Chapter 22
Application of the IO Methodology to the Energy and Environmental Analysis of a Regional Context

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Introduction

Aims of the Study

Performing an energy and environmental analysis, researchers have to face many problems regarding the data quality and availability. Data are often out-of-date, not representative and consistent or, frequently, referred to faraway geographic and productive contexts. The Input-Output (IO) model, due to its simplicity, allows to acquire information regarding the energy and environmental performances of productive sectors.

The present paper describes an application of the energy and environmental IO based model to a regional context: the case study of Sicily (Italy). The main aims of the study are:

- *To investigate the advantage/disadvantages of IO approach*
- *To evaluate the possibility of employing the IO model as a tool to support regional strategies*
- *To employ the results as a basis for further environmental analysis (i.e. as support to regional studies of Life Cycle Assessment - LCA)*

The study also focused the attention on the limits of such approach and the problems arisen in the showed application. A sensitivity analysis of the method and of available data has been performed.

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S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

The IO approach can be employed to continuously monitor the environmental evolution of productive sectors and to assess if and how an economy is moving towards a trend of sustainability. Following the Kyoto protocol agreements, Italy should decrease its CO_2 emissions of about 6% till 2012. An IO based environmental model can support stakeholders to individuate the sectors with the higher margin of environmental improvement, to monitor their emission trends and to evaluate the efficacy of energy and environmental policies.

Input-Output Model

The economic IO analysis, developed by W.W. Leontief, studies the relations between economic sectors (Leontief 1941, 1966). Since Leontief's first publications, hundreds of books and papers on IO analysis have been published. A state-of-the-art overview is given by Miller and Blair (1985), Sohn (1986), Rose and Miernyk (1989).

The IO method assumes that the economy structure of a country can be represented by the following economic subjects:

- Industries or sectors that produce goods and services
- Household sector that demands private consumer goods
- Government sector that demands public consumer goods
- Foreign trade sector that demands exports and supplies imports

The sum of the above demands represents the sector of the final demand. Outputs of an industry may be employed by that industry itself, to be sold to other industries, which uses those as inputs for the production process, or to the final demand sector.

The input-output table is the starting point of an IO analysis. Such table is a description, in terms of monetary exchanges, of the flows of goods and services through the sectors of the examined economy. Usually it refers to a 1-year period (Wilting 1996). As known, the IO table is necessarily square and consists of three major sections (Camagni 1993; Schachter 1988):

- The core of the table is the matrix of intermediate flows. It describes the selling (by rows) and the purchasing (by columns) flows among the n productive sectors.
- In the second section, a series of columns represent the industry deliveries to the final demand (private and public consumptions, investments, supplies and exports).
- The third section completes the matrix with the rows that represent the payments to the productive factors (value added), the imports and the taxes, interpreted as purchasing.

The generic element X_{ij} of intermediate flows represents the quantity of input of sector i needed to produce the output of sector j. In monetary term, it is possible to evaluate by row in monetary term, the quantity of output that sector i sells to itself, to other industries j and to the final demand. It is also possible to evaluate by column the quantity of input that sector j purchases by other sectors, including productive factors (land, labor, capital) to manufacture the final output.

If the IO table is balanced the total input will equal the total output for production sectors. That represents the general constraint of the IO table where the sum per column has to equal the sum per row.

The main equation of the IO method is the following:

$$X = (I - A)^{-1} \cdot y \tag{22.1}$$

where A is the technology matrix, I is the unit matrix, y is the vector of final demand and X is the vector of total outputs. The matrix $(\mathrm{I} - \mathrm{A})^{-1}$ is generally known as Leontief inverse matrix.

The assumptions of IO framework involve many limitations. These are briefly described in the following (OECD 1998):

(a) *Input-output analysis assumes constant returns to scale*. The model assumes that the same relative mix of inputs will be used by an industry to create output, regardless to the quantity produced. It implies that:

   1. *Technical coefficients are assumed to be constant*. The amount of input necessary to produce one unit of certain output is assumed to be constant. Hence, the amount of input purchased by a sector is exclusively based on the level of output desired; no consideration regarding the price effects, changes in technology or economies of scale is developed.
   2. *Input-output analysis assumes linear production functions*. The input-output process assumes that if the output level of an industry changes, the input requirements will change in a proportional way.

(b) *It is supposed that each sector produces only one product.*
(c) *There are not resource's constrains*. Supply is assumed infinite and perfectly elastic.
(d) *Local resources are efficiently employed*. There is no underemployment of resources.
(e) *Actuality of input-output data*. There is a long time lag between the collection of data and the availability of the input-output tables.

Extension of IO Analysis to Energy and Environmental Applications

From the 1970s to nowadays many authors have investigated the extension of the IO model to environmental issues nowadays (Wright 1974; Bullard and Herendeen 1975; Miller and Blair 1985; Wilting 1996; Cruz 2002).

The main aim of the IO energy analysis is the calculation of energy intensities (Wilting 1996). The energy intensity of an economic sector gives the total amount of energy, both direct and indirect, that is needed for one financial unit of production of that sector.

The direct energy use of an economic sector comprises the energy directly used in the production process of that sector. The indirect energy use includes all the energy that is needed for the production and delivery of goods and services that are used in the production process.

The IO analysis applied to the energy system relates the energy flows with the economic flows, assigning to each sector the corresponding quantity of indirect energy consumption induced by its use of goods or services. In order to evaluate the overall energy consumption, all the energy quantities are valued as primary,[1] according also to the methodology usually applied in the redaction of life cycle inventory (ISO 14040 1998).

Worth of note are some "hybrid" models, where the results of the IO analysis are employed to support studies of LCA (Treloar 1996; Lenzen 2001). Such models allow to benefit of advantages of both IO model and traditional process analysis.

The Energy Analysis Model

The energy analysis of an economic system has been performed employing the mathematical relationships introduced by Gay and Proops (1993), Wilting (1996) and Cruz (2002).[2] The resulting model assumes that the used fossil fuel can be split into the energy directly demanded by household consumers (for lighting, heating/cooling, transport, etc.), and the energy (directly and indirectly) demanded by industrial and agricultural producers of goods (Proops 1988). The former is designated as 'direct consumption demand' and the latter (direct plus indirect) as 'production demand' (Cruz 2002).

The energy model assumes that the energy, via the intermediate deliveries, is attributed to the final demand (Wilting 1996).

The total energy consumption is calculated by means of *specific consumption coefficients* that represent the quantity of primary energy used by a generic sector per unit of total output.[3] Being that every fossil fuel has different emission factors, energy sources have to be handled separately. It is possible to use as many *consumption coefficients* as the number of employed energy sources.

Energy intensities are so calculated by means of the Leontief inverse matrix and the primary energy consumption of sectors, as following:

$$E = C \cdot (I - A)^{-1} \tag{22.2}$$

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[1] The energy content of energy carriers that have not yet been subjected to any conversion is defined "primary energy" (VDI 1997].

[2] A detailed description of the energy IO model is presented by Cruz in the Chapter "Application of IO Energy Analysis".

[3] Consumption coefficients can be easily obtained dividing the direct energy requirements of a sector by the total sector outputs. Direct energy requirements are generally derived from national energy balances.

where E is the vector of energy intensities, C is the matrix of the consumption coefficients and I and A are the above mentioned matrixes (see Equation (22.1)). The number of rows and columns of matrix C is equal, respectively, to the number of the economic sectors and the considered energy sources.

A critical matter is the management of secondary energy sources. They have to be transformed into primary quantities by means of specific conversion factors that represent the energy necessary to deliver the energy sources to the end-user. In particular, electricity should be express as sum of the energy sources that have produced it, following the national electricity production mix.

Limits and Assumptions of the Energy Model

It has been underlined that one of the basic assumptions of the IO analysis is the price uniformity. It means that all production sectors and the final demand sectors pay the same price for all deliveries from a generic sector. Since, in practice, this is not the case of the energy sector, the deliveries from the energy sectors, in monetary terms, do not correspond to the physical deliveries (Wilting 1996).

To solve this problem some authors have suggested an hybrid IO model in which the deliveries of the energy sectors are given in physical units and the deliveries of the non-energy sectors in monetary units (Bullard and Herendeen 1975; Miller and Blair 1985). However this method requires a detailed IO table with a low aggregation of sectors.

Furthermore, the model allows to calculate an average value of energy intensity of sectors. These data are strongly aggregated and, consequently, they have a low usefulness for a detailed environmental analysis.[4]

The Environmental Analysis Model

Analogously to the energy analysis, the environmental analysis aims to assess the environmental effects due to the production of each sector. In particular, such analysis focuses on the main air pollutants arisen from the use of fossil fuels. The proportionality between production, use of energy sources and released pollutants is assumed by means of specific emission factors.

We point out that the fuel stocks are not entirely burnt for energy production (with consequent release of emissions) but a percentage of them is employed for non-energy uses (as feedstock). These fuel quantities shall be not considered in the emission calculation.

Some limits affect the environmental model. For instance, other emission sources due to production processes should be included (i.e. emissions released during

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[4] In fact, following the eco-design approach, more than an average sector indicator it is important the availability of detailed information regarding every component and life cycle step of the product.

processes like cement production, welding, etc.). These contributions are usually neglected because a lack of information about the regional productive system.

Another weak point is revealed when the study aims to estimate the effective emissions related to the domestic demand. In this case the country's emissions related to exports should not be considered as far as the emissions taking place in foreign countries, but resulting from the production of the country's imports, should be added on (Gay and Proops 1993). The study of CO_2 emissions due to imports is very difficult to assess. In fact, the calculation of the energy intensities should include the energy embodied into imports, valued on the basis of the IO tables of the countries from which imports are acquired.

The Case Study: IO Analysis Applied to the Sicilian Regional Context

An energy and environmental balance of the economy system of the Sicily region through the application of the IO analysis is now presented. Energy intensities and specific environmental impacts per unit of economic output have been calculated. Comparing the results of different years it is possible to state the trend of the energy and environmental efficiency of each sector and to assess if the regional economy is moving towards sustainable development or not.

The employed model is that previously described in paragraph 2. Actually, the analysis of a region does not methodologically differ from applications to a wider national context. The peculiarities of such application to the regional context are related to the structure of a regional economy, characterised by a restricted number of dominant sectors and by problems related to data quality as: aged data, aggregated data and discrepancies between energy and economic statistics.

The IO table, referred to the Sicilian regional context, has been performed by Schachter (Schachter et al. 1985). The table has been updated through the RAS (Reiterative Assessment System) methodology.[5] This is a technique frequently used to update the IO table when national income data (such value added and final demand) are available in spite of an absence of information on the processing sector.

The energy data are referred to the "energy regional informative system" performed by the ENEA (Italian National Agency for the Energy and the Environment) (ENEA 1989–1996). Table 22.1 shows the regional energy balance. Energy consumptions grew from 1989 to 1992, returning in 1995, after an economic crisis, to the levels of 1989. It is possible to observe a reduction of the coal use during this time step; renewable energy sources were more than doubled but represented however less than 1% of the overall energy requirement.

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[5] The RAS method is an iterative bi-proportional normalisation of rows and columns that spreads the errors between the theoretical and unknown marginal vectors when the structure of flows (the direct requirement coefficient matrix) is available (Schachter 1988). This technique permits to approximate the input output coefficients for an updated IO table by estimating the comparative data of value added and final demand applied to the base year.

Table 22.1 Regional Energy Balance

Year	Energy sources (10^3 TJ)				Total
	Coal	Oil	Gas	Renewable sources	
1989	2.8	541.1	89.5	1.6	635.0
1992	3.5	633.2	81.4	3.8	721.9
1995	2.0	542.2	88.1	5.8	638.0

Economic and energy data have been inserted respectively into the matrix A (the matrix of technical coefficients) and C (the matrix of specific consumption coefficients). In our case study, oil, natural gas, coal and renewable energy sources have been considered.

The IO analysis is a useful tool to state the variations of energy and environmental impacts. Results are as much detailed as more sectors are included. However, the regional economy has been subdivided in 15 sectors contrarily to the initial 17-sectors structure.[6] Analogously, energy sectors have been aggregated into 15 sectors. These modifications have been necessary in order to adapt the dimension of the economic matrix to the energy one.[7] In detail, Table 22.2 shows the correspondence between economic and energy sectors.

Some problems arise with the "energy sector" because, due to the low detail into IO table, it was not possible to state exactly what activities were included. The consequent uncertainty causes a not perfect correspondence between economic flows and their related energy consumption.[8]

The next step is the analysis of primary and secondary energy sources. The energy consumption of each sector has been converted into primary energy by means of conversion factors. We have estimate direct and indirect consumption of each sector. This procedural choice allows to respect the effective consumptions of each sector, congruously to the regional energy balance.[9] We remark that, due to the aggregations of sectors in the IO tables, it was not possible to build a *hybrid* matrix (see paragraph 2.1.1).

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[6] In the energy balances, petrochemistry sector is separately managed but there is not an equivalent sector into economic tables. For this reason, petrochemistry industry has been aggregated to the "energy" sector. Furthermore, agriculture and fishing has been jointly managed in the analysis.

[7] In Italy, the National Energy Balance and the IO table are not harmonised. It means that the sectors considered into the energy balance do no fit with sectors included in the economic tables. This circumstance forces the researchers to aggregate sectors in order to respect a correspondence between energy and economic data. This procedure represents a limit of the study, because the aggregation causes an irreversible loss of information.

[8] This uncertainty can affect the reliability of results. A deep sensitivity analysis has been developed to assess the influence of the factors of uncertainty.

[9] An alternative procedure supposes to entirely assign the energy consumption for electricity generation to the "energy" sector. Successively the IO model provides to ascribe the energy consumption to all the other sectors. This alternative has been checked in paragraph 4.2.

Table 22.2 Correspondence Between Economic and Energy Sectors

No	Final denomination	Denomination into regional IO table	Denomination into the energy balance
1	Agriculture and fishing	Agriculture, tobacco	Agriculture Fishing
2	Energy sector	Energy sector	Extractive industry, petrochemistry
3	Metal industries	Metal industries	Metal industries
4	Non metallic mineral industries	Non metallic mineral industries	Glass and ceramic Construction materials
5	Chemical and pharmaceutical industry	Chemical and pharmaceutical industry	Chemical industry
6	Engineering industry	Metal works, machinery, electric materials	Metallurgy
7	Mechanic industry	Motorvehicle, transportation equipment	Mechanic industry
8	Agro-industrial products	Meat, dairy, other foods, beverages	Agro-industrial products
9	Textile products	Textile and clothing, leather	Textile products
10	Paper products	Paper	Paper products
11	Other industries	Wood products, rubber, Other products	Wood products, plastic products, rubber products, Jewels
12	Constructions and public works	Constructions	Constructions and public works
13	Tertiary	Hotel and restaurant, trade Credit and insurance Miscellaneous services	Services
14	Transports	Transports and communications	Transports
15	Local authorities and not saleable services	Government, public health and education, household services	Local authorities

Particular attention needs the electricity production. Figure 22.1 shows the regional energy mix of 1992. The efficiency of electricity production can be calculated as:

$$\eta = \frac{E_{Production}}{E_{Primary}} \tag{22.3}$$

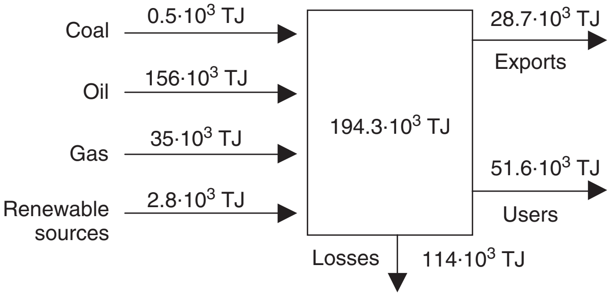

Fig. 22.1 Production of Electricity – Regional Production Mix in 1992

or, analogously:

$$\lambda_{el.} = \frac{1}{\eta} = \frac{E_{Primary}}{E_{Production}} \tag{22.4}$$

where:

- $E_{Production}$ is the total energy production, inclusive of the internal demand and exportations.
- $E_{Primary}$ is the total primary energy consumption.

The term "$\lambda_{el.}$" represents the conversion factor of electricity from "*end*" to "*primary energy*". For example, in the 1992 the two previous indexes resulted: $\eta = 0.41$ and $\lambda_{el.} = 2.42$. It means that the use of 1 MJ of electricity causes the consumption of 2.42 MJ of primary energy.[10] Analogous conversion factors have been calculated for the other energy sources.

The environmental analysis is based on the specific CO_2-emission factor "e_j" (Table 22.3). They have been calculated on the basis of data from IPCC (Intergovernmental Panel on Climate Change) (IPCC 1996). The largest emission factor is related to the coal use, the lowest to the natural gas. Renewable energy sources have not been included in the CO_2 emission calculation. Although these sources have not generally direct CO_2 emissions related to their use,[11] the emissions released during the entire life cycle of the plants should be added. Being the use of renewable sources in our case study very small, their contribution to CO_2 balance is negligible.

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[10] We recall that the conversion factors are not constant but yearly change yearly referring to mix of the electricity production.

[11] Actually, the combustion of the biomass causes the production of CO_2. Being that biomasses absorb carbon dioxide from atmosphere when alive, we can consider null the global CO_2 balance throughout the life cycle. However, the combustion of biomasses shall be included into the evaluation of other air pollutants as NO_x, SO_x, particulates, etc.

Table 22.3 Emission Factors ($103\,\text{kgCO}_2/\text{TJ}$)

Coal	Oil	Gas
94.6	73.3	56.1

The Energy Analysis

The economic and the energy data have been used to fill the matrixes of the IO model. The first step has been the calculation of the energy intensities regarding each economic sector of Table 22.2. The variation of the yearly energy intensities can represent a useful tool to assess the energy trend of economic sectors. In fact, we can assess if the production of one monetary unit would involve a growing or decreasing energy consumption.[12]

Figure 22.2 shows the results referred to the production during the three investigated years. All the quantities are expressed as GJ per thousands of euro. We can observe that:

- The highest energy intensity is related to the "energy sector". It means that energy products involve the highest specific energy consumption. This primacy is not modified during the years. "Transport" and "non metallic mineral" sectors show large specific energy consumptions.
- The analysis points out a general decreasing trend of energy intensities.[13] Highest reductions have interested, "energy sector" (−39%), "non-metallic mineral" (−34.2%) and "local authorities" (−33.5%). An opposite trend characterises other sectors as "agriculture and fishing", "mechanic industry" and "agro-industrial products".
- Extremely variable is the incidence of direct and indirect consumptions. Direct consumption is dominant into "energy", "transports", "metal industries" and "non metallic mineral industries" sectors, with a percentage incidence from 51.8% to 70.5%. On the contrary, "textile products", "constructions" and "paper products" have a direct rate equal to $5 \div 10\%$ of the overall consumption.
- Direct and indirect ratios have small variations during the years.

Results of Fig. 22.2 confirm the trend of regional energy data. In fact, the large reduction of energy intensities can be ascribed to a general improvement of the "energy" sector. The efficiency of the electricity production grew from 39.1% in 1989 to 40.6% in 1995, thanks to economic investments in the sector to gradually substitute solid and liquid fossil fuels with natural gas and renewable sources. Furthermore, due to the increase of the costs of energy products, the "energy" sector raised its economic outputs with a significant decrease of the energy intensity of its products. That decrease had also a positive effect on the reduction of energy intensities of all the other sectors.

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[12] Comments are subject to the previously investigated methodological limits.

[13] Variations valued in 1995 respect to 1989.

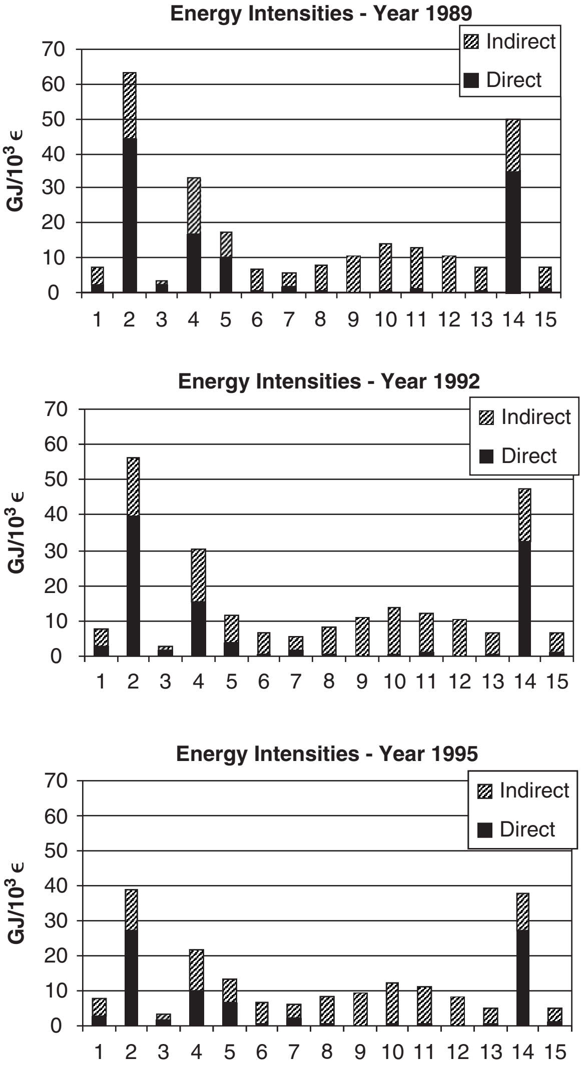

Fig. 22.2 Energy Intensities – Yearly Trend per Sector

A global picture of the regional economy is described by the energy consumptions per sector. Table 22.4 shows that the "energy" and "tertiary" sectors have the largest consumptions; "metal industries", "paper" and "non metallic mineral" industries have a very small incidence into the regional energy balance.

It is also worth noting that the highest yearly energy consumption is related to 1992. In the following period, after an economic crisis, the energy consumption decreased, returning in 1995 to the levels of 1989. The detail about energy sources (Table 22.4) shows that oil is the most important fuel, followed by natural gas; small quantities of solid fuels and renewable sources have been employed. The energy

Table 22.4 Total Energy Consumption of Productive Sectors per Energy Sources (1992)

Sector	Energy source (10^3 T)			
	Coal	Oil	Gas	Renewable
1	–	8.3	0.7	0.03
2	0.3	144.3	24.9	2.0
3	–	0.02	0.03	0.0001
4	0.3	3.9	0.5	0.02
5	–	8.6	5.2	0.04
6	–	15.6	2.3	0.06
7	–	8.1	1.4	0.05
8	–	29.3	3.4	0.12
9	–	25.4	3.02	0.088
10	–	4.1	0.5	0.015
11	–	13.2	1.8	0.05
12	–	51.1	5.8	0.19
13	–	113.2	13.3	0.5
14	–	75.3	2.2	0.08
15	–	75.9	8.9	0.4
Total	0.6	576.4	74.0	3.6

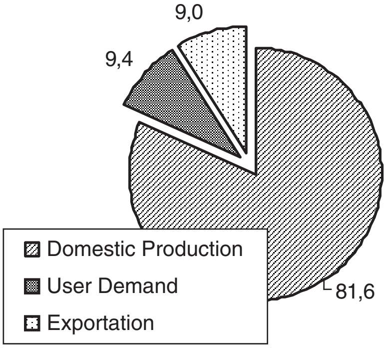

Fig. 22.3 Energy Consumption Detail – 1992

employed by productive sectors has to be added to the energy directly consumed by citizens, mainly as electricity and other secondary energy sources (in 1992 that request amounted 68.2 10^3 TJ).

Further details in the energy analysis can be obtained splitting the total final demand in three segments: consumption for the domestic production, energy necessary to satisfy the user demand and the energy demand for exports. Figure 22.3 shows that, in the 1992, the largest amount of the consumption has been related to the production for the domestic demand (81.6%), while the remaining ratio is subdivided between user demand (9.4%) and the production for the exports (9%). These percentages did not change sensibly during the observed years.

The export demand is particularly significant into the "metal industries" (36.4% of the consumption is employed for exports), "energy sector" (22% for exports) "non metallic mineral" (21.5% for exports) and into the "chemical sector" (16.9% for exports). These results agree with the industrial regional structure, where the exports involve mainly energy and chemical products. The "construction" and "local authorities" sectors do not have exports.

We remark that the estimated energy intensities are average values not totally representative of all the products enclosed into a sector. The structure of the regional IO table is strongly aggregated and, consequently, the low detail of results does not allow their employment for regional studies of LCA. Consequently, it was not possible to apply the "hybrid" energy analysis method (see paragraph 2).

The Environmental Analysis

Starting from the results of the energy analysis, the airborne pollutants released by each sector have been calculated. Figure 22.4 shows the CO_2 emission intensities that represent the total amount of carbon dioxide released by each sector to produce one financial unit (expressed as 10^3 kg_{CO2} per thousands of euro). There is an obvious correlation between energy and emission intensities. However, differences between results of Figs. 22.2 and 22.4 are due to the "non-energy use" of energy sources (feedstock[14]).

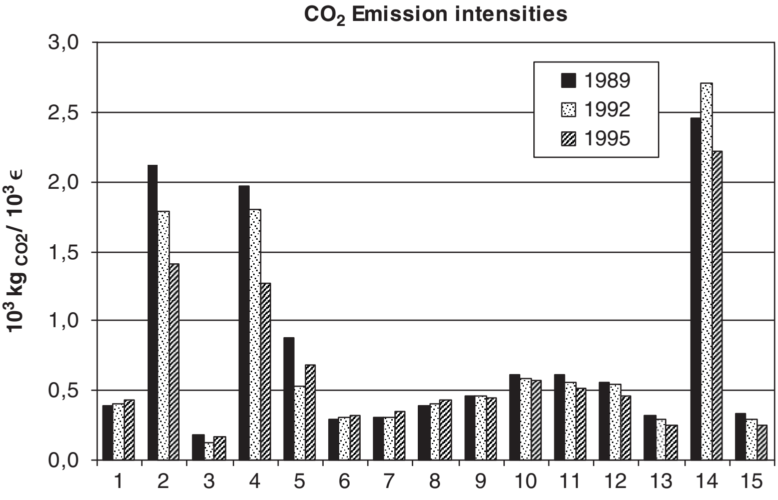

Fig. 22.4 CO_2 Emission Intensities

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[14] For further detail about feedstock energy see paragraph 4.2.

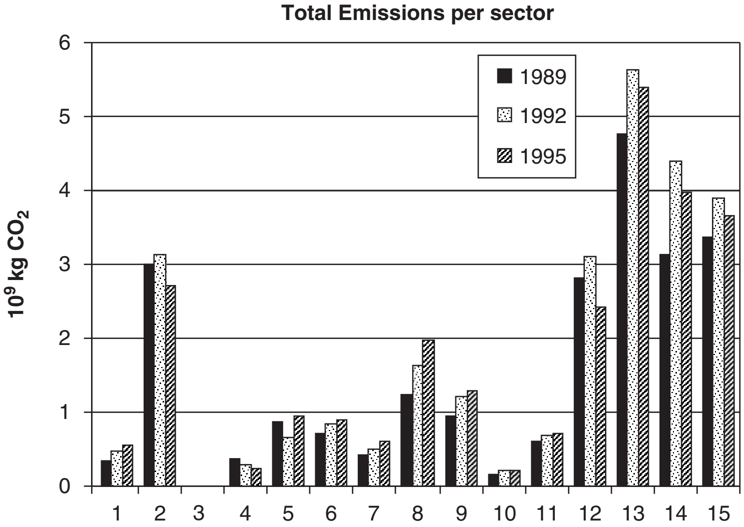

Fig. 22.5 CO_2 Emissions per Sector Due to the Domestic Demand

By this way, it is possible to observe a general decreasing trend of CO_2 intensities through years. From 1989 to 1995, the most remarkable variations have interested the "energy" sector, "non-metallic mineral" and "chemical" industries, showing similar decreasing rates as observed for the energy intensities. Figure 22.5 shows the total CO_2-emissions per sector.

The economic sectors have generally registered an increment of total CO_2 releases in spite of the reduction of the CO_2 intensities. Remarkable increments have interested "agriculture and fishing", "mechanic", "agro-industrial" and "transport" sectors, +61.8%, +58.8%, +44.6% and +27% respectively. More than 60% of the regional CO_2 emissions are ascribable to "tertiary", "transports", "local authorities" and "energy" sectors. Contribution of "metal industries" is negligible.

We point out that in 1992 many sectors had a large increase of CO_2 emissions, but this trend has been successively inverted due to a regional economic crisis.

The yearly carbon dioxide emissions for the domestic demand changed from the amount of $22.7 \times 10^9\,\mathrm{kg}_{CO2}$ in the 1989 to $25.6 \times 10^9\,\mathrm{kg}_{CO2}$ in the 1995. Significant is also the incidence of direct emissions due to the user demands, responsible of $3.4 \times 10^9\,\mathrm{kg}_{CO2}$ in 1989, $3.9 \times 10^9\,\mathrm{kg}_{CO2}$ in 1992 and $4.9 \times 10^9\,\mathrm{kg}_{CO2}$ in 1995. Opposite trend had the emissions due to the production of exports that decreased from $2.5 \times 10^9\,\mathrm{kg}_{CO2}$ in 1989 to $1.7 \times 10^9\,\mathrm{kg}_{CO2}$ in 1995. The total regional emission balance estimates that CO_2 emission grew from $28.8 \times 10^9\,\mathrm{kg}_{CO2}$ in 1989 to $32.2 \times 10^9\,\mathrm{kg}_{CO2}$ in 1995, *with an average increment of 12%.*

This analysis resulted very interesting being possible to monitor the regional trend of greenhouse gas emissions and to individuate the sectors responsible of greatest impacts. Furthermore, in order to comply with the Kyoto agreements, the IO analysis can also be employed to address regional funds and initiatives and to state the efficacy and the efficiency of the regional energy and environmental policies.

Uncertainty and Sensitivity Analysis

The previous paragraphs have shown many problems and limits that arise in the application of IO method. In order to state the precision and reliability of results, it is necessary to perform a sensitivity and uncertainty analysis (Wilting 1996). The sensitivity analysis investigates the influence of variations in the input parameters on the outcomes. The uncertainty analysis investigates the uncertain aspects of the method, the input data and the way they are interpreted, and it studies the effects of these uncertainties on the outcomes of the method itself.

Sensitivity Analysis of IO Parameters

Sensitivity Analysis (SA) aims to manage uncertainties due to elements of the IO table. In particular, SA assess the effects of the variations of "X_{ij}" elements on the Leontief inverse matrix. In the analysis, we have to comply with the general constraint that the total Input equals the total Output for production sector. Consequently it is possible to modify directly only the elements X_{ij} when $i = j$.

Following we demonstrate that energy intensities do not change if an element X_{ii} will be modified (Figs. 22.6 and 22.7).

Let we suppose to have a simplified IO matrix (dimension 2 × 2) whose elements a_i ($i = 1 \ldots 4$) are the IO coefficients and elements A_j ($j = 1, 2$) are the total sector outputs (Fig. 22.6). Using the previous notation: A is the technology matrix; I is the unit matrix; D is the term $[(A_1 - a_1) \cdot (A_2 - a_4) - a_2 a_3]$; C is the matrix

$$IO = \begin{pmatrix} a_1 & a_2 \\ a_3 & a_4 \end{pmatrix} \qquad A = \begin{pmatrix} \dfrac{a_1}{A_1} & \dfrac{a_2}{A_2} \\ \dfrac{a_3}{A_1} & \dfrac{a_4}{A_2} \end{pmatrix} \qquad C = \begin{pmatrix} \dfrac{e_1}{A_1} & \dfrac{e_2}{A_2} \end{pmatrix}$$

$$(I\text{–}A)^{-\mathbf{1}} = \begin{pmatrix} \dfrac{A_1\,(A_2 - A_4)}{D} & \dfrac{a_2 A_1}{D} \\ \dfrac{A_2 a_3}{D} & \dfrac{A_2\,(A_1 - a_1)}{D} \end{pmatrix}$$

$$E = C \cdot (I\text{–}A)^{-1} = \begin{pmatrix} \dfrac{e_1\,(A_2 - a_4) + e_2 a_3}{D} & \dfrac{e_1\, a_2 + e_2 (A_1 - a_1)}{D} \end{pmatrix}$$

Fig. 22.6 Sensitivity Analysis – Calculation of Energy Intensities for an Exemplary IO Matrix (Dimension 2 × 2)

$$IO' = \begin{bmatrix} a_1-a & a_2 \\ a_3 & a_4 \end{bmatrix} \qquad A' = \begin{bmatrix} \dfrac{a_1-a}{A_1-a} & \dfrac{a_2}{A_2} \\ \dfrac{a_3}{A_1-a} & \dfrac{a_4}{A_2} \end{bmatrix} \qquad C' = \begin{bmatrix} \dfrac{e_1}{A_1-a} & \dfrac{e_2}{A_2} \end{bmatrix}$$

$$(I-A')^{-1} = \begin{bmatrix} \dfrac{(A_1-a)\,(A_2-A_4)}{D} & \dfrac{a_2\,(A_1-a)}{D} \\ \dfrac{A_2 a_3}{D} & \dfrac{A_2\,(A_1-a_1)}{D} \end{bmatrix}$$

$$E' = C' \cdot (I-A')^{-1} = \begin{bmatrix} \dfrac{e_1\,(A_2-a_4)+e_2 a_3}{D} & \dfrac{e_1\, a_2 + e_2(A_1-a_1)}{D} \end{bmatrix} = E$$

Fig. 22.7 Sensitivity Analysis – Calculation of Energy Intensities for an Exemplary IO Matrix Modifying an Element of the Main Diagonal of the IO Table

constituted by the consumption coefficients, obtained dividing the energy consumption per sector $(e_j : j = 1, 2)$ by total sector outputs (see note 3). Figure 22.6 shows the structure of the vector E of energy intensities.

Let we assume to modify an element of the main diagonal (for example, the element a_1 is decreased of an arbitrary quantity $a \leq a_1$). Figure 22.7 shows that this modification does not influence the new vector E' of energy intensities. These results can be extended to any positive or negative variations of the main diagonal elements in a general n-dimension IO matrix. In fact, modifications of IO table and C matrix leave unaltered the E vector.

Although modifies of X_{ii} elements do not affect the total energy intensities, they change the ratio between directs and indirect contributes. For example, increasing of $+10\%$ the element $X_{2,2}$ in 1992, the energy intensity of “energy” sector remains 56.3 GJ/€10,000 but the direct contribution moves from 70.5% to 68.6%.

The energy intensities change if we assume to leave unaltered the energy consumption coefficients. The case study of paragraph 3.1 has been repeated supposing to leave unaltered the matrix C and changing the IO coefficients. Table 22.5 shows the variation of energy intensities by changing of $\pm 10\%$ the elements X_{ii} of the main diagonal of the IO table in 1992. We point out that:

- Positive variations of X_{ii} involve an increase of energy intensities. This is due to the increase of outputs that each sector sells to itself. In the same manner, negative variations decrease energy intensities.
- Doubling the variations of the elements of IO table, energy intensities change proportionally.
- Even increasing of 20% the elements X_{ii}, variations of energy intensities are enclosed in the range $(2.2\% \div 5.6\%)$.

Table 22.5 Sensitivity Analysis – Variations of Energy Intensities by Changing of +10% and +20% the Elements of the Main Diagonal of IO Table

No	Sector	+10%	+20%
1	Agriculture and fishing	2.1	4.3
2	Energy sector	2.8	5.6
3	Metal industries	1.1	2.2
4	Non metallic mineral industries	1.8	3.6
5	Chemical industry	1.7	3.4
6	Engineering industry	2.0	4.1
7	Mechanic industry	1.4	2.8
8	Agro-industrial products	2.0	4.1
9	Textile products	2.3	4.5
10	Paper products	2.3	4.6
11	Other industries	2.2	4.5
12	Constructions and public works	1.9	3.8
13	Tertiary	2.2	4.4
14	Transports	1.4	2.8
15	Local authorities	1.9	3.9

- Variations of energy intensities related to the economic sectors are not equal. In particular, largest variations are related to "energy" and "paper" products; "mechanic", "metal industry" and "transport" sectors are less influenced.
- Negative variations of IO table cause symmetric changes of energy intensities.

Another attempt to perform the sensitivity analysis focused on the X_{ij} elements $\forall i \neq j$. These elements cannot be changed without re-balancing the matrix in order to respect the mentioned constraint. A method to face this problem is following described:

- To change the generic X_{ij} element of row i and column j, adding (or subtracting) the generic quantity z.
- The quantity $\frac{-z}{n-1}$(or $\frac{+z}{n-1}$) is summed to the elements of row i and to the elements of column j.
- The quantity $\frac{z}{(n-1)^2}$ (or $\frac{-z}{(n-1)^2}$) is summed to all the other elements $X_{kh} \forall k \neq i$ and $\forall h \neq j$.

This method allows to respect the matrix constraints and to leave unaltered the sums of elements per rows and the sums per columns. On the other side, this procedure modifies all the elements of the matrix and some items could become negative. To cope with this problem, some alternatives are possible:

- *To set negative elements to zero*. This alternative makes the constraints no more respected. This option is feasible when the sums of elements per rows and the sums per columns do not heavily differ. In this case we have to fix an acceptable percentage of difference.
- *To repeat the same procedure for negative elements* in order to turn them into positive. This alternative could involve an iterative process.

Table 22.6 Sensitivity Analysis – Variations of Energy Intensities by Changing of ±10% the Element $X_{2,14}$ of the IO Table

No	Sector	Without re-balancing the IO table		Rebalancing the IO table	
		$X_{2,14}$ decreased of 10% (%)	$X_{2,14}$ increased of 10% (%)	$X_{2,14}$ decreased of 10% (%)	$X_{2,14}$ increased of 10% (%)
1	Agriculture and fishing	−0.16	0.16	0.62	−0.63
2	Energy sector	–	–	–	–
3	Metal industries	−0.23	0.22	8.9	−8.4
4	Non metallic mineral industries	−0.19	0.18	0.35	−0.37
5	Chemical industry	−0.27	0.26	0.80	−0.81
6	Engineering industry	−0.63	0.61	0.69	−0.68
7	Mechanic industry	−0.43	0.41	1.88	−1.86
8	Agro-industrial products	−0.29	0.28	0.75	−0.76
9	Textile products	−0.47	0.46	0.59	−0.61
10	Paper products	−0.52	0.50	1.2	−1.3
11	Other industries	−0.42	0.40	0.81	−0.83
12	Constructions and public works	−0.45	0.43	0.39	−0.41
13	Tertiary	−0.47	0.46	−0.15	0.14
14	Transports	−1.6	1.5	−1.6	1.6
15	Local authorities	−0.44	0.42	–	–

- *To share the generic quantity z not equally to the elements of rows and columns*, in order to avoid negative elements. It would require higher difficulties to respect the constraints.

For example, we applied this sensitivity analysis to the element $X_{2,14}$ that represents the outputs of "energy" sector to the "transport" sector. The value of $X_{2,14}$ has been modified of ±10% (results in Table 22.6). Initially the analysis has been carried out without rebalancing the IO table and supposing the C matrix constant. Successively the analysis has been repeated proceeding with the suggested rebalancing method and setting negative elements to zero. Variations lower than 1% have not been considered.

Results of Table 22.6 show that, without the rebalancing process, the variations of energy intensities are lower. An increment of $X_{2,14}$ causes the growth of all the energy intensities and, in particular, of the "transport" sector (+1.5%). Analogous results are obtained decreasing the $X_{2,14}$.

The re-balancing process causes higher modifies. Particularly significant is the variation of "metal industries" (−8.4%). This sector is characterised by low values in the IO matrix and, consequently, the method of re-balancing the matrix has involved sensible variations of its values. Regarding all the other sectors, modifying the $X_{2,14}$ of ±10%, the energy intensities have variations enclosed in the range (−1.9%; +1.3%).

As previously discussed, setting to zero negative elements the general IO constraint results to be no more accomplished. However, discrepancies among total Inputs and Outputs are lower than 1%.

The sensitivity analysis showed that the variations of IO elements do not affect significantly the energy intensities. Consequently, large variations into energy intensities detected into paragraph 3 cannot be generally ascribed to the RAS methodology to update IO table.

The previous considerations regarding energy intensities can be analogously extended to CO_2 intensities.

Uncertainty Analysis

Uncertainty analysis has been applied to input data and, in particular, to energy quantities and the way they are interpreted.

We have assumed to increase by 10% the energy consumption of one sector per time, supposing to leave unaltered the energy conversion factors and the elements of the IO table. Table 22.7 shows the variation of energy intensities (variations lower than 1% have been not considered).

For example, increasing of 10% the energy consumption of sector 1 (column 1 in Table 22.7), the energy intensity of agriculture increases of 4.5% while energy intensity of "agro-industrial" sector increases of 2.3%.

Table 22.7 gives a picture of the energy relationships among sectors. We point out that the regional economy is strongly based on a small number of activities that, in accordance with Figs. 22.2 and 22.4, are also the sectors with the higher energy intensities and environmental impacts. In particular, the analysis shows that:

Table 22.7 Sensitivity Analysis of Energy Input Data

		Sector Increased of 10%														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	14
Percentage variation of energy intensities	1	4,5%	4,4%	-	-	-	-	-	-	-	-	-	-	0,1%	0,8%	-
	2	-	9,9%	-	-	-	-	-	-	-	-	-	-	-	0,1%	-
	3	-	3,2%	5,5%	0,1%	-	-	-	-	-	-	-	-	-	1,1%	-
	4	-	2,9%	-	6,1%	-	-	-	-	-	-	-	-	-	0,9%	-
	5	-	4,5%	-	0,4%	3,6%	-	-	-	-	-	-	-	-	1,3%	-
	6	-	5,2%	0,2%	0,4%	-	0,7%	-	-	-	-	-	-	0,2%	3,0%	-
	7	-	3,8%	0,1%	0,3%	-	-	3,3%	-	-	-	-	-	0,2%	2,1%	-
	8	2,3%	4,9%	-	0,2%	-	-	-	0,9%	-	-	-	-	0,1%	1,4%	-
	9	0,3%	6,6%	-	0,1%	0,2%	-	-	-	-	-	-	-	0,3%	2,3%	-
	10	0,1%	6,3%	-	0,2%	0,2%	-	-	-	-	0,5%	-	-	0,2%	2,5%	-
	11	0,1%	5,9%	-	0,4%	0,3%	-	-	-	-	-	0,9%	-	0,2%	2,0%	-
	12	-	4,2%	-	3,1%	-	-	-	-	-	-	-	0,2%	0,1%	2,2%	-
	13	0,1%	6,1%	-	0,1%	-	-	-	-	-	-	-	-	1,3%	2,3%	-
	14	-	2,3%	-	-	-	-	-	-	-	-	-	-	-	7,7%	-
	15	-	5,8%	-	0,2%	-	-	-	-	-	-	-	-	0,1%	2,1%	1,5%

- Energy intensities are generally sensitive to the energy consumption variations.
- Changing the energy consumption of a sector, the energy intensity of the sector itself has the highest variation.
- Variations occurring to "transports" and "energy" sectors strongly influence the other sectors.
- Many sectors (as "local authorities", "paper products", "construction", "textile", etc.) have a small incidence on other sectors, while "energy sector" is low influenced by other sectors.

The SA can also be employed to foresee the changes of energy consumptions of sectors. For example, it would be possible to state how all sectors could benefit of the efficiency improvement of a generic sector (due, for example, to the introduction of new technologies or plants). Te IO analysis is then an important tool to support planning strategies and to analyse future scenarios.

Regarding the "petrochemistry" industry, the energy and environmental analysis has shown its critical role, because this sector is responsible of about a half of the total energy consumption. The previous calculations have supposed to include the petrochemistry industry to the "energy" sector (see note 6). However, other alternatives have been checked. For example, we have supposed to include petrochemistry into the "chemical industry". This assumption has sensibly modified the values of energy and emission intensities, leading chemicals to become the most energy consuming products. However this choice is in contrast with economic tables where the "chemical" sector appears as a marginal sector of the regional economy.

A key point of the analysis is the definition of the consumption coefficient of the C matrix. Previous calculations have been based on data coming from the regional energy balance. As described in paragraph 3, secondary energy sources (as electricity) have been transformed into primary sources by means of energy conversion factors. An alternative procedure supposes to entirely assign the primary energy consumption for electricity generation to the "energy" sector. Successively, on the basis of the economic IO flows, the IO model re-distributes the energy consumptions to every sector. The analysis has therefore been repeated following these new assumptions. The results of 1992 showed that the energy intensity of "energy" sector had a large variation (+36.9%); the other sectors had smaller positive or negative variations enclosed in the range (−19.7%; +13.4%). The moderate variations show a good reliability of the IO analysis but, in the meantime, underline a limit of the model. Differences between the two approaches concerning secondary energy sources are due to different prices of energy sold to sectors. The low quality of the regional IO data, characterised by a strongly aggregated energy sector, has also affected the detected differences.

A final consideration regards the feedstock energy. It represents the energy contained into fuels employed as raw material. Feedstock is not burned and therefore do not release CO_2. These energy quantities have been therefore included into the energy balance but excluded in the estimation of emissions. In the regional energy balance feedstock energy sources represents about 34% of the total energy use, mainly due to refinery and chemical factories that produce many different oil derived products. Including feedstock into the CO_2 estimation we would have overestimated the incidence of the "energy" sector with its value of CO_2 intensity almost doubled. The total CO_2 emissions to satisfy the internal demand in 1992 would be $50.610^9\,kg_{CO2}$, about 54% bigger than the previous value. This experience shows that the inclusion or exclusion of feedstock energy into the environmental balance could sensibly change the results of the model.

Conclusion and Comments

The IO analysis has many limits that increase the uncertainty of results. First of all, these are referred to methodological assumptions (as constant technical coefficients and linear production functions) that it is not possible to avoid. Although economy does not change rapidly, IO table can not be reliable for a long time period. On the other side, the necessity to update frequently the IO tables contrasts with hard computational difficulties typical of this method. When a new technology allows either input substitution or greater efficiencies in the use of inputs, impacts to supplying industry sectors may be seriously misrepresented.

In addition, the assessment of economic flows is generally affected by large uncertainties due to the quality of data. The more disaggregated is the table the more precise and reliable are the results. Unfortunately, IO tables have often many different sectors joined together. It means a loss of information due to the aggregation operations. Furthermore, the assumption of homogeneity of production represents a strong limit; it permits an average estimation per productive sectors.

The lack of reliability of the results grows in the energy and environmental applications because of additional uncertainties as: availability of energy data, calculation of the energy flows, use of conversion factors, links between economic and energy data, use of emission factors, etc.

All these limits have been checked in the presented case study. In particular, the only available IO table, aged 1992, strictly affects results. Tables referred to other years have been indirectly estimated.

Furthermore, the employed IO table has a high aggregation level that compromises the detail of results, especially in a regional context where economy is mainly based upon a small number of sectors. Large uncertainty of results is also related to the exclusion of imports, being the regional economy largely dependent on external productions.

The greatest problems have concerned the discordance between economy and energy data. To face this problem, sectors have been further aggregated, causing so many difficulties in the attribution of primary energy consumptions. A key point was the aggregation of the petrochemistry sector, which represents about a half of the regional energy consumption.

The application of IO analysis to the regional case study should be considered as rough estimations and the employment of obtained data for Life Cycle Inventories or other detailed applications could be difficult.

However the IO analysis has many advantages, mainly due to the simplicity of the method. It allows to calculate the energy and environmental impacts per sector and to observe their trend through the years. The link among indirect consumptions, environmental impacts and products is an interesting parameter to assess sustainable/unsustainable paths. The model describes a rough but useful picture of the economy, especially if results are employed as support to the energy and environmental planning or to evaluate future scenarios related to variations of energy consumptions.

Sensitivity analysis has shown that the variations of economic data do not heavily influence the results. Furthermore, we have demonstrated that elements of main diagonal of the IO table do not affect the energy results. A larger incidence is related to the energy data. Consequently, the reliability of the model strictly depends on the reliability of energy input data.

In the Sicilian case study, authors have checked a growing trend of the energy consumptions (and air emissions) from 1989 to 1992. Because of an economy crisis, this trend has been successively inverted and the energy and environmental impacts in 1995 have been estimated similar to those in 1989. Regarding the disaggregated analysis, greatest impacts are related to “energy products” and “tertiary”. Significant is the contribution of “local authorities”, “transports” and “constructions”, while negligible are “metal industries”.

The analysis points out a general decreasing trend of energy intensities. Highest reductions have interested “energy sector”, “non-metallic mineral” and “local authorities”. These large reductions of energy intensities are mainly due to a general improvement of the “energy” sector and to a jointly increment of economic outputs of the sector itself.

However the positive effect of this energy improvement has been balanced by the growing consumptions. The analysis has shown an average increment ($+12\%$) of CO_2 emissions in 1995 respect to 1989, confirming a growing trend largely far from the reduction targets of Kyoto’s protocol.

The analysis has also shown the importance of feedstock energy sources. They have to be included into the energy model but successively excluded from the environmental analysis. In the case study, feedstock energy plays a key role, representing about 34% of the regional consumption. Including these sources into the CO_2 assessment, emissions would be strongly overestimated.

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