# Open IO: Developing a Transparent, Fully Accessible Economic Input-Output Life Cycle Assessment Database

Robert W. Cox
The Sustainability Consortium
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## Abstract

Economic input-output models have become an accepted tool of analysis in Life Cycle Assessment (LCA), yet most environmentally extended IO models do not provide their users with complete access to data and underlying methodologies. Open IO intends to provide users with this information to allow for a greater understanding of the model structure and environmental data collected as a part of the project. This paper describes the adaptation for LCA purposes of the US economic input-output accounts developed by the Bureau of Economic Analysis. The input-output model encompasses 430 commodities based on the North American Industrial Classification System, which is crosswalked to greater commodity detail by associating the IO commodities with 2,923 product "bricks" identified in the Global Production Classification code. Attached to each of these are environmental resource requirements for and emissions resulting from production in each industrial sector or GPC brick. Details relating to the assembly of this environmental data including sources and methodology are reported here. Open IO allows users to isolate impacts for each stage of the product's life cycle.

## Introduction

Recent years have seen the rise of environmentally extended input-output life cycle assessment models as a tool to estimate life cycle environmental impacts of industrial processes. Earlier Life Cycle models were process-based, and relied extensively on detailed information collected specifically for purposes of LCA. A basic building block of LCA is the unit process, which is defined by the International Organization for Standardization (ISO) as "the smallest portion of a product system for which data are collected when performing a Life Cycle Assessment".[1] Although process-based models continue to be widely used, the expense of data collection and limitations in model completeness regarding upstream impacts in the supply chain have led researchers to explore LCA models based on input-output analysis. These models typically append environmental impact data to existing economic input-output models. Most US-based models, such as that built by The Green Design Institute at Carnegie Mellon University (Henrickson, Lave, & Matthews, 2006) or the Comprehensive Environmental Data Archive (CEDA) (Suh, 2005) rely on the US Benchmark Input-Output Tables constructed every five years by the U.S. Bureau of Economic Analysis (BEA). (Stewart, Stone, & Streitwieser, October 2007) Similarly, Open IO is based on the same BEA data.

Existing environmentally extended IO models are either proprietary or limit the user's ability to identify sources and methods employed to determine impacts. Thus where deeper understanding of the estimates is required, deriving satisfactory answers can be problematic. Open IO is proposed as a fully accessible, transparent database that will permit complete access to the user desiring a greater knowledge of the development of the database, and will allow for model data and results to be available for other applications. This addresses a concern that has been expressed by those users of environmentally extended IO models who find themselves puzzled by the outcome of a particular analysis. Open enables identification of environmental or social "hot spots" in supply chains for individual commodities or industries. It can also assist in prioritizing their supply chain data collection efforts. A beta version of Open IO along with complete source data and documentation may be accessed on-line at http://www.sustainabilityconsortium.org/open-io. Work is continuing on developing Open IO to include additional emissions and impacts.

## Theory and Structure

An input-output model provides an economic tool to quantify the relationships between various industries in the economy. The tables that comprise an IO model, which typically are displayed in a matrix format, show the commodity inputs that are used by each industry to produce its output, the types of commodities produced by each industry, and the use of commodities by final consumers. Economic input-output analysis can be used to answer the following question: When a given dollar amount is spent on a particular good or service, how much total activity is generated in the economy, and how is that activity distributed among the various economic sectors?

The Open IO database requires two stages. The first stage is the traditional economic input-output model, which describes all the purchases made in the economy by various economic agents. The IO model allows use of quantitative, supply chain models to be built as described above. To account for the resource use and emissions of each sector, the second stage consisting of a "satellite matrix" is constructed. The satellite matrix provides estimates of the so-called elementary flows or resource requirements and emissions of certain substances from the activity of each sector in the economy. When one dollar is spent on the output of a particular industry, the resulting stimulation of economic activity can be translated into environmental impacts using the satellite matrix. These emission factors can be applied to the economic activity happening throughout the supply chain, and we thus calculate cradle-to-gate emissions.

## Economic Exchanges (Input-Output Analysis)

A life-cycle assessment must model and quantify supply chain impacts from material extraction to final production. This part of the life-cycle, known as "cradle-to-gate," requires that purchasing activity is known for each actor in the economy. To reduce data and computational requirements, industry purchasing data as well as environmental resource requirements or emissions data can be grouped into sectors that include output from similar industries.

A building block used to construct an economic IO matrix describes the relationships between sectors in the economy. The purchases and sales for each sector are arranged in a matrix so that the columns represent the sectors' purchases, and rows represent the sectors' sales to other sectors. For example, Table 1 presents a partial look at –sector, "Dog and cat food manufacturing". In 2002, the sector's top purchases were Grains, Animal slaughtering, Soybeans, and Metal cans.

The supply chain framework begins to emerge here by examining any of the first tier supply sectors to Dog and Cat food manufacturing. For example, the metal can, box, and other metal container manufacturing sector will have its own column that will include details of its suppliers. And so on, up the supply chain.

The compilation of input-output datasets is often carried out on a national level. In the United States, the US Department of Commerce is responsible for publishing benchmark input/output tables every five years, with interim updates. Open IO is based on the 2002 benchmark table compiled by the U.S. Commerce Department's (BEA).[2]

**Table 1. Selected purchases for Dog and Cat food sector**

**(CY 2002 Purchases in Million USD)**

| | |
|---|---|
| 1111B0 - Grain farming | $1,016.60 |
| 31161A - Animal (except poultry) slaughtering, rendering, and processing | $687.10 |
| 31122A - Soybean and other oilseed processing | $590.50 |
| 332430 - Metal can, box, and other metal container (light gauge) manufacturing | $575.70 |
| 420000 - Wholesale trade | $557.20 |
| 550000 - Management of companies and enterprises | $524.60 |
| 32222B - All other paper bag and coated and treated paper manufacturing | $366.20 |
| 484000 - Truck transportation | $220.80 |
| All other sectors | … |

BEA produces redefined IO tables at the detailed level. The redefinition consists of moving commodity outputs to their primary sector. This is used when the input structure for a secondary product made by an industry differs significantly from the primary product of that industry. For example, newspapers produce both newspapers and advertising. In this case, the advertising commodity would be re-defined as an output of the advertising industry Open IO uses the detailed redefined IO tables with approximately 430 commodities.

The process of constructing the total requirements matrix (i.e., a matrix of total economic output required to produce a given output of a commodity delivered for final use) begins with the "Make" and "Use" tables from BEA. The Make table shows the value of each commodity produced by each industry, and the Use table shows the uses of commodities by industries as intermediate inputs and by final users. The Make table is organized as industry by commodity, and it describes which commodities are made by which industries. The Use table is organized as commodity by industry, and it describes which industries use which commodities. The Use and Make tables are rearranged to create symmetrical matrices indexed by producing industries along the horizontal axis, and commodities produced along the vertical axis. Thus indexed, the Raw Use matrix can identify the inputs or intermediate commodities required to produce each industry's final output. The Raw Make matrix, on the other hand, identifies for each commodity the industry producing that commodity. With a few intermediate steps, the Raw Use matrix and Raw Make matrix are combined to obtain direct requirement coefficients.

Depending on the needs of the analyst, the Raw Make and Raw Use tables may be combined into one single table that is industry by industry, commodity by commodity, or a mix of the two. The Open IO project has chosen the commodity by commodity approach, and accordingly derived a single Direct Requirements table that is commodity by commodity.

The Direct Requirements matrix details the goods and services used as direct inputs into the production process for the commodity involved. Both the Raw Make and Raw Use tables undergo a similar transformation. Industry output distributed in the Raw Use matrix is summed across all columns to yield total industry output, and the each element in the matrix is divided by the relevant column total to get use coefficients. Value-added sectors are removed so only intermediate industries remain. This process is mirrored with the Raw Make matrix, except the rows are reordered, and the process for removing value-added sectors is not needed since they are not represented in the original Make matrix.

The new matrices containing use and make coefficients are multiplied, and the result is known as the Direct Requirements coefficients matrix. In standard Leontief IO methodology, this matrix is subtracted from an identity matrix, and then inverted to derive the total economic requirements matrix. This matrix shows the production required both directly and indirectly of the commodity at the beginning of each row per dollar of the commodity delivered to the final user at the top of the column.

In addition to data used for creating the Total Requirements matrix, Open IO includes the "margin" costs applied to products delivered to the consumer. The margins data show inputs of each margin sector that apply whenever an industry buys a commodity. Margin data for transportation, wholesale trade, and retail trade are used to calculate the impacts of delivering commodities from the producer to the consumer. Margin expenditures were then divided by total expenditures in the use matrix to yield margin percentages. This is used elsewhere in the model where cradle-to-consumer (C2C) impacts are estimated.

The Open-IO model provides cradle-to-gate (C2G) emissions by 430 IO sectors. However, results thus classified are not useful for certain types of analysis due to aggregation issues. Open IO includes a crosswalk that maps particular IO industries to more specific products listed under their GPC code. Many organizations use GS1's Global Product Classification (GPC) code to classify their products.[3] In order to assign environmental emissions data to GPC ”bricks”, two relevant mappings were developed as a component of Open IO. First, a concordance table that links each GPC product to an industry as classified by the North American Industrial Classification System (NAICS) was compiled.[4] Next, a NAICS-to-IO mapping was compiled.[5] Results from Open IO are available in both NAICS and GPC code format. GPC code format offers the advantage over NAICS codes in that it is much more detailed with 2,923 product bricks enumerated, meaning that the use phase of products can be described more accurately.

GPC codes are mapped at the brick level of the most recently available (June 2008) GPC codes. As stated above, GPC codes are particularly geared towards manufactured goods. The product bricks included in the GPC code map to 220 unique BEA IO codes, 206 of which are manufacturing sectors.

## Satellite and Impact Method Data

Open IO includes estimates of inputs used in the production, transportation, sales, and use phases that have environmental consequences over the lifetime of the product. Similarly, impacts from those phases are also estimated. Specific estimates for each IO sector were obtained when available for the requirements of energy, land, and water. Emissions data included greenhouse gases, criteria pollutants, toxic substances, and agricultural chemicals. The resource or emissions data in each category for each industry was then divided by economic output as shown in to yield impacts per dollar of economic output in the year 2002.

The resulting LCI data generated by Open IO could be applied to many impact assessment methods such as Impact 2002+[6] or ReCiPe[7].

**Greenhouse Gas Emissions**

Open IO’s Greenhouse Gas (GHG) satellite matrix uses 2002 data from the US Environmental Protection Agency’s (EPA) Greenhouse Gas inventory as a central source.[8] Emissions listed in the GHG inventory were apportioned to the various IO sectors based on an assignment algorithm (described below). Greenhouse gases are divided into two conceptual categories in order to aid the computations. First, Carbon Dioxide (CO2) emissions from combustion, which comprise approximately 75% of the total emissions, were apportioned based on each sector’s fuel combustion. (Feedstock use of fuels was removed.) Second, all other emissions (chiefly CO2 and CH4, although 13 other greenhouse gases are included in Open IO) were apportioned to IO sectors based on a match between EPA industrial processes and NAICS sectors. Where exact matches were not found, other techniques were used to fine-tune the apportionment. Finally, these two categories of emissions were combined and normalized by sector output to produce the emission factors of Kg CO2 per dollar output for each sector.

The GHG emissions are drawn directly from EPA’s 2007 GHG inventory Table 3-3: “CO2 Emissions from Fossil Fuel Combustion by Fuel Type and Sector (Tg CO2 Eq.)”[9] This table gives emissions by fuel type from each broad sector (industrial, commercial, transportation, etc.) GHG emissions from each broad sector were allocated across the corresponding IO sectors based on each IO sector’s combustion of a given fuel as estimated by the BEA Use Table. Purchases of natural gas by each industry were converted into physical units using appropriate price data. For example, Table 2 below (based on EPA Table 3-3) notes that the transportation sector emitted 37.2 Tg of CO2 from the combustion of natural gas in 2002. Nine IO transportation industries share these emissions based on their combustion of natural gas.

The Greenhouse Gas Inventory lists emissions by type of gas, by year for a number of industrial processes.[10] This level of industrial disaggregation in most cases enables direct translations to NAICS codes and ultimately to IO codes. However, direct translations to NAICS are not always possible when the EPA industrial processes are more aggregated than NAICS sectors (overly broad), or when the EPA processes are less aggregated than NAICS sectors (overly fine). In the first instance, the emissions from the EPA process are apportioned to the many IO sectors through a variety of allocation methods. This is generally accomplished on the basis of sector economic output (although product use, such as fuel, is sometimes a useful guide). The economic output data used is that from the US BEA 2002 Supplementary Use[11] table. The same dynamic happens when translating between the NAICS sectors and IO industries. In the latter case the NAICS sector is overly fine for the translation, and emissions are simply summed to the total emissions for the IO industry.

**Table 2: Example of Apportioned Emissions for the Transportation Sector**

| IO Industry | Share NG Consumption | NG Consumption (mmBTU) | 2002 Emissions (Gg CO2) from NG combustion |
|---|---|---|---|
| **481000 - Air transportation** | 0.45% | 8.46E+05 | 168.22 |
| **482000 - Rail transportation** | 0.09% | 1.69E+05 | 33.64 |
| **483000 - Water transportation** | 4.93% | 9.23E+06 | 1,835.51 |
| **484000 - Truck transportation** | 14.27% | 2.67E+07 | 5,308.41 |
| **485000 - Transit and ground passenger transportation** | 0.00% | 0.00E+00 | - |
| **486000 - Pipeline transportation** | 20.46% | 3.83E+07 | 7,611.21 |
| **48A000 - Scenic and sightseeing transportation and support activities for transportation** | 37.73% | 7.06E+07 | 14,037.38 |
| **492000 - Couriers and messengers** | 0.00% | 0.00E+00 | - |
| **491000 - Postal service** | 22.06% | 4.13E+07 | 8,205.61 |
| **Total** | **100%** | | **37,200.00** |

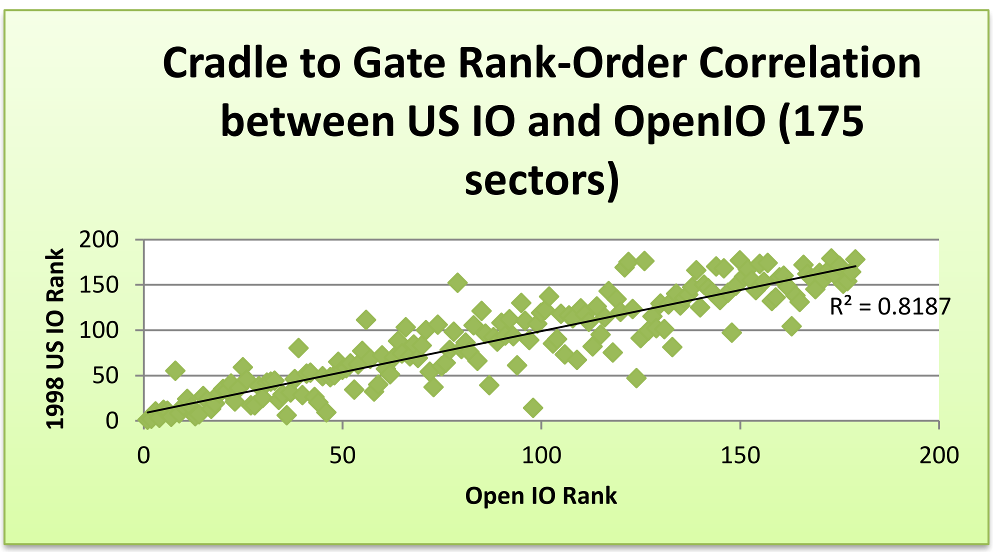
Fuel expenditures by IO sector are given in the Benchmark Use table.[12] Open IO does not use raw fuel expenditures to apportion the GHG emissions, because different sectors pay different prices for fuels. Furthermore, some of those purchased fuels are not combusted, but rather used as feedstock. The price each industry pays for the various fuels is determined using data from the Manufacturers Energy Consumption Survey (MECS)[13] and the State Energy Data System (SEDS)[14] , both produced by the US Energy Information Administration (EIA). Because some industries, such as chemical manufacturers, use a significant amount of fuel for feedstock purposes, each industry's consumption is adjusted by a 'feedstock ratio,' which gives the percentage of feedstock to total fuel use. The feedstock ratio is determined based on MECS "Table 2.2: Nonfuel (Feedstock) Use of Combustible Energy, 2002."[15]

All other greenhouse gas emissions include all gases that are not CO2 emissions from combustion. These include CO2 emissions from industrial processes, CH4 and N2O emissions from stationary and mobile combustion, and a number of other gases. These other gases are chiefly employed in industrial processes (e.g., SF6, c2F6, and NF3) or are used as refrigerants (e.g., the class of gases known as hydrofluorocarbons or HFCs).

The resulting greenhouse gas satellite matrix was reviewed for quality. Basic validation included a comparison with processes available in the 1998 US Input-Output database.[16] Of the approximately 430 sectors available for comparison, 175 were thought to match well enough to be compared.

For each database, the 175 sectors were ordered from lowest to highest cradle-to-gate emissions. Emissions per dollar were corrected for changes in overall price levels. The IPCC 100a time horizon impact assessment method was used to express impacts as carbon dioxide-equivalents (CO2e). These sectors were then ranked from 1 to 175, and as shown in Figure 1 revealed a high level of correlation ($R^2$ = 0.81) between Open IO and the 1998 US IO database in terms of emissions per dollar of output.

**Figure 1: Cradle to Gate Emissions - Rank-Order Correlation between US IO and Open IO**




**Criteria Pollutants**

This section provides 2002 emissions of EPA criteria pollutants per USD of economic output for 430 detailed BEA sectors. Criteria air pollutants as listed by EPA are those air pollutants that are common and found all over the United States. These include carbon monoxide (CO), sulfur oxides (SOx), nitrogen oxides (NOx), ozone (O3), lead (Pb),and particulate matter (a general term for a heterogeneous mixture of solid particles and liquid droplets found in the air, including dust, dirt, soot, and smoke). Although ammonia (NH3) is included in the Criteria Pollutants database, it is removed when combined with the Toxics Release Inventory data to avoid double counting. This is because the EPA includes ammonia in the National Emission Inventory as a precursor to particulate matter formation.

Criteria pollutant data are provided by the EPA in four categories: Point source, nonpoint source, mobile source off-road and mobile source on-road.[17] Point source emissions are assigned to NAICS codes by EPA. This data was then translated into IO codes. The other data (nonpoint and mobile sources) are sectored by Source Classification Codes (SCC), which are 8- or 10-digit codes used by EPA to categorize individual processes or unit operations that generate air emissions. The data sectored by SCC was assigned to IO codes according to patterns of each relevant sector's purchases as listed in the 2002 US Benchmark Input-Output use table. For example, mobile off-road pollutants were apportioned to each IO sector based on that sector's purchases from the IO industries: 333112 - Lawn and garden equipment manufacturing, 333911 - Pump and pumping equipment manufacturing, 333912 - Air and gas compressor manufacturing, 33399A - Other general purpose machinery manufacturing, and 335312 - Motor and generator manufacturing. Emissions from wildfires were not assigned to any sector, and therefore are not included in the estimates.

**Toxic Substances**

All toxic emissions data in the current version of Open IO are from The EPA Toxic Release Inventory (TRI) program with data for year 2002.[18] TRI data are not a complete representation of all toxics released in the US. Reporting requirements exempt facilities that generate toxics less than specific thresholds, and particular sectors of the economy are exempted altogether (e.g., agriculture). This last problem is rectified by including a module in Open IO called "Agricultural Chemicals," which is described later in this article. TRI chemical names were mapped to the names that appear in impact assessment methods.

The TRI data provide the Standard Industrial Classification (SIC) code for each release rather than NAICS code because facilities were not required to report their NAICS codes until 2006. The EPA has since assigned NAICS codes for all but a few facilities for which was listed a SIC code. Where the EPA was not able to provide a NAICS code for a facility, NAICS codes were assigned in-house using the US Census Bureau's SIC 1987 to NAICS 2002 crosswalk. This was necessary for only a relatively small number of facilities (895 of >96,000 entries, or less and 0.9 percent).

There are many different types of toxic releases. For example, a few release types are Fugitive Air, Stack Air, Surface Water, and Surface Impoundment. Emissions from these different release sources were assigned to LCA emission categories as indicated in **Error! Not a valid bookmark self-reference.**3 below. If it is considered to be an emission, then it is included as an emission from the reporting industry. If it is classified as a technosphere product, this indicates the substance has remained in the economy. Substances to the technosphere are not considered emissions in Open IO due to a lack of knowledge of their fates.

**Agricultural Chemicals**

The primary sources for agricultural chemical use are the US Department of Agriculture (USDA) and the Pesticide database from the National Center for Food and Agricultural Policy (NCFAP). The amount of a specific chemical applied to agricultural land according to type of crop or animal being raised was assembled

## Table 3: Treatment of TRI Emission Types in Open IO Database

| Release Category (TRI) | Notes | LCA Category | LCA sphere |
|---|---|---|---|
| 5.1 Fugitive Air | | air | emission |
| 5.2 Stack Air | | air | emission |
| 5.3 Water | | water | emission |
| 5.4.1 Underground Class | | land | technosphere |
| 5.4.2 Underground Class | | land | technosphere |
| 5.5.1A RCRA C Landfills | | land | technosphere |
| 5.5.1B Other Landfills | | land | technosphere |
| 5.5.2 Land Treatment | | land | emission |
| 5.5.3 Surface | | land | emission |
| 5.5.3A RCRA C Surface | | land | technosphere |
| 5.5.3B Other Surface | | land | emission |
| 5.5.4 Other Disposal | | land | emission |
| 6.1 POTW - Metals and | | water | technosphere |
| 6.1 POTW - Non-Metals | | water | technosphere |
| 6.2 M10 | Transfers to off site facilities for storage | land | technosphere |
| 6.2 M41 | Transfers to off site for solidification/stabilization | land | technosphere |
| 6.2 M62 | Transfers to off-site wastewater treatment | water | technosphere |
| 6.2 M71 | Underground injection | land | technosphere |
| 6.2 M81 | Transfers for Underground Injection into Class I Wells. This transfer specification/code enacted in reporting year 2003 to replace M71. | land | technosphere |
| 6.2 M82 | Transfers for Underground Injection into Class II-V Wells. This transfer specification/code enacted in reporting year 2003 to replace M71. | land | technosphere |
| 6.2 M72 | Landfills/surface disposal impoundments | land | emission |
| 6.2 M63 | Surface impoundment | land | emission |
| 6.2 M66 | Heavy metal residues | land | emission |
| 6.2 M67 | Transfers for Other (non RCRA subtitle C) Surface Impoundment. This transfer specification/code enacted in reporting year 2003 to replace M63. | land | emission |
| 6.2 M64 | other landfills | land | technosphere |
| 6.2 M65 | RCRA subtitle C landfills | land | technosphere |
| 6.2 M73 | Land treatment | land | emission |
| 6.2 M79 | Other land disposal | land | emission |
| 6.2 M90 | Other offsite management | land | technosphere |
| 6.2 M94 | Transfer to waste broker for disposal | land | technosphere |
| 6.2 M99 | Unknown | land | emission |
| 6.2 M20 | Recycling | land | technosphere |
| 6.2 M24 | Recycling | land | technosphere |
| 6.2 M26 | Recycling | land | technosphere |
| 6.2 M28 | Recycling | land | technosphere |
| 6.2 M93 | Recycling | land | technosphere |
| 6.2 M56 | Recycling | land | technosphere |
| 6.2 M92 | Recycling | land | technosphere |
| 6.2 M40 | Recycling | land | technosphere |
| 6.2 M50 | Recycling | land | technosphere |
| 6.2 M54 | Recycling | land | technosphere |
| 6.2 M61 | Recycling | land | technosphere |
| 6.2 M69 | Recycling | land | technosphere |
| 6.2 M95 | Recycling | land | technosphere |

and transformed into LCI database format via a match of each agricultural chemical as reported by NCFAP or USDA to a registry number assigned by the Chemical Abstracts Service (CAS), a division of the American Chemical Society.[19]

For most field crops and fruits, data on the amount of chemicals applied to crop land are available from USDA, National Agricultural Statistics Service (NASS) through its Quickstats website. Year of coverage may vary, but in general the data covers years between 2005 and 2007. USDA compiles this data for selected program states, and states with minor levels of production of a particular crop may not be included in the statistics.[20]

Vegetable chemical use in 1997 was available from NCFAP.[21] Data from NCFAP were compared when possible to more recent data on chemical use published by the US Department of Agriculture.[22] USDA publishes selected information on chemical use, but the data are not comprehensive. Only "Program States" are surveyed—in aggregate these account for 90 percent of US acreage devoted to the production of vegetables. These states may vary from crop to crop. Also, only selected vegetables are included in the survey. USDA data obtained for Program States was expanded to include all acreage for the relevant crops by taking a ratio of planted acres in Program States to total US acreage devoted to that crop in the year surveyed. This data is generally available from USDA.[23] Information on acres planted in 2007 was obtained by adding harvested acres and acres on which crops failed or were abandoned. In some cases, acreage in Program States is larger than total acreage reported in the 2007 Census of Agriculture. This is usually due to comparing acres planted in the chemical survey to acres harvested in the Census data. Since the former is at least as large as the latter, then the expansion of the chemical usage reported for Program States to the US will understate the magnitude of chemical usage overall. Unfortunately, for certain crops, planted acreage is unavailable for any year. This problem also exists for citrus fruits as reported by NASS.[24]

Data for livestock[25] as well as for nursery and floriculture[26] sales was reported for program states and was expanded to include all states based on the ratio of Program States' output to total US output for the agricultural category being analyzed.

The data from NCFAP and USDA were merged to obtain broad coverage of all crops surveyed by either agency.

Since the use of agricultural chemicals was surveyed over a number of years, output in dollars for each crop was converted to its equivalent in 2002 prices to make it compatible with the input-output model. Crop output values for the relevant years were obtained from the USDA NASS web site for annual crop value summaries.[27] Price information needed for the conversion was obtained from NASS for the period 1996 – 2007.[28]

Because data on chemical usage is available for only certain years for each crop, it was necessary to compile output data for the relevant year for each crop and then aggregate the output for each IO sector into a "generic" year, stated in 2002 prices. Chemical use was then aggregated into associated IO sectors.

**Water Use**

Water use per 2002 USD of sector output, when available, was assembled for detailed IO sectors. Special attention was given to water use by the agricultural and electricity sectors, as they account for a large portion of water use in the United States. Water data were gathered for most other sectors in the economy as well. The concepts of Water Withdrawal (removing the water from a source for use) and Water Consumption (water withdrawn and not returned to a source) were distinguishable for electricity production.

Water use was assigned to agricultural industries included in Open IO sectors. The basic agricultural water use data was obtained from the US Department of Agriculture's 2008 Farm & Ranch Irrigation Survey, Table 28 and Table 33.[29] The basic survey data included number of farms, irrigated acres harvested and average acre-feet of water applied per irrigated acre per year. However, because of aggregation differences between the two tables used from the survey, in some cases irrigation values for specific crops were summed to derive an estimate of acre-feet of water applied per acre. The estimated per-acre water use was multiplied by acres irrigated to derive total water usage in acre-feet per year. This multiplied by a constant for gallons/acre-foot (325,851.429) yields water consumption for each farming sector per year. This result was used for all sectors except greenhouse, nursery, and floriculture, which is explained below.

The USDA surveyed farms during years 2003 and 2008, requiring an adjustment to the output data to make it compatible with the irrigation data. Output measured in USD for each sector was obtained from the 2002 Make Table column totals (commodity output). The adjustment consisted of a ratio of output for 2002 and 2003, using USDA production data from a variety of sources. In each instance, the cash marketings of each crop for 2002 and 2003 are used as proxies for output.[30] The water usage was divided by the output per farming sector in 2003 to yield water consumption per USD of output.

The Farm & Ranch Irrigation Survey did not include the greenhouse, nursery and floriculture sectors, so for those sectors a different methodology was employed. 2007 Agricultural Census data states that there are 721,458 irrigated acres in US Nursery, greenhouse, and floriculture. This number is multiplied by 24,500 gallons/day, which is the average value for the "rules of thumb" for water consumption per acre in nurseries and greenhouses (Robbins and Klingaman). This is then scaled to a year by multiplying by 180, an assumed average number of growing days per year.

For dairy cattle and milk production, an alternative methodology was developed using data derived from the University of Idaho (Falk, 2010). This quantifies annual consumption of water per dairy cow and annual output (gallons) of milk per cow. Milk prices received by the farm are available from the US Department of Agriculture, National Agricultural Statistics Service.[31]

A calculation based on Falk using milk prices from USDA yielded a water usage per USD of milk equal to 11.25 gallons. Compared to the original estimate using the methodology described above (33.84 gallons per USD) this estimate is considerably lower. Both methodologies have validity; therefore the decision was made to take an average of 22.55 gallons per USD milk output.

Industry-specific water use data are not available for much of the mining sector; a generic water withdrawal value is available for mining from the USGS for 2005.[32] This water use was applied to the output from the 2002 Make Benchmark Table prepared by BEA, which yielded gallons used per dollar of output. The generic value was applied to oil and gas drilling and extraction, coal mining, stone mining and quarrying, and supporting activities.

For the metal mining sectors, a 2004 life cycle analysis undertaken on the Australian mining (Norgate & Lovel, 2004, September) contained relevant data in Tables 3 and 4 from their report. This data was in the form of cubic meters of water per ton of ore extracted for the mining of aluminum, copper, nickel, lead, zinc, titanium, iron, and gold. This data was used based on an assumption that water used in mineral extraction in Australia would be similar to levels used in the US. The data was converted to gallons per US dollar of output incorporating prices for ores mined in 2002.[33]

Water use for the electrical power generation, transmission and distribution was estimated using data from a variety of sources. Estimates for both water withdrawals and consumption for each type of generating facility were obtained. Generating facilities were typed according to the fuel used: coal, natural gas, nuclear, hydroelectric, and other organic fuels. “Water withdrawals” are defined as water withdrawn from its source for use in generating. “Water consumption” is the water withdrawn minus the water discharged, i.e., water placed directly back into the environment in liquid form. The release of steam and all other uses are considered consumption.

For coal-fired and nuclear-powered electrical generation facilities, each facility’s water consumption and generation measured in megawatt hours (MWh) in 2000 were obtained from the U.S. Energy Information Administration to develop overall water use.[34] The EIA is also the source for fuel use (2003 workbook used, with plants constructed in 2003 removed from consideration).[35]

For natural gas-fired generation, water usage per MWh was obtained from the Electric Power Research Institute (EPRI).[36] Total water use was weighted by percentages of gas-fired plants that operate using once-through cooling and recirculated cooling, which was obtained from the EIA.

Generation through combustion of other organic fuels was obtained from EPRI. It was assumed that plants using once-through cooling and recirculated cooling were split evenly, based on the split for natural gas-fired generation.

Hydroelectric water withdrawal and consumption consists of evaporation from reservoirs used for electrical generation purposes. Water use per KWh measured both in terms of withdrawals and consumption is available per KWh from the National Renewable Energy Laboratory.[37] Each type of power plant’s water use was weighted along with other types of generating facilities to obtain average water withdrawal and consumption per US dollar of output. Because of the fungible nature of electricity, pricing data for the sale of power generated by each means is not available. Standard national prices of delivered electricity to the industrial, transportation and commercial sectors were averaged and applied to each type of facility’s output weighted by that type’s share of US electricity generation as measured by the International Energy Agency.[38] Sales and price information was obtained from the EIA.[39] Using retail prices implies that impacts of generation, transmission and distribution are identical.

Currently no estimate of water use by the construction industry is available. The operating assumption is that construction uses negligible water.

Basic data for the remaining industrial sectors (except rail transportation which is discussed below) comes from the Pacific Institute report, *Waste Not, Want Not: The Potential for Urban Water Conservation in California*[40]*.* This report estimated water use for the year 2000 per employee per day for California industrial sectors. The assumption in expanding use of this data to national levels is that water use in California's industrial processes closely resembles water use for industries in the entire nation. The Pacific Institute data was converted to gallons/USD by deriving revenue per employee, and using a constant of 225 days of economic activity per year. Total water use per employee was multiplied by total employment in each sector and the constant, and then dividing by total revenue for that sector.

Employment and revenue were derived using a mixture of 2000 US and California employment and gross receipts data (sales, shipments, receipts, or revenue) as interpolated using the 1997 and 2002 economic censuses.[41] Where data for California was not disclosed due to confidentiality issues, US data was substituted for that particular industry.

Water use for every transportation industry except for rail transportation was estimated using Pacific Institute data as described above. For rail transportation, estimates were derived using data from the MTR Corporation, a major rail transportation provider in Hong Kong and southeastern China.[42] Relevant data include overall water use and gross revenue from operations, which was converted from Hong Kong dollars to US dollars.

**Primary Energy**

Energy output expressed in terms of megajoules (MJ) per physical unit for each type of energy extracted was derived using conversion factors from the US Energy Information Administration.[43] Price information per physical unit of output (tons, cubic feet, or barrels) was obtained from the EIA web sites for domestically-produced coal, natural gas, and oil.[44]

All prices were in 2002 dollars, and are those received by the producer at the first point of sale, a necessary clarification since fuels are typically bought and sold several times on their journey to the final consumer.

To get output in terms of MJ, first it is necessary to obtain output in physical units and then convert using price data discussed above.[45] This can be converted to dollar output using MJ/ton information obtained from the energy conversion calculator web site cited above.

As an alternative, output expressed in US dollars is available from the 2002 US Benchmark Input-Output Model. This model combines oil and natural gas to a single sector. To get output for coal expressed in MJ, the IO output is first divided by the 2002 price of coal to get tons. The result is then multiplied by the MJ/ton figure.

Calculating the coal output in MJ by either measure produces similar results. The two estimates varied by just 3.5%, but since either method is valid, it is recommended that the average of these two figures be used.

For oil and natural gas, output in MJ is estimated in the same manner for coal. To compare directly to the IO data, which is available only for the combined oil and natural gas sector, a weighted average of the MJ/$ estimate is calculated based on EIA information. To accomplish this, several steps are needed. First, output in MJ for oil and for natural gas each must be converted to dollar units, which is done using price information referenced above. These results are summed and divided by the total output in MJ for combined oil and natural gas. Dividing output in MJ by output in USD yields a value for MJ/$. This number is then multiplied by the total output for oil and gas from the IO model, to yield total output in MJ for oil and gas. As is the case for coal, to minimize potential errors, an average of the two estimates is recommended.

**Land Use**

Land use is measured in terms of square meters per dollar of output. Following Suh (2005), only uses of land by major land-covering activities are included.[46] These consist of agriculture and forestry, transportation (except water-borne transportation), parks, and national defense. In addition, mere occupation of land by covered activities is all that is considered, with differences in neither land-use intensity nor land transformation being accounted for. According to Lubowski, et. al, these activities account for 91.8 percent of land use in the 48 contiguous states, and 87.3 percent of all 50 states.[47] Although land use for national defense is estimated in the satellite model, in Open IO this is moved to the final demand sector. Similarly, land use for parks has been ignored.

Output data for 2002 by industry was obtained from the US Benchmark Make Matrix. Acreage sources for each measured industry were obtained from the following sources.

Acreage devoted to farming by NAICS code was measured in the 2002 US Census of Agriculture.[48] Data used in Open IO was based on “land in farms”. According to the 2002 Census, this includes farm lands not actively cultivated or used for pasture or grazing, if it is part of the farm operator’s total operation. An alternative would be to use another metric, “Harvested cropland (acres)” which would yield only those acres of planted cropland actually harvested. For Open IO land in farms is a better measure, but the analyst should be aware that farms with large amounts of unused acreage will show a higher requirement for land than is actually needed.

Land held in timber for forestry purposes was estimated by The US Department of Agriculture, Forest Service, Northern Research Station.[49] Forest land held in reserves or devoted to other uses was not included. Acreage used in transportation was obtained from two sources: Lubowski, et al., cited above, and Canadian researcher Todd Litman (2005).[50] Litman’s data for rural road acreage was applied to truck transportation, and urban acreage was assigned to transit and ground passenger transportation. The embodied assumption is that intercity rural road and highways are used primarily as a means to move goods, while urban roads and highways primarily move people. Lubowski was used to assign acreage to air and rail transportation by removing the highway acreage reported by Litman from the total acreage estimated by Lubowski, and assigning the remainder equally to air and rail.

## Damage Assessments

**Damage by Life Cycle Stage**

Cradle-to-Gate (C2G) impacts consist of those impacts arising from the production of the good to the point at which it is assembled and ready for delivery (i.e., at the factory gate). Margins for services are not possible because a service, unlike a physical product, is delivered to the final consumer as it is produced. Services may, however, be delivered to intermediate industries rather than to final demand. Total economic requirements (direct and indirect output) are paired to the C2G damage from each selling sector. Results are stated in terms of the reference units.

For those industries in the Raw Use matrix that sell products used by final consumers, margin costs (i.e., transportation of finished goods, wholesale and retail trade costs) are calculated as a percentage of all costs to derive cradle-to-consumer (C2C) impacts. Each such industry includes Personal Consumption Expenditures (PCE) in the raw use matrix. Impacts for each margin sector are calculated, and then for each PCE sector, the impact of the margin is calculated. For each product which has PCEs, the C2G impact is combined with the margin impacts. To get a full table of impacts for all products including those with no PCEs, zeroes are added to the remaining industries.

Use phase impacts are calculated only for those products that directly use some form of energy (e.g., either by burning fossil fuels, accessing electrical energy from the grid, or from batteries). Products that require energy in order to be viable (e.g., fresh milk requiring refrigeration) are not included in these estimates to avoid double-counting of impacts. The unit of estimation is the annual unit energy consumption (UEC) per dollar of the energy-using product, typically stated in watts/year. UECs are calculated for those products where not explicitly provided in the data.

The information needed to calculate UECs is available in a variety of on-line or published resources.[51] Power requirements (usually in watts) are calculated for each appliance, as well as the average number of hours per year that the appliance is in operation (as well as estimates for products that have an “inactive”, “idle”, “standby” or “sleep” mode). Although the values for UECs thus calculated are typically watts/yr or Kw/yr, there are exceptions, which require a conversion that maps the units to a common metric. The UEC for each GPC brick is divided by price of the product. This yields energy use per year. Fuel use is multiplied by appropriate price per unit, and the result is UEC per dollar.

To derive lifetime impacts, product lifetimes were estimated based on data from multiple sources.[52] Classes of life spans were assigned to products based on how they compared with known life spans from various sources. Factors that affected the durability include wear, product material, interaction with elements or fluids, whether the product has moving parts, or requires maintenance. Lifespan data from the National Association of Home Builders (2007) was used as a rough guide for determining the lifespan of building products; however these data are projections for material durability.[53] Several products were given a decreased range to reflect the "consumer lifespan" of these products, defined as a period of practical use to consumers, accounting for such eventualities as renovations or changes in tastes. To get energy impacts by GPC over the lifetime of the product, impacts from annual energy use were multiplied by this. The result was then crosswalked to IO categories.

One of the unique features of Open IO is its ability to parse LCA impacts into discrete stages of a product's life cycle. These are then compared in each damage category, and the relative importance of each stage in the life cycle can be displayed.

Open IO identifies four discrete "stages" in the cradle-through-consumer life cycle. These stages include:

1. Indirect impacts of the materials and services used as inputs to the product as well as the transportation of the input materials.
2. Direct impacts from the production process itself.
3. Distribution impacts from the wholesale trade, retail trade, and transportation of the finished good to market.
4. User phase impacts due to energy required by the product for its operation.

Indirect impacts, i.e., impacts that arise from upstream purchases made from other industries by the producing industry, are calculated by applying the direct coefficients from the technology matrix to the C2G impacts. Direct impacts per USD are identified midpoint C2G impacts for the commodity being analyzed, obtained, as calculated earlier. For margin impacts, the impacts calculated as a part of the C2C impacts are used. Finally, use phase impacts are included as calculated earlier.

## Future Developments

The development of Open IO is intended to allow researchers to fully understand the computational background of an environmentally extended input-output LCA database. The ability to de-mystify LCA models, and in particular, the input-output model with its accompanying satellite matrices, should assist in the use and acceptance of such databases. As these models gain acceptance, it should become possible to advance the state of the art more rapidly. In particular, databases such as Open IO increase the demand for reliable data not only on the economic interactions but also for the environmental impacts that can be associated with economic production. It is hoped that this increase in the demand for reliable data will lead to improved efforts to monitor and collect the relevant statistics that support input-output LCA models.

As for Open IO, future efforts will build in several areas. Use phase impacts should be more fully developed to include impacts from non-energy using goods and services, and end-of-life (cradle-to-grave) impacts should also be included. To be a fully global model, extending the input-output sectors to include detailed information on the nature of international trade will improve the ability to model global environmental impacts. Social accounting satellite matrices could also be appended to the model to determine social as well as environmental impacts. Some of the limitations of the input-output model as a foundation for LCA models behave been mitigated by developing a type of hybrid model that uses both macroeconomic data for the entire US or global economy supplemented by detailed information on the production process being analyzed. Ultimately, Open IO will explore the possibilities of this approach.

# Endnotes

[1] (Henrickson, Lave, & Matthews, 2006), p. 22
[2] (U.S. Bureau of Economic Analysis, 2008)
[3] (GS1, 2010)
[4] (U.S. Census Bureau, 2007)
[5] (Stewart, Stone, & Streitwieser, October 2007)
[6] (Humbert, Margni, & Jolliet, 2005, October)
[7] (Goedkoop M.J., Struijs J., & Van Zelm R, 6 January 2009)
[8] (U.S. Environmental Protection Agency, n.d.)
[9] (U.S. Environmental Protection Agency, n.d.)
[10] (U.S. Environmental Protection Agency, n.d.)
[11] (U.S. Bureau of Economic Analysis, 2008)
[12] (U.S. Bureau of Economic Analysis, 2008)
[13] (U.S. Department of Energy, Energy Information Administration, 2007)
[14] (U.S. Department of Energy, Energy Information Administration, 2010)
[15] (U.S. Department of Energy, Energy Information Administration, 2007)
[16] For a description of this database, see (Suh, 2003).
[17] All data was retrieved from the U.S. Environmental Protection Agency, Technology Transfer Network Clearinghouse for Inventories & Emssions Factors: 2002 National Emissions Inventory Data & Documentation. Specific pages as follows. Point source: ftp://ftp.epa.gov/EmisInventory/2002finalnei/2002_final_v3_2007_summaries/point/allneicap_annual_11302007.zip. Nonpoint source: ftp://ftp.epa.gov/EmisInventory/2002finalnei/2002_final_v3_2007_summaries/nonpoint.zip. Mobile source, on-road: ftp://ftp.epa.gov/EmisInventory/2002finalnei/mobile_sector_data/onroad/national_&_state.zip. Mobile source: off-road: ftp://ftp.epa.gov/EmisInventory/2002tinalnei/mobile_sector_datga/nonroad/national_&_state.zip.
[18] (U.S. Environmental Protection Agency, 2004) A convenient description of the M waste codes can be found at: http://www.epa.gov/enviro/html/tris/column/total_off_site_release.html.
[19] (Pesticide Action Network, 2010)
[20] (U.S. Department of Agriculture, National Agricultural Statistics Service, n.d.)
[21] (National Center for Food and Agricultural Policy (NCFAP))
[22] (U.S. Department of Agriculture, National Agricultural Statistics Service, 2005, July)
[23] (U.S. Department of Agriculture, National Agricultural Statistics Service, Various)
[24] (U.S. Department of Agriculture, National Agricultural Statistics Service, 2008, September)
[25] Dairy cattle: (U.S. Department of Agriculture, National Agricultural Statistics Service, 2007, May); beef cattle: (U.S. Department of Agriculture, National Agricultural Statistics Service, 2000, April); swine: (U.S. Department of Agriculture, National Agricultural Statistics Service, 2006, December); sheep: (U.S. Department of Agriculture, National Agricultural Statistics Service, 2001, May)
[26] (U.S. Department of Agriculture, National Agricultural Statistics Service, 2007, December)
[27] (U.S. Department of Agriculture, National Agricultural Statistics Service, 1995-2010)
[28] (U.S. Department of Agriculture, National Agricultural Statistics Service, 2000, July), and (U.S. Department of Agriculture, National Agricultural Statistics Service, 2008, July)
[29] (U.S. Department of Agriculture, National Agricultural Statistics Service, 2009, November)
[30] Vegetable and melon farming: (U.S. Department of Agriculture, Economic Research Service, 2004, July); tree nut farming and fruit farming: (U.S. Department of Agriculture, Economic Research Service, 2004, October); greenhouse, nursery and floriculture production: (U.S. Department of Agriculture, Economic Research Service, 2004, June); dairy cattle and milk production: (U.S. Department of Agriculture, National Agricultural Statistics Service, 2004, April); meat animal production, except poultry and eggs: (U.S. Department of Agriculture, National Agricultural Statistics Service, 2004, April); and (U.S. Department of Agriculture, National Agricultural Statistics Service, 2005, April); poultry and egg production: (U.S. Department of Agriculture, National Agricultural Statistics Service, 2004, April).
[31] (U.S. Department of Agriculture, National Agricultural Statistics Service, 2003, July)

[32] (U.S. Geological Survey, 2010)
[33] (U.S. Geological Survey, 2009)
[34] (U.S. Department of Energy, Energy Information Administration, n.d.)
[35] (U.S. Department of Energy, Energy Information Administration, 2004)
[36] (Electric Power Research Institute, 2002, March)
[37] (Torcellini, Long, & Judkoff, 2003)
[38] (International Energy Agency, 2009)
[39] (U.S. Department of Energy, Energy Information Administration, n.d.)
[40] (Glieck, et al., 2003, November)
[41] (U.S. Census Bureau, 2007)
[42] (MTR Corporation, 2007)
[43] (U.S. Department of Energy, Energy Information Administration, n.d.)
[44] For coal: (U.S. Department of Energy, Energy Information Administration, 2010, August) Table 7.8 (p.. 221); oil: (U.S. Department of Energy, Energy Information Administration, 2009, September); natural gas: (U.S. Department of Energy, Energy Information Administration, n.d.).
[45] Output data for coal: (U.S. Department of Energy, Energy Information Administration, 2010, August), Table 7.2 (p. 221); natural gas: (U.S. Department of Energy, Energy Information Administration, n.d.); oil: (U.S. Department of Energy, Energy Information Administration).
[46] (Suh, Developing a Secoral Environmental Database for Input-Output Analysis: the Comprehensive Environmental Data Archive of the U.S., 2005)
[47] (Lubowski, Vesterby, Bucholtz, Baez, & Roberts, 2006)
[48] (U.S. Department of Agriculture, National Agricultural Statistics Service, 2004, June)
[49] (U.S. Department of Agriculture, Forest Service, 2010)
[50] (Litman, 2005)
[51] (U.S. Environmental Protection Agency and the U.S. Department of Energy, 2008); (Lawrence Berkeley National Laboratory, Technology Evaluation Modeling and Assessment Group, 1998); (Lawrence Berkeley National Laboratory, Environmental Energy Technologies Division, 2010); (ABS Alaskan, Inc.); (American Council for An Energy Efficient Economy); (National Resources Canada, Office of Energy Efficiency, 2009); (Hendron & Eastment, 2006, August); (Federal Trade Commission); (TIAX LLC, 2006, September)
[52] (Coachbuilt.com, Inc., 2000 - 2010); (Oguchi, Kameya, Yagi, & Urano, 2008, January); and (Spon & Sjostrom, 1996, July)
[53] (National Association of Home Builders/Bank of America Home Equity, 2007)

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