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Environmentally Extended Input-Output (EEIO) Modeling for Industrial Decarbonization Opportunity Assessment: A Circular Economy Case Study

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Abstract
In increasingly complex supply chains, technology changes in one sector can have cascading impacts in other sectors that are not fully considered in most emissions analyses. Environmentally extended input-output (EEIO) models enable top-down analysis of the interactions between sectors and across the entire economy, including characterization of Scope 1, 2, and 3 emissions. EEIO models utilize matrix-based techniques to infer flows of material resources and emissions between economic sectors. Here we describe a new Excel-based EEIO model and scenario analysis tool designed for rapid "what-if" opportunity assessment. Baseline data in the model are drawn from publicly available sources, including recently released data from the U.S. Energy Information Administration's 2018 Manufacturing Energy Consumption Survey and the Bureau of Economic Analysis's economic input-output accounts data for the same year. A user interface allows for modification of fuel, electricity, and demand assumptions in each industrial sector—facilitating rapid assessment of the potential impacts of sustainability interventions, such as reduced demand, increased use of recycled material, or a change in energy sourcing to low-carbon options. Scenario analyses such as these can inform policymakers on priorities for decarbonization and improved resource utilization, while also enabling researchers and manufacturers to understand the drivers of cumulative emissions impacts in different products and sectors. We will demonstrate capabilities of this unique tool through a pair of illustrative case studies focused on the circular economy.

Keywords: EEIO, supply chain emissions, industrial decarbonization

55.1 Introduction

One of the most powerful available tools for supply-chain analysis is economic input-output (EIO) modeling – a comprehensive, top-down technique that can be used to analyze interactions across entire economies. Environmentally extended input-output (EEIO)

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models leverage EIO techniques to examine environmental impacts involving energy, emissions, and other environmental factors. These models can provide robust data for holistic analysis of decarbonization and supply chain opportunities, including opportunities to increase circularity and resource efficiency. Major EEIO models for the United States, including the Environmental Protection Agency's (EPA's) USEEIO model [1, 2] and Carnegie Mellon University's EIO-LCA webtool [3, 4], have demonstrated the powerful capabilities of EEIO to reveal systemic opportunities for emissions reduction in supply chains through top-down analysis of resource flows. Input-output methods are mature, and have been deployed recently to explore many aspects of industrial sustainability, including emissions hotspots [5–7], supply chain risk [8], social impacts of manufacturing [9], and effects of recycling/demand reduction [5, 8, 10, 11]. However, a limitation of EEIO models in general is that the underlying economic, energy, and environmental data are typically static (and therefore provide only a "snapshot" of the economic, technology, and energy conditions of the model base year). Data recency and lack of adjustability can constrain the utility of these models for forward-looking analysis, especially for the rapidly evolving industries, supply chains, and energy systems that characterize the circular economy. Researchers have made recent strides in adjustable input-output tools for specific use-cases, such as the multiregional RaMa-Scene webtool for the circular economy [5]. Nonetheless, facile adjustability remains rare in EEIO models and tools, and no existing EEIO tool yet enables rapid scenario modeling of industrial decarbonization strategies through user-defined "what-if" queries.

In this paper, we report on a new "EEIO for Industrial Decarbonization Analysis" (EEIO-IDA) scenario modeling tool that is now under development by the U.S. Department of Energy's (DOE's) Industrial Efficiency and Decarbonization Office. This interactive, Excel-based tool is designed for rapid "what-if" analysis based on user-defined decarbonization assumptions. Grid conditions, energy use, and decarbonization technology status for individual manufacturing sectors are user-adjustable, as summarized in Table 55.1. The scenario-building dashboard in the EEIO-IDA tool is aligned with the industrial decarbonization pillars presented in the DOE *Industrial Decarbonization Roadmap* [12]. For each user scenario, CO_2-equivalent (CO_2e) greenhouse gas emissions (for each sector and for the economy overall) are automatically calculated and summary results are presented. This scenario-modeling functionality is made possible by the fuel-use vectors that comprise the basis of the underlying model dataset. Rather than deploying emissions vectors (such as CO_2 emissions by sector) as the foundational environmental impact vectors of the environmentally extended model, as EPA's USEEIO and other models do, the foundational environmental vectors in the EEIO-IDA model reflect energy consumption (electricity and fuel use) drawn from primary sources such as the U.S. Energy Information Administration (EIA) Manufacturing Energy Consumption Survey (MECS) and other sources. These fuel-use vectors are supplemented by vectors for process emissions in applicable sectors (such as nonmetallic mineral products, where cement manufacturing processes emit significant non-energy-related CO_2), to complete the foundational model accounting. Based on user scenario inputs in the tool, electricity and fuel use breakdowns by sector are automatically adjusted from the base-case (2018) data, and subsequently the emissions for each sector (CO_2, CH_4, N_2O, and fluorinated compounds) are automatically calculated based on standard emissions factors for stationary and/or mobile combustion.

Table 55.1 User-adjustable features in the scenario-building dashboard of the EEIO-IDA tool.

Dashboard element	Description of user-adjustable assumptions in EEIO-IDA tool
U.S. Electric Grid	The user can define the U.S. average electric grid makeup by specifying the fraction of electricity generated from each of the following energy sources: coal, natural gas, petroleum, nuclear, biofuels, and renewable sources other than biofuels. Eight built-in grid scenarios are provided, ranging from the current U.S. grid to a hypothetical net-zero 2050 grid. The user can select one of these scenarios or build a custom scenario.
Energy Mix	For each of the 26 industrial sectors in the model (19 manufacturing sectors plus 7 non-manufacturing industrial sectors), the user can define the energy mix by specifying the fraction of energy supplied by the following energy sources: electricity, coal, natural gas, petroleum, biofuels, and green hydrogen. Reference values for the year 2018 are provided as the default and can be retained or adjusted for each sector.
Energy Requirements	For each of the 26 industrial sectors in the model, the user can specify the total energy requirements of the sector (in trillion Btu). Reference values for the year 2018 are provided as the default and can be retained or adjusted for each sector.
Non-Energy-Related Emissions	For the 8 industrial sectors in the model with significant non-energy-related process emissions, the user can specify the total non-energy-related emissions of CO_2, CH_4, N_2O, and fluorinated compounds resulting from the industrial activity (in million metric tons). Reference values for the year 2018 are provided as the default and can be retained or adjusted for each sector.
Carbon Capture	For each of the 26 industrial sectors in the model, the user can specify the fraction of energy- related CO_2 and (for applicable sectors) the fraction of non-energy-related CO_2 captured using carbon capture, utilization, and storage (CCUS) technologies. The reference value for all sectors is zero (i.e., no carbon capture). This value can be retained or adjusted for each sector.
Waste or Demand Reduction	For each of the 26 industrial sectors in the model, plus 4 additional user-selected sectors (commercial or governmental), the user can specify a percent demand reduction. A reduction in final product demand in one sector will result in upstream impacts to supplier sectors, and this dashboard element captures those impacts. The reference value for all sectors is zero (i.e., product demand is the same as in 2018). This value can be retained or adjusted for each sector.
Biogenic Emissions	User can toggle “on” or “off” inclusion of biogenic emissions from combustion of biofuels in CO_2-equivalent greenhouse gas emissions totals.

With its scenario-building user interface and capabilities for dynamic updating of environmental impact vectors, the EEIO-IDA tool provides a unique sandbox for rapidly exploring the potential impacts of technology changes in the industrial sector. Supply and demand relationships between industrial sectors are integral to the EEIO methodology, and therefore built into the tool. This makes the EEIO-IDA tool well suited for analysis of circular economy strategies and their potential role in reducing economy-wide emissions in the United States. Case studies from the cement and automobile industries are offered as examples in this paper.

55.2 Methods

EEIO-IDA is powered by publicly available data sources for energy use, economic flows, and emissions across the U.S. economy. Table 55.2 summarizes model data sources for electricity and fuel use by sector. These data are used to calculate baseline energy-related greenhouse gas emissions (of CO_2, CH_4, and N_2O), applying standard emissions factors for stationary and mobile combustion from the Intergovernmental Panel on Climate Change (IPCC) [13]. Table 55.2 also shows the data sources for process emissions by sector, which were primarily drawn from EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks (1990-2020)* [14], with adjustments made to avoid double-counting with energy-related emissions calculated based on fuel use. Process emissions considered include CO_2, CH_4, N_2O, and fluorinated compounds. For summary reporting, greenhouse gas emissions are converted to a CO_2-equivalent value utilizing 100-year global warming potential (100-year GWP) values from IPCC's Fifth Assessment Report [15]. Equation 55.1 below shows how these data are used to calculate the emissions (e) for each industry k and greenhouse gas t.

$$e_{k,t} = C_{1,k} * \Sigma_i(f_i * x_{i,t}) + C_{2,k} * p_t \tag{55.1}$$

Here, f is the quantity of fuel i, x is the emissions factor for fuel i and greenhouse gas t pulled from the IPCC factors for stationary and mobile combustion [13], p is the process emissions of greenhouse gas t, and C_1 and C_2 are constants which are utilized in the user-defined scenarios (both equal to 1 in the base case scenario). Electricity is treated as a "fuel" in the model with a weighted-average emissions factor defined based on the assumed grid mix. All user-adjustable features (except for demand reductions, which induce a proportional decrease in the final demand vector for the selected industry) will modify portions of this equation, producing a new vector of emissions by industry to use in the EEIO calculation.

The model base year is 2018, corresponding to the most recent available EIA MECS dataset for industrial energy use [16] as well as Bureau of Economic Analysis (BEA) economic input-output data [17] for the same year. For economic data, a 2018 base year is achieved by selecting a mid-resolution representation of the overall economy (73 commodities).

Table 55.2 Data sources for electricity, fuel use, and non-energy-related emissions by sector.

Industries and corresponding NAICS codes	Data sources – electricity and fuel use	Data sources – non-energy-related emissions
Agriculture, Forestry, Fishing, and Hunting (11)	Farm Production Expenditures 2018 Summary [20]; Census of Agriculture - 2017 [21]; Census of Irrigation - 2018 [22]; Census of Horticultural Specialties - 2019 [23]; BEA - IO Tables - 2012 & 2018 [18]; EIA - Electric Power Monthly - 2020 [24]	US EPA - GHG Inventory, Chapter 5 [14]
Mining (21)	Economic Census 2017 [25]	US EPA - GHG Inventory, Chapter 3 [14]
Utilities (22)	BEA - IO Tables - 2012 & 2018 [18]; EIA - Electric Power Monthly - 2020 [24]	US EPA - GHG Inventory, Chapter 3 [14]
Construction (23)	EIA - AEO [26]	n/a
Manufacturing (31-33)	EIA - MECS 2018 [16]; ASM 2018 [27]	US EPA - GHG Inventory Chapter 4 [14]
Wholesale Trade (42)	BEA - IO Tables - 2012 & 2018 [18]; EIA - Electric Power Monthly - 2020 [24]	n/a
Retail Trade (44)	BEA - IO Tables - 2012 & 2018 [18]; EIA - Electric Power Monthly - 2020 [24]; EIA - CBECS 2018 [28] Economic Census 2017 [25]	n/a
Transportation and Warehousing, Excluding Postal Service (48, 49)	Transportation Energy Data Book [29]; BEA - IO Tables - 2012 & 2018 [18]; EIA - Electric Power Monthly - 2020 [24]; CBECS 2018 [28]	US EPA GHG Inventory Chapter 2 [14]; Alternative Fuels Data Center [33]; IPCC 2005 [34]
Other Service-Providing Industries, Except	BEA – IO Tables – 2012 & 2018 [18]; EIA – Electric Power Monthly – 2020 [24]; EIA – CBECS 2018 [28]	US EPA GHG Inventory Chapter 7 [14]; CalRecycle [35]; Bureau of Labor Statistics [36]; U.S. Census [37]
Government (51-81)		
Government (no NAICS code)	Comprehensive Annual Energy Data and Sustainability Performance [30]; Association of American Railroads, Railroad Facts [31]; EIA - CBECS 2018 [28]; FTA Annual Database Energy Consumption 2018 [32]	n/a

BEA releases input-output accounts data annually at this level of resolution.[1] In certain cases, time-based adjustments to datasets for years other than 2018 were made to project data to 2018. To do this, the project team utilized growth factors based on relevant data points from multiple years. An example of this type of growth factor is BEA's Chain Type Quantity Index [18]. Fuel usage data for some sectors were estimated based on energy purchases (of electricity, petroleum, natural gas, and coal) as specified in the Make/Use tables of BEA's 2012 benchmark dataset—following a similar methodology to that of the EIO-LCA model [19] for energy purchase allocation to sectors. These data were then projected to 2018 utilizing the Chain Type Quantity Index values for that sector. While energy consumption and fuel allocations estimated using this method are not as accurate as U.S. Energy Information Administration (EIA) or other governmental data reported explicitly for an industry, this provides a reasonable allocation strategy for those sectors for which no better data sources are available.

55.3 Results

Figure 55.1 shows model results for direct (scope 1) and indirect (scope 2 and 3) emissions for the 26 industrial sectors included in the EEIO-IDA model. The results highlight the significance of supply chains in the embodied emissions of industrial goods. For many sectors, such as the food and beverage sector and the motor vehicles sector, supply chain emissions account for a large majority of the embodied emissions. These scope-3 emissions reflect scope-1 or scope-2 emissions for other industries. For example, a large majority of the scope 3 emissions of the food and beverage and tobacco products sector (grey bar in Figure 55.1) coincide with the scope 1 and 2 emissions of the farms sector (blue bars in Figure 55.1). Importantly, scope 3 emissions should never be summed across multiple sectors due to the inherent (and purposeful) double-counting. However, this visualization of emissions-by-sector provides a valuable view into the final fate of industrial emissions as they accrue through suppy chains and ultimately become embodied into products. In particular, IO-based accounting of cumulative scope 1, 2, and 3 emissions can facilitate identification amd quantification of major industrial opportunities to reduce economy-wide emissions through demand-based strategies such as waste reduction (because such strategies have ripple effects on emissions in upstream sectors). The two case studies that follow provide examples of the impact of material efficiency strategies (reduced material requirements and improved product longevity) on the supply chain emissions of an industry or product.

[1]The current EEIO-IDA model (73 commodities) makes use of BEA's annual summary-level input/output accounts datasets. BEA's detail-level benchmark datasets (405 commodities) are released less frequently—only every five years. At the 73-sector level of resolution, most industrial sectors are represented at the level of their three-digit North American Industry Classification System (NAICS) code. Our team plans to develop a full-resolution version of EEIO-IDA (405 commodities) following the anticipated late 2023 release of the 2017 benchmark economic dataset from BEA. This level of aggregation will be consistent with EPA's USEEIO and other major EEIO models for the United States.

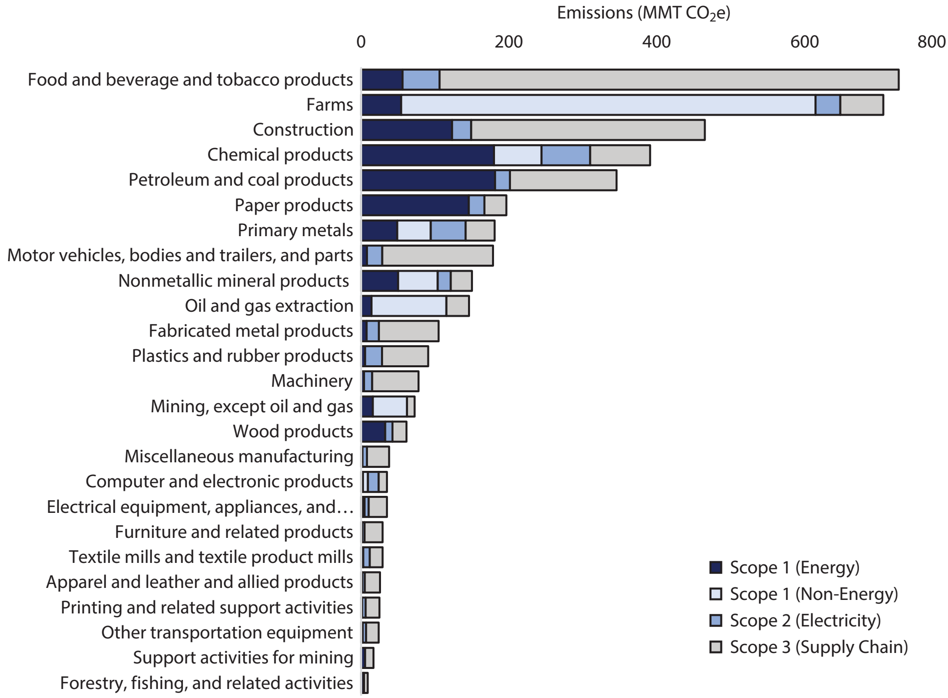

Figure 55.1 Direct sector and indirect supply chain emissions for industrial sectors for base year 2018 in million metric tons (MMT) CO_2e.

55.3.1 Case Study 1: Construction Improvements to Reduce Cement Emissions

The first case study looks at the cement industry, contained within the "nonmetallic mineral products" sector (NAICS 327) which also includes other products such as lime, glass, and clay. The cement industry is a major source of greenhouse gas emissions for the United States, producing 67 million metrics tons of CO_2e direct onsite emissions annually [38] —about 3.7% of the total U.S. industrial sector emissions [14]. Figure 55.2 shows the emissions for the entire nonmetallic mineral products sector by source. Many of the emissions in this sector are process-related (Scope 1, non-energy) and are considered difficult to abate, with most of these emissions coming from the chemical process of converting limestone ($CaCO_3$) to lime (CaO) which emits CO_2. As these emissions are inherent to the process, the only available mitigation strategies are carbon capture, alternative cement chemistries, or alternative routes to cement production [12]. These routes tend to require significant research and development (R&D) and most are capital intensive.

Another option to reduce emissions from the cement industry is to reduce the demand for cement. The EEIO-IDA tool can be utilized to understand the accrual of cement-related emissions in downstream industries. Model results indicate that 40% of the emissions from nonmetallic mineral products are embodied in the construction sector. Therefore, reducing concrete required for construction is a viable strategy for reducing cement industry emissions. Improvements in construction techniques (such as post-tensioning, precasting, and reducing overdesign) can significantly reduce cement demand while maintaining required structural properties. Estimates show a reduction of up to 50% of cement demand may be

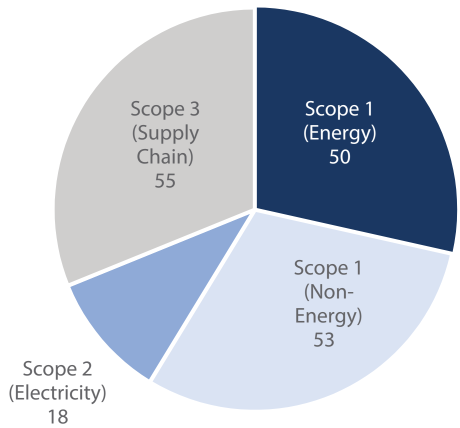

Figure 55.2 Emissions by source for the nonmetallic mineral products industry (million metric tons CO_2e) – 2018 base case.

Table 55.3 Decarbonization scenarios for nonmetallic mineral products industry.

Scenario	**Model parameters**	**Remaining emissions for nonmetallic minerals (MMT CO_2e)**	**% reduction in emissions from base case**
Base Case	• Base case, no emissions reductions	121	
Scenario #1	• 20% Reduction in demand for construction industry	110	9%
Scenario #2	• 50% Reduction in demand for construction industry	94	23%
Scenario #3	• Replacement of 30% of cement with SCM • 25% reduction in energy use for cement production • 90% carbon capture applied to cement industry • IEA's "Net Zero by 2050" electric grid 2050 scenario	41	67%
Scenario #4	• 50% reduction in demand for construction industry • Replacement of 30% of cement with SCM • 25% reduction in energy use for cement production • 90% carbon capture applied to cement industry • IEA's "Net Zero by 2050" electric grid scenario	31	74%

possible with these and other techniques [39]. In the EEIO-IDA tool, this reduction can be modeled by reducing final demand for the construction industry.

Several scenarios were evaluated and compared to the 2018 base case for these industries. The first scenario assumes a moderate increase in the usage of material-efficient construction techniques, for an overall 20% reduction in cement requirements for construction. The second is a more aggressive scenario, assuming 50% reduction. A third scenario adds other decarbonization options for the cement industry, including carbon capture (of 90% of cement industry CO_2 emissions), a net zero electric grid (following the International Energy Agency's (IEA's) "Net Zero by 2050" scenario for year 2050 [40]), replacement of 30% of current cement use with supplementary cementitious material (SCM, low carbon alternative materials such as fly ash) [41], and a 25% improvement in energy efficiency for cement production through implementation of state of the art technologies identified in the DOE Energy Bandwidth analysis for cement [42]. The last scenario combines scenarios #2 and #3.

A summary of the scenarios analyzed and the resulting emission reductions for the nonmetallic mineral products industry are shown in Table 55.3. Results show that reducing construction demand for cement can cut emissions in the nonmetallic mineral products industry by up to 23%. Many of the methods for reducing concrete requirements for construction are available now [39], making this an option for near-term emissions reductions. Material efficiency strategies can also offer cascading benefits in other upstream industries, such as truck transportation for carrying cement to construction sites, increasing impacts beyond the construction and cement industries.

55.3.2 Case Study 2: Improving Longevity of Motor Vehicles

The second case study evaluates the motor vehicles, bodies and trailers, and parts sector (also referred to as the "motor vehicle" sector in this paper for brevity). Unlike the cement sector, which is dominated by scope 1 and 2 emissions, 84% of emissions embodied in motor vehicle products are attributed to scope 3 sources in the supply chain (Figure 55.3). Figure 55.4 shows the supply chain industries that contribute most to the emissions embodied in

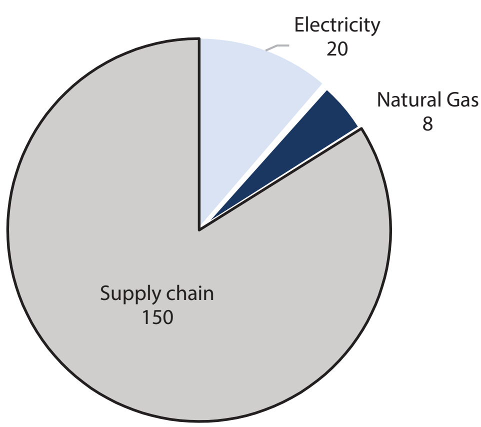

Figure 55.3 Emissions by source for the motor vehicles, bodies and trailers, and parts sector (million metric tons CO_2e) – 2018 base case.

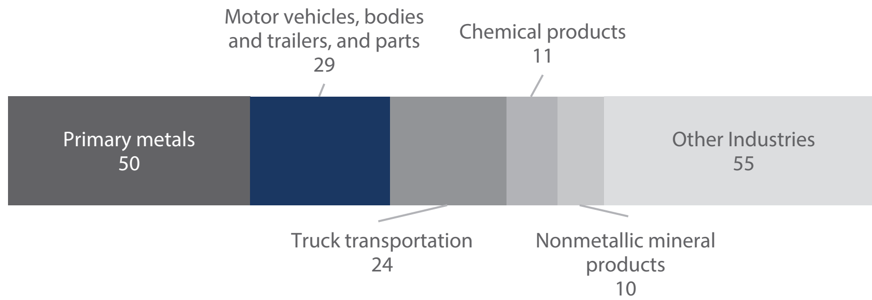

Figure 55.4 Cradle-to-Gate emissions (Scope 1, 2, &3) for the motor vehicles, bodies and trailers, and parts sector (MMT CO_2e) – 2018 base case.

motor vehicle products. As shown, the primary metals sector is the largest contributor to cradle-to-gate emissions, followed by truck transportation.

Because the embodied emissions of motor vehicles are dominated by upstream supply chain effects, there is relatively little room for reducing emissions of motor vehicles through process changes in the industry. Even switching current electricity use for the industry to 100% renewables would only reduce embodied emissions by 11%. Strategies that target the supply chain provide the best opportunity for reducing life-cycle emissions. One way to do this is by increasing the lifespan of motor vehicles to reduce demand for new vehicle production. The average age of vehicles in the U.S. in 2021 was 12 years [43], with estimates of the lifespan of these vehicles being 13-17 years [44]. The average age of the U.S. vehicle fleet has steadily increased over the years, with the average vehicle age increasing by 3 years since the year 2000 [43]. Assuming a similar average yearly increase going forward, the average age of cars would reach 14 years in 2035 and 16 years in 2050. These cases could correspond to a 14% and 25% decrease in demand for new vehicles in 2035 and 2050, respectively.

Table 55.4 shows the potential emission-reduction results for the two decreased-vehicle-demand scenarios (Scenarios #1 and #2), in addition to scenarios with additional decarbonization interventions included for comparison. Scenario #3 assumes that the electric grid follows IEA's "Net Zero by 2050" pathway using the year 2030 values [40]; that primary metals energy requirements are reduced through state-of-the-art steel and aluminum production methods [45, 46]; and that 20% of the truck transportation fleet is electrified. Scenario #4 further intensifies these decarbonization assumptions by assuming that the U.S. electric grid matches IEA's "Net Zero by 2050" grid scenario (for the year 2050); that energy requirements for primary metals are reduced through R&D to practical minimum values for steel and aluminum [45, 46]; and that 50% of the truck transportation fleet is electrified. A final scenario (#5) combines the decarbonization assumptions of Scenario #4 with a 25% reduction in motor vehicle demand.

As shown in Table 55.4, demand reduction has a significant impact on embodied emissions in motor vehicle products. A 25% reduction in product demand (Scenario #2) has a net emissions impact comparable with the multi-faceted decarbonization strategy of Scenario #3, which combines energy efficiency, grid decarbonization, and electrification interventions. While increasing longevity of vehicles alone is not sufficient to reach net zero emissions, this analysis shows the importance of circularity in an overall strategy to reach U.S goals of net zero carbon emissions by 2050.

Table 55.4 Decarbonization scenarios for the motor vehicles, bodies and trailers, and parts sector.

Scenario	Model parameters	Remaining emissions for automotive industry (MMT CO_2e)		% Reduction in emissions, scope 1, 2, & 3
		Scope 1 & 2	Scope 1, 2, & 3	
Base Case	• Base case, no emissions reductions	29	179	
Scenario #1	• 14% reduction in demand for motor vehicles	25	156	13%
Scenario #2	• 25% reduction in demand for motor vehicles	22	138	23%
Scenario #3	• Reduce energy demand for primary metals by bringing industry up to state of the art • 20% electrification of truck transportation industry • IEA's "Net Zero by 2050" electric grid year 2030 scenario	19	142	20%
Scenario #4	• Reduce energy demand for primary metals to practical minimum • 50% electrification of truck transportation industry • IEA's "Net Zero by 2050" electric grid year 2050 scenario	12	114	36%
Scenario #5	• 25% reduction in demand for motor vehicles • Reduce energy demand for primary metals to practical minimum • 50% electrification of truck transportation industry • IEA's "Net Zero by 2050" electric grid year 2050 scenario	10	88	51%

55.4 Conclusions and Recommendations

This paper highlighted the capabilities of the new EEIO-IDA tool to identify targets for reducing embodied emissions through demand reduction and material efficiency strategies, using cement and automobile production industries as examples. EEIO-IDA is a unique tool for rapid quantification and comparison of decarbonization opportunities in the U.S. industrial sector. The authors plan to make the present (73-sector) version of the

EEIO-IDA tool available to the public in 2023 for review and use by the community. This tool can help inform decision-makers on the strategies likely to yield the greatest potential emissions reductions—and the scale of implementation required to reach net-zero. Modeled scenario results reflect "big picture" estimated outcomes and can be combined with technology deep-dives to explore the practical opportunities for decarbonization at a more granular level. The case studies presented illustrate the flexibility of the model in handling various decarbonization assumptions. The 2018 model base year of EEIO-IDA provides greater data recency than existing U.S.-focused EEIO models with a 2012 base year (an important attribute for industries and energy systems that are rapidly changing). While a recycling module is not yet available in the tool, researchers have used EEIO modeling previously to evaluate such scenarios [47], and this tool can be modified in the future to include these capabilities. Future updates to the tool are also expected to include an expansion to the 405-sector level once BEA releases the 2017 benchmark input-output data set, expected in late 2023. This update will address the broad sector definitions that represent one of the key limitations of the mid-resolution (73-sector) version of the EEIO-IDA tool, which is the assumption of homogeneity in industries that manufacture diverse products (in terms of economic value and environmental impact) in practice.

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