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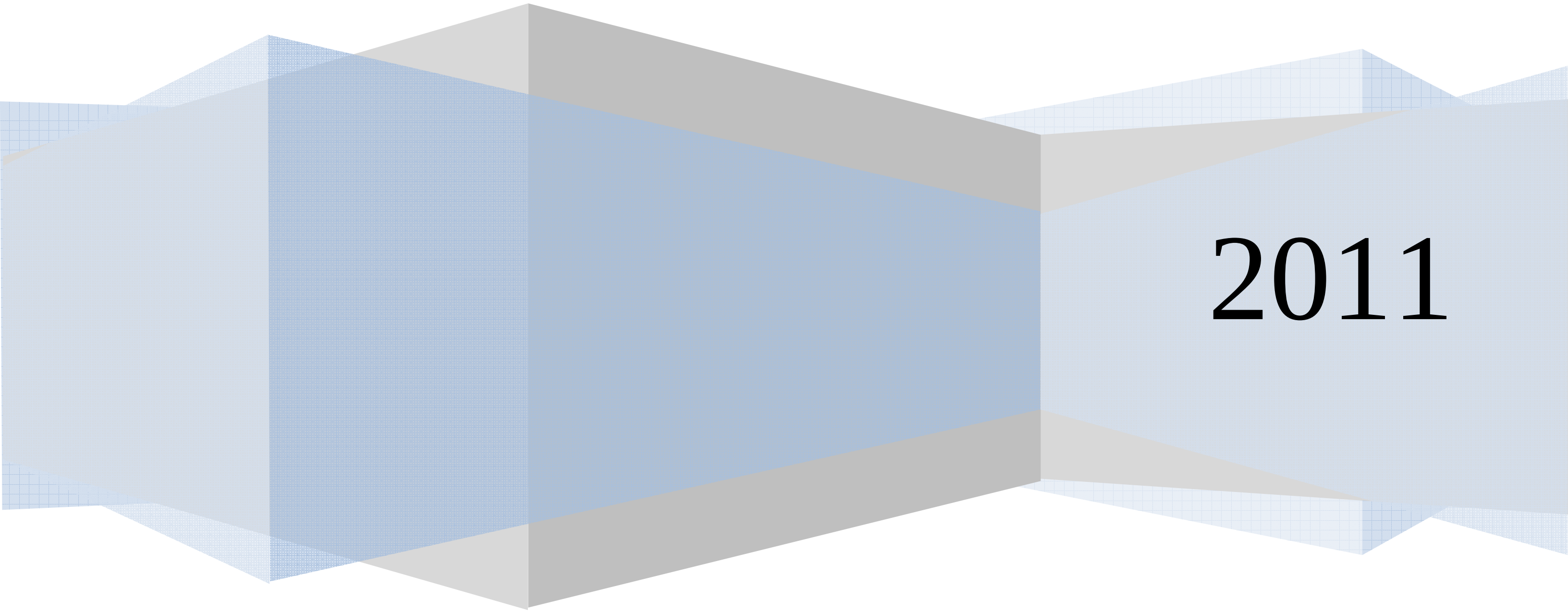
The structure of life-cycle environmental impact of the U.S. economy

Using a multi-regional hybrid framework

Sangwon Suh



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Abstract

Environmental impacts associated with the U.S. economy pose significant global implications. This paper integrates hybrid, multi-regional input-output and Life Cycle Impact Assessment (LCIA) approaches to quantify the environmental impact of the U.S. economy. An integrated system is constructed using various data sources that embrace about 2,600 environmental pressures, over 400 commodities for the U.S, 123 sectors for China, 8 final demand categories, over 4,000 process Life Cycle Inventories and over 1,200 environmental impact characterization factors, which, altogether represent one of the most comprehensive frameworks for analyzing environmental impacts. The structure of the hybrid input-output framework is analyzed, and the generality of the hybrid frameworks proposed Suh (2004) over Konijn et al. (1997) is shown. The composition and the structure of the environmental impacts induced by the U.S. final consumption are analyzed using contribution analyses and environ analysis developed by Patten (1982). Particularly, environ analysis results are used to visualize the network structure of the life-cycle environmental impact of the U.S. economy. The results show that private household consumption and investment is responsible for about 66% of the total environmental impacts induced by the U.S. economy, half of which is caused by the consumption expenditures for the provision of ‘Mobility’, ‘Food’ and ‘Shelter’. Major industrial activities that generate direct environmental impacts were ‘Natural gas, Electricity and Utility’, ‘Mining, Drilling and Refining’ and ‘Agriculture, Forestry and Fishery’. Overall, it is shown that provision of energy, transportation, food and materials are the major conduits of environmental impacts in the U.S. economy. The contribution of environmental impacts by imports to the U.S. is estimated to be responsible for about 28% of the total impact created by the U.S. economy. The current study demonstrates a novel combination of tools and techniques that are developed in the fields of natural science, engineering, ecosystem science and input-output economics in addressing major environmental policy imperatives. The results are expected to inform the U.S. EPA in prioritizing major areas of effort needed to reduce the environmental impact of the U.S. economy.

Keywords: hybrid approach, LCA, input-output, multi-regional IO, environmental impact

1. Introduction

As the largest economy in the world in Gross Domestic Product (GDP), environmental impacts associated with the U.S. economy pose significant global implications. With about 5% of global population share, the U.S. has been consuming about 20–25% of global energy supply (EIA, 2010). The motorization rate[1] of the U.S. is nearly 800, while those of China and India remain under 20 as of year 2006 (IEA, 2007). Historically, the U.S. is responsible for about a quarter of the entire Greenhouse Gas (GHG) emissions generated over the last 100 years (EPA, 2010). Furthermore, the global environmental impact induced by U.S. consumption is considered to be even larger than its domestic counterpart considering the increasing offshoring and imports (see the evidence in GHG emissions in Peters and Hertwich, 2009; Davis and Caldera, 2010). Therefore, understanding the structure of the environmental impacts in the U.S. economy would be an important first step to identify hotspots and to eventually reduce them.

The problem of environmental pollution has long been a topic of interest in the field of Input-Output Analysis (IOA) since the pioneering work by Wassily Leontief (Leontief and Ford, 1970). Over the last four decades, IOA has been successfully applied to address various environmental and energy issues (Ayres and Kneese, 1969; Wright, 1974; Berry and Fels, 1973; Bullard and Herendeen, 1975; Bullard et al., 1978; Chapman, 1974; Cleveland et al., 1984; Duchin, F., 1992; Duchin and Lange, 1994). Nevertheless, adequately addressing the entire spectrum of environmental impacts of a national economy has been a challenge due to a number of obstacles that are elaborated below:

First, there are thousands of environmental pressures such as emissions of pollutants and consumption of resources causing various environmental problems. Apart from a few well-known pollutants, such as CO_2, SO_2 and NO_X, information on environmental pressures by industrial sectors, however, has been lacking for most of the countries. Many studies have relied on these limited number of pollutants as a proxy for overall environmental impact (Dasgupta et al., 2002; Cole, 2000; Suri and Chapman, 1998; Grossman and Krueger, 1995). Even for those countries that do compile environmental statistics regularly, such data are scattered around many

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[1] The number of motor vehicles per 1,000 capita.

branches and agencies and compiling them into a harmonized dataset has been a challenge. In the U.S., for instance, a number of government branches are involved in compilation of environmental emission data including the Environmental Protection Agency (EPA), United States Department of Agriculture (USDA), Energy Information Administration (EIA), and United State Geological Survey (USGS), and their areas of coverage and frequency of compilation widely varies between them. Even within an agency, there are often multiple programs that compile different environmental datasets often without much coordination between them.

Second, even in a few exceptional studies (Wheeler, 2001; Mani and Wheeler, 1997; Hettige et al., 1992), where more than a few environmental emissions are compiled, the analysis stops at the total mass of pollutants in lieu of adequate means to quantify their collective impacts. Quantifying environmental impacts requires a comprehensive understanding on the behavior of the pollutants in the environment and the risks that they pose. There are thousands of pollutants generated by industrial economy, and these pollutants pose different environmental risks in varying magnitude. Quantifying a toxic impact of a pollutant, for instance, requires an examination of its fate, transport, exposure and toxicity, which requires the information on physicochemical and toxicity characteristics of and modeling techniques for the pollutant. Furthermore, quantifying the environmental impacts of an economy requires more than just natural science: once the magnitude of two environmental impacts, say, climate change and human toxicological impacts are quantified using scientific knowledge, it is still necessary to weigh the relative magnitude of importance of these impacts to arrive at an aggregate environmental impact score, which is often indispensible for effective policy communication.

Third, input-output tables provide a comprehensive coverage for the inter-industry transactions, but in order to cover the entire life-cycle,[2] a better representation of the downstream, i.e., use and disposal phases, is needed. Movement of wastes and recycled materials between industries and households, in particular, are poorly represented in input-output tables, as these flows often involve little or no monetary transaction. Apart from the efforts in Japan around the Waste Input-

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[2] The term, ‘life-cycle’ represents raw materials extraction, manufacturing, transportation, use and disposal as is used in Life Cycle Assessment (LCA) (ISO, 1998).

Output (WIO) framework (Nakamura and Kondo, 2001; Kondo and Nakamura, 2004), incorporating post-consumer waste and recycled material flows within an input-output framework has been a challenge due to the serious data limitation. On the upstream side, with the increasing importance of international trade and the emergence of China as a manufacturing powerhouse, a better specification is desirable for imported commodities possibly by using multi-regional input-output approach.

In recent years, progresses have been made to address some of these challenges: on the environmental data front, efforts have been made to compile environmental data beyond GHGs and criteria pollutants[3] for input-output applications (Suh, 2005a; Green Design Institute, 2009; Suh, 2010). On the environmental modeling front, major progresses have been made in the field of Life Cycle Impact Assessment (LCIA): Environmental impacts factors—called ‘characterization factors’—have been developed for thousands of chemical species considering their behavior in and their risks to the environment (see e.g. Rosenbaum et al., 2008). Gloria et al. (2007) developed the weights[4] between environmental impacts based on a panel method to assist in the U.S. government’s efforts on environmentally preferable purchasing. Using these weights, environmental impacts can be aggregated into a single impact score based on an authoritative government study. On the life-cycle coverage front, hybrid methods have been adopted to input-output analysis under the framework of Life Cycle Assessment (LCA) (Joshi 1999, Heijungs and Suh, 2002; Suh, 2004; Suh et al., 2004; Suh and Huppes, 2005), and multi-regional input-output analysis have been applied to better assess pollution embodied in international trades (Davis and Caldeira, 2010; Hertwich and Peters, 2009; Weber and Matthews, 2007).

Such improvements have enabled the environmentally-extended input-output tables to inform major environmental policy directives in the past a few years: Huppes et al. (2006), for instance, adjusted the U.S. input-output table and the environmental data from Suh (2005a) to represent European economic structure and analyzed the environmental impacts of products, which was conducive to the European Comission’s Integrated Product Policy (IPP) directive. In the U.S.,

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[3] Criteria pollutants in the U.S. refers to 6 common air pollutants including Ozone, Particulate Matter, Carbon Monoxide, Nitrogen Oxides, Sulfur Dioxide, and Lead for which data infrastructure is well established.

[4] In LCA, these weights are applied to normalized environmental impact result, which is the ratio between the environmental impact of a product system and that of a reference system, which is often a nation (ISO, 1998; Guinée et al., 2002).

EPA used the database by Suh (2005a) to analyze environmental impacts of products, which was used to inform the revision process of the Resource Conservation and Recovery Act (RCRA) of the U.S. (EPA, 2009; Allen et al., 2009). Nevertheless, these progresses are yet to be harmonized and assembled together to materialize their full potential.

The current paper builds upon these recent progresses. This paper presents a novel integration of hybrid, multi-regional IO and LCIA approaches with the state-of-the-art data and analytical methods to quantify the environmental impact of the U.S. economy and to analyze its composition and structure.

2. Methodology and data

2.1. Overall framework

2.1.1. Hybrid approach

Hybrid approach in this paper refers to the use of both input-output table and process-specific data. For the sake of clarity, the use of both monetary and physical units in a single technology matrix, which is often referred to as hybrid approach as well, is noted here as mixed-unit approach. Hybrid approach came into wide practice since the 1970s in the field of energy analyses (Bullard and Pillarti, 1976; van Engelenburg, 1994; Wilting, 1996). Hybrid approach combines the strengths of both process analysis and the input-output analysis, namely high granularity (per process analysis) and the completeness (per IOA).

The interest around hybrid approach has been rejuvenated with the emergence of Life Cycle Assessment (LCA) in the 1990s. LCA is a tool to quantify environmental impacts of a product from raw materials extraction to manufacturing, transportation, use and recycling/disposal (ISO, 1998). Conventional process-based LCA suffers from the same limitations of process-based energy analysis in that practitioners have to stop collecting data from upstream processes at certain point as upstream processes propagate and proliferate along the supply-chain, which is referred to as ‘truncation’ problem (see Lave et al., 1995; Lenzen, 2000). By combining process LCA and environmentally-extended input-output analysis, the process-specificity of process

LCA can be maintained while the truncation problem can be minimized (Treloar, 1997; Josh, 1999; Suh and Huppes, 2002).

An innovation along this line was the use of both a mixed-unit technology matrix (describing the process-LCA part) and a monetary-unit input-output table (describing the rest of the economy) in a single technology matrix (Suh, 2004). In the field of LCA, a mixed-unit technology matrix has been used to describe the exchanges of goods and services between unit processes (Heijungs, 1994; *c.f.* Lin and Polenske, 1997). Suh (2004) linked the process-LCA matrix directly with an input-output table within a single matrix, which is referred to as 'integrated hybrid' approach (Suh and Huppes, 2005; Suh et al., 2004).

Using an integrated hybrid approach, the matrix of total life-cycle environmental pressure, **Q** for a given final demand vector is derived by

(1)
$$\mathbf{Q} = \left[\mathbf{B}_{process} \;\vdots\; \mathbf{B}_{IO}\right] \left[\begin{array}{c:c} \mathbf{I} - \mathbf{A}_{process} & -\mathbf{C}^{\mathrm{d}} \\ \hdashline -\mathbf{C}^{\mathrm{u}} & \mathbf{I} - \mathbf{A}_{IO} \end{array}\right]^{-1} \left[\begin{array}{c} \mathbf{y}_{process} \\ \hdashline \mathbf{y}_{IO} \end{array}\right],$$

where $\mathbf{B}_{process}$ is an environmental pressure per unit process output matrix, $\mathbf{B}_{IO}$ is an environmental pressure per unit industry output matrix, $\mathbf{A}_{process}$ is a mixed-unit LCA technology matrix describing exchanges within unit processes, $\mathbf{A}_{IO}$ is a monetary IO technology matrix, **I** is an identity matrix with arbitrary dimension, $\mathbf{C}^{\mathrm{u}}$ is an upstream cut-off matrix describing the amount of inputs from the IO sectors to unit processes, $\mathbf{C}^{\mathrm{d}}$ is a downstream cut-off matrix describing the amount of inputs from the unit processes to IO sectors, $\mathbf{y}_{processes}$ is a vector of final demand on unit process outputs and $\mathbf{y}_{IO}$ is a vector of final demand on IO sector output (Suh, 2004; Suh et al., 2004; Suh and Huppes, 2005; see also Peters and Hertwich, 2006; Suh, 2006). The matrix **B** can describe any desired quantity such as materials input, water use, land use or emissions of pollutants.

As discussed earlier, recycling and disposal operations are relatively poorly represented in an IOT. In this paper, mixed-unit LCA matrices from the Ecoinvent[5] database are combined with the environmentally-extended input-output tables of the U.S. to better describe the recycling and disposal operations. In this work, information on absorption, disposal and distribution of waste and recycled materials by recycling and disposal operations are estimated using various statistics, and they are used to compile the matrices that link the IOT with relevant processes in Ecoinvent database (see section 2.1.4 for data sources).

2.1.2. Generalization of hybrid approach

In the course of the development, a number of different formulations emerged to combine detailed, process models with input-output framework. Konijn et al. (1997), for instance, combined detailed, physical material flows with input-output sectors in estimating iron, steel and zinc content in products. Konijn et al. (1997) used seemingly very different equations in combining the two systems than that in integrated hybrid approach. It has been unclear how the two seemingly different problem formulations are related. In this section, it will be shown that the problem formulation in Konijn et al. (1997) is a special case of the integrated hybrid approach.

In Konijn et al. (1997), total domestic output, x_p from the combined, physical-monetary system is derived by:

$$
\begin{aligned}
x_p &= \mathbf{C}_{op}(I-\mathbf{C}_{os})^{-1}\mathbf{C}_{esi}(I-\mathbf{A})^{-1}(F\mathbf{i}-m)+\mathbf{E}_{sF}\mathbf{i}-m_s \\
&+\mathbf{C}_{epi}(I-\mathbf{A})^{-1}(F\mathbf{i}-m)+\mathbf{E}_{pF}\mathbf{i}-m_p \\
&=(\mathbf{C}_{op}(I-\mathbf{C}_{os})^{-1}\mathbf{C}_{esi}+\mathbf{C}_{epi})(I-\mathbf{A})^{-1}(F\mathbf{i}-m) \\
&+(\mathbf{C}_{op}(I-\mathbf{C}_{os})^{-1}(\mathbf{E}_{sF}\mathbf{i}-m_s)+\mathbf{E}_{pF}\mathbf{i}-m_p)
\end{aligned}
\tag{2}
$$

where $\mathbf{C}_{op}$ is the use of primary materials per physical unit of output of secondary materials; C_{os} is the use of secondary materials per physical unit of output of secondary materials; $\mathbf{C}_{esi}$ is the final use of secondary materials per unit monetary output of activities, $\mathbf{A}$ is activity-by-activity

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[5] Ecoinvent is the largest public LCA database that covers over 4,000 unit processes and over 1,500 environmental pressures.

matrix of monetary input-output coefficients, F is final demand, m is import by activities, $\mathbf{E}_{sF}$ is final demand of secondary materials, ms is import of secondary materials, $\mathbf{C}_{epi}$ is a final use of primary material per unit monetary output of activities, $\mathbf{E}_{pF}$ is final demand of primary materials, mp is import of primary materials and **i** is a summation vector. All original notations from Konijn et al. (1997) are retained to assist a direct comparison.

Consider equation (3) where the integrated hybrid form of equation (1) and the notations of equation (2) are combined:

$$x_p = \begin{pmatrix} \mathbf{C}_{op} & \mathbf{C}_{esi} \end{pmatrix} \left(I - \begin{pmatrix} \mathbf{C}_{os} & \mathbf{C}_{esi} \\ \mathbf{0} & \mathbf{A} \end{pmatrix} \right)^{-1} \begin{pmatrix} \mathbf{E}_{sF}\mathbf{i} - m_s \\ F\mathbf{i} - m \end{pmatrix} + \mathbf{E}_{sF}\mathbf{i} - m_s \tag{3}$$

Equation (3) follows the same logic of the integrated hybrid approach as in equation (1), while direct final demand ($\mathbf{E}_{sF}$) and imports (m_s) of secondary materials are added at the end of the right-hand-side.

Internalizing the inverse into each of the concatenated matrices, equation (3) becomes:

$$\begin{aligned} &= \begin{pmatrix} \mathbf{C}_{op} & \mathbf{C}_{esi} \end{pmatrix} \begin{pmatrix} (I - \mathbf{C}_{os})^{-1} & (I - \mathbf{C}_{os})^{-1}\mathbf{C}_{esi}(I - \mathbf{A})^{-1} \\ \mathbf{0} & (I - \mathbf{A})^{-1} \end{pmatrix} \begin{pmatrix} \mathbf{E}_{sF}\mathbf{i} - m_s \\ F\mathbf{i} - m \end{pmatrix} \\ &+ \mathbf{E}_{sF}\mathbf{i} - m_s \end{aligned} \tag{4}$$

Deploying the concatenated form in equation (4) becomes:

$$\begin{aligned} &= \mathbf{C}_{op}(I - \mathbf{C}_{os})^{-1}(\mathbf{E}_{sF}\mathbf{i} - m_s) + \mathbf{C}_{op}(I - \mathbf{C}_{os})^{-1}\mathbf{C}_{epi}(I - \mathbf{A})^{-1}(F\mathbf{i} - m) \\ &+ \mathbf{C}_{epi}(I - \mathbf{A})^{-1}(F\mathbf{i} - m) + \mathbf{E}_{sF}\mathbf{i} - m_s \\ &= (\mathbf{C}_{op}(I - \mathbf{C}_{os})^{-1}\mathbf{C}_{esi} + \mathbf{C}_{epi})(I - \mathbf{A})^{-1}(F\mathbf{i} - m) \\ &+ (\mathbf{C}_{op}(I - \mathbf{C}_{os})^{-1}(\mathbf{E}_{sF}\mathbf{i} - m_s) + \mathbf{E}_{pF}\mathbf{i} - m_p) \end{aligned} \tag{5}$$

which are identical to the two right-hand-side notions in the original equation (2) used by Konijn et al. (1997). Thus it is shown that the integrated hybrid model is a general form of the seemingly very different modular approach proposed by Konijn et al. (1997). Note that Konijn et al. (1997) treated the lower-left block matrix in the technology matrix as **0**, whereas the integrated hybrid approach does not necessarily impose such a restriction. The integrated form of hybrid approach has also been proposed by Hoekstra and van den Bergh (2006) for accounting material flows. Suh and Huppes (2005) showed that other forms of hybrid approaches used in LCA, viz. tiered hybrid and input-output hybrid approaches, are also special cases of the integrated hybrid formulation.

2.1.3. Integrated, multi-regional framework

In this section, a multi-regional IO model is combined with the integrated hybrid framework. As discussed earlier, ideally, the use of multi-regional IO framework is desirable to better understand the implications of the increasing import and its environmental impacts. For instance, Weber & Matthews (2007) showed that U.S. import is responsible for about 30% of the total GHG emissions induced by the U.S. final demand (see also Peters and Hertwich, 2009; Davis and Caldera, 2010). Dietzenbacher (2010) showed that, however, actual GHG emissions from China associated with Chinese exports can be much lower than previously estimated, as re-export with minimal alterations is commonly practiced in China.

Despite the conceptual benefits, however, using multi-regional framework comes with its own costs: Environmental data for most of the countries outside the U.S. are either limited in availability or poor in quality. Therefore, most of the multi-regional IO studies for environmental applications have been focused on GHGs and a smaller number of well-known air pollutants. Due to the significant gap in environmental data compiled by the rest of the world, substantial underestimation of the environmental impacts by imports to the U.S. is inevitably. Addressing the poor environmental data availability for Chinese IOT, Yi and Suh (2010) developed an environmentally-extended input-output table of China focusing on the emissions that are known to be the major contributors to each environmental impact category when life-cycle impact assessment (LCIA) method is applied.

China is the largest trade partner sharing about 20% of total import to the U.S. (Census Bureau, 2010). Given that comparable environmental data are not available for the rest of the foreign countries than China and that China shares significant portion of the total import to the U.S., it is assumed that all imports to the U.S. are made from China. Exceptions were made for those that are apparently not from China and that are from the countries of which economic structure is closer to the U.S. such as forestry product from Canada. Such imports that are linked to U.S. domestic technology matrix. Despite the efforts made in this study, the environmental impact results associated with foreign trades are considered to be highly uncertain and should be interpreted with caution.

The overall structure of the technology matrix used in this study is illustrated in Figure 1.

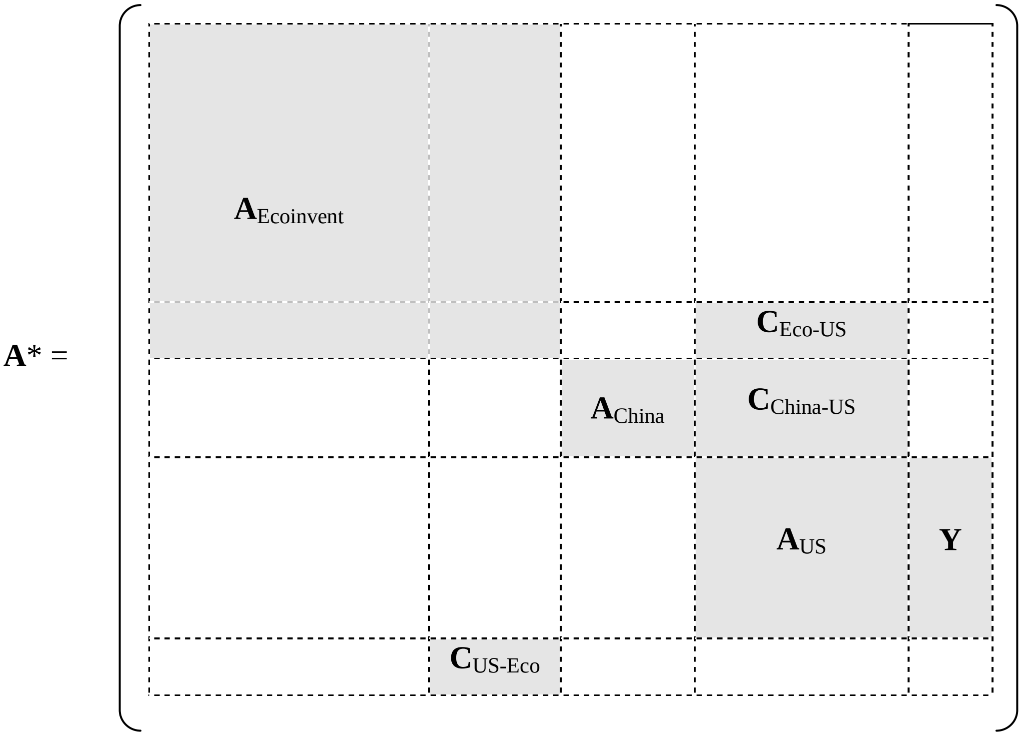

Figure 1. The structure of the technology matrix in the integrated, multi-regional framework

Grey scale blocks represent non-zero matrices, and blank cells are zero matrices. The sizes of the block matrices are indicative of the actual dimensions. $\mathbf{A}_{\text{Ecoinvent}}$ is the technology matrix of the

Ecoinvent database, $\mathbf{C}_{\text{Eco-US}}$ is the recycled materials input to U.S. commodities, $\mathbf{C}_{\text{US-Eco}}$ is the post-consumer wastes and recyclable materials from private household and government consumers to Ecoinvent processes, $\mathbf{A}_{\text{China}}$ is the technology matrix of China, $\mathbf{A}_{\text{US}}$ is the technology matrix of the U.S. and **Y** is the final demand matrix that distinguishes 8 different consumption activities. The 8 consumption activities are described in Table 1.

Table 1. Consumption activities distinguished in this study

Consumption activities			Description	Monetary share
Private	Expenditure	Mobility	gas, automobile and repair for passenger cars, air, water and railway transportation, etc.	6%
		Food	grocery, prepared food, refrigerator, gas and electricity for food preparation and refrigeration, restaurants, etc.	9%
		Shelter	building construction, renovation, electricity and gas for lighting, heating and cooling, gardening, etc.	6%
		The rest	all other private consumption expenditures	38%
	Investment		private investment	13%
Government	Expenditure		government expenditure	19%
	Investment		government investment	3%
Export			all exports	7%

Overall calculation of the total environmental pressure from the U.S. final consumption, **Q*** is calculated by:

$$\mathbf{Q}^* = \mathbf{B}^*(\mathbf{I}-\mathbf{A}^*)^{-1}\begin{bmatrix}\mathbf{0}\\ \mathbf{I}\end{bmatrix}, \tag{6}$$

where **B*** is the environmental pressure matrix for the integrated matrix, **A*** is the integrated technology shown in Figure 1, and **I** is a 8-by-8 identity matrix that extracts the results from the final consumption activities in the last 8 columns of the result (*c.f.* Huppes et al., 2006). If coefficient form instead of the total expenditures is used for **Y** in Figure 1, **I** in equation (6) can be replaced by expenditure figures.

2.2. Life Cycle Impact Assessment framework

Once the life-cycle environmental pressure matrix, **Q*** is calculated, it is multiplied by a characterization factor matrix. Characterization factor matrix is an environmental impact categories-by-environmental pressure matrix that converts the quantity environmental pressures into impact scores per each impact category. This step is noted as ‘characterization’ in LCIA. A recent update of the TRACI factors (Bare et al., 2010) originally developed by EPA (Bare et al., 2003) were used for characterization in the current study. The list of impact categories is shown in Table 2. The characterized results are then each divided by respective total environmental impact of the U.S., which is referred to as ‘normalization’ step in LCIA, and then appropriate weighting factors are multiplied to aggregate them into a single score. The current study uses Kim et al. (2010) and Gloria et al. (2007) for normalization references and weighting factors, respectively. Table 2 shows the weighting factors used in the current study. Once characterization, normalization and weighting are completed, the resulting value represents a composite environmental impact score considering the relative importance between the 12 environmental impact categories determined for environmentally preferable purchasing of the U.S. government.

Table 2. Impact categories and respective weighting factors used in this study

Impact categories	Unit	Weighting factors
Human health cancer	kg benzene-eq	8
Global warming	kg CO_2-eq	29
Acidification	moles of H^+-eq	3
Human health criteria	kg PM2.5-eq	9
Human health noncancer	kg toluene-eq	5
Ozone layer depletion	kg CFC-11-eq	2
Eutrophication	kg N	6
Photochemical smog	kg NO_X-eq	4
Ecotoxicity	kg 2,4-D-eq	7
Land use	km^2	6
Water withdrawal	liter	8
Primary energy consumption	Million BTU	10

Overall calculation that aggregates environmental pressure matrix, **Q*** into composite environmental impact scores, **m** can be carried out using the following equation:

$$(7) \qquad \mathbf{m} = \mathbf{w}\hat{\mathbf{n}}^{-1}\mathbf{C}\mathbf{Q}*,$$

where **m** is the weighted results-by-consumption activity row vector, **n** is the normalization reference vector, **C** is the impact categories-by-environmental pressure matrix that contains characterization factors (see Heijungs and Suh, 2002).

2.3. Analytical toolbox

The framework presented in the earlier section is capable of implementing various analytical tools. A straightforward analytical tool to be applied is the contribution analysis, which returns the contribution of total weighted or unweighted environmental impact by consumption activities, by final consumption products, or by direct generators of the impact (see the various contribution and numerical analysis methods in LCA in Heijungs and Suh, 2002; Suh, 2005a). These methods can be combined with visualization tools such as Sanky diagram, which represents the volume of flow (e.g., embodied impact of incoming commodity) by the thickness of a line.

Another powerful analytical tool barely known to input-output economist is the environ analysis used by ecological network analysis (ENA) communities (see Suh, 2005b). The notion of environ was developed in through the series of contributions by Bernard C. Patten and his colleagues (Patten et al., 1976; Patten, 1982; Patten, 1990). The environ refers to the relative interdependency between ecosystem components. The interdependency can be measured by any metrics including nutrient or energy flows. Environ analysis can also be applied to measure relative interdependency between industries through environmental impact flows. In this case, the results of environ analysis show the flows of embodied environmental impacts between industries induced by final consumption activities (output environ analysis) (see Suh, 2005b for details).

2.4. Data sources

Various data sources have been used to compile the basic data needed for the current analysis. For the U.S. input-output table, 2002 U.S. benchmark supply and use matrices are used. These supply and use matrices are converted into analytical tables using the mixed-technology model (see Konijn, 1994; Steenge, 1990; ten Raa, 1988; ten Raa et al., 1984; ten Raa and Rueda-Cantuche, 2003 for details of the technology models). The resulting analytical table distinguishes 430 products. For the Chinese input-output table, again 2002 standard input-output table is used, which distinguishes 123 products. Compilation of the consumption activity matrix followed the U.S. Department of Energy data including end use energy consumption surveys (DOE, 2010). The amount of post-consumer recyclable materials and waste generation is calculated based on various data sources from the Office of Solid Waste (OSW) of the U.S. EPA (EPA, 2010). The Comprehensive Environmental Data Archive (Suh, 2005; Suh, 2010) provides the basic environmental data for the current analysis. The environmental database for the U.S. input-output table presented in Suh (2010) is further extended to cover about 2,600 environmental pressures, which represents the most comprehensive list of environmental data compiled for input-output applications. For the environmentally-extended IOT for China, Yi and Suh (2010) is used in this study. The Ecoinvent database is used for recycling and disposal activities. Ecoinvent database distinguishes over 4,000 unit processes and over 1500 environmental pressures. Bare et al. (2010) supplied the characterization factors, Gloria et al. (2007) was used for weighting factors. Normalization references were derived from Suh (2010).

3. Results

Figure 2 shows the composition of the total environmental impacts induced by the 8 consumption activities shown in Table 1. It is notable that the results are weighted based on the preference on relative importance between environmental impact categories designed for the U.S. government’s environmentally preferable purchasing program (Gloria et al., 2007), and that all weighted results are subject to any bias or subjectivity by the panel who developed the weighting factors. Therefore, the particular weighting scheme used in the current study may not suit to the need of a particular application. According to the results, ‘Global warming’ was the largest impact caused by the U.S. economy sharing 24% of the total impact, followed by ‘Ecological toxicity' impact (12%), 'Carcinogenic human toxicity' impact (10%), 'Primary energy consumption' (9%), 'Water withdrawal' (9%), 'Respiratory impact to human' (9%) and 'Land use' impact (7%). It is notable that, when combined, the various toxic impacts to humans and to the ecosystem share the largest part of the total impact.

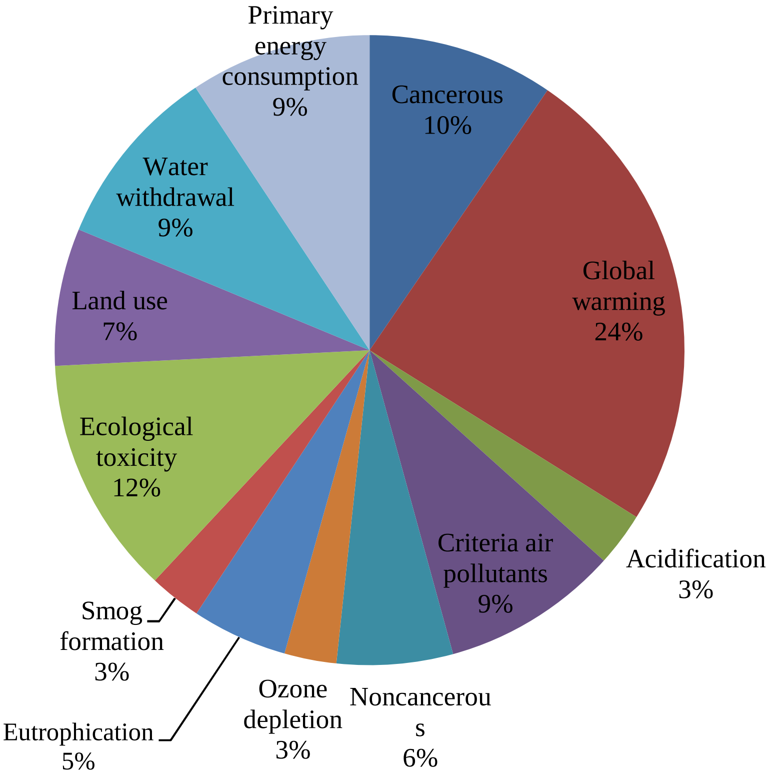

Figure 2. Total environmental impact share by impact categories

Given the large number of commodities involved, the commodities are aggregated into 6 categories for the sake of sensible presentation of the results. They are 'Mining, drilling and refining', 'Import', 'Gas and electricity', 'Food and agriculture', 'Transportation' and 'the rest'. Dividing the total impact over the sources of direct impact generators using the aggregated categories, the largest source of direct impact was 'Import' (28%), followed by 'Mining, drilling and refining' (25%), 'Gas and electricity' (14%), 'Food and agriculture' (14%) and 'Transportation' (14%) (Figure 3).

The results can be divided into the 8 consumption activities. Figure 4 shows the share of the total impact by the 8 consumption activities. According to the result, 'Private household' induces 66% of the total environmental impacts by the U.S. economy, and the rest is by 'Government' (18%) and 'Export' (15%). Under the 'Private household' category, provision of 'Mobility' was responsible for 13%, provision of 'Food' was for 12%, provision of 'Shelter' was for 8% of the total environmental impacts by the U.S. economy (Figure 4).

These results and the first tier supplier impact are summarized using Sanky diagram in Figure 5.

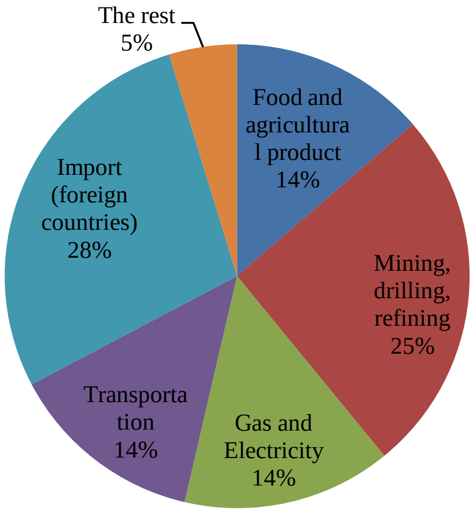

Figure 3. Total environmental impact share by direct impact generators

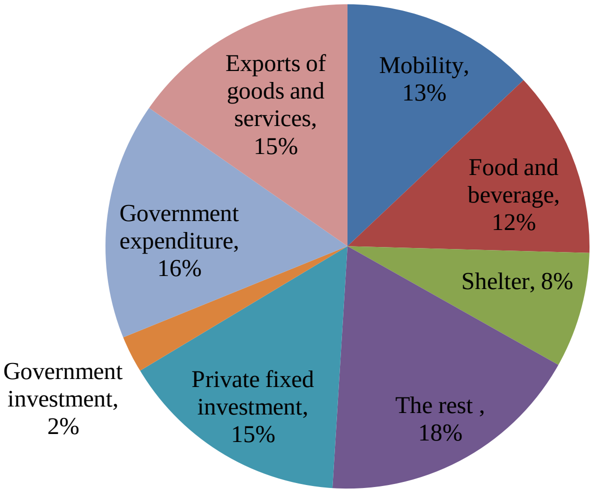

Figure 4. Total environmental impact share by consumption activities

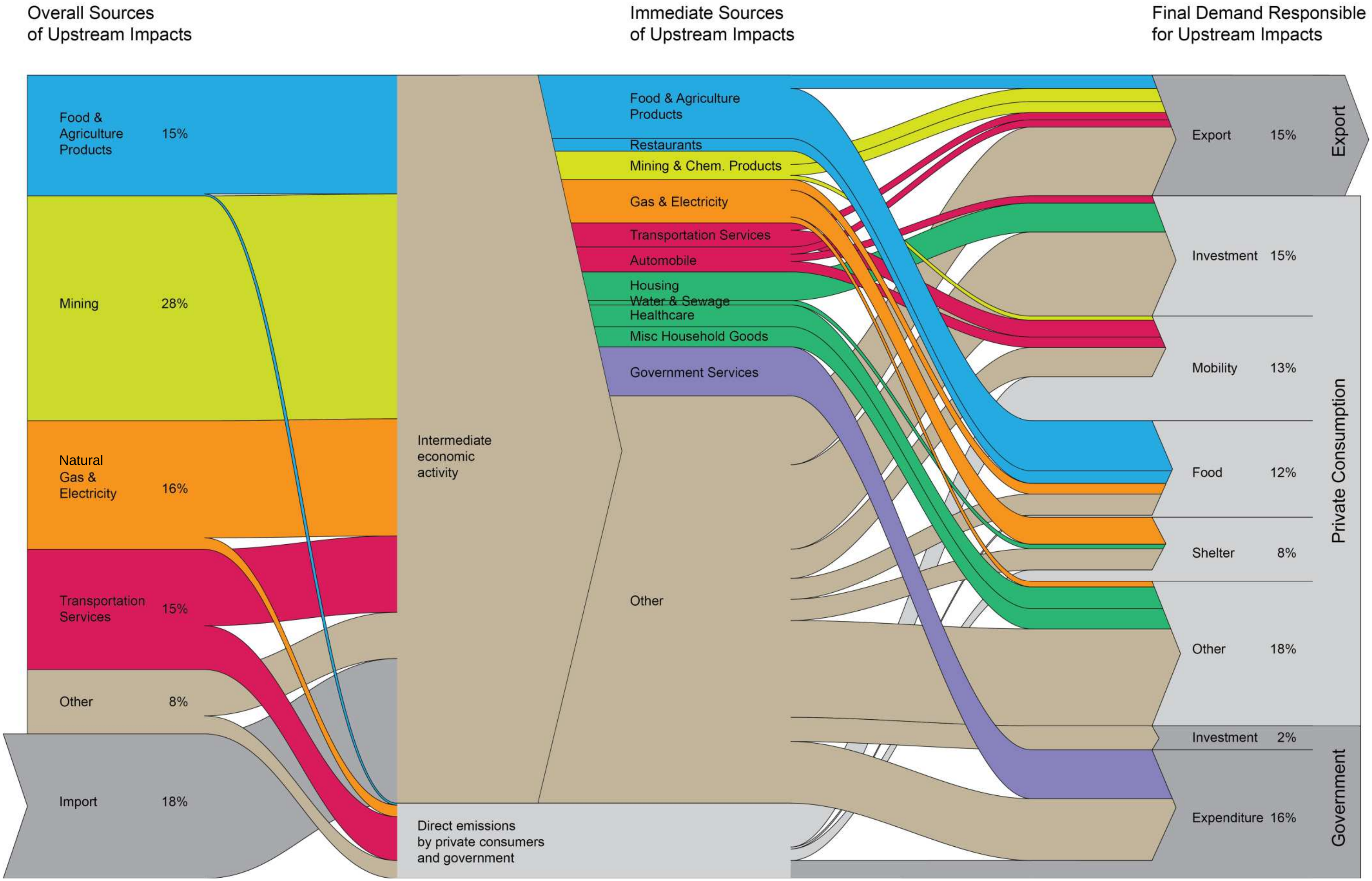

Figure 5. Sanky diagram of embodied weighted impact of the U.S. economy

Figure 6 shows the direct output environ analysis results highlighting major direct impact induced by subsequent downstream demand. In this diagram, flows that are connected to the bottom of the circle represent the direct impact induced by subsequent downstream supply-chain, while those connected to the top do the direct impact from the upstream supplier induced by the circle itself. The thickness of the flows indicates the relative magnitude of impact. As shown in Figure 6, the direct impacts generated by ‘Gas, Electricity and Utility’ to meet the demand by private households, the direct impact by ‘Mining and Drilling’ to meet the demand by ‘Metal smelters and foundries’, and the direct impact by ‘Agriculture, Forestry and Fishery’ to meet the demand by ‘Food and beverage’ constitute the major structural elements in the life-cycle environmental impact of the U.S. economy.

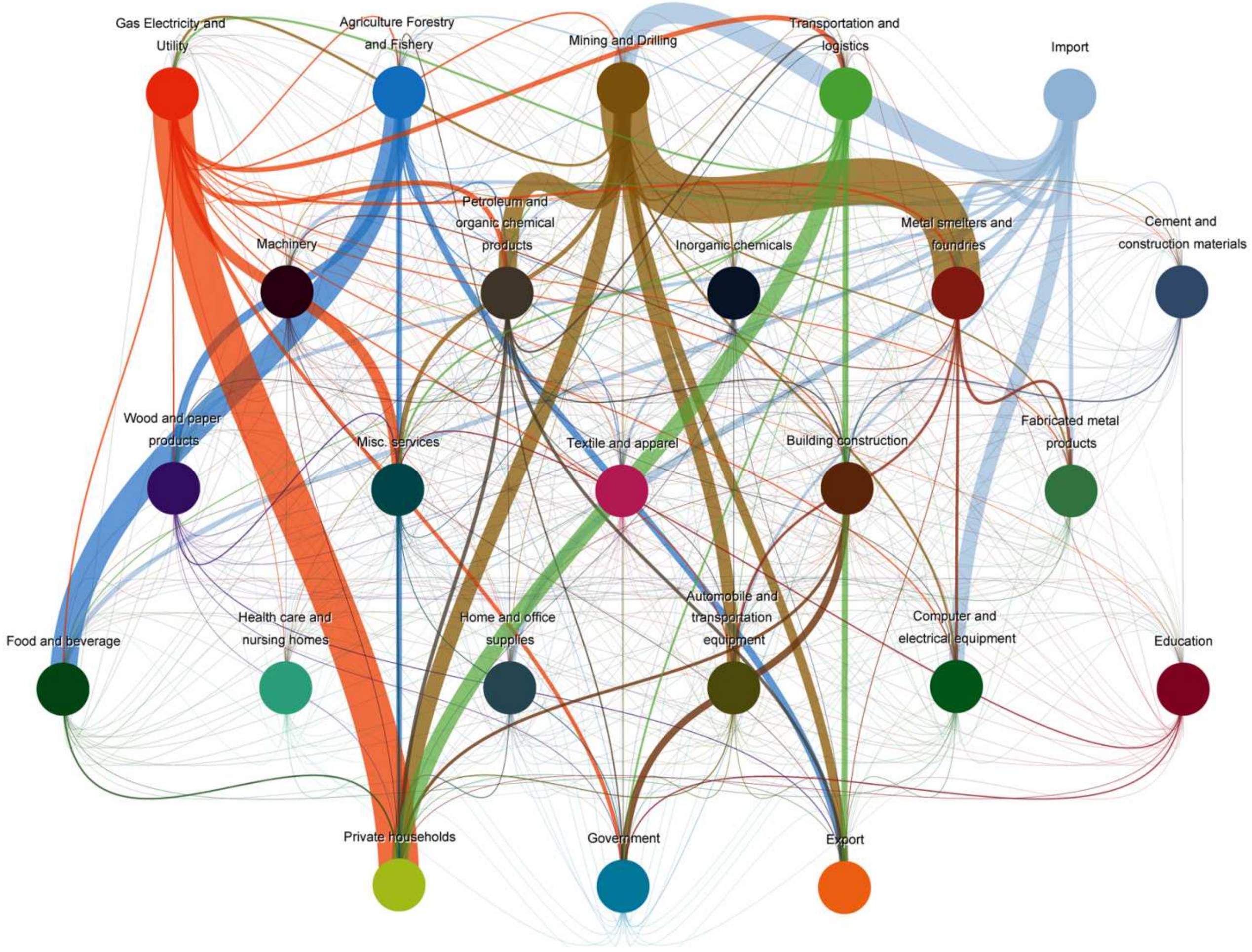

Figure 6. Direct output environ analysis based on weighted impact

Similarly, output environ analysis can be applied in a cumulative form, where environmental impact of upstream inputs of a process is passed onto its outputs. Figure 7 shows cumulative output environ analysis results showing major cumulative impact induced throughout the supply-chain of the U.S. economy. Again, flows connected to the top of each node represent the magnitude of environmental impacts by the inputs to the node, and those to the bottom show the magnitude of cumulative environmental impacts by the outputs from the node. Obviously, the cumulative impact by the output of a node equals the cumulative impact from its inputs plus direct impact generated by the node. In Figure 7, each node shows two bars: the length of the upper bar is the total cumulative impact from the inputs (upstream) and the length of the lower bar is the total cumulative impact of the output from the node. The difference in length between the two is the direct impact from the node.

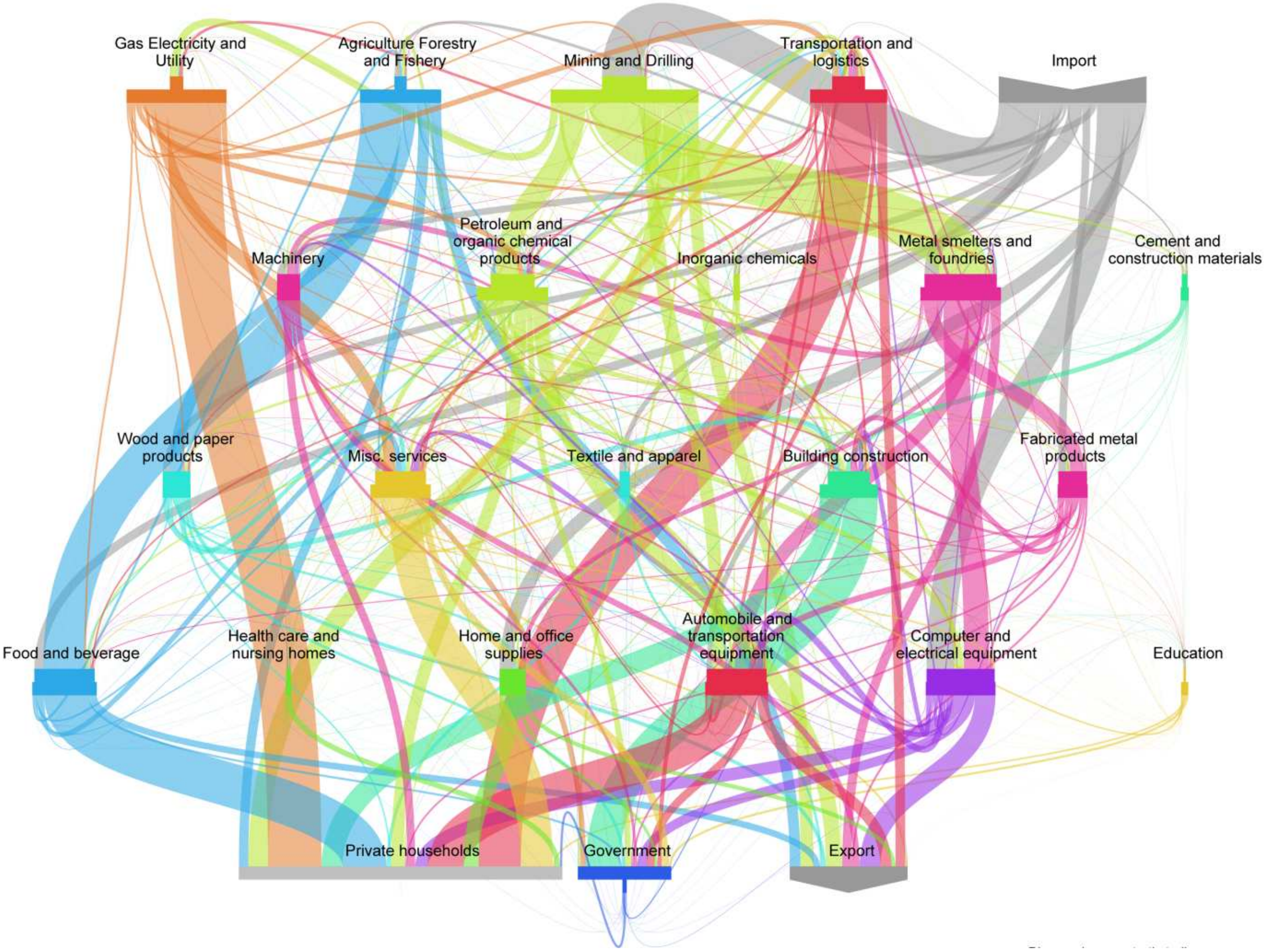

Figure 7. Cumulative output environ analysis based on weighted impact

It is notable that ‘Misc. services’, ‘Building construction’, ‘Automobile and transportation equipment’, and ‘Computer and electrical equipment’ did not stand out in Figure 6, while those small direct impacts caused by them eventually add up into a substantial sum as shown in Figure 7. The significance of these supply-chain nodes cannot be recognized by looking at only one sector at a time.

4. Conclusions and Discussion

In this study, the environmental impacts of the U.S. economy have been analyzed covering the wide spectrum of environmental pressure and environmental impacts. Analyses have been performed using contribution analysis and environ analysis, and the results are visualized using, among others, Sanky diagram and weighted network graphics.

The results show that private household consumption and investment is responsible for about 66% of the total environmental impacts induced by the U.S. economy, half of which is caused by the consumption expenditures for the provision of ‘Mobility’, ‘Food’ and ‘Shelter’. Major industrial activities that generate direct environmental impacts were ‘Gas, Electricity and Utility’, ‘Mining and Drilling’ and ‘Agriculture, Forestry and Fishery’.

Overall, it is shown that provision of energy, transportation, food and materials are the major conduits of environmental impacts in the U.S. economy. The contribution of environmental impacts by imports to the U.S. is estimated to be responsible for about 28% of the total impact created by the U.S. economy, while the share of imports is particularly uncertain. As compared to the previous study performed in Europe (Huppes et al., 2006), the impacts of mining and drilling, imports, and transportation-related activities are shown to be relatively high in the U.S. economy. Policy to reduce the environmental impacts of the U.S. economy will need to address those major conduits of environmental impacts identified in this study.

The current study demonstrates a novel combination of various tools and techniques developed in natural science, engineering, ecosystem science and input-output economics and its application for addressing major environmental policy imperatives. The results are expected to inform the U.S. EPA in prioritizing major areas of effort needed to reduce the environmental impact of the U.S. economy.

The results of the current analysis need to be interpreted with caution: the weighted results are subject to any bias or subjectivity by the panel members participated in the study. While the current study uses the state-of-the-art science for its LCIA method, quantifying the environmental impacts of various chemicals is subject to uncertainty. The current results should be understood as a best available practice in modeling the overall environmental impacts rather than ultimate reality. In a follow-up study, key sector identification methods, uncertainty analysis and sensitivity analysis will be applied and the current results will be further refined.

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