Categorization of Scope 3 Emissions for Streamlined Enterprise Carbon Footprinting

Y. ANNY HUANG,*
CHRISTOPHER L. WEBER, AND
H. SCOTT MATTHEWS

Department of Engineering & Public Policy and Department of Civil & Environmental Engineering, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213

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Many organizations look to carbon footprint protocols for guidance on measuring their greenhouse gas emissions, or *carbon footprint*. Existing protocols generally require estimation of direct emissions (Scope 1) and emissions from direct purchases of energy (Scope 2), but focus less on indirect emissions upstream and downstream of the supply chain (optional Scope 3). Because on average more than 75% of an industry sector's carbon footprint is attributed to Scope 3 sources, better knowledge of Scope 3 footprints can help organizations pursue emissions mitigation projects not just within their own plants but also across their supply chain. In this work, Scope 3 footprints of U.S. economic sectors are categorized using an Economic Input—Output Life Cycle Assessment (EIO-LCA) model to identify upstream emission sources that are likely to contribute significantly to different sectors' footprints. The portions of the upstream footprint captured by the sector's top-10 upstream suppliers are estimated at 3 different levels of specificity: general economy-wide, industry specific, and sector specific. The results show that enterprises can capture a large portion of their total upstream carbon footprint by collecting full emissions information from only a handful of direct suppliers, and Scope 3 footprint capture rates can be improved considerably by sector-specific categorization. Employee commuting and air transportation may be more important (7%—30%) for the services industries, but should not be a focus of detailed Scope 3 footprint estimates for the manufacturing industries (<1% of the total analyzed footprint). Protocol organizations should actively make more specific Scope 3 guidelines available for their constituents by developing sector-specific categorizations for as many sectors as they feasibly can and create broader industry-specific protocols for others.

Introduction

As the effects of climate change are becoming more pronounced in recent years, governments, corporations, and individuals alike are becoming more concerned with the contributions of their own activities to climate change. Many are engaging in discussions on managing climate change and measuring their "carbon footprint", or greenhouse gas (GHG) emissions resulting from products or activities, to identify strategies to reduce their climate impacts. For guidance in how to prepare their footprint inventories, these groups look to existing carbon footprint protocols including the GHG Protocol from the World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) (*1*), the General Reporting Protocol and sector-specific protocols from The Climate Registry (*2*), ISO 14064 from the International Organization for Standardization (*3*), PAS 2050 from the British Standards Institute (*4*), and the International Local Government GHG Emissions Analysis Protocol from the International Council on Local Government for Sustainability (*5*).

These existing protocols vary in scope, but generally require reporting of emissions from sources under the company's direct control ("Scope 1") and emissions from direct purchased energy ("Scope 2"), with less focus on indirect emissions upstream and downstream in the company's value chain (optional "Scope 3"). For most business sectors—with the exception of a few sectors with large and well-known GHG emissions like power generation, transportation suppliers, and cement manufacturing—carbon footprints from direct emissions and purchased energy use have been shown to be a small portion of the total carbon footprint (*6*). Previous estimates have indicated that on average, Scope 1 emissions from an industry are only 14% of the total upstream supply chain carbon emissions, and the sum of emissions from Scopes 1 and 2, on average, only 26% of total upstream supply chain emissions (*6*), leaving a significant portion of the supply chain emissions in the nonmandatory "Scope 3" category, which combines all non-Scope 1 and 2 sources of emissions. Currently companies can choose to voluntarily disclose Scope 3 emissions, but they do not have much guidance or framework for doing so, and the resulting Scope 3 disclosures are not necessarily consistent or comparable between companies even in the same sector. Although Scope 3 emissions are widely known to be important, they are rarely estimated because they are not well understood, and there is little motivation or technical capacity to do so in current carbon footprint protocols.

Due to this omission, decision-makers may be lulled by existing protocols into assumptions that carbon legislation will mean little to them if they are not aware of the effect supply chain emissions will have on their input prices or how consumer preferences may change in favor of low-carbon and energy-efficient goods (i.e., so-called carbon risk assessment). Better informing and estimating the process of Scope 3 supply chain footprint information can help firms pursue emissions mitigation projects both within their own plants and also across their supply chain. As companies can often influence their suppliers, a broader estimation can similarly motivate more effective corporate climate change policies.

For the reasons stated above, protocol organizations (which we define as groups that are developing carbon footprint protocols, including standard-setting bodies that are developing guidance for carbon footprint analysis) have recognized the importance of Scope 3 emissions and are in the process of developing better Scope 3 guidelines for their constituents. Currently, a major focus is to identify Scope 3 categories that are relevant and should be included in footprint analysis. However, for protocol organizations to provide more comprehensive guidelines to firms, governments, and institutions conducting footprint analyses ("footprinting enterprises"), and to achieve reductions, further characterization of Scope 3 emissions is necessary. Fortu-

* Corresponding author e-mail: yah@alumni.cmu.edu; phone: (630)303-1468.

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nately, such knowledge already exists within the Life Cycle Assessment (LCA) community (*7*), many of whose members are involved with current protocol development. Two types of LCA exist: process-based and economic input–output (IO) approaches, and the data from each type of model will form the basis of complex and uncertain Scope 3 footprints (*8, 9*). The advantages and disadvantages of each have been well-documented (*8, 9*). Process LCA models are generally more precise but also more time-consuming due to difficulty in obtaining detailed inventory data (*10–12*), while IO models are efficient and eliminate cutoff error while introducing significant aggregation errors and uncertainties related to prices.

For reasons of practicality there is an inherent trade-off between how much primary data (i.e., measured as opposed to modeled) any enterprise can collect and what portion of their footprint this amount of data will capture (*9*). Thus scoping assessments using generic sector-level data (such as is available from IO-LCA models) are invaluable to helping organizations determine where the "hot spots" in their supply chains are to invest precious data collection resources. Such scoping is not only possible, but is consistent and time-efficient using IO-LCA methods (*13, 14*).

In this work we characterize the Scope 3 footprints of U.S. economic sectors using a modified form of the 2002 US benchmark Economic Input–Output Life Cycle Assessment (EIO-LCA) model developed by Carnegie Mellon University (*13, 15*). The EIO-LCA model uses relatively recent and detailed economic IO data derived from the Bureau of Economic Analysis (BEA) and publicly available environmental data from governmental agencies such as the U.S. Environmental Protection Agency (EPA) and the Department of Energy (DOE). It captures the entire upstream supply chain, and is capable of evaluating economic and environmental impacts for any of 426 sectors in the U.S. economy (*13, 16–18*), providing a fast and consistent way to perform scoping analysis for a large number of sectors simultaneously. Of course, such sector averages will not be representative for every enterprise, but for many companies, communities, and projects, they can provide an efficient and consistent method to estimate supply chain emissions before undertaking more complex efforts.

The goal of this work is to categorize upstream emission sources to identify the significant Scope 3 categories (industry or sector) that should be included in Scope 3 footprint guidelines. Because there currently is no established method or accounting framework for downstream emissions, and protocol organizations are still discussing the question of what downstream emission sources are considered parts of an intermediate sector's footprint, this work only focuses on upstream Scope 3 footprint of enterprises (and not of products). Moreover, although we recognize that the singular focus on GHG emissions can be misleading in holistic environmental management decision making, because currently there are only protocols and standards written for GHG, this work focuses on GHG emissions to demonstrate the analysis framework.

By pursuing this goal, our findings can help protocol organizations provide relevant and effective guidelines for conducting Scope 3 footprints and to help footprinting enterprises efficiently focus their GHG reduction efforts on the important parts of their supply chain. A specific focus is on whether it would be better for protocol organizations to compile a single aggregate list of Scope 3 emissions sources for all enterprises to include or compile sector-specific lists. In addition, our findings demonstrate that a large portion of the Scope 3 footprint can be captured by including only a handful of suppliers, help the community see the variations in capture rates among the different industries, and demonstrate the value of increasing specificity in Scope 3 footprint guidelines so protocol organizations are encouraged to develop guidelines as specific to industries and sectors as they feasibly can. The following section details our method, followed by observed results, and a discussion of significant implications.

Methods

Economic Input–Output Life Cycle Assessment. This section provides a brief overview of the methods pertinent to the results and discussion presented in later sections. These methods have been described previously in Huang et al. 2009 (*19*) and Matthews et al. 2008 (*6*). A more detailed summary of the IO methods and the EIO-LCA model can also be found in Supporting Information (SI)-A.

Economic IO models were first developed by Leontief in 1936 (*20*) to aid manufacturing planning. Using linear algebra common in the economics literature (*13*), the models estimate all purchases and activities in a supply chain leading up to final manufacture in an industry. When the economic IO model is augmented with environmental information in matrix form, it estimates upstream life cycle environmental impacts of production activities by any sector in the economy. The basic IO model derives the total economic purchases (i.e., supply chain) across an economy required to make a desired output. Once the supply chain is calculated, environmental emissions can be estimated by multiplying the output of each sector by its environmental impact per dollar of output:

$$\mathbf{b_i} = \mathbf{R_i}(\mathbf{I} + \mathbf{A} + \mathbf{AA} + \mathbf{AAA} + ...)\mathbf{y} = \mathbf{R_i}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \quad (1)$$

where $\mathbf{b_i}$ is the vector of environmental burdens (such as GHG emissions for each production sector), $\mathbf{R_i}$ is a matrix with diagonal elements representing the emissions per dollar of output for each sector, $\mathbf{I}$ is the identity matrix (a table of all zeros except for the diagonal entries containing a 1), $\mathbf{A}$ is the direct requirements matrix (with rows representing the required inputs from other sectors to make a unit of output), and $\mathbf{y}$ is the vector of desired production or "final demand." Terms in eq 1 represent the production of the desired output itself ($\mathbf{I} \times \mathbf{y}$), contributions from the direct or first level ("tier-1") suppliers ($\mathbf{A} \times \mathbf{y}$), those from the second level ("tier-2") indirect suppliers ($\mathbf{A} \times \mathbf{A} \times \mathbf{y}$), and so on. Direct emissions from a sector (i.e., Scope 1), including on-site emissions from activities like natural gas or petroleum combustion, and indirect emissions (Scopes 2 and 3) upstream of a sector can be calculated using modified forms of eq 1 by selectively including certain terms from the equation and certain elements in the $\mathbf{A}$ matrix (*6*). This is described in more detail in SI-A.

Sub-Total Supply Chain Emissions. The sectoral emissions calculated using eq 1 give the sum of emissions occurring at the supplier sector across all levels of the supply chain, but they do not shed light on the emissions embedded upstream of those specific suppliers. In this work, we denote the portion of the total supply chain embedded upstream of a specific supplier, including the supplier itself, "sub-total supply chain" (STSC). For example, the STSC of an electricity provider would include the emissions from generating the power as well as mining and transportation of coal upstream of it. Because a purchaser may have more influence with a direct supplier than an indirect one, knowledge of STSC impacts will help footprinting enterprises understand which of their direct suppliers contribute most to their total footprint. Moreover, estimation of STSC footprints of suppliers is useful for understanding the life cycle benefit of reducing consumption and use of certain inputs or materials. For example, if a firm reduces its overall electricity consumption by making its process more efficient, a reduction in direct purchased electricity means that there are also

TABLE 1. Summary of Industries

industry	abbreviation	NAICS	number of IO sectors included
Agriculture	Ag	11	19
Mining	Mine	21	11
Power Generation	Power	2211	3
Food, Beverage, & Tobacco	Food	311−312	34
Textile, Apparels, & Shoes	App	313−316	20
Forest Products & Printing	For	321−323	20
Petroleum & Basic Chemicals	Petro	324−3253	17
Chemical Products & Drugs	Chem	3254−3259	10
Plastics & Rubber	Plas	326	11
Non-Metallic Minerals	Min	327	17
Metals	Met	331	11
Fabricated Metal	F. Met	332	22
Machinery Manufacturing	Mach	333	31
Electronics & Electrical Equipment	EE	334−335	42
Transportation Vehicle & Equipment	Veh	336	19
Other Manufacturing	O. Mfg	337−339	25
Transportation	Transp	48−49	9
Wholesale, Retail, & Warehousing	Wh/R	42, 44, 45	3
Information, Financial, Insurance, Real Estate	IFIR	51−53	26
Professional Services	Prof	54−56	24
Education	Edu	61	3
Healthcare & Social Assistance	Health	62	8
Entertainment	Enter	71−72	12
Other Services	O. Srv	811−813	13

impact reductions in the supply chain upstream of the power generation suppliers. To isolate the STSC contributions of tier-1 suppliers from the perspective of final producer sectors and estimate the STSC impacts of tier-1 suppliers for every producing industries in the economy, eq 1 is modified as follows:

$$\mathbf{B_i} = <\mathbf{r_i}(\mathbf{I} - \mathbf{A})^{-1}> \times \mathbf{A} \qquad (2)$$

where $\mathbf{B_i}$ is the matrix of environmental burdens, $\mathbf{r_i}$ is a single-row matrix containing the emissions per dollar output for each final producing industry for pollutant i, and the term $<\mathbf{r_i}(\mathbf{I} - \mathbf{A})^{-1}>$ denotes the diagonalization of $\mathbf{r_i}(\mathbf{I} - \mathbf{A})^{-1}$. See SI-A for a detailed description of the derivation.

Employee Travel. A key focus of current Scope 3 efforts is to determine how to provide more guidance and to break out the most important upstream activities. Employee business travel and commuting are often mentioned in these discussions. Emissions from the transportation of their employees, both for business travel and commuting, is of particular interest to companies conducting footprint analyses because it is relatively easy to quantify with local data sources, it can be done without significant effort in data collection from suppliers, and companies can directly influence employee travel by implementing certain company policies or changing the ways business is done to require less travel (e.g., make more use of teleconferencing, telework, or ride-share programs). Many member companies of the Carbon Disclosure Project have chosen to voluntarily include employee transportation in their reporting (*21*).

In the EIO-LCA model, employee business travel is already accounted for under purchases from the transportation supplier sectors, but in the basic IO account, differentiations between passenger and freight transportation are not made. Employee commuting is not a part of most LCA models because it is accounted for in household energy use and not corporate energy use. However, because it is of considerable interest to protocol organizations and footprinting enterprises, we estimated employee travel emissions and incorporated them into the model for this scoping study. Further description of the estimation methods for employee travel can be found in SI-A.

Results

Using the modeling techniques described above, we categorized the largest contributors to upstream Scope 3 footprints for each of the 426 sectors of the U.S. economy in 2002. The total analyzed footprint (TAF) in this study includes emissions from Scopes 1 and 2, upstream Scope 3, and employee commuting. In this section, a high-level, economy-wide overview of the results is introduced, followed by presentations of results aggregated into industry groups and a discussion of increasing specificity in Scope 3 categories. Because 426 detailed sectors in the U.S. economy are too numerous to show and analyze individually, detailed sectors are grouped into 24 industry groups (Table 1) based on similarity in their upstream footprint profile and their North American Industrial Classification System (NAICS) industry code. Sector aggregation uncertainties are discussed further in the uncertainty section. Because protocol organizations are likely to develop "sector-specific protocols" for a few well-known carbon intensive sectors like power generation and cement manufacturing, but (due to resource constraints) create more general "industry-specific protocols" listing mandatory Scope 3 reporting categories for other less carbon intensive sectors based on their industry classifications, reviewing the results at the 24 industries level is appropriate for informing protocol design.

General Economy-Wide Characterization. Using eq 2, the STSC impacts of tier-1 suppliers for all 426 $\times$ 426 combinations of supplier−producer pairs are estimated. If organizations were to collect GHG emissions data from every tier-1 supplier in their value chain (across hundreds of sectors and/or companies), they would have to spend an impractical amount of time and resources in working with all these suppliers for data. A better goal would be for footprinting efforts to focus on the relevant suppliers whose STSC emissions contribute most significantly to an industry's total footprint. For each sector, the top 10 tier-1 suppliers are identified and ranked on a STSC basis. (The choice of 10 is meant to provide a round number for a consistent comparison across all sectors in this analysis, and is admittedly arbitrary. Increasing the number of top suppliers to be examined will increase the portion of carbon footprint captured, and this is discussed further in SI-B.) If a supplier

TABLE 2. General Economy-Wide Top Suppliers List

top supplier sectors by STSC	% portion of TAF captured		number of appearances in top-10 lists	
	rank[a]	% mean (range[b])	% appearances[c]	rank
Iron and steel mills	1	5.2 (0, 19.4)	27%	3
Truck transportation	2	2.1 (0.6, 3.7)	60%	2
Petroleum refineries	3	1.9 (0.1, 3.8)	25%	4
Plastics material and resin manufacturing	4	1.6 (0, 4.3)	17%	9
Other basic organic chemical manufacturing	5	1.4 (0, 2.9)	18%	8
Wholesale trade	6	1.2 (0.2, 2.3)	20%	6
Real estate	7	1.1 (0, 3.6)	22%	5
Motor vehicle parts manufacturing	8	1 (0, 1.2)	8%	23
Other plastics product manufacturing	9	0.9 (0, 2.7)	16%	11
Grain farming	10	0.9 (0, 0)	7%	27
Alumina refining and primary aluminum production	11	0.9 (0, 2.1)	10%	18
Paperboard container manufacturing	12	0.9 (0, 2.5)	16%	10
Air transportation	13	0.9 (0.1, 2.2)	13%	13
Scope 3 portion of tier-1 power generation and supply	14	0.8 (0.2, 1.5)	15%	12
Plastics packaging materials, film and sheet	15	0.8 (0, 2.2)	12%	16
Natural gas distribution	17	0.8 (0.2, 1.7)	19%	7
Paperboard Mills	19	0.7 (0, 0.8)	6%	29
Animal (except poultry) slaughtering and processing	20	0.7 (0, 0.6)	7%	25

[a] The ranking shown in this table does not include emissions released directly from tier-1 power generation suppliers because it is designated as Scope 2, but the Scope 3 portion of tier-1 power generation sector (indirect emissions upstream of power generation, e.g. coal mining and coal transportation) is included. See SI-C for a list including the Scope 2 portion of power generation sector but sorted by frequency of appearances in top-10 lists. [b] Range indicates 10th and 90th percentile values, respectively. [c] This column indicates the percentage of respective supplier sector's appearances in the top-10 lists of all 426 sectors. The maximum number of top-10 list appearances is 426 because there are 426 sectors and each has a unique top-10 list. For example, truck transportation appears in 257 of 426 top-10 lists, or 60% of all sectors.

sector frequently appears on the "top-10 list" of the 426 sectors, it is an indication that the supplier sector is both ubiquitous and also likely more GHG-intensive than other supplier sectors, hence making it a good candidate for explicit recognition in a general Scope 3 protocol. Table 2 shows the average portion of TAF captured by each top supplier sector's STSC when averaged across all 426 sectors in the economy and the frequency of their appearances in the top-10 supplier list of those 426 sectors.

As shown in Table 2, emissions from truck transportation appear in the top-10 list for 2/3 of all sectors in the economy and rank second in average portion of footprint captured, which indicates its general importance in Scope 3 footprint evaluation. Iron and steel mills ranks first in portion of TAF captured, with an economy-wide average of 5%, but it appears in only a third of all the sectors' top-10 lists. This implies that the embodied carbon footprint in input iron and steel materials is relatively high, but this category is not as ubiquitous as truck transportation. (The model excludes embedded capital stocks of any types, e.g., iron or steel in a factory built years ago.) Similarly, emissions from petroleum refineries rank third in average portion of footprint captured, but it only appears in the top-10 list of a quarter of all sectors. This indicates that including the production of petroleum fuels in the Scope 3 footprint estimate will be sensible for some sectors, but may not be the most effective Scope 3 category to pursue generally for other sectors, especially if footprint enterprises need to be selective in Scope 3 footprint estimation under resource constraints. Even less ubiquitous are motor vehicle parts manufacturing and grain farming, ranking eighth and tenth in the portion of footprint captured when averaged across the economy, but playing an important role in less than 10% of all the top-10 lists.

Not shown by design in Table 2 is the power generation sector, which is the most ubiquitous and GHG-intensive supplier sector, appearing in 97% of all the top-10 lists, and responsible for a quarter of TAF on average. This is evidence that designating direct purchased electricity as Scope 2 is prudent in prioritizing indirect carbon footprint. Shown in the table are estimates of the Scope 3 portion of the STSC emissions of the tier-1 power generation sector (i.e., emissions upstream of tier-1 power generation, e.g. coal mining and coal transportation); the emissions released directly from the tier-1 power generation supplier are covered in Scope 2, which are deliberately taken out of Table 2. See SI-C for a similar list including the entire emissions of the power generation sector in the ranking. A review of the top suppliers in Table 2 shows that for the purpose of a "general protocol," there are a handful of suppliers that are useful to include in a general Scope 3 footprint for many different types of businesses, e.g., iron and steel, petroleum fuel production, truck transportation, plastics, and chemicals. However, because each sector's upstream Scope 3 profile is inherently different, a general guideline containing these categories would only be applicable to some types of businesses, as discussed below.

Industry-Specific Characterization. To identify the potential upstream Scope 3 categories for informing the design of "industry-specific protocols," the top-10 supplier analysis described above is applied to the 24 industry groups in Table 1. In this case, the portion of TAF captured by each supplier sector is averaged across all the sectors belonging to the given industry group. The average portion captured is then ranked to identify the top-10 suppliers for that industry. Similarly, a supplier that ranks high in average portion captured indicates that it is likely GHG-intensive, but it does not necessarily mean that it will be relevant for all sectors in that industry group, because each sector may have a unique Scope 3 profile and this may be an effect of sector aggregation. In practice, protocol organizations will need to fine-tune industry classifications as well as the recommended top supplier list to minimize such inefficiency. Furthermore, many supplier companies may fall into the same supplier sector classification; therefore, the actual number of suppliers that a footprinting entity needs to work with may be greater than the number of sectors shown in this scoping analysis. A complete list of top-10 suppliers, chosen on the basis of average portion of footprint captured, for each industry group is included in SI-D. The footprint portions captured by these top-10 suppliers are summarized graphically in Figure 1,

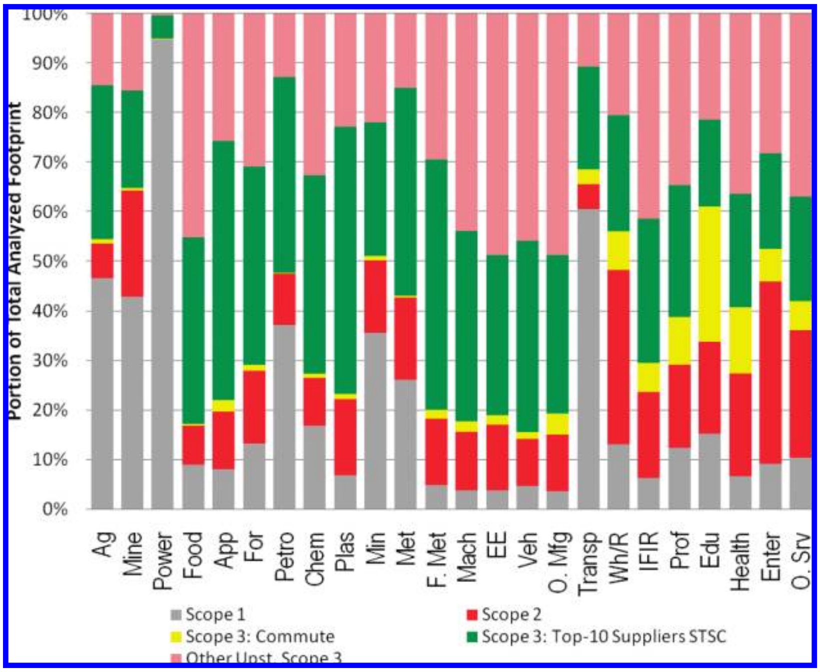

FIGURE 1. Portions of total analyzed footprint consisting of Scopes 1, 2, and 3, including industry-specific top-10 suppliers and employee commute. The key for the categories in *x*-axis can be found in Table 1.

along with the footprint portions attributed to Scope 1, Scope 2, and employee commuting.

As can be seen in Figure 1, upstream Scope 3 emissions are responsible for 70%−80% of TAF for most manufacturing industries, and a significant portion of the upstream Scope 3 footprint can be attributed to the STSC emissions of top-10 suppliers. For the manufacturing industries, approximately 50%−70% of their total upstream Scope 3 footprint can be traced to their industry's top-10 suppliers. This has significant implication for Scope 3 protocol development. If manufacturing companies are to follow an "industry-specific protocol" which includes a recommended list of the top suppliers informed by this type of analysis, they would likely be able to capture 60%−90% of their TAF with data support from their upstream suppliers (assuming either full Scopes 1−3 accounting for suppliers or a hybrid approach of supplier scope 1 and 2 reporting and scope 3 estimated). Similarly, for the services industries (e.g., banks, consulting companies, schools, hospitals, nursing homes, etc.), including employee commuting and top-10 suppliers in their footprint estimate would lead to capturing 70%−80% of the TAF. These results demonstrate that guidelines for Scope 3 footprint estimation can benefit considerably when protocol organizations invest the resources to develop industry-specific protocols that include customized lists of upstream Scope 3 categories for each type of industry. Including relevant Scope 3 categories in protocol guidelines will assist companies in identifying the most relevant indirect emissions to pursue in their carbon footprint and reduction efforts.

Our results show that STSC emissions of the tier-1 transportation suppliers (which include freight and passenger transport by truck, rail, water, and air) generally contribute to less than 5% of TAF, and this is graphically illustrated in SI-E. Although air business travel is a footprint category of interest to many footprinting enterprises, our estimates revealed that air transportation is responsible for less than 1% of TAF for 95% of all the sectors in the economy, and its contribution is even smaller for the manufacturing sectors, implying that air transportation emissions should be a focus of only a few sector's detailed footprinting efforts. Employee commuting also contributes little to the manufacturing sectors' footprint, but its contribution can be more significant (7%−30%) for the service sectors. These results show that even if an enterprise includes upstream transportation suppliers and employee travel in its Scope 3 footprint, there is still a significant portion of the upstream Scope 3 footprint yet to be quantified.

Sector-Specific Characterization. Clearly, estimating upstream Scope 3 emissions with industry-specific Scope 3 guidelines is an improvement from using an economy-wide general guideline in terms of the portion of upstream Scope 3 footprint captured. However, in reality, each detailed business type, and in actuality each company, has a unique Scope 3 profile, and there are probably some important Scope 3 categories that are unique to each sector that are not explicitly identified in industry-specific guidelines. In a perfect world, if a footprinting enterprise has the foresight of knowing which upstream Scope 3 categories contribute most to its total footprint, and thus focuses its footprint efforts only on those relevant suppliers that matter the most, it would be able to most efficiently capture the largest portion of its upstream Scope 3 footprint using the least amount of resources.

To gain an understanding of how footprint capture rate can be improved by increasing specificity in Scope 3 category guidelines, we identified the top-10 suppliers for each of the 426 sectors based on the portions of TAF attributed to the STSC of these suppliers. The sum of STSC footprints for each set of *sector-specific* top-10 suppliers is then compared with the sum of STSC footprint obtained from the *industry-specific* top-10 list and the generic economy-wide top-10 list. Although results are available for 426 sectors in the economy, they are too numerous to show at once; therefore, the comparison is again grouped into 24 industry groups for presentation in this paper. In Figure 2, the portion of upstream Scope 3 footprint captured by a general economy-wide top-10 supplier list is represented as the bottom bar. The *additional* capture achieved by using *industry-specific* top-10 lists (as represented by our aggregation of 24 industries specified in Table 1) is shown as the middle second bar, and the *additional* capture achieved by using *sector-specific* top-10 lists is represented by the top bar. In other words, the total portion of upstream Scope 3 footprint captured using the sector-specific list is the sum of the quantities represented by all 3 bars.

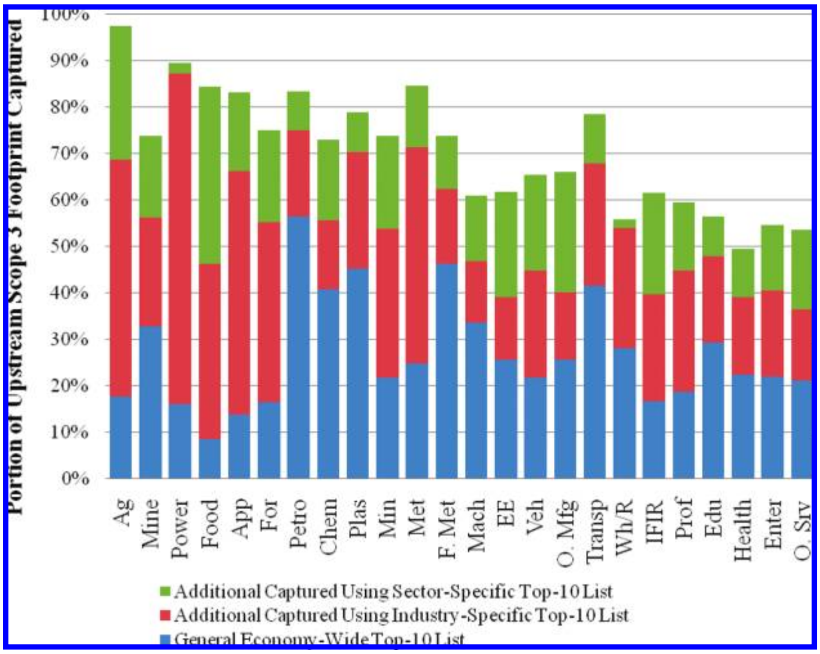

FIGURE 2. Portion of footprint capture with increasing Scope 3 category customization. The capture rates can be significantly improved by using industry-specific top-10 list instead of a general top-10 list. The improvement is even greater when using sector-specific top-10 list. The key for the categories in *x*-axis can be found in Table 1.

The results show that a footprint estimate guided by the general top-10 list produces highly variable capture rates, ranging from just under 10% for Food to more than 50% for Petroleum. When the footprint estimate is guided by more informative industry-specific top-10 lists, 40%−70% of the total upstream Scope 3 footprint can be captured for most industries. If footprinting enterprises have the foresight of knowing which suppliers are the largest contributors to the total footprint of a typical company in its specific sector class, manufacturing sectors can expect to capture up to 90% of their total upstream Scope 3 footprint, while service sectors can expect to capture 50%−60%, without investing impractical resources and efforts to collect footprint information from hundreds or thousands of suppliers and still not achieving the same footprint capture rate. These results demonstrate that although sectors in the same industry group may display certain similarities in their Scope 3 footprint profiles, because each sector's Scope 3 footprint profile is inherently unique, footprinting enterprises will be able to more efficiently estimate their footprints if detailed sector-specific Scope 3 guidelines are available in protocols. Protocol organizations should actively develop Scope 3 guidelines as specific to each industry/sector as they feasibly can. The results produced from the type of IO-LCA analysis in this work are especially useful for informing Scope 3 protocol development.

Discussion

Uncertainties. As with any calculation based on IO-LCA methods, this method has substantial uncertainties related to sectoral aggregation; price, temporal, and spatial variation; and several other issues, as discussed elsewhere (*9, 13, 22*). Since discussions of uncertainties inherent in IO-LCA can be found in other literature, and they are not unique to the approach used in this work, this section will focus on the type of uncertainty particularly relevant to application of these findings to carbon footprint protocol design: sector aggregation uncertainties.

Sector aggregation occurs when technically and environmentally distinct operations are combined into larger groups to form a sector or groups of sectors (*22*). In the basic IO framework on which our methods are based, sector aggregation is decided by the BEA in compiling IO tables from survey data. In most cases, more detailed disaggregated IO data are not publicly available. Working with each sector's environmental intensity information faces similar challenges. Because original environmental or energy consumption data sources may be organized by different industry classification systems (e.g., NAICS), bridging them with IO sector classification system inevitably results in losing information about more detailed sectors, and in some cases, introduces additional uncertainties from disaggregation of sectors. Even if sector aggregation is not the most significant issue, the environmental intensity information used in the model represents a national average of all the companies in the sector. It does not account for the variability in different companies' actual environmental intensity. For example, the carbon intensity of electricity production can vary significantly depending on the geographic region and the respective energy generation portfolio for the electricity grid. Under a certain sector aggregation scheme, aggregation errors may vary substantially depending on the sector or product considered (*22*). Using data specific to the footprinting entity will produce more accurate footprint results, though allocation issues can confound even such specific data, as discussed in ref *1*.

At the 426 sector level, the results produced by our IO model are subject to the typical aggregation uncertainties mentioned above. However, when performing analyses using 24 industry groups to inform industry-specific protocols or when grouping 426 distinct sets of analysis results into 24 industries for legible presentation of results, an additional layer of uncertainty is introduced. Graphical illustration of these sector aggregation uncertainties can be found in SI-B and -E. Using footprint contributions from transportation suppliers as an example (Figure SI-3), it is found that the portion of footprint captured by direct transportation suppliers displays large variations among the detailed sectors within the same industry, with half of the 24 industries having coefficient of variance (COV) greater than 0.5. Figure SI-1 shows the average, standard deviation, and range of footprint captured using industry-specific top-10 suppliers lists as they are applied to each sector in the given industry.

When developing industry-specific Scope 3 guidelines, protocol organizations should keep in mind the effects of sector aggregation on the performance (amount of footprint capture) of carbon footprint estimates. Because every sector's Scope 3 footprint profile is unique (and the same thing can be said about an individual company's Scope 3 profile not being exactly the same as the other companies within the same sector), footprinting enterprises following the same footprint standard may produce different levels of footprint capture.

Implications for Footprint Protocol Design. This research utilizes IO-LCA methods to analyze supply chains of sectors and industries for informing development of Scope 3 carbon footprint guidelines. The results show that direct upstream transportation suppliers are responsible for less than 5% of TAF. Employee commuting and air transportation may be more important (7%−30% of TAF) for the service industries, but they make up a negligible portion (<1%) for the manufacturing industries. Thus, protocol design must look beyond the easily measured sources of Scope 3 emissions such as employee travel and commuting if footprinting enterprises want to identify the most effective areas for potential footprint reduction.

Reviews of subtotal supply chain impacts in each sector's value chain show that footprinting enterprises can efficiently capture a large portion of their total upstream footprint by modeling and/or collecting emission information from only a handful of Scope 3 emissions sources. In some cases, of course, collecting data will be more helpful (i.e., where Scope 1 and 2 represent a large portion of the supplier's TAF, as in iron and steel and truck transport) than in others. Using 10 top upstream suppliers in the analysis, we found that Scope 3 guidelines can be considerably improved by increasing the level of protocol customization based on the types of industry or sector. A Scope 3 footprint estimate guided by a "general protocol" will likely produce small and variable capture rates (9%−55% of the total upstream Scope 3 footprint), depending on the type of industry. Using slightly more customized "industry-specific" guidelines, in which footprinting enterprises are provided lists of upstream suppliers that are important for their industry, footprint capture rate can be improved to 40%−80% of the total upstream Scope 3 footprint (when including Scopes 1 and 2 portions in the quantification, this is achieving a total capture rate of 50%−90% of TAF). However, because each sector's Scope 3 footprint profile is unique, if footprinting enterprises have the foresight of knowing which suppliers matter the most for its sector class in contributing to their total carbon footprint, they can efficiently capture the largest amount of their total footprint while investing the least amount of resources dedicated to footprint effort by using "sector-specific" Scope 3 guidelines. We found that using a sector-specific approach, a substantial majority (50%−95%) of the total upstream Scope 3 footprint can be captured by the STSC emissions of only 10 top supplier sectors. These findings are significant as increasingly more specific Scope 3 guidelines are valuable in terms of making the footprint process more efficient for the footprinting enterprises, and they also enable better performance of footprint estimate.

Given that upstream Scope 3 footprint generally is considerably larger than Scopes 1 and 2 combined, we recommend protocol organizations to actively make more specific Scope 3 guidelines available for their constituents by developing sector-specific protocols for as many carbon intensive sectors as they feasibly can and create broader industry-specific protocols for other relatively less carbon intensive sectors. The IO-LCA approach introduced in this work provides an informative first step in the Scope 3 guideline development. Furthermore, to fully consider an enterprise's total life cycle environmental implications, including downstream carbon footprint and other impact categories, more future work is needed to address these issues.

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Supporting Information Available

Detailed description of the methods, transportation mode results and uncertainties, discussion on the number of top suppliers, and industry specific top suppliers list. This material is available free of charge via the Internet at http://pubs.acs.org.

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