Excerpt from "Introduction to Energy Analysis"

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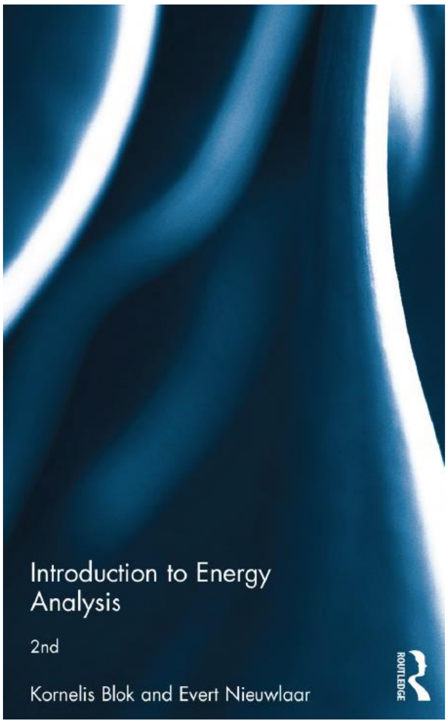
Kornelis Blok and Evert Nieuwlaar



This document contains the chapter on input-output analysis only.

9.3 Input-output energy analysis

Process energy analysis follows the flows of materials in order to determine how much primary energy is required to deliver a certain product or service.

Table 9.1 Selected figures for the cumulative energy demand (CED) of a number of important materials

Material	*CED (GJ/tonne)*	*Material*	*CED (GJ/tonne)*
Steel – low alloyed, hot rolled	24	Polyethylene	80
Steel – chromium, hot rolled	69	Polypropylene	76
Aluminium – primary ingot	218	Polystyrene	89
Copper	97	Printing paper	48
Container glass	15		

Source: Ecoinvent 3.1 (2014). CED data produced with data from the Ecoinvent 3.1 database with permission by Ecoinvent (Zürich, Switzerland).

The flows are expressed in physical terms, like tonnes of material. Input-output energy analysis does the same, but now the flows are expressed in monetary terms. Once again, the question is, when a sector produces something, how much primary energy is needed, including for *all* upstream activities?

The result is generally expressed as the energy intensity (or cumulative energy intensity) of the output of this sector: the primary energy requirement per unit of monetary output.

Input-output analysis is widely used by economists to analyse policy issues, such as the effect changing government investments might have on employment and gross domestic product.

What are input-output statistics?

One way to describe an economy is to map all the deliveries between each producer, trader and consumer. To do this would require an enormous amount of data and would be hardly manageable. A useful summary of all these deliveries can be made in the form of a so-called input-output table. Here, the economy is broken down into a number of sectors (say, 60) and all the deliveries between these sectors are mapped. Such input-output tables are usually published by national statistics bureaus as part of the national accounts.

What deliveries occur in an economy? First of all, there are the final deliveries: products are delivered to the final consumers. These deliveries can be to households, and the government, but they also include investments, exports and stockpiling. Second, there are the intermediate deliveries: companies deliver goods and services to each other. These are deliveries that are needed in order to produce other products: e.g. feedstock materials, parts of products, production equipment, office supplies, maintenance services and security. Finally, there are imports: some of the products originate from abroad. Both companies and final consumers import products. Of course, other expenditures of companies also need to be described: depreciation on investments, salaries, taxes and profits.

An input-output table for an economy is organised by sector. If an input-output table is broken down into n sectors (typically $n = 60$), the core of the input-output table is an n by n matrix, in which each cell describes the deliveries between two particular sectors. On the rows one finds the supplying sectors, in the columns the receiving sectors (both make up the same sets of sectors). So, at the intersection of row *i* and column *j*, one would find the monetary value of the goods and services that are delivered from companies in sector *i* to companies in sector *j*. Additional rows and columns of size *n* are used to describe final deliveries, imports and exports and the other cost components of companies.

Input-output analysis

To get accustomed to the input-output approach, here is a simple fictitious economy, consisting of three sectors, only households as final consumers and no exports or imports. The three sectors are basic metal production, electrotechnical industry and the machinery industry. The input-output (I/O) table could look as shown in Table 9.2.

In this example, the basic metal industry delivers products worth 217 million euros to the electrotechnical industry and the machinery industry delivers products worth 4,271 million euros to the households. The intermediate deliveries (columns 1 to 3 and rows 1 to 3) form the core matrix of intermediate deliveries that we will call D in the following. Table 9.2 can be written in a more general way as shown in Table 9.3.

Note that x_i is not only the total deliveries from sector *i*, but also the total input (including added value) of sector *i*. Thus:

$$x_i = \sum_{j=1}^{n} d_{ij} + f_i = \sum_{k=1}^{n} d_{ki} + w_i \qquad [9.1]$$

In our example, the total deliveries of the basic metal industry, $x_1 = 784 + 217 + 135 + 2 = 1{,}138$ M€. To produce these deliveries, an equal input of 1,138 M€, including the added value, was needed ($x_1 = 784 + 32 + 300 + 22 = 1{,}138$ M€).

Ultimately, we are interested in the energy that is used to deliver the products. To this end, we need to know what activities are generated when something is delivered. Let us consider a concrete purchase in more detail.

Table 9.2 Input-output (I/O) table of a simplified economy (in million euros)

		1	*2*	*3*	*4*	*5*
		Basic metal industry	*Electrotechnical industry*	*Machinery industry*	*Households*	*Total*
1	*Basic metal industry*	784	217	135	2	**1,138**
2	*Electrotechnical industry*	32	737	234	1,066	**2,069**
3	*Machinery industry*	300	89	160	4,271	**4,820**
4	*Added value*	22	1,026	4,291	0	**5,339**
5	***Total***	**1,138**	**2,069**	**4,820**	**5,339**	**13,366**

Table 9.3 General representation of an I/O table

		1	*2*	*3*		
		Basic metal industry	*Electrotechnical industry*	*Machinery industry*	*Final deliveries*	*Total*
1	*Basic metal industry*	d_{11}	d_{12}	d_{13}	f_1	x_1
2	*Electrotechnical industry*	d_{21}	d_{22}	d_{23}	f_2	x_2
3	*Machinery industry*	d_{31}	d_{32}	d_{33}	f_3	x_3
	Added value	w_1	w_2	w_3		
	Total	x_1	x_2	x_3		

Legend:

d_{ij} = deliveries from sector *i* to *j*
f_i = final deliveries from sector *i* to the end users (including export)
w_i = added value from sector *i* (added value is the total of sales minus the total of purchases; added value can be used to pay salaries and dividends etc.)
x_i = total deliveries from sector *i*

Assume that a household purchases a product of the electrotechnical industry that costs one euro – e.g. a light bulb. First of all, this generates a delivery (and associated activity) by the electrotechnical industry itself, which we call the zero order delivery: if the consumer spends one euro, the electrotechnical industry has to deliver one euro.[3]

The electrotechnical industry cannot produce the light bulb out of thin air: it has to purchase materials, machinery or services from other sectors. To determine these indirect deliveries, we use the input-output table, and derive a so-called technology matrix, **A**. The technology matrix does not represent the total deliveries between the sectors, but the deliveries that are needed per unit of total output (i.e. per euro of output). Hence, each value in the core matrix **D** is divided by the total delivery x_i (row 5 in Table 9.2). In our simplified case, the technology matrix is a 3 × 3 matrix, and its values can be calculated to be:

$$\mathbf{A} = \begin{bmatrix} 0.689 & 0.105 & 0.028 \\ 0.028 & 0.356 & 0.049 \\ 0.264 & 0.043 & 0.033 \end{bmatrix} \qquad [9.2]$$

In the formal way this is written as:

$$a_{ij} = \frac{d_{ij}}{x_j} \qquad [9.3]$$

E.g. $a_{13} = d_{13}/x_3 = 135/4{,}820 = 0.028$.

In each column we can see the purchases producers in that sector need to make to deliver a product with a value of one euro. Column two represents the purchases by the electrotechnical industry: if we buy a light bulb of one euro, this sector needs to spend 0.105 euro in the basic metal industry, 0.356 euro in the electrotechnical industry, and 0.043 euro in the machinery industry. These are called the first order deliveries.

In fact this outcome can be considered as the result of the multiplication of the matrix **A** with the vector $\begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$, where the latter vector represents the purchase of one euro from the electrotechnical industry. This vector is called the extra final deliveries and is represented by **F**. So, the first order deliveries are $\mathbf{A} \cdot \mathbf{F}$.

This is not the end of the story. If the electrotechnical industry purchases 0.105 euro from the basic metal industry, this sector in turn needs to purchase 0.105 × 0.689 euro from the basic metal industry, 0.105 × 0.028 euro from the electrotechnical industry, and 0.105 × 0.264 euro from the machinery industry. These are called the second order deliveries. They can be represented as: $\mathbf{A} \cdot \mathbf{A} \cdot \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$ or more generally as $\mathbf{A} \cdot \mathbf{A} \cdot \mathbf{F}$ or $\mathbf{A}^2 \cdot \mathbf{F}$.

To make a long story short: for our simple light bulb purchase, there are also third order deliveries, fourth order deliveries and so on. The total deliveries by the sectors such that one euro is delivered by the electrotechnical industry is:

$$[\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \mathbf{A}^4 + \mathbf{A}^5 + \ldots] \cdot \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \qquad [9.4]$$

Note that the unit matrix **I** (with 1 on the main diagonal from upper left to lower right and 0 in all the other places) represents the zero order deliveries.

The sum of the series of matrices $\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \ldots$ is called **P**. From matrix algebra, we know that the sum of the series of matrices can – under certain conditions – be replaced by a simple expression:

$$\mathbf{P} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \mathbf{A}^4 + \mathbf{A}^5 + \ldots = (\mathbf{I} - \mathbf{A})^{-1} \qquad [9.5]$$

For our simplified case, the matrix **P** takes the following form:[4]

$$\mathbf{P} = \begin{bmatrix} 3.37 & 0.56 & 0.13 \\ 0.22 & 1.59 & 0.09 \\ 0.93 & 0.22 & 1.07 \end{bmatrix} \qquad [9.6]$$

The matrix **P** is called the Leontief inverse, after the economist W. Leontief who played a key role in developing input-output analysis.

It should be clear that the figures in matrix **P** represent the total direct and indirect activities that are needed to provide a certain delivery. More precisely, the figures in a column represent how much each sector should deliver in order to provide one unit of final output for the sector associated with that column. For the case of our simple input-output table this means that if the electrotechnical industry wants to deliver one euro of final product, the total of direct and indirect production needed for this delivery is 0.56 euro by the basic metal industry, 1.59 euro by the electrotechnical industry, and 0.22 euro by the machinery industry. The extra (cumulative) deliveries are called **X**.

This is an important result: we are now able to describe how much activity is required to supply something to a final consumer. The above calculation can be written formally as:

$$\Delta \mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \Delta \mathrm{F} = \mathbf{P} \cdot \Delta \mathrm{F} \qquad [9.7]$$

where:

X = cumulative (direct and indirect) deliveries

P = Leontief matrix

F = extra final deliveries

In the case of the light bulb:

$$\Delta \mathrm{X}_{lightbulb} = \begin{bmatrix} 3.37 & 0.56 & 0.13 \\ 0.22 & 1.59 & 0.09 \\ 0.93 & 0.22 & 1.07 \end{bmatrix} \begin{bmatrix} 0 \\ 1\text{Euro} \\ 0 \end{bmatrix} = \begin{bmatrix} 0.56 \\ 1.59 \\ 0.22 \end{bmatrix} \qquad [9.8]$$

Note that **P** · **F** (where **F** is the vector with the final deliveries f_i) is equal to the total deliveries **X**, as all the intermediate deliveries are allocated to the final consumers:[5] $x_1 = 3.3716 \cdot 2 + 0.5577 \cdot 1{,}066 + 0.1257 \cdot 4{,}271 = 1{,}138$ M€. In matrix form we get:

$$\mathbf{X} = \begin{bmatrix} 3.3716 & 0.5577 & 0.1257 \\ 0.2173 & 1.5945 & 0.0864 \\ 0.9290 & 0.2230 & 1.0724 \end{bmatrix} \begin{bmatrix} 2 \\ 1{,}066 \\ 4{,}271 \end{bmatrix} = \begin{bmatrix} 1{,}138 \\ 2{,}069 \\ 4{,}820 \end{bmatrix} \qquad [9.9]$$

Input-output energy analysis

We will use these findings to determine how much energy is required to deliver one unit of product. To go back to our simple economy, we know that if we purchase one euro from the electrotechnical industry, this induces the production of 0.56 euro in the basic metal industry. We now need to know how much direct energy is needed in the basic metal industry to produce this 0.56 euro. Here, a simple last step is required: we need to add information on the total amount of energy that is needed for each of the sectors. To this end, we assume the figures shown in Table 9.4:

Table 9.4 Primary energy use figures for our simplified economy

Sector	*Energy use (TJ)*
Basic metal industry	25
Electrotechnical industry	4
Machinery industry	6

From this table, for each sector *i* we can derive the so-called direct energy intensity $_{dir,i}$. This is the energy use of the sector divided by its total output (found in the last column in Table 9.2). For instance, for the basic metal industry $_{dir,1}$ = 25 TJ / 1.138 G€ = 22 kJ/€, which means that the basic metal industry needs 22 kJ of energy to deliver 1 € of product. For the other two sectors, the figures are 1.9 kJ/€ and 1.2 kJ/€ (rounded figures). The last step in our light bulb problem is now to multiply these energy intensities with the extra activity in each sector that was generated by the light bulb purchase: 22 kJ/€ · 0.56 € + 1.9 kJ/€ · 1.59 € + 1.2 kJ/€ · 0.22 € = 15.6 kJ.

In matrix notation, this takes the following form. Note that the first vector denotes the three ratios of energy input divided by output for each sector.

$$
\begin{aligned}
E_{lightbulb} &= [25\ \mathrm{TJ}/1.138\ \mathrm{G€} \quad 4/2.069 \quad 6/4.820] \\
&\quad \begin{bmatrix} 3.37 & 0.56 & 0.13 \\ 0.22 & 1.59 & 0.09 \\ 0.93 & 0.22 & 1.07 \end{bmatrix} \begin{bmatrix} 0 \\ 1\,Euro \\ 0 \end{bmatrix} \\
E_{lightbulb} &= [21.97\ \mathrm{kJ/€} \quad 1.933 \quad 1.24] \\
&\quad \begin{bmatrix} 3.37 & 0.56 & 0.13 \\ 0.22 & 1.59 & 0.09 \\ 0.93 & 0.22 & 1.07 \end{bmatrix} \begin{bmatrix} 0 \\ 1\,Euro \\ 0 \end{bmatrix}
\end{aligned}
\qquad [9.10]
$$

Check that again $E_{lightbulb}$ = 15.6 kJ.

We can generalise our findings as follows. Assume that we carry out a set of purchases denoted by the vector **F**, where each row denotes the purchase from the sector associated with that row. We further define the vector $_{\mathbf{dir}}$ as the vector describing the direct (normalised) energy intensities of the various sectors. $_{dir,i}$ is the ratio E_i/X_i, where:

> E_i = primary energy requirement associated with the direct energy use of sector *i* (see Table 9.4)
>
> X_i = total deliveries of sector *i* (the total of the rows in the input-output table – e.g. column 5 in Table 9.2).

We can now describe the total extra energy **E** required for the delivery of **F** as:

$$\Delta \mathbf{E} = \boldsymbol{\varepsilon}_{dir}{}^{t}\,(\mathbf{I} - \mathbf{A})^{-1}\,\Delta \mathbf{F} = \boldsymbol{\varepsilon}_{dir}{}^{t} \cdot \mathbf{P} \cdot \Delta \mathbf{F} \qquad [9.11]$$

Note that the superscript *t* for vector $\boldsymbol{\varepsilon}_{dir}$ is only to denote that the vector is transposed (the vertical vector is written horizontally).

In general we are not interested in the total energy requirement, but in the specific value: the amount of energy needed per unit of purchase. This is what is called the cumulative energy intensity of production. Cumulative means that all the direct and indirect energy requirements are included in this calculation. The cumulative energy intensities can be described as a vector $_{cum}$, where the elements $_{i}$ represent the cumulative energy intensities of sectors *i*:

$$\boldsymbol{\varepsilon}_{cum}{}^{t} = \boldsymbol{\varepsilon}_{dir}{}^{t}\,(\mathbf{I} - \mathbf{A})^{-1} \qquad [9.12]$$

The cumulative energy intensities in our example are equal to:

$$\begin{aligned} \boldsymbol{\varepsilon}_{cum}{}^{t} &= \boldsymbol{\varepsilon}_{dir}{}^{t}(\mathbf{I} - \mathbf{A})^{-1} \\ &= \begin{bmatrix} 25/1.138 & 4/2.069 & 6/4.820 \end{bmatrix} \begin{bmatrix} 3.37 & 0.56 & 0.13 \\ 0.22 & 1.59 & 0.09 \\ 0.93 & 0.22 & 1.07 \end{bmatrix} \qquad [9.13] \\ \boldsymbol{\varepsilon}_{cum}{}^{t} &= \begin{bmatrix} 75.6 & 15.6 & 4.3 \end{bmatrix} \text{ kJ/Euro} \end{aligned}$$

The cumulative energy demand *E* for the increase in final demand $\Delta\mathbf{F}$ can now be calculated as:

$$E = \boldsymbol{\varepsilon}_{cum}{}^{t} \cdot \Delta \mathbf{F} \qquad [9.14]$$

For our example, the total cumulative energy needed for an extra purchase becomes:

$$E = \begin{bmatrix} 75.6 & 15.6 & 4.3 \end{bmatrix} \text{kJ/€} \cdot \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \text{€} = 15.6 \text{ kJ} \qquad [9.15]$$

But E is NOT:

$$E \neq \boldsymbol{\varepsilon}_{cum}{}^{t} \cdot \mathbf{X} \qquad [9.16]$$

as in this case the intermediate deliveries would be counted twice; they are included in the cumulative energy intensity $_{cum}{}^{t}$ and in the cumulative deliveries **X**.

Note that we can calculate the total energy input by multiplying the cumulative energy vector with the final demand (see column 4 of Table 9.2). We then get $E_{tot} = 75.7 \cdot 2 + 15.7 \cdot 1{,}066 + 4.4 \cdot 4{,}271$ (kJ/€ · M€) = 35.7 TJ. Apart from a rounding error, this is equal to the total energy input of 35 TJ (see Table 9.4).

The energy sector in input-output tables

The simple input-output tables we have used (Tables 9.2 and 9.3) do not contain an energy sector. Of course, all real input-output tables include one or more energy sectors in the core matrix. There are three ways to treat deliveries by the energy sector in energy input-output analysis:

- The first is to treat the energy sector as a normal sector. A country's energy extraction plus its energy imports are delivered to the energy sector. Through the regular I/O formalism, this energy is re-allocated to the other sectors. In practice, this means that the energy vector $\boldsymbol{\varepsilon}$ contains values representing extraction and imports. However, this approach has trouble dealing with the differences in energy prices (e.g. households often pay twice as much per kWh as large consumers of electricity). If the distribution of energy inputs were done on the basis of monetary flows, this would lead to a wrong allocation (too much primary energy use would be allocated to the households).
- The second approach takes figures from energy statistics that are directly allocated to all the sectors in the I/O table and distributes them manually. This is the approach described above. To avoid double counting, the energy deliveries to the energy sector need to be set to zero. This approach requires some extra work, but it is more accurate. Whether this accuracy gain is important will depend on the aim of the analysis.
- National statistics offices sometimes publish gross and net energy consumption for the sectors in the national accounts. The net energy consumptions are usable for input-output analysis. The net energy consumption for each sector reflects the final energy consumption of the sector. Conversion losses in the energy sectors are allocated to the energy sectors.

Table 9.5 shows some results for sectors in the Netherlands for the year 2013, using the third approach mentioned.

The accuracy of input-output energy analysis

The most important drawback of input-output analysis is its implicit assumption that all deliveries between sectors are homogeneous, which is not always the case. For example, we have seen that the energy prices may be different for each sector. Another example is where the chemical industry is considered as one sector in an input-output table. This sector produces both feedstocks for plastic (like polyethylene) and pharmaceuticals. The first requires very energy-intensive feedstocks from refineries, whereas the second uses high-value, low

Table 9.5 Direct and cumulative energy intensities of sectors in the Netherlands (2013)

Sector	$(\overset{dir}{M}J/€)$	$(\overset{cum}{M}J/€)$	*Sector*	$(\overset{dir}{M}J/€)$	$(\overset{cum}{M}J/€)$
Agriculture, forestry and fishing	4.99	7.77	Transport equipment	0.38	1.34
Food, beverages and tobacco	1.29	3.59	Construction industry	0.70	2.01
Textile and leather products	1.50	3.44	Trade	0.71	1.38
Wood products	1.34	2.15	Transport over land	3.57	5.24
Paper industry	4.36	7.11	Transport over water	14.46	15.34
Publishing industry	1.47	2.76	Air transport	17.38	18.72
Petroleum products	4.84	5.66	Business activities, renting of movables	1.09	1.19
Chemicals and pharmaceuticals	16.46	22.04	Information and communication	0.35	0.78
Rubber and plastics	1.04	5.12	Financial services	0.23	0.46
Building materials	4.62	6.66	Real estate	0.18	0.74
Basic metals	16.52	19.09	Business services	0.31	0.88
Metal products	0.68	2.91	Governmental services and activities	0.71	1.51
Electrotechnical industry	0.07	0.30	Education	0.66	0.98
Electrical equipment industry	2.30	2.91	Health and social work	0.66	1.21
Machine industry	0.30	1.09	Culture, sport and recreation	1.25	2.56

Source: own calculations based on I/O and energy data published by CBS (2014)

energy-intensity materials. Aggregating the various outputs of the chemical industry as one group of deliveries may lead to senseless results.

This problem makes input-output energy analysis less suitable for detailed analysis (e.g. of individual products), than for getting an overall picture. Furthermore, input-output analysis may be useful in combination with process energy analysis (see the next section).

Another complication is that the input-output tables are based on the average technology mix in use in an economy. Deliveries for new technologies or new products can differ significantly from average purchases or investments.