16%	18%	1.61	0.22	30%	-1%	86%	40%
19	Slovenia	-10%	-4%	33%	1.90	0.28	33%	-6%	147%	42%
20	United States	-10%	-6%	31%	1.83	0.33	20%	-14%	28%	12%
21	Uzbekistan	-10%		190%	5.17	1.89	35%	49%	43%	-7%
22	Croatia	-9%	-2%	25%	1.70	0.31	27%	-9%	97%	28%
23	Switzerland	-7%	12%	29%	1.76	0.06	26%	-3%	114%	16%
24	Andorra	-6%		20%	1.54	0.16	12%	-26%		
25	Netherlands	-6%	-21%	18%	1.49	0.19	20%	-19%	154%	22%
26	Suriname	-4%		84%	2.81	0.46	28%	10%	93%	77%
27	Cyprus	-3%	-13%	23%	1.53	0.30	11%	-46%	122%	-11%
28	Japan	-3%	-5%	12%	1.30	0.21	29%	-12%	36%	80%
29	Canada	-3%	6%	34%	1.74	0.31	29%		66%	-21%
30	Poland	-1%	0%	71%	2.44	0.57	34%	5%	96%	58%

More than 90 percent of the countries that decoupled GDP and GHG emissions between 2000 and 2014 reduced the industrial sector share of their economies. However, the exceptional cases of Bulgaria and Uzbekistan demonstrate that GDP-GHG decoupling is also feasible in countries with expanding industrial activity (not to mention Switzerland and the Czech Republic, where the industrial portion of GDP remained essentially steady). Across the 21-country group, the average change in the industry share of GDP was a 3 percent reduction over the period, with an average CO_2 reduction of 15 percent.

Hypothesis Testing and Results

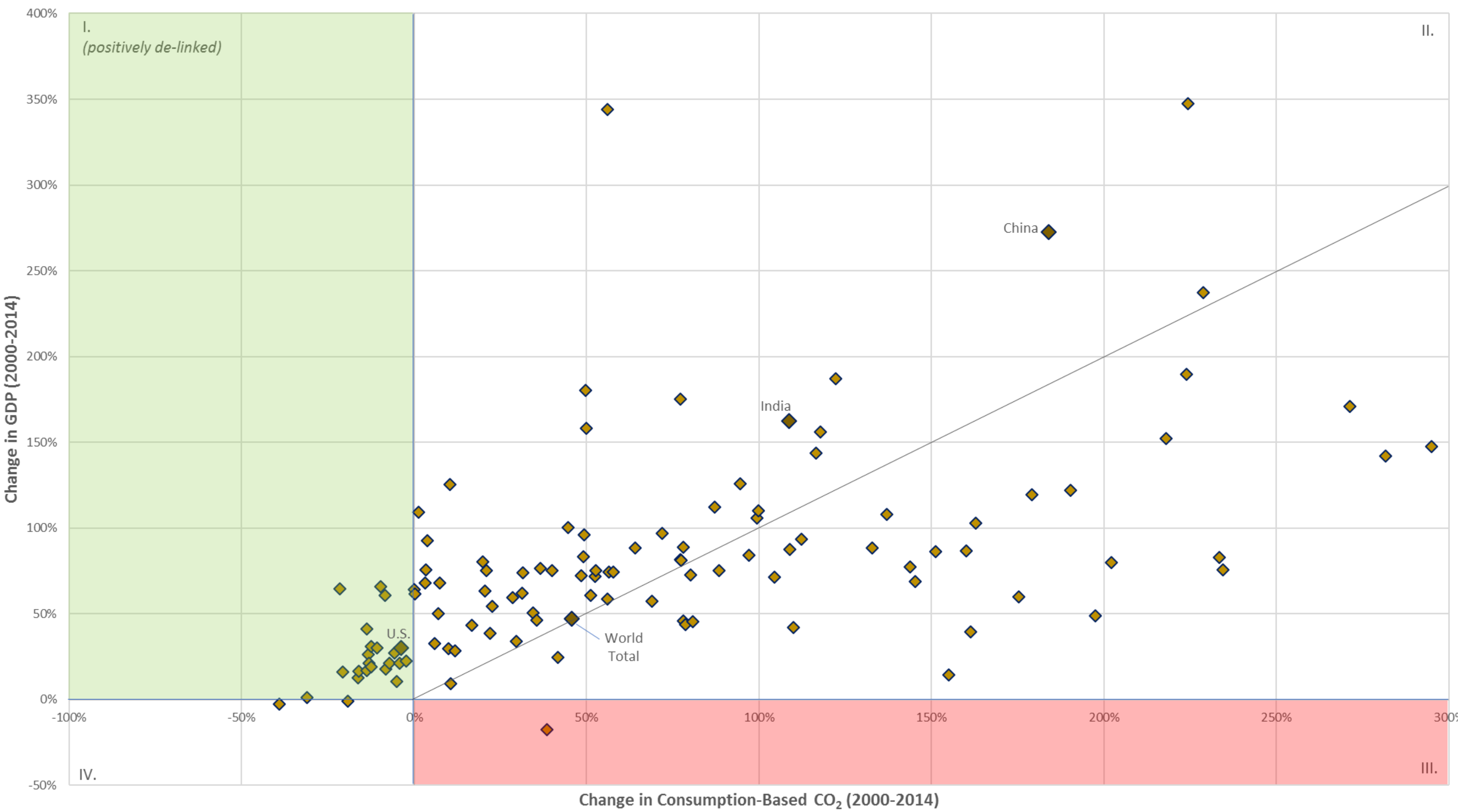
1. Deindustrialization drives country-level GHG-GDP divergence
   Theory: structural shift to services reduces emissions intensity of economy
   Data: industry annual value-added per country
   Results: theory weakly affirmed with negative correlation, R2=0.067

2. Emissions leakage drives country-level GHG-GDP divergence via growth of imports
   Theory: divergent countries 'outsource' GHG emissions importing goods instead of producing them domestically
   Data: country data on value of annual merchandise imports
   Results: theory refuted with negative correlation between imports and ICGGD

3. Economic development drives country-level GHG-GDP divergence
   Theory: environmental Kuznets curve (Aden & Sinton (2006); Huang, et al 2008)
   Data: country-level household expenditure per capita (proxy for economic development)

4. Clean energy deployment drives country-level GHG-GDP divergence
   Theory: energy transition to renewables drives transition to low-carbon economy
   Data: country-level renewable share of annual total final energy use

Figure 15: Scatterplot of 114 Country Changes in GDP versus Consumption-Based CO_2 Emissions (2000-2014)

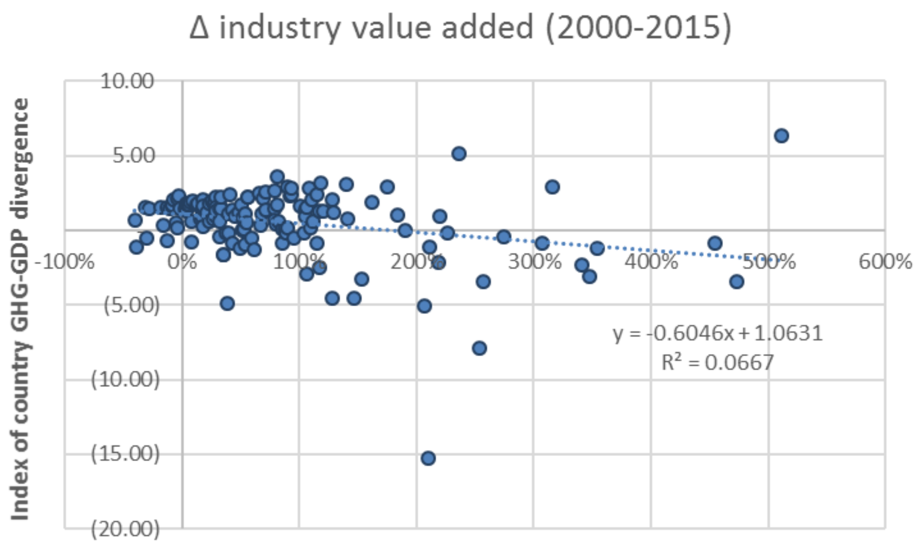


Sources: UNFCCC (2016), Boden et al. (2016), World Bank. Note that carbon dioxide emissions data cover fossil fuel combustion and cement-related emissions related to country-level consumption, i.e., including international transfers from trade; GDP data are based on market prices (constant 2010 US$). A dozen countries display 2000-2014 data due to missing 2015 data; 4 outlier countries are not displayed (Vietnam, Togo, Cambodia, and Mongolia); see Appendix for individual country data and details.

The ICGGD serves as the dependent variable for quantitatively evaluating the four hypotheses.

All data for these correlations was sourced from the World Bank's World Development Indicators online databank.

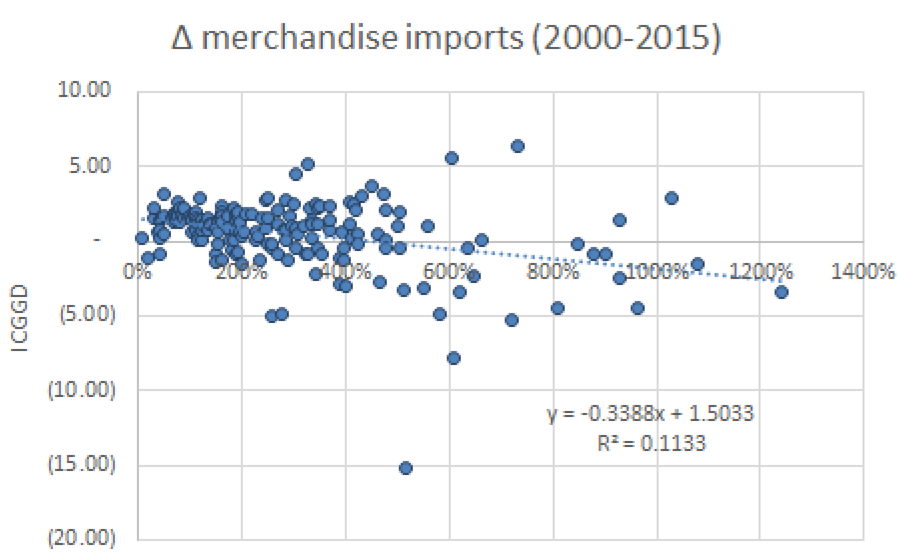
Figure 16: Correlation between country ICGGD values and change in industry value added



Note that country industry value added is measured in constant 2010 U.S. dollars.

The negative correlation provides an unsurprising result that increasing industrial sector value-added generally reduces country emissions performance as measured by the ICGGD.

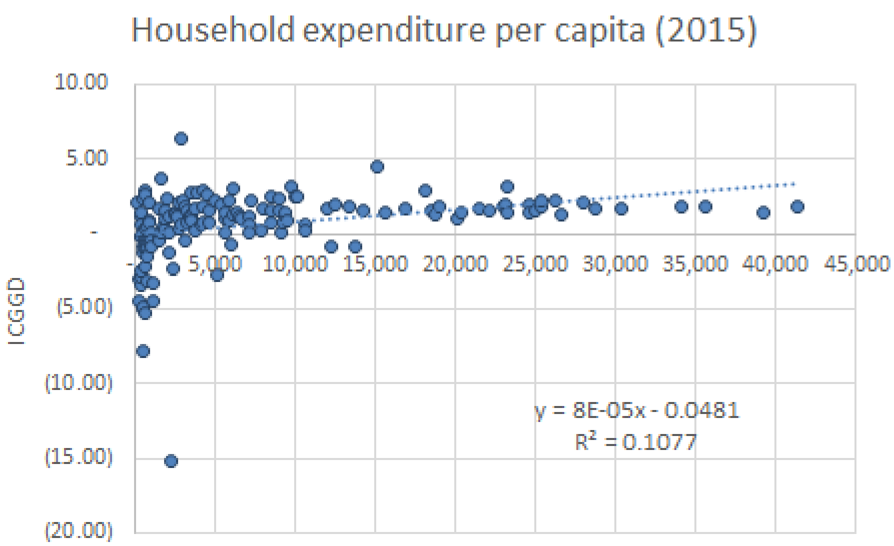
Figure 17: Correlation between country ICGGD values and change in value of merchandise imports



Note that merchandise imports data are based on the c.i.f. value of goods received from the rest of the world valued in current U.S. dollars.

This negative correlation provides an unexpected result that countries with larger growth of merchandise imports generally had lower ICGGD scores. The novelty of this finding is reinforced by the relative robustness of the correlation as reflected in the R-squared value of 0.11. This finding appears to contravene leakage theories of emissions reductions via increased import substitution and suggests an area that could benefit from further empirical, theoretical, and narrative research.

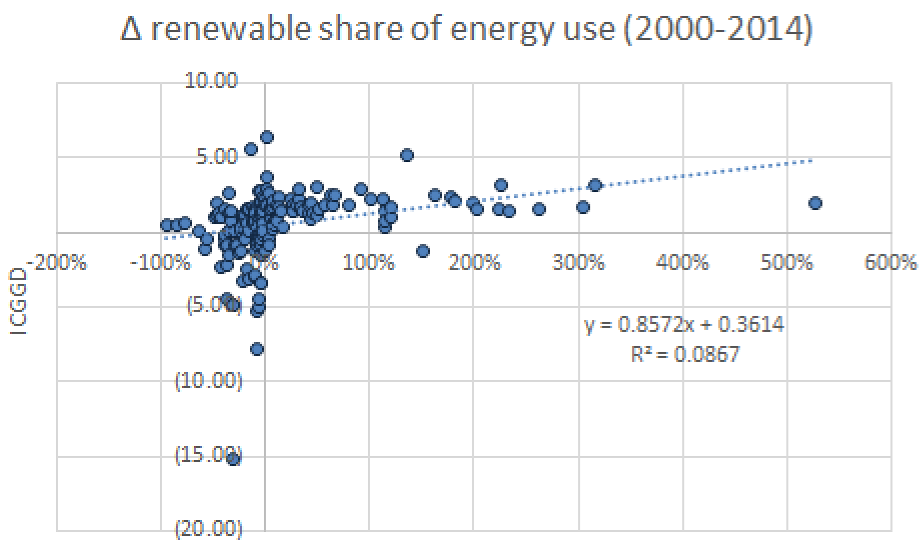
Figure 18: Correlation between country ICGGD values and 2015 household expenditure per capita



Note: the ICGGD values are calculated on the 2000-2015 period while the household expenditure per capita (x-axis) data are only for the year 2015 (measured in constant 2010 U.S. dollars)—endpoint rationale.

As predicted by the environmental Kuznets curve and other theories of development, countries ICGGD values were positively correlated with measurements of wealth such as household expenditure per capita (in this case, the country-average 2015 value expressed in constant 2010 U.S. dollars at market exchange rates).

Figure 19: Correlation between country ICGGD values and change in renewable share of total energy use per country



Finally, the fourth correlation shows that countries with higher growth of renewable energy shares of total energy use had better emissions performance as measured by ICGGD values. The energy component of country divergence is significant and provides an optimistic data point for scaling up the number of divergent countries.

Conclusions, Implications, and Questions for Further Research

These empirical results indicate that there's no single driver that explains all 30 GHG-GDP divergent countries ICGGD scores. De-industrialization, as measured with value added or industry share of GDP data, is not required for country divergence though there's general correlation with emissions performance. Trade results are unexpected and point to the possibility of local production, likely at smaller scales and with new production technologies, as a way to reduce industrial sector GHG emissions. One implication of these findings is that global value chain retrenchment, i.e., the return of manufacturing activities to areas closer to final demand, may advance industrial sector low-carbon transformation.

Data indicate that import growth is related to country-level GHG-GDP divergence, but in the opposite direction as suggested by the leakage theory. Increased growth of trade and merchandise imports in particular appear to correlate with lower ICGGD index values. Trade impacts on low-carbon economic transformation is an area that would benefit from further research.

Regarding the second research question, the third and fourth correlations indicate that economic development and clean energy technology deployment are conducive to improved country emissions performance as measured by ICGGD values.

Further research is also needed on the human and social impacts of climate change and low-carbon economic transformation. Additional questions for further research include:

Distributive impacts of GHG-GDP divergence

a. How does divergence relate to 2-degree scenarios? What's the current gap?
b. Where are the tipping points and how are they defined?
c. When is global divergence required?

Could ICGGD serve as the metric of low-carbon economic transformation? How can ICGGD figure into the emerging new societal deal between governments and citizens?

Are downward shifts of the environmental Engel Curve (the relationship between households' income and pollution embodied in goods and services they consume) an explanation for divergence?

What's the role of policy and institutions?

What's needed to achieve divergence in China and globally?

These questions for further research can help countries to improve their ICGGD values and better align environmental and economic imperatives. Beyond immediate country emissions assessment, the ICGGD introduces a new metric into the conversation about desired outcomes.

Chapter 4. Policy and Institutional Options to Accelerate Inclusive Industrial Transformation

"The art of progress is to preserve order amid change and to preserve change amid order." (Alfred Whitehead)

The inherent GHG emissions-intensiveness of industrial production, for example lime calcination to produce clinker for cement, leaves manufacturing as the most challenging sector for low-carbon transformation. The mitigation challenge is compounded by rising demand for many industrial products linked to economic development and related equity issues. Beyond environmental externalities, knowledge spillover effects represent an additional market failure that requires industry-oriented climate policy.[86] The lack of successful global climate policy for industry has abetted the ongoing global growth of GHG emissions. Finally, political developments of 2016 underscore the growing need for a new societal contract that identifies future sources of inclusive prosperity.

A primary reason for the lack of coherent industrial policy is confusion about its purpose. The traditional role of industrial policy has been to broadly accelerate economic growth and provide opportunity to a broad range of citizens. From the late 19th to late 20th century, four components were used to increase industrial activity: 1) unified domestic markets via internal tariff elimination and building infrastructure; 2) erecting external trade barriers to reduce import competition; 3) chartering banks to finance industrial investments and stabilize currency values; and 4) establish mass education to facilitate farm-to-factory transition.[87] These components shifted rapidly at the end of the 20th century, for example from trade protection to openness and integration into international supply chains. While the components of industrial policy have shifted, the supportive government role in industrial production has remained widespread.[88]

The confusion about policy does not stem from whether government should be involved in industrial production, but indecision on desired outcomes. For example, some groups construe the purpose of industrial policy to be replenishment of manufacturing jobs. Others are focused on maintaining production capacity and a particular manufacturing value-added share of GDP. A third focus area is the role of manufacturing in innovation, green growth, and international competitiveness. While these policy outcomes are not mutually exclusive, they echo ongoing debates about the future of industry.

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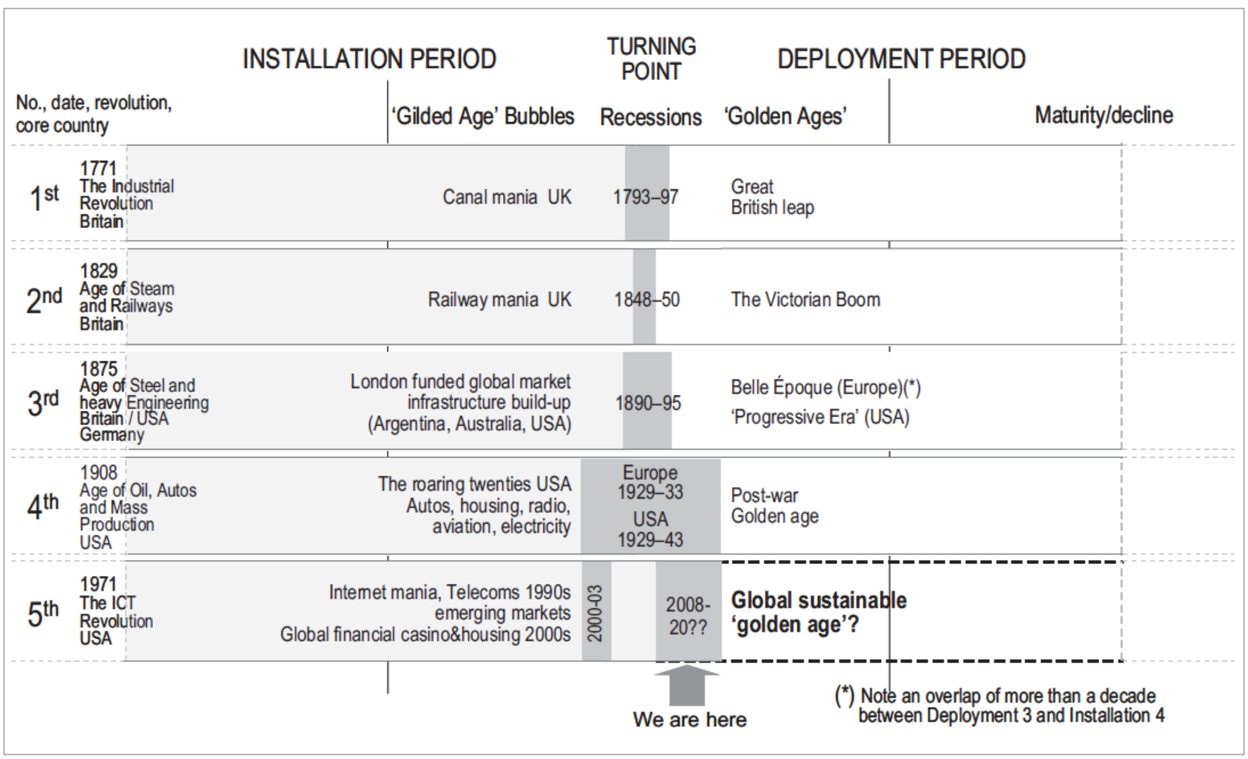
[86] See Popp (2010) for additional discussion of the role of market failures and innovation policy.
[87] Allen (2011) as discussed in Baldwin (2016).
[88] See Smil (2013) and Uchitelle (2017) for discussion of the role of government support in manufacturing.

The pessimistic perspective on the future of industry and growth can be summarized by Robert Gordon, who in his 2016 assessment of the American economy finds that "headwinds are sufficiently strong to leave virtually no room for growth over the next 25 years in median disposable real income per person."[89] Gordon's book on "The Rise and Fall of American Growth" argues that innovation-fueled rapid U.S. growth of the 1870-1970 period will not return due to the headwinds of rising inequality, diminishing growth of educational attainment, decreasing hours worked per person, and demographic pressures. These are not insurmountable barriers for low-carbon industrial transformation, but they do point to the need for a new societal deal that re-orients the metrics of progress away from simple GDP, perhaps toward the index of country-level GHG-GDP divergence discussed in chapter 3.

The optimistic perspective on the future of industry is represented by proponents of the "fourth industrial revolution". After the first industrial revolution of mechanization and steam power, the second of mass production and electricity, and the third of computers and automation, the fourth industrial revolution is heralded by internet-connected cyber-physical systems.[90] As illustrated in Figure 20 below, some analysts find that we are in the midst of a fifth industrial revolution.

Figure 20: Historical Cycles of Industrial Innovation and the Possibility of a Golden Age of Global Sustainability



[89] Gordon (2016), p.642.

[90] Schwab (2016) provides an overview of expected growth opportunities with the fourth industrial revolution.

Source: Perez (2015).

Regardless of the number of industrial revolutions, many analysts agree that industry is at a turning point. Not only is industrial activity central to climate outcomes this century, industrial stakeholders are politically powerful veto players who have exerted extensive influence over climate policy regimes, and the lack thereof. One indicator of this influence is the profusion of emissions allowance that have been granted to industrial companies covered by California's cap and trade program and the European Emissions Trading System. These industrial allowances have created conditions of oversupply that have kept carbon prices at globally-low levels insufficient to stimulate manufacturing investment in mitigation activities. However, they did serve to ameliorate stakeholder concerns to a degree that allowed policies to be implemented. A question here is whether it is possible for existing, emissions-intensive industrial stakeholders to support effective mitigation policies without financial inducements.

Governments generally take a supportive approach when it comes to industrial GHG emissions mitigation. This is partially grounded in the debate between conventional economists such as Greenstone who argue that environmental regulation is fundamentally detrimental to manufacturing activity and not beneficial for the regulated and interdisciplinary analysts such as Michael Porter, whose eponymous hypothesis suggests that regulations can improve firms environmental and business performance.[91] Governments more or less sympathetic to these perspectives us the range of policy instruments described in Table 4 to govern industrial sector emissions.

Table 4: Typology of Policies Used to Govern Industrial Emissions

Policies		**U.S. and Hypothetical Examples**
Prescriptive		
	Regulations for equipment	Emissions performance standards, e.g. Boiler MACT (Major Source Boiler Maximum Achievable Control Technology rules), NSPS (New Source Performance Standards and Permitting Requirements)
	Regulations for process and configuration	Benchmark targets &/or emissions goals
	Regulations for energy management	Energy management standards, e.g. ISO 50001
	Negotiated agreements	Benchmark targets &/or emissions goals with implementation & tracking, e.g., Better Buildings Better Plants Program
Economic		

[91] See Greenstone (2001) and Ambec, et al. (2013).

	Emissions taxes	Taxes, exemptions, credits, and deductions
	Directed financial incentives	Preferential loans, subsidies, accelerated depreciation, & rebates; e.g., Advanced Energy Manufacturing Tax Credit
	Cap & trade schemes	GHG emissions trading with allowances and banking
	Differentiated energy pricing	Emissions-linked energy tariffs
Supportive		
	Identification of efficiency opportunities	Collection of consumption and technology installation data with benchmarking
	Cooperative measures	Challenge, partnership, and recognition programs; e.g., Climate Leadership Awards
	Capacity building	Equipment labels, best practice info, advising, training, & education; e.g., ENERGY STAR, Industrial Assessment Centers
Government R&D		
	Long-term, blue-sky research	Research grants; e.g., ARPA-E, National Network for Manufacturing Innovation; SBIR (Small Business Innovation Research Program)
Investment		
	Government procurement	Market growth for certified new products

Source: adapted from Tanaka (2011)

All the policy mechanisms listed in Table 4 will be needed for achieving low-carbon industrial transformation commensurate with a global 2-degree pathway. Four additional components of industrial policy for achieving inclusive low-carbon transformation are increased public-private partnerships to streamline policy and business objectives, data governance frameworks to provide institutional support for digital technology integration and intellectual property management, expanded lifelong training programs for worker re-skilling, and development of new metrics such as the index of country-level GHG-GDP divergence to set goals and track performance, as well as additional indicators of human impacts of industrial transformation.[92] With the understanding that the employment and economic-development role of manufacturing has changed since the 20th century, these four components can serve as building blocks of a new industrial policy for inclusive transformation.

Between the prospect of secular stagnation marked by a shrinking economic pie and the rosy scenario of technology-fueled growth, governments have a range of policy options for achieving

[92] OECD (2017b) includes extensive discussion of policy options for advancing environmental objectives with new production technologies.

industrial GHG emissions mitigation. Lack of policymaker consensus on desired outcomes has caused persistent energy and climate policy incoherence, for example with subsidies for fossil fuel production and voluntary programs aimed at reducing resulting emissions. In the absence of government vision and policies, technology innovation and market forces are gradually pushing manufacturers to reduce GHG emissions through adoption of efficiency measures and lower-cost renewable energy sources. The efficiency and renewable electricity transition is necessary but not sufficient for achieving 2-degree outcomes.[93] A related policy question that could use further research is the role of trade. While the index regression analysis in chapter 3 indicate a mitigation pathway with reduced imports and more local production, the emissions impacts of trade appear to vary by sector and country. Development of climate-integrated industrial policy for the 21st century will be an iterative process—these are a few potential components and ideas.

[93] IEA (2017) quantifies the role of efficiency versus other mitigation wedges in reducing industrial sector emissions to a 2-degree level.

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Appendix

Table 5: Metrics of 182 Countries' GHG-GDP Divergence (2000-2015)

	Country Name	ΔCO_2 2000-2015 (Production)	ΔCO_2 2000-2014 (Consumption)	ΔGDP 2000-2015	Index of GHG-GDP Divergence	CO_2 Intensity of GDP (kg CO_2/$ 2015 GDP)	Industry Share of GDP (2015)	Δ Industry Share of GDP (2000-2015)	Trade Share of GDP (2015)	Δ Trade Share of GDP (2000-2015)
1	Albania	61%	49%	88%	1.02	0.37	24%	46%	72%	28%
2	Algeria* (2000-2013)	71%		72%	0.52	0.79	39%	-33%	60%	-4%
3	Andorra	-6%		20%	1.54	0.16	12%	-26%		
4	Angola	246%		201%	(4.82)	0.32			70%	-54%
5	Antigua and Barbuda	59%		28%	0.27	0.43	19%	20%	94%	-20%
6	Argentina	36%	35%	50%	1.10	0.42	28%		23%	1%
7	Armenia	61%	50%	166%	2.07	0.49	29%	-26%	72%	-3%
8	Australia	14%	34%	54%	1.71	0.31	25%	-5%	41%	
9	Austria	0.4%	-4%	22%	1.44	0.16	28%	-10%	102%	19%
10	Azerbaijan	30%	56%	349%	6.33	0.65	49%	9%	73%	-6%
11	Bahamas	95%		9%	(0.81)	0.41	14%	-22%	86%	-6%

	Country Name	ΔCO_2 2000-2015 (Production)	ΔCO_2 2000-2014 (Consumption)	ΔGDP 2000-2015	Index of GHG-GDP Divergence	CO_2 Intensity of GDP (kg CO_2/$ 2015 GDP)	Industry Share of GDP (2015)	Δ Industry Share of GDP (2000-2015)	Trade Share of GDP (2015)	Δ Trade Share of GDP (2000-2015)
12	Bahrain	78%	49%	102%	0.68	1.08	40%		156%	15%
13	Bangladesh	175%	179%	134%	(2.15)	0.49	28%	21%	42%	44%
14	Barbados	27%		12%	0.67	0.33	11%	-36%	83%	-6%
15	Belarus	13%	10%	117%	2.91	1.00	38%	-4%	116%	-18%
16	Belgium	-21%	-7%	23%	1.93	0.20	22%	-20%	164%	16%
17	Belize	31%		68%	1.51	0.34	17%	-18%	126%	
18	Benin	268%	202%	84%	(4.92)	0.67	23%	-27%	68%	21%
19	Bermuda* (2000-13)	-22%		4%	1.53	0.07	6%	-49%	77%	
20	Bhutan	136%		200%	(0.45)	0.45	43%	20%	93%	13%
21	Bolivia	102%	77%	90%	(0.14)	0.80	33%	9%	68%	49%
22	Bosnia and Herzegovina	57%		62%	0.74	1.18	27%	19%	88%	-15%
23	Botswana	63%	109%	89%	0.93	0.38	33%	-34%	106%	15%
24	Brazil	57%	69%	52%	0.59	0.22	22%	-16%	27%	19%

	Country Name	ΔCO_2 2000-2015 (Production)	ΔCO_2 2000-2014 (Consumption)	ΔGDP 2000-2015	Index of GHG-GDP Divergence	CO_2 Intensity of GDP (kg CO_2/$ 2015 GDP)	Industry Share of GDP (2015)	Δ Industry Share of GDP (2000-2015)	Trade Share of GDP (2015)	Δ Trade Share of GDP (2000-2015)
25	Brunei Darussalam	94%	155%	14%	(0.73)	0.67	61%	-4%	85%	-18%
26	Bulgaria	6%	-8%	67%	2.18	0.87	28%	8%	128%	64%
27	Burkina Faso	198%	190%	131%	(2.93)	0.27	21%	-1%	64%	84%
28	Burundi	5%		58%	2.03	0.13	18%	4%	36%	59%
29	Cabo Verde	141%		89%	(1.28)	0.25	20%		101%	15%
30	Cambodia	202%	392%	205%	(3.09)	0.38	30%	28%	128%	15%
31	Cameroon	109%	145%	78%	(0.46)	0.24	28%	-21%	50%	16%
32	Canada	-3%	6%	34%	1.74	0.31	29%		66%	-21%
33	Central African Republic	13%		-7%	0.61	0.21	16%	12%	47%	3%
34	Chad	251%		246%	(5.29)	0.05	14%	25%	67%	30%
35	Chile	38%	48%	83%	1.48	0.31	32%	-6%	59%	
36	China	186%	184%	298%	(2.33)	1.16	41%	-10%	40%	2%
37	Colombia	71%	77%	87%	0.71	0.27	33%	14%	39%	18%

	Country Name	ΔCO_2 2000-2015 (Production)	ΔCO_2 2000-2014 (Consumption)	ΔGDP 2000-2015	Index of GHG-GDP Divergence	CO_2 Intensity of GDP (kg CO_2/$ 2015 GDP)	Industry Share of GDP (2015)	Δ Industry Share of GDP (2000-2015)	Trade Share of GDP (2015)	Δ Trade Share of GDP (2000-2015)
38	Comoros	94%		37%	(0.50)	0.27			63%	23%
39	Congo, Dem. Rep.	246%		130%	(4.53)	0.09	35%	55%	70%	160%
40	Congo, Rep.	152%		92%	(1.60)	0.18	55%	-24%	166%	34%
41	Costa Rica	45%	40%	85%	1.35	0.18	22%	-22%	62%	-29%
42	Côte d'Ivoire	50%	161%	53%	0.79	0.30	32%		73%	-3%
43	Croatia	-9%	-2%	24%	1.70	0.31	27%	-9%	97%	28%
44	Cuba	58%		91%	1.13	0.56	23%	-13%	32%	2%
45	Cyprus	-3%	-13%	23%	1.53	0.30	11%	-46%	122%	-11%
46	Czech Republic	-22%	-14%	48%	2.51	0.43	38%	2%	160%	62%
47	Denmark	-36%	-16%	14%	2.07	0.10	23%	-16%	103%	24%
48	Djibouti	81%		90%	0.46	0.42				
49	Dominica	35%		30%	0.81	0.27	13%	-25%	92%	-5%
50	Dominican Republic	17%	4%	106%	2.60	0.34	27%	-18%	54%	-35%

	Country Name	ΔCO_2 2000-2015 (Production)	ΔCO_2 2000-2014 (Consumption)	ΔGDP 2000-2015	Index of GHG-GDP Divergence	CO_2 Intensity of GDP (kg CO_2/$ 2015 GDP)	Industry Share of GDP (2015)	Δ Industry Share of GDP (2000-2015)	Trade Share of GDP (2015)	Δ Trade Share of GDP (2000-2015)
51	Ecuador	112%	151%	86%	(0.49)	0.51	34%	-4%	44%	-25%
52	Egypt	55%	57%	83%	1.09	0.87	36%	9%	35%	-11%
53	El Salvador	15%	10%	33%	1.30	0.28	27%	-16%	68%	-3%
54	Equatorial Guinea	1309%		383%	(68.16)	0.39	60%		105%	-69%
55	Eritrea* (2000-2011)* partial	11%		19%	1.13	0.26			38%	-45%
56	Estonia	31%	0%	64%	1.46	0.86	27%	-1%	154%	22%
57	Ethiopia	210%	229%	272%	(3.45)	0.23	18%	45%	40%	
58	Fiji	112%		44%	(0.86)	0.47	18%	-19%	110%	-19%
59	Finland	-23%	-8%	18%	1.87	0.18	27%	-26%	74%	-1%
60	France	-18%	-14%	18%	1.75	0.12	20%	-16%	61%	11%
61	Gabon	7%		48%	1.80	0.27	51%	-2%	74%	-27%
62	Gambia	82%		63%	0.11	0.47	15%	-1%	54%	-4%
63	Georgia	67%	95%	133%	1.41	0.51	25%	10%	107%	71%

	Country Name	ΔCO_2 2000-2015 (Production)	ΔCO_2 2000-2014 (Consumption)	ΔGDP 2000-2015	Index of GHG-GDP Divergence	CO_2 Intensity of GDP (kg CO_2/$ 2015 GDP)	Industry Share of GDP (2015)	Δ Industry Share of GDP (2000-2015)	Trade Share of GDP (2015)	Δ Trade Share of GDP (2000-2015)
64	Germany	-11%	-16%	18%	1.61	0.22	30%	-1%	86%	40%
65	Ghana	139%	116%	153%	(0.83)	0.32	28%	-3%	99%	-14%
66	Greece	-26%	-39%	-3%	1.46	0.31	16%	-25%	64%	9%
67	Greenland	12%		29%		0.26	16%	6%	83%	-10%
68	Grenada	67%		39%		0.36	15%	-29%	67%	-37%
69	Guatemala	44%	51%	68%	1.17	0.29	27%	-4%	51%	4%
70	Guinea	82%	79%	44%	(0.13)	0.44	37%	11%	78%	46%
71	Guinea-Bissau	78%		49%	0.04	0.26	14%	-5%	62%	12%
72	Guyana	26%		60%	1.51	0.72	22%	-24%	108%	-48%
73	Haiti	84%		19%	(0.45)	0.32			71%	53%
74	Honduras	89%	53%	78%	0.08	0.51	28%	-14%	109%	-9%
75	Hong Kong	18%	7%	72%	1.97	0.18	7%	-42%	389%	57%
76	Hungary	-22%	-11%	34%	2.19	0.32	32%	1%	173%	26%

	Country Name	ΔCO_2 2000-2015 (Production)	ΔCO_2 2000-2014 (Consumption)	ΔGDP 2000-2015	Index of GHG-GDP Divergence	CO_2 Intensity of GDP (kg CO_2/$ 2015 GDP)	Industry Share of GDP (2015)	Δ Industry Share of GDP (2000-2015)	Trade Share of GDP (2015)	Δ Trade Share of GDP (2000-2015)
77	Iceland	24%		47%	1.35	0.22	23%	-16%	100%	39%
78	India	121%	109%	187%	0.04	0.99	30%	-5%	42%	55%
79	Indonesia	104%	137%	118%	0.05	0.54	40%	-13%	42%	-41%
80	Iran	71%	81%	62%	0.40	1.42	24%	-40%	39%	-5%
81	Iraq	137%		88%	(1.22)	0.90			76%	-39%
82	Ireland	-17%	-21%	84%	3.17	0.12	42%	18%	216%	23%
83	Israel	19%	29%	63%	1.76	0.26			58%	-18%
84	Italy	-22%	-19%	0%	1.44	0.18	24%	-13%	57%	13%
85	Jamaica	-21%	11%	10%	1.66	0.59	23%	-9%	75%	-8%
86	Japan	-3%	-5%	12%	1.30	0.21	29%	-12%	36%	80%
87	Jordan	65%	99%	111%	1.18	0.85	30%	16%	98%	-11%
88	Kazakhstan	70%	77%	179%	1.91	1.26	33%	-20%	53%	-50%
89	Kenya	32%	133%	100%	2.02	0.26	19%	13%	44%	-17%

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90	Kiribati	104%		24%	(0.84)	0.37	7%	-41%	109%	4%
91	Korea, Rep.	32%	31%	79%	1.67	0.47	38%	1%	84%	23%
92	Kuwait	90%	160%	90%	0.20	0.73	51%		100%	15%
93	Kyrgyzstan	113%	233%	90%	(0.48)	1.62	28%	-9%	111%	24%
94	Laos	145%	271%	190%	(0.84)	0.22	31%	86%	75%	1%
95	Latvia	3%	3%	73%	2.39	0.26	23%	-14%	119%	46%
96	Lebanon	52%		89%	1.27	0.56	21%	-8%	122%	143%
97	Liberia	128%		46%	(1.23)	0.59	13%	195%	126%	79%
98	Lithuania	8%	20%	84%	2.44	0.29	30%	1%	152%	83%
99	Luxembourg	13%	197%	52%	1.76	0.16	12%	-33%	420%	54%
100	Macao	44%		234%	4.54	0.07	11%	-26%	116%	-22%
101	Macedonia (Republic of)	-32%		51%	2.81	0.78	27%	5%	114%	42%
102	Madagascar	84%	110%	46%	(0.14)	0.35	16%	10%	79%	15%

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103	Malawi	51%	78%	94%	1.39	0.16	16%	-11%	65%	7%
104	Malaysia	98%	112%	103%	0.09	0.75	36%	-25%	134%	-39%
105	Maldives	145%		141%	(1.12)	0.38	23%	53%	172%	
106	Mali	27%		109%	2.35	0.08	19%	-18%	52%	-6%
107	Malta	4%	22%	55%	1.85	0.23	15%	-49%	280%	14%
108	Marshall Islands *(2001-15)	44%		30%	0.59	0.62	11%			
109	Mauritania	129%		102%	(0.89)	0.49	29%	2%	109%	45%
110	Mauritius	58%	21%	81%	0.98	0.36	22%	-30%	108%	-12%
111	Mexico	23%	30%	37%	1.19	0.39	33%	-6%	72%	36%
112	Micronesia, Fed. Sts.	17%		1%	0.68	0.54	7%	-25%		
113	Mongolia	503%	504%	204%	(15.25)	3.87	34%	35%	90%	-26%
114	Montenegro	29%		56%	1.38	0.49	20%	-13%	104%	18%

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115	Morocco	87%	64%	97%	0.36	0.56	29%	-3%	76%	29%
116	Mozambique	210%	224%	209%	(3.40)	0.29	22%	-7%	104%	99%
117	Myanmar	40%		341%	5.64	0.20	35%	256%	47%	3959%
118	Namibia	84%	72%	107%	0.57	0.20	31%	11%	112%	31%
119	Nepal	125%	234%	80%	(0.90)	0.35	15%	-30%	53%	-4%
120	Netherlands	-6%	-21%	18%	1.49	0.19	20%	-19%	154%	22%
121	New Zealand	10%	17%	46%	1.72	0.21	22%	-10%	55%	-20%
122	Nicaragua	27%	31%	74%	1.68	0.42	27%	18%	98%	60%
123	Niger	200%		109%	(3.00)	0.27			57%	30%
124	Nigeria	32%	122%	195%	3.64	0.22	20%	-61%	21%	-70%
125	Norway	4%	42%	27%	1.44	0.09	35%	-16%	69%	-7%
126	Oman	189%	175%	69%	(2.71)	0.88	52%		109%	36%
127	Pakistan	61%	53%	84%	0.94	0.79	20%	-14%	28%	-2%

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128	Palau	112%		17%	(1.09)	1.09	9%	-50%	134%	-10%
129	Panama	89%	282%	156%	0.97	0.26	28%	25%	106%	-21%
130	Papua New Guinea *(2000-2014)	147%		104%	(1.39)	0.49				
131	Paraguay	41%	80%	78%	1.42	0.20	30%	-17%	84%	-2%
132	Peru	99%	100%	117%	0.19	0.32	33%	3%	45%	27%
133	Philippines	55%	45%	112%	1.54	0.43	31%	-10%	63%	-40%
134	Poland	-1%	0%	71%	2.44	0.57	34%	5%	96%	58%
135	Portugal	-23%	-31%	3%	1.52	0.22	22%	-20%	80%	19%
136	Qatar	162%	224%	363%	(0.84)	0.54	59%	-71%	92%	3%
137	Romania	-20%	-10%	72%	2.99	0.40	34%	0.5%	83%	17%
138	Russian Federation	7%	37%	71%	2.23	0.99	33%	-14%	49%	-28%
139	Rwanda	53%	50%	217%	2.88	0.10	18%	55%	49%	58%

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140	Samoa	85%		43%	(0.20)	0.37			76%	-6%
141	Sao Tome and Principe	142%		108%	(1.22)	0.47	15%			
142	Saudi Arabia	102%	163%	79%	0.02	0.88	45%	-16%	72%	6%
143	Senegal	123%	105%	82%	(0.82)	0.55	23%	1%	75%	16%
144	Serbia	13%		57%	1.81	1.11	31%	-6%	103%	327%
145	Seychelles	15%		59%	1.81	0.52	14%	-59%	181%	
146	Sierra Leone	184%		129%	(2.48)	0.38	5%	-84%	67%	16%
147	Singapore	12%	1%	115%	2.88	0.19	26%	-25%	330%	-10%
148	Slovakia	-17%	3%	82%	3.13	0.34	35%	-3%	185%	67%
149	Slovenia	-10%	-4%	33%	1.90	0.28	33%	-6%	147%	42%
150	Solomon Islands	46%		69%	1.15	0.25			101%	60%
151	South Africa	22%	23%	57%	1.56	1.10	29%	-9%	62%	20%
152	Spain	-13%	-12%	23%	1.74	0.19	24%	-23%	64%	6%

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153	Sri Lanka	68%	87%	123%	1.26	0.22	29%	8%	50%	-44%
154	St. Kitts and Nevis	59%		43%	0.53	0.35	28%	-6%	104%	10%
155	St. Vincent and the Grenadines	49%		40%	0.63	0.30	17%	-12%	78%	-19%
156	Sudan	209%		114%	(3.27)	0.22	3%	-88%	19%	-35%
157	Suriname	-4%		78%	2.81	0.46	28%	10%	93%	77%
158	Swaziland	3%		71%	2.21	0.23	38%	-8%	97%	-36%
159	Sweden	-22%	-12%	36%	2.25	0.08	26%	-13%	86%	5%
160	Switzerland	-7%	12%	29%	1.76	0.06	26%	-3%	114%	16%
161	Tajikistan	61%		208%	2.65	0.46	28%	-28%	53%	-74%
162	Tanzania	334%	295%	165%	(7.89)	0.26	26%	36%	48%	43%
163	Thailand	72%	88%	81%	0.58	0.79	36%	-1%	127%	4%
164	Togo	66%	340%	58%	0.46	0.56	18%	-4%	110%	34%
165	Tonga	137%		22%	(1.59)	0.57	20%	-8%	78%	46%

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166	Trinidad and Tobago	89%	97%	83%	0.13	1.99	40%	-18%	98%	-6%
167	Tunisia	58%	20%	65%	0.76	0.65	28%	-7%	92%	12%
168	Turkey	66%	58%	109%	0.77	0.36	32%	5%	49%	17%
169	Turkmenistan	142%		246%	(0.41)	2.44			118%	-33%
170	Uganda	256%	218%	165%	(5.04)	0.19	20%	-12%	46%	40%
171	Ukraine	-26%	7%	36%	2.31	1.66	26%	-29%	107%	-11%
172	United Arab Emirates	57%	144%	85%	1.06	0.48			196%	119%
173	United Kingdom	-26%	-13%	29%	2.17	0.16	19%	-23%	57%	10%
174	United States	-10%	-6%	31%	1.83	0.33	20%	-14%	28%	12%
175	Uruguay	50%	56%	59%	0.91	0.17	29%	18%	45%	23%
176	Uzbekistan	-10%		189%	5.17	1.89	35%	49%	43%	-7%
177	Vanuatu *(2000-2013)	36%		42%	0.97	0.15	9%	-29%	98%	12%
178	Venezuela	15%	78%	52%	1.55	0.42	49%	-1%	54%	13%

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179	Viet Nam	244%	305%	153%	(4.54)	1.19	37%		179%	73%
180	**World**	**46%**	**46%**	**51%**	**0.87**	**0.48**	**27%**	**-12%**	**58%**	**13%**
181	Yemen	78%		2%	(0.54)	1.26	48%	6%	33%	-57%
182	Zambia	123%	118%	164%	(0.18)	0.16	35%	34%	84%	40%
183	Zimbabwe	19%	38%	-5%	0.31	1.14	24%	-8%	60%	-19%