Modeling Pollution using Input-Output Analysis

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Abstract

Using data on pollution facilities across the US, input-output tables based on BEA data, and US Census Bureau data, we determine which sectors contribute most to the lead and sulfuric acid pollution. We compare these results with a measure of pollution weighted by population density. We find that for sulfuric acid and lead the sectors with the highest pollution are electrical power generation and electrical components, respectively.

Executive Summary

A change in demand for goods from any one sector generates not just an increase in production in that sector, but also an increase in production of all sectors that provide inputs to that sector, and so on. A by-product of production is pollution. Thus, an increase in demand for goods from one sector generates new pollution from many different sectors. Input-output analysis, which models inter-sector effects, is therefore an appropriate tool for estimating increases in pollution caused by a change in demand.

We use 2002 input-output tables from the Bureau of Economic Analysis to produce an input-output table. Using 2002 data from the EPA's Toxic Release Inventory Program, and the Commission for Environmental Cooperation, we analyze pollution generated by each sector, and pollution weighted by population density in each facility's county. We estimate the changes in two pollutants, sulfuric acid and lead, caused by a change in demand for each of 133 sectors.

We find that the sector that generates the most lead pollution is "Other Electrical Equipment and Components." An increase in demand for goods from that sector generates more than twice as much indirect pollution as direct. The industry that generates the must sulfuric acid is "Electric Power Generation and Distribution." That sector generates only a small fraction in indirect pollution.

Introduction

An economy is said to be efficient when it maximizes its net benefits. Economists theorize that free markets lead to efficiency if several stringent conditions are met. For example, there can be no externalities, i.e., all costs and benefits must be internalized by those producing the product and those consuming it. When one of the conditions is not met, there is said to be "market failure," which leads to inefficiency, and justifies government intervention. For government action to be effective, it must be informed about complex and dynamic variables.

One form of a negative externality is pollution (there can be positive externalities, such as those from flu vaccines). Pollutants are by-products of production or consumption that are released into the environment through a variety of mediums, and which have a negative effect on people or the environment. If a factory generates pollution, then there is a cost borne by society that is omitted from the cost of production. If some costs aren't internalized, then the marginal social cost lies above the marginal private costs. The market is presumed to lead to a production level in which marginal private costs equal marginal benefits, but this leads to over production, as the marginal unit costs society more than it benefits society.

Effective government intervention, i.e., intervention that produces an efficient outcome, requires some understanding of the magnitude of the external costs. If the external costs are known, then there are several tools that governments can use to effect an efficient outcome, including mandating a minimum level of pollution, imposing a marginal tax rate on pollutants, or selling permits that allow factories to produce a prescribed amount of pollutants.

For each of these tools, governments influence the production level for specific sectors by influencing the production costs for those sectors. However, it's important to note that changes in one sector influence other sectors as well. Each industry requires as inputs to its production outputs from other industries. Thus, it's important for government to consider the inter-sector effects of a change in production.

Input-output models are well suited to this task. They are designed to analyze the change in production in all sectors that results from a change in one sector. They can easily be adapted to analyze the change in total pollution that would result from increased demand in any one sector. In this paper, we endeavor to apply input-output analysis to emissions of two particular pollutants, sulfuric acid and lead.

Literature Review

The input-output model was created by Wassily Leontief [5, c.f. chapter 7]. Input-output models measure inter-sector effects created by each sector's demand for inputs from another sector. For N sectors, the model can be put in the form of an $N * N$ matrix. Each cell x_{ij} in the matrix represents the output from sector i used as input for j. Given an exogenous change in demand, it's possible to solve for the total number of goods produced by each sector. An important insight given by input-output models is that a change in demand in one sector affects demand in many other sectors.

In [4], Leontief pointed out that input-output analysis can be adapted to model changes in pollution. If the amount of pollution per unit of output (measured in any unit, e.g., dollars) can be determined, then another row can be added to the matrix that captures pollution per sector. Alternatively, as Leontief notes, the above method may be used to solve for the output of each sector, and then the total output for each sector can simply be multiplied by the pollution per unit of output for that sector. Leontief also explains that the pollution abatement industry can be included in the analysis. This leads to the interesting conclusion that pollution abatement efforts cause some increase in pollution, in the generation of inputs for the abatement industry.

Baumol and Wolff [1] underscore the importance of input-output analysis in estimating the effects of various policies aimed at reducing pollution. As an example, they analyze polices to reduce our dependence on oil. Using input-output analysis, they conclude that a tariff on oil would be more effective than subsidies for alternative fuel production. A tariff, they note, affects oil use in all sectors, and a subsidy for alternative energy production might actually reduce the nation's energy stocks.

The Economic Input-Output Life Cycle Analysis (EIO-LCA) project of Carnegie Mellon has applied Leontief's model to pollution measurement [6]. Indeed, they take his approach further, by seeking to capture, as the name of the project suggests, the life cycle effects of each good. Thus, in addition to accounting for the inter-sector effects of producing, e.g., a paper cup, they also include the costs of disposing of that cup and the costs of its portion of a landfill. They have several models based on 1997 data, and an interactive data generator on their website, with which one can estimate the total costs caused by demand for any one sector.

Model

The input-output model, as described above, can be used to determine the change in production in every sector caused by a change in demand for goods from any one sector using Leontief's method of solution. The key to that solution is his use of input-coefficients. For each cell x_{ij}, its input coefficient a_{ij} can be found by:

$$a_{ij} = \frac{x_{ij}}{x_j}$$

It represents the unit of input from sector i used by sector j per unit of output from sector j.

In equilibrium, the following equations must hold, where y_n is demand for goods from sector n:

$$\begin{array}{ccccccc}(x_1 - x_{11}) & - & x_{12} & - & x_{1n} & = y_1 \\ x_{21} & + & (x_2 - x_{22}) & - & x_{2n} & = y_2 \\ \vdots & & \dots & \ddots & & = \vdots \\ -x_{n1} & - & x_{n2} & & (x_n - x_{nn}) & = y_n\end{array}$$

Substituting a_{ij} yields

$$\begin{array}{ccccccc}(1 - a_{11})x_1 & + & -a_{12}x_2 & - & a_{1n}x_n & = y_1 \\ -a_{21}x_1 & + & (1 - a_{22})x_2 & - & a_{2n}x_n & = y_2 \\ \vdots & & \dots & \ddots & & = \vdots \\ -a_{n1}x_1 & - & a_{n2}x_2 & & (1 - a_{nn})x_n & = y_n\end{array}$$

which can be written in matrix form as

$$(\mathbf{I} - \mathbf{A})\mathbf{x} = \mathbf{y}$$

the solution to which is

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$$

We use an input-output model based on input-output tables for 133 sectors from 2002, the most recent year for which detailed tables are available, generated by The Bureau of Economic Analysis [2]. Their data need some conversion, for which we followed the method outlined by [8]. Using data from [3] for almost 61,500 facilities in 2002, we were able to determine the lead and sulfuric acid generated by each sector in pounds. We then follow

Leontief's advice, and rather than incorporating the pollution coefficients directly into the matrix, we solved for output per sector, and multiplied this by the pollution per unit of output for each sector. To determine which sector had the greatest impact on pollution, we increased demand for each of the 133 sector one at a time.

Also, as [7] point out, pollution has a greater impact in areas with high population density. Thus, using data from the US Census Bureau [9], we weighted the pollution from each of almost 61,500 facilities by the population density of each respective county. We then repeated the above analysis with the weighted pollution figures for sulfuric acid and lead.

Results

Tables 1 and 2 list the sectors that produce the most sulfuric acid and lead, respectively, and their pounds of pollution per million dollars worth of output. We found that by increasing the demand for output from each of 133 sectors by 100 million dollars, the sector that generated the largest increase in lead was "Other Electrical Equipment and Components," which includes storage battery manufacturing, primary battery manufacturing, etc. Increasing demand for other electrical equipment and components increased total lead pollution by 347,000 pounds. The pollution coefficient of lead for that sector is 1,670 per million dollars, so an increase of 100 million dollars generated 167,000 pounds of additional pollution directly. More than twice that amount was generated indirectly by an increase in other inputs to that sector.

The sector that generated the most increase in sulfuric acid was "Electric Power Generation, Transmission and Distribution." An increase for demand for electrical power generation of 100 million dollars increased sulfuric acid pollution by 23,000 pounds. The pollution coefficient of sulfuric acid for that sector is 217 per million dollars; thus, 21,700 pounds of pollution are generated directly from the increase in demand for that sector, and 1,300 pounds are generated by increased demand for inputs into that sector.

For both pollutants, the results for the weighed coefficients were similar to the respective non-weighted results. Lead has a weighed coefficient of 1,294,711 per million dollars of output. Other electrical equipment and components had the largest effect, generating 418,000,000 more weighted lead, of which 129,000,000 came directly from an increase in production in that sector, while more than three times as much was generated by the necessary increases in output from other sectors.

Sulfuric acid had a weighted coefficient of 105,000. Electric power generation, transmission and distribution again had the greatest effect, causing 16,000,000 more weighted pounds of sulfuric acid. The direct increase was 10,500,000.

Table 1, Sulfuric Acid Emissions

Sector	Output, Mill. $	Pollution Pounds	Pollution per Mill. $ of Output
Elec. Power Generation Transmission, Dist.	228,069	50,000,000	218
Petroleum and Coal	211,697	3,900,000	18
Pulp, Paper Paperboard	70,025	1,700,000	24
Nonmetallic Mineral Products	93,321	840,000	9
Food Products	445,174	370,000	.82

Table 2, Lead Emissions

Sector	Output, Mill. $	Pollution Pounds	Pollution per Mill. $ of Output
Other Electrical Equip. and Compon.	36,263	60,000,000	1,670
Primary Nonferrous Metal Products	49,737	28,000,000	567
Petroleum and Coal Products	211,697	10,000,000	47
Elec. Power Generation Transmission, Dist.	228,069	3,900,000	17
Ordnance and Accessories	5,197	2,800,000	537

Conclusions

The above analysis reinforces the idea that an increase in production in one industry causes pollution to increase, not just in that industry, but in all the industries that supply it (and those that supply the suppliers). Electrical equipment and components produces a tremendous amount of lead, yet an increase in demand for goods from that sector causes a much greater increase in lead pollution from other sectors. Conversely, electric power generation and transmission generates significant sulfuric acid, but an increase in demand for goods from that sector does not generate as much of an increase in sulfuric acid from all other industries.

This analysis assumes constant returns to inputs of production. As [6] points out, this is a short-coming of input-output analysis. For example, this analysis assumes that doubling production of coal will require all other inputs to exactly double. It's far more likely that industries experience either economies of scale, in which input required per unit of output decreases, or diseconomies of scale, where the opposite is true. Further analysis of inter-sector effects of pollution should consider this.

Additionally, as pointed out in [3], firms are only required to report pollution above a certain threshold. Thus, this analysis understates the true increase in pollution cause by an increase in demand from one sector. Also, in future analyses, a more sophisticated method should be employed for weighting the pollutants by population. Such methods exist, c.f. [7].

Appendix

Data Processing Methods

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From US Census Bureau: Population by 3 digit zip code, total pop, sex by age
http://factfinder.census.gov/servlet/DTGeoSearchByListServlet?ds_name=DEC_2000_SF1_U&_la

From http://www.epa.gov/tri/tridata/tri02/data/index.htm
2002 EPA TRI Facility info

From CEC.org http://cec.org/takingstock/takingstock.cfm?activityId=27&varlan=english
Commission for Environmental Cooperation
2002 NPRI/TRI (Bilateral) Dataset
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From BEA: http://www.bea.gov/industry/xls/2002summary_makeuse.xls

Make-Use Tables, NAICS to IO conversion table

From US Census Bureau: Conversion table SIC to NAICS

http://www.census.gov/cgi-bin/sssd/naics/naicsrch?chart=2002

2002 Input-Output Tables

http://www.the-idea-shop.com/article/197/building-an-input-output-table-from-bea-make-an

http://www.the-idea-shop.com/data/2002%20Input-Output%20Table.xls

Data processing:

In NPRI/TRI dataset

Have 84,200 entries + column headings

Deleted Records with no TRIFID, i.e., info for Canadian facilities

Have 76138 Records

Focused on those for which there's only one sector id, i.e., facilities that fit only on

Have 61498 Records

In EPA TRI Facility Data

Have 93380 entries + column headings

Deleted all columns accept TRIFID, and Facility name and location info. E.g., deleted "

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Deleted duplicate facilities

Have 24379 entries + column headings

Did find and replace on TRIFID to delete dashes, to match CEC dataset format


In new sheet,

created column with TRIFID from NPRI/TRI dataset

Created Column "Facility Name" with =VLOOKUP(A2, EPA_TRIFData!I2:$GS$93381, 2, FALSE) to


Using pivot table, created total sulfuric acid released by sector


Converted SIC codes into NAICS codes


Converted NAICS codes into I/O codes


In 2002 Input Output Tables

Created A Matrix from input output table.

cell a_{ij} in A = x{ij}/x{j} from input output table.

Created Identity matrix 133X133

Created (I-A)

Created (I-A)^1
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References

[1] W.J. Baumol and E.N. Wolff. A key role for input-output analysis in policy design. *Regional Science and Urban Economics*, 24(1):93–113, 1994.

[2] Bureau of Economic Analysis, December 2008. http://www.bea.gov/industry/.

[3] Commission for Environmental Cooperation, December 2008. http://cec.org/takingstock/.

[4] W. Leontief. Environmental Repercussions and the Economic Structure: An Input. 1970.

[5] Wassily Leontief. *Input-Output Economics*. Oxford University Press, New York, New York, 1966.

[6] Carnegie Mellon. EIO-LCA, December 2008. http://www.eiolca.net.

[7] N.Z. Muller and R. Mendelsohn. Measuring the damages of air pollution in the United States. *Journal of Environmental Economics and Management*, 54(1):1–14, 2007.

[8] The Idea Shop, December 2008. http://www.the-idea-shop.com/article/197/building-an-input-output-table-from-bea-make-and-use-tables.

[9] US Census Bureau, December 2008. http://factfinder.census.gov/.