This is the postprint version of the article:
Alcántara, V., Padilla, E., Piaggio, M. (2017) "Nitrogen oxide emissions and productive structure in Spain: an input-output perspective", *Journal of Cleaner Production*, Vol. 141, pp. 420–428.
https://doi.org/10.1016/j.jclepro.2016.09.088

Nitrogen oxide emissions and productive structure in Spain: an input–output perspective

Alcántara, Vicent[a]; Padilla, Emilio[a*]; Piaggio, Matías[b,c]

[a] *Department of Applied Economics, Univ. Autónoma de Barcelona, 08193 Campus de Bellaterra, Cerdanyola del Vallès, Spain.*

[b] *Centro Agronómico Tropical de Investigación y Educación, Campus CATIE, 30501 Turrialba, Cartago, Costa Rica.*

[c] *Instituto de Economía, Universidad de la República, Joaquín Requena 1375, 11200 Montevideo, Uruguay.*

E-mails: vicent.alcantara@uab.es; emilio.padilla@uab.es; matias.piaggio@catie.ac.cr

*Corresponding author

Abstract

We analyse the nitrogen oxide gas emissions of different productive sectors in Spain. Using input–output analysis, we study all sectors as subsystems of the economy and decompose into different components the total (direct and indirect) emissions generated by their final demand. This analysis provides guidance on the type of policies that should be developed in the different sectors with the aim of mitigating nitrogen oxide emissions. Some sectors that seem less important when looking at their direct emissions turn out to be highly relevant in terms of their total emissions. The results indicate that demand policies can be effective in these sectors, especially in construction, but also in some service sectors that do not appear to be important polluters at first sight. These policies can complement technical improvements applied to directly polluting sectors.

Keywords: input–output analysis, NOx emissions, subsystems.

1. Introduction

Nitrogen oxides (NO_X) refer to the combination of nitric oxide (NO) and nitrogen dioxide (NO_2), the main component. These emissions are a by-product associated with combustion at high temperatures, mainly generated in the combustion processes of motor vehicles and power plants. NO_2 emissions have significant adverse effects on health and the environment[1]. The directive on National Emission Ceilings for certain pollutants (NEC Directive, Directive 2001/81/EC) set limits for each EU country for emissions of the pollutants responsible for eutrophication, acidification and ground-level ozone pollution (NO_X, non-methane volatile organic compounds (NMVOCs), sulphur dioxide (SO_2) and ammonia (NH_3)). Each country determined its own specific measures to attain compliance. These targets had to be achieved by 2010. The EEA (2012) highlighted the serious problem that NO_X pose for Europe. According to the technical report of the European Environment Agency (EEA, 2014) Spain was among the 11 countries that did not meet their target for 2010. In 2011, eight member states (Austria, Belgium, France, Germany, Ireland, Luxembourg, Slovenia and Spain) still exceeded their ceilings. Table 1 shows the NO_X emissions ceilings for 2010 and emission data for 2010 and 2011 in the different countries affected by the directive.

[TABLE 1]

Spain clearly failed to meet the objectives established in the directive. It thus seems especially relevant to research the role of different economic activities in the generation of NO_X emissions in Spain to contribute to the design of appropriate mitigation policies. NO_X emissions in Spain decreased 30.6% between 1990 and 2011. The share of Spanish emissions in total EU-27 emissions in 2011 was 10.3%. Although Table 1 shows that emissions in 2011 were close to the target for 2010, there is little cause for celebration. In the crisis period, the downward trend of emissions seems to have been linked more to a decline in production than to possible structural changes motivated by economic and environmental policies aimed at reducing emissions. Indeed, there was even a

[1] They are corrosive to the skin and the respiratory tract and prolonged exposure can affect the immune and respiratory systems. They react with moisture-forming nitric acid (HNO3) and give rise to the phenomenon of acid rain, the precipitation of which causes major damage to forests and the acidification of surface waters. Furthermore, they react with volatile organic compounds (VOCs) forming ozone (O3), which is a threat in terms of respiratory-related health problems. NO_X is therefore an acidifying and eutrophying pollutant and an ozone precursor (MAGRAMA, 2016a).

stabilisation in 2011. Figure 1 shows that in 2007 (the year chosen for our analysis) emissions were very similar to those of 1990 and 2006 (EEA, 2014).

[FIGURE 1]

However, this does not mean that there have not been changes in the period. Table 2 shows some of the variations in the distribution of emissions by major groups of polluting processes in the classification of the CORINAIR inventory (MAGRAMA, 2016b).

[TABLE 2]

Input–output models developed by Leontief (1936) provide a powerful tool for the analysis of several issues taking into account the structure and sectoral linkages of an economy. He was also the first author to employ these methods to study environmental issues (Leontief, 1970). The input–output analysis extended to environmental variables allows a deeper understanding of the relationship between economic structure and environmental degradation (Miller and Blair, 2009). There is a growing amount of applications of input–output analysis to the study of different environmental pressures caused by economic activity (a review can be found in Hoetskra, 2010). There are, however, few applications of the methodology to the study NO_X emissions. Moreover, most of the previous works computed the impacts of different economic activities on NO_X emissions just as a part of several pollutants, however, most of them did not take detailed look to which policies would be more suitable to diminish this gas emission. Shmelev (2010) analysed key polluting sectors of UK taking into account various physical flows, including $NO_{X.}$ Peters and Hertwhich (2006a, 2006b) computed the emissions associated with production and consumption perspectives of three different gases (CO_2, NO_X and SO_2) in Norway. Similar analysis was done by Deng et al. (2016), looking at the air pollution of consumption and trade in China, disaggregating NO_X and other pollutants. The environmental impact of private consumption considering energy and 10 environmental pressures (including NO_X) was analysed by Benders et al. (2012) through a hybrid approach for The Netherlands. A hybrid input–output life cycle assessment approach was used to analyse the embodied NO_X and other pollutants emissions of the building sector in Sweden and China by Toller et al. (2011) and Chang et al. (2016) respectively. For the specific case of Spain, Alcántara (1995) studied key sectors for VOCs, NO_X and SO_X pollution and made a first contribution for the application of input–output subsystems to analyse these pollutants; Roca and Serrano (2007a) applied a structural decomposition in three different effects (technology, structure and scale) to the changes in nine pollutants (including NO_X), and analysed the emissions associated to the patterns of consumption of expenditure groups; and, finally, Roca and Serrano (2007b) analysed the Spanish emissions embodied in international trade through an environmentally extended input–output model for the same pollutants.

The input–output subsystems approach is a methodology especially suited to study the type of relationships between the different sectors and its application to environmental analysis is of great utility to ascertain the kind of mitigation policies that are more suited for each sector according to its role in the productive structure. To identify policy measures that can complement end-of-pipe policies and increase mitigation, and in which sectors they are going to be more effective, this paper analyses NO_X emissions in Spain using an input–output subsystems approach. Our specific methodology treats each industry as a subsystem and analyses its relationships with the rest of the economy. In this way, our technique allows us to investigate in detail the different components of the total (direct and indirect) emissions generated to satisfy the final demand of the different sectors. The relevance of the different components studied indicates us which type of policies would be more fitted for each case. Our analysis can thus be of help in orientating the appropriate mitigation policies to be applied to the different relevant polluting sectors.

The paper continues as follows. Section 2 sets out the methodology. Section 3 describes the data employed. Section 4 presents the results of the application of the methodology to the analysis of NO_X emissions in Spain in 2007. Section 5 concludes.

2. Methodology

A subsystem allows us to examine the particular production structure of each sector of the economic system, considering its relationship with the rest of the economy, "in such a way that each part forms a smaller self-replacing system" (Sraffa 1960, p. 89). This concept was later developed by Harcourt and Massaro (1964) and Pasinetti (1973). Alcántara (1995) was the first to apply the subsystem concept from an environmental perspective, developing a widely disaggregated analysis of pollution-generating subsystems. Analogous to Sraffa's *commodity-by-commodity* concept, these subsystems can be interpreted as *pollution-by-pollution* generators. This is complemented by the work Sánchez-Chóliz and Duarte (2003), who applied the former methodology to the study of water pollution according to economic activity in the Spanish region of Aragon. Other applications can be found in Alcántara and Padilla (2009) and Butnar and Llop (2011) for CO_2 emissions in the service sector in Spain, Navarro and Alcántara (2010) for the methane emissions of the agroindustrial subsystem in the Spanish region of Catalonia, and Piaggio et al. (2015) for the CO_2 emissions of the service sectors in Uruguay. Llop and Tol (2012) approach the analysis of greenhouse gases in Ireland from the subsystems perspective, considering all productive branches as subsystems. A complementary application of subsystems analysis was implemented by Fritz et al. (1998) to analyse the pressure of non-polluting sectors on polluting sectors in the region of Chicago.

In this paper, we propose a decomposition into different components of the emissions associated with economic activity developing the methodology initially proposed by Navarro and Alcántara (2010). This simple decomposition does not require discussion of the analysis of the different internal components of the subsystem, given that in this case each subsystem is a unique productive branch.

We start from the well-known Leontief (1936) model, which is given by the next equations system[2]:

(1) $$\mathbf{x} = \mathbf{A}\mathbf{x} + \boldsymbol{y}$$

Where **x** is a (*n x 1*) vector that expresses the total output of each one of the productive sectors *i, j = 1, 2, …i…j…n*; **y** is the (*n x 1*) vector of net sectoral outputs or final demands; and **A** is a (*n x n*) matrix of technical coefficients, where the characteristic

[2] For a thorough review of the theoretical and empirical developments of input–output analysis, see Miller and Blair (2009).

element a_{ij} shows the consumption of inputs, in money terms, from sector *i* per unit of output, in money terms, of sector *j*. That is:

(2) $$a_{ij} = \frac{x_{ij}}{x_j}$$

The solution of the system is then given by the next expression:

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

Where $(\mathbf{I} - \mathbf{A})^{-1}$ is the well-known Leontief inverse, being **I** the identity matrix.

Let us consider the following matrix product, in which ^ expresses the diagonalisation of a vector:

$$(\mathbf{I} - \mathbf{A})^{-1}\hat{\mathbf{y}} \qquad (4)$$

This product determines $\mathbf{x}^{(j)}$, expressing the amount of output that all sectors have to produce to obtain the final demand of sector *j*, such that:

$$\sum \mathbf{x}^{(j)} = \mathbf{x} \qquad (5)$$

denotes the total output of the economy.

Therefore, the subsystem generating the final output of sector *j* is given by:

$$\mathbf{A}\mathbf{x}^{(j)} + \mathbf{y}^{(j)} = \mathbf{x}^{(j)} \qquad (6)$$

where $\mathbf{y}^{(j)}$ is a vector in which all elements take the value zero, except the value corresponding to the final demand or net output of the productive branch *j*.

The system of equations in (6) is solved as:

$$\mathbf{A(I - A)^{-1}y}^{(j)} + \mathbf{y}^{(j)} = \mathbf{x}^{(j)} \tag{7}$$

Column *j* of the matrix product $\mathbf{A}(\mathbf{I}-\mathbf{A})^{-1}$ expresses the vertically integrated output that the whole system has to obtain per unit of net output of industry *j*.

The construction of a pollution-generating subsystem is immediate. A first step in subsystems methodology is the decomposition of the vector of the pollution directly and indirectly generated by a sector to obtain its final demand into two components: emissions generated to obtain productive inputs and emissions directly generated by the sector to obtain its final demand.

Let **c** be the vector of the NO_X emissions directly generated per unit of output of the different industries. Diagonalising this, we obtain:

$$\mathbf{\hat{c}A(I - A)^{-1}y}^{(j)} + \mathbf{\hat{c}y}^{(j)} = \mathbf{\hat{c}x}^{(j)} \tag{8}$$

Column *j* of the matrix product $\mathbf{\hat{c}A}(\mathbf{I}-\mathbf{A})^{-1}$ expresses the generation of vertically integrated pollution that the whole system has to generate per unit of net output of industry *j*.

To consider all industries as subsystems, we compute the following expression:

$$\mathbf{\hat{c}A(I - A)^{-1}y} + \mathbf{\hat{c}y} = \mathbf{\hat{c}(I - A)^{-1}y} = \mathbf{\hat{c}x} \tag{9}$$

Taking into account that $\mathbf{A(I\text{-}A)^{-1}= (I\text{-}A)^{-1}\text{-}I}$, and let $\mathbf{B}=(\mathbf{I}\text{-}\mathbf{A})^{-1}$, with the end of simplifying later expressions, we can transform expression (9) into:

$$\mathbf{\hat{c}}[\mathbf{B}-\mathbf{I}]\mathbf{y} + \mathbf{\hat{c}y} = \mathbf{\hat{c}x} \tag{10}$$

The elements of the main diagonal of the matrix product $\mathbf{\hat{c}AB}$ express the pollution generated by an industry per each unit of net output of this industry. The rest of elements in a given column, that is, excluding the elements corresponding to the main diagonal of the column, express the pollution generated by the rest of the industries per each unit of net output of this industry. According to our approach, total (direct and indirect) emissions generated by the final demand of an industry have at least two components: the *internal component*, $c_j(b_{jj}-1)y_j$, which is given by the magnitude of the corresponding element of the main diagonal and shows the emission generated in the production of intermediate inputs by the own sector required to satisfy its final demand, and the *spillover*, $\sum_{i\neq j} c_i b_{ij} y_j$, which is given by the rest of the elements of the corresponding column and indicates the emission generated by the rest of sectors in the production of the inputs sold to sector *j*. In addition, from the second term of the left hand side of equation (10) we can derive a *scale component*, which is given by $c_j y_j$ and indicates the emissions directly related with the magnitude of the final demand. We have then a first decomposition of total emissions of sector *j* given by the next expression:

$$Total\ emissions\ sector\ j = \underbrace{c_j(b_{jj}-1)y_j}_{\text{internal component}} + \underbrace{\textstyle\sum_{i\neq j} c_i\, b_{ij} y_j}_{\text{spillover}} + \underbrace{c_j y_j}_{\text{scale component}} \qquad (11)$$

Although from the computation of expression (8) some indicators for the characterisation of subsystems could be obtained (Alcántara, 1995), given the aim of this paper, it seems more appropriate to approach the analysis from another perspective. We wish to analyse the factors behind the impact of each sector considering its relationship with the rest of the system to indicate in each case which are the most appropriate policies to mitigate emissions. In this sense, if the internal component is, for example, much greater—in relative terms—than the spillover component, this would suggest policies oriented to technological improvements in the considered industry. This component, however, is more complex as we will see that it contains two different aspects that may suggest different mitigation policies. To show this, we consider again the elements of the main diagonal.

Considering the inversion by parts of a square matrix, the elements of the main diagonal of the Leontief inverse are given by the following expression:

$$b_{jj} = \left[(1-a_{jj})^{-1} - 1 \right] + (1-a_{jj})^{-1} \sum_{i \neq j} a_{ji}\, b_{ij} + 1 \qquad (12)$$

And so we can write:

$$b_{jj} - 1 = \left[(1-a_{jj})^{-1} - 1 \right] + (1-a_{jj})^{-1} \sum_{i \neq j} a_{ji} b_{ij} \qquad (13)$$

The first term on the right-hand side shows the internal need of industry *j* for its own production to obtain its final demand. This can be denoted *own internal component*. The second term shows the output from industry *j* required for the production of inputs that it demands from other industries. It is own production of industry *j* induced through its requirement of inputs from other industries. It is thus a *feed-back component*.

Total (direct and indirect) emissions of sector *j* can be decomposed now as:

$$Total\ emission\ sector\ j = \underbrace{c_j \left[\left(1-a_{jj}\right)^{-1} - 1 \right] y_j}_{\text{own internal component}} + \underbrace{c_j \left(1-a_{jj}\right)^{-1} \textstyle\sum_{i \neq j} a_{ji}\, b_{ij} y_j}_{\text{feed-back}} + \underbrace{\textstyle\sum_{i \neq j} c_i\, b_{ij} y_j}_{\text{spillover}} + \underbrace{c_j y_j}_{\text{scale component}} \qquad (14)$$

Emissions can then be decomposed into four components: own internal component, feed-back, spillover and scale component. This last decomposition involves a greater detail of the relationship between each sector and the rest of sectors and defines in more detail the internal component. The information provided by expression (14) allows to orientate the kind of policies that would be more appropriate to the different sectors. While direct polluters can be directly tackled through different measures that encourage them to diminish emissions through technical improvements, indirect pollution can be tackled by demand policies that encourage sectors and consumers to reduce or change the demand of polluting inputs. The four components allow us to have a greater detail in the fact if input substitution should be encouraged in reference to inputs provided from the sector itself, from the sectors of the rest of the economy, or directed to final consumers. The design of the different policies requires from a deep analysis of the sector or sectors in which to act, taking into consideration its behaviour in the framework of the productive structure (expression (14)) and the magnitude of its total (direct and indirect) emissions in the whole system. The decomposition proposed provides a useful tool for the study of the productive structure of each sector according to its relationship with the rest of sectors of the economy. The relative relevance of the different components shows the different intersectoral linkages of the economic sectors, indicating the best ways to tackle emissions in each case. We discuss in the policy implications of the application of our methodology in Section 5, after a presentation of the results of the methodology in the next section.

3. Data

The data are taken from the World Input–Output Database (WIOD) (Timmer et al., 2012). WIOD provides input–output national matrices disaggregated into 35 sectors at basic prices (in current US$) for 27 countries of the European Union and another 13 relevant economies for the period 1995–2009. In addition, WIOD provides environmental accounts for greenhouse gases, air pollutants and materials use. The vectors of air pollution are built following the methodology of EUROSTAT (2008).

The analysis is applied to Spain for the year 2007. This year is chosen because it was the last year of economic stability prior to the beginning of the current economic crisis. In this way, we can analyse the Spanish economic structure avoiding the conjunctural effects of the decline in activity. Table 3 summarises the share of sectors in total output, value-added and direct emissions of NO_X. The main direct emitters are electricity, Gas and water supply (17), Agriculture, hunting, forestry and fishing (1), Inland transport (23) and Other non-metallic mineral (11) sectors, which amount to 66.8% of direct emissions (26.1%, 16.3%, 14.9% and 9.5% respectively). The share of these sectors in total output and value-added of the economy does not exceed 3% in any case.

It is also relevant to highlight the role of the Construction (18) sector. Even though its share of direct emissions is lower than that of the aforementioned sectors (5.7%), it represents 15.9% of total output and 11.9% of total value-added. Taking into account these data, it would seem that in comparison to the other sectors, the construction sector has a relatively low environmental impact per unit of output.

[TABLE 3]

4. Results

Table 4 presents the results of the decomposition of total sectoral emissions into the different components defined in the methodology section. While a bit less than half of total emissions are produced (directly or indirectly) by the different sectors to satisfy their final demand (scale, own internal and feedback components), the other half is a consequence of the pollution generated in the production of inputs required from other sectors (spillover component). Moreover, it is worth noting that total emissions generated by the final demand of the sectors of the economy are less concentrated in a small group of sectors than direct emissions.

The four main direct polluters—Electricity, gas and water supply (17), Agriculture, hunting, forestry and fishing (1), Inland transport (23) and Other non-metallic mineral (11) sectors—have a share of 66.8% of direct emissions, but only 22.78% of total (direct and indirect) emissions. Total emissions of these sectors are mainly explained by the scale component, while the own internal component is also significant for sector 17.

On the other hand, the Construction (18) sector is the major polluter when total emissions are considered, amounting to 16% of total emissions. Of these emissions, 70% are a consequence of the indirect pollution induced in the rest of the economy by its demand for inputs. While the sector has an impact well below the average per unit of final demand with regard to its direct emissions, its impact in total emissions is above average. This, jointly with its disproportionally large share compared to the European context (Bielsa and Duarte, 2011), make the sector the most polluting industry. Others that are also important due to the spillover component are Food, beverages and tobacco (3) and Hotels and restaurants (22), which together represent 13.7% of total emissions for the economy.

[TABLE 4]

Figure 2 shows the relationship between the components associated with own emissions and the component related to the emissions that are required from the rest of the economy (weighted by their final demand). Figure 3 shows each sector's total emissions, decomposed into the four components described above. These figures allow us to identify in which sectors are indirect emissions more important in relative terms.

Besides the three aforementioned sectors, Transport equipment (15), and some service sectors, such as Other community, social and personal services (34), Public administration (31), Real estate activities (29), Health and social work (33) and Renting of machinery and equipment (30) can be highlighted. The policy implications of these results are discussed in the next section.

[FIGURE 2]

[FIGURE 3]

[FIGURE 4]

Figure 4 shows the production layer in which the total emissions of each of the sectors of the Spanish economy are produced. During the first layer 41% of total NO_X emissions are produced. Emissions increase until reaching 98.9% of total emissions in the fifth production layer. Looking at how long the emissions of the more polluting sectors stays in the production chain we see two different patterns. On the one hand, the pollution of Electricity, gas and water supply (17), Agriculture, hunting, forestry and fishing (1), and Inland transport (23) are produced mostly during the first production layer. This is because these sectors are mostly input suppliers to the rest of the economy, being usually in the early stages of the production chain. On the other hand, the pollution of the Construction (18) and Other non-metallic mineral (11) sectors are produced in higher levels of the production layer. This is explained because these sectors require inputs that need to be previously processed. This analysis reinforces our previous findings, highlighting the importance of decomposing direct and indirect emissions to design the best mitigation policies.

5. Discussion and policy implications

Sterner and Coria (2011) proposed four classes of policy instruments for diminishing environmental pollution: i) using markets (e.g., subsidies for technological improvements, taxes and charges), ii) creating markets (e.g., tradable permits), iii) Environmental regulations (e.g., standards, bans, permits), and iv) public engagement (e.g., public participation, information disclosure). The four components described before allow to identify in which part of the production chain this instruments are going to be more effective. E.g., using market instruments to encourage technical improvements is going to be effective in directly polluting sectors, while information campaigns to encourage dirty inputs substitution or consumption are going to be effective in non-directly polluting sectors. Also, policies of any kind focused on final demand would be relevant to diminish pollution in sectors with a relevant scale component.

The application of input–output analysis has allowed us to identify the responsibility of each sector according to the total NO_X emitted to satisfy its final demand. Using input–output subsystems methodology, we have been able to decompose the responsibility of each sector into four different components, three of which indicate the emission generated in the production processes of the sector (scale, own internal and feed-back components) and other that shows the emission generated by the induced activity in the rest of the economy (spillover component). This classification provides useful information on the appropriate mitigation policies to apply in each case. A sector that mainly pollutes through its own production process in order to satisfy its own demand can be appropriately tackled with policies oriented to improve its technical processes, like more efficient and cleaner technologies or end-of-pipe measures, and to adopt best practices, like changing habits and behaviours during the production process that can increase environmental efficiency. This can be encouraged through both market and non-market based policies, as suggested by Sterner and Coria (2011). In contrast, if a sector responsibility in total emission is mainly due to the induced emissions in other sectors, demand policies that encourage the reduction of the demand of inputs from directly polluting sectors by changing the inputs demand to more environmental friendly inputs would be effective. This includes both market as well as non-market policies, like processes certification and information campaigns. These measures could complement technical improvements and the implementation of best practice in the sectors that pollute through their own production processes.

Four sectors are responsible of two-thirds of direct NO_X emissions (Electricity, gas and water supply (17), Agriculture, hunting, forestry and fishing (1), Inland transport (23) and Other non-metallic mineral (11)). Consequently, policy measures oriented to improve the technical processes in these sectors will be appropriate and can be highly effective in mitigating emissions.

Our analysis also shows that, according to the magnitude of the spillover component, more than half of total NO_X emissions of the economy are produced as a result that the different sectors pull other sectors of the economy to pollute when they demand intermediate inputs. The most relevant case is Construction (18), which is the major polluter in the case of total emissions because of the pollution incorporated in the inputs it demands to other industries. This result shows the importance of building activities for the design of NO_X mitigation policies. A housing market more based on the improvement of second-hand houses, instead of building new ones, could be a possible measure to reduce emissions (Piaggio et al., 2014), while requiring suppliers in the sector to provide emissions information and setting minimum standards for procuring buildings may also be a channel through which reducing emissions (Acquaye and Duffy, 2010).

Other important sectors according to their indirect emissions (spillover component) are Food, beverages and tobacco (2) and Hotels and Restaurants (22). In addition, besides the most important indirect emitters, the information on Figure 2 and Figure 3 allows to identify in which sectors demand policies will be more effective, according to the relative magnitude of their spillover component. In particular, most of these sectors are service activities, the role of which could wrongly be considered irrelevant if only indirect emissions were evaluated. The importance of various service activities in explaining total emission in Spain was also found in a previous study for the case CO_2 emissions (Alcántara and Padilla, 2009). Indirect emissions can be tackled by demand policies that complement the intervention on direct polluters. Sterner and Coria (2011) provide a menu of options that vary from market-based measures to decrease the demand of specific products, to policies based on engaging the public, like information disclosure through product labelling or education campaigns. At the firm level, this can include also certification programs encouraging input substitution. Usually, price-based policies are more efficient because they can exploit information that is not observed but captured by the price. However, it has been tested that they complement each other. In the case of service sectors, process certification and service labelling will provide consumers with better information and help them to change their demand to less polluting products.

6. Conclusions

To guide mitigation policy, this research has applied the input–output subsystems methodology to analyse the relationship between the Spanish productive structure and NO_X emissions for the year 2007, the last year before the economic crisis. We have analysed each industry as a subsystem, thus taking into account its relationship with the rest of the system. In this way, we have been able to determine the factors behind emissions and hence the type of policies that best fit in each case.

The results show the importance of some sectors that do not seem significant when looking only at their direct emissions. In short, when looking at the total emissions generated to satisfy its final demand, a sector that stands above the rest is the construction sector. This sector becomes the most important in terms of total emissions mainly due to the indirect pollution that it induces in the sectors that provide the inputs required to satisfy its final demand. Other sectors that stand out for the pollution they induce in the rest are foods, beverages and tobacco, hotels and restaurants and various service sectors. A relevant result of this research is the importance of various sectors associated with service provision. The role of these sectors in NO_X emissions may wrongly be seen as unimportant if one only looks at their direct emissions. Our analysis has allowed us to indicate the possible effectiveness in these sectors of various demand policies aimed at complementing technological and supply policies in those sectors with greater significance in terms of their direct emissions.

Acknowledgements

We are very grateful for the useful comments of four reviewers. We acknowledge the support of the projects ECO2015-67524-R (Spanish Ministry of Economy and Competitiveness), 2014SGR950 and XREPP (DGR).

References

Acquaye, A.A., Duffy, A.P. (2010) "Input–output analysis of Irish construction sector greenhouse gas emissions", *Building and Environment*, 45, 784–791.

Alcántara, V. (1995) Economía y contaminación atmosférica: hacia un nuevo enfoque desde el análisis input-output. PhD dissertation, Univ. de Barcelona, Barcelona.

Alcántara, V., Padilla, E. (2009) "Input–output subsystems and pollution: An application to the service sector and CO_2 emissions in Spain", *Ecological Economics*, 68, pp. 905–914.

Benders, R.M.J., Moll, H.C., Nijdam, D.S. (2012) "From Energy to Environmental Analysis Improving the Resolution of the Environmental Impact of Dutch Private Consumption with Hybrid Analysis", *Journal of Industrial Ecology*, 16, pp. 163–175.

Bielsa, J., Duarte, R. (2011) "Size and linkages of the Spanish construction industry: key sector or deformation of the economy?", *Cambridge Journal of Economics*, Oxford University Press, 35, pp. 317–334.

Butnar, I., Llop, M. (2011) "Structural decomposition analysis and input-output subsystems: Changes in CO_2 emissions of Spanish service sectors (2000–2005)", *Ecological Economics*, 70, pp. 2012–2019.

Chang, Y., Huang, Z., Ries, R.J., and Masanet, E. (2016) "The embodied air pollutant emissions and water footprints of buildings in China: a quantification using disaggregated input–output life cycle inventory model", *Journal of Cleaner Production*, 113, pp. 274–284.

Deng, G., Ding, Y., Ren, S. (2016) "The study on the air pollutants embodied in goods for consumption and trade in China — Accounting and structural decomposition analysis", *Jornal of Cleaner Production*, 135, pp. 332–341.

Environmental European Agency (EEA) (2012) Nitrogen oxide emissions still a major problem in Europe. Available at: http://www.eea.europa.eu/highlights/nitrogen-oxide-emissions-still-a (Accessed on April 6th, 2015)

Environmental European Agency (EEA) (2014) NEC Directive status report 2013 Reporting by the Member States under Directive 2001/81/EC of the European Parliament and of the Council of 23 October 2001 on national emission ceilings for certain atmospheric pollutants. EEA Technical report No 10/2014 (http://www.eea.europa.eu/publications/nec-directive-status-report-2013/ (Accessed on June 3rd, 2016).

European Council (EC) (2001) Directive 2001/81/EC of the European Parliament and of the Council of 23 October 2001 on national emission ceilings for certain atmospheric pollutants. OJ L 309, 27.11.2001, pp. 22–30.

Eurostat (2008) *Eurostat Manual of Supply, Use and Input-Output Tables*. Eurostat, Luxembourg.

Fritz, O.M., Sonis, M., Hewings, G.J.D. (1998) "A Miyazawa analysis of interactions between polluting and non-polluting sectors", *Structural Change and Economics Dynamics*, 9,pp. 289–305.

Harcourt, G.C., Massaro, V.G. (1964) "A note on Mr. Sraffa's sub-systems", *The Economic Journal*, 74, pp. 715–722.

Hoekstra, R. (2010) "(Towards) a complete database of peer-reviewed articles on environmentally extended input–output analysis", 18th International Input–Output conference of the International Input–Output Association, June 20–25th, Sydney, Australia.

Leontief, W. (1936) "Quantitative input and output relations in the economic system of the United States", *The Review of Economic and Statistics*, 18, pp. 105–25.

Leontief, W. (1970) "Environmental Repercussions and the Economic Structure: An Input-Output Approach", *The Review of Economics and Statistics*, 52(3), 262–271.

Llop, M., Tol, R.S.J. (2012): "Decomposition of sectoral greenhouse gas emissions: a subsystem input-output model for the Republic of Ireland", *Journal of Environmental Planning and Management*, 56, pp. 1316–1331.

Miller, R.E., Blair, P.D. (2009) *Input–Output Analysis Foundations and Extensions*. (2nd Edition). Cambridge University Press. Cambridge.

Ministerio de Agricultura, Alimentación y Medio Ambiente (MAGRAMA) (2016a) Registro Estatal de Emisiones y Fuentes Contaminantes. (Spanish Register of Emissions and Pollutant Sources), http://www.en.prtr-es.es/conozca/Sustancias-contaminantes-1026062012.html (Accessed on June 18th, 2016).

Ministerio de Agricultura, Alimentación y Medio Ambiente (MAGRAMA) (2016b) Inventario Contaminantes Atmosféricos 2016 - Serie 1990–2014. (Athmospheric Pollutants Inventory), http://www.magrama.gob.es/es/calidad-y-evaluacion-ambiental/temas/sistema-espanol-de-inventario-sei-/ (Accessed on June 18th, 2016)

Navarro, F., Alcántara, V. (2010) Las emisiones de metano (CH_4) en el subsitema agroalimentario catalán: un análisis input-output alternativo. *Econonomía Agraria y Recursos Naturales*, 10, pp. 25–39.

Pasinetti, L.L. (1973) The Notion of Vertical Integration in Economic Analysis, *Metroeconomica* , 25, pp. 1–29.

Peters, G.P., Hertwich, E.G. (2006a) "The importance of imports for household environmental impacts", *Journal of Industrial Ecology*, 10, pp. 89–109.

Peters, G.P., Hertwich, E.G. (2006b) "Structural analysis of international trade: Environmental impacts of Norway", *Economic Systems Research*, 18, pp. 155 –181.

Piaggio, M., Alcántara, V., Padilla, E. (2015) "The materiality of the immaterial. Services sectors and CO_2 emissions in Uruguay", *Ecological Economics*, 110, 1–10.

Roca, J., Serrano, M. (2007a) "Income growth and atmospheric pollution in Spain: An input–output approach", Vol. 63 (1), pp. 230–242.

Roca, J., Serrano, M. (2007b) "Trade and atmospheric pollution in Spain: an input-output approach", 2nd Spanish Conference on Input-Output Analysis, Zaragoza, Spain.

Sánchez Chóliz, J., Duarte, R. (2003) "Analysing pollution by vertically integrated coefficients, with an application to the water sector in Aragon", *Cambridge Journal of Economics*, 27, pp. 433–448.

Shmelev, S.E. (2010) "Environmentally Extended Input-Output Analysis of the UK Economy: Key Sector Analysis", *QEH Working Paper* 183, Queen Elizabeth House, University of Oxford.

Sraffa, P. (1960) *Production of Commodities by Means of Commodities*. Cambridge University Press, Cambridge.

Sterner, T., Coria, J. (2011) *Policy Instruments for Environmental and Natural Resources Management.* (2nd edition). RFF Press, Routledge, New York and London.

Timmer, M., A.A. Erumban, J. Francois, A. Genty, R. Gouma, B. Los, F. Neuwahl, O. Pindyuk, J. Poeschl, J.M. Rueda-Cantuche, R. Stehrer, G. Streicher, U. Temurshoev, A. Villanueva and G.J. de Vries (2012), The World Input-Output Database (WIOD): Contents, sources and methods, WIOD, Background document available at http://www.wiod.org/publications/source_docs/WIOD_sources.pdf (Accessed on April 6th, 2015).

Toller, S., Wadeskog, A., Finnveden, G., Malmqvist, T., Carlsson, A. (2011) “Energy Use and Environmental Impacts of the Swedish Building and Real Estate Management Sector”, *Journal of Industrial Ecology*, 15, pp. 394–404.

Table 1: NO_X emission data for 2010 and 2011 and emission ceilings for 2010

Member State	NO_X final emission data 2010 (Gg)	NO_X final emission data 2011 (Gg)	NO_X ceilings for 2010
Austria	147.9	144.6	103
Belgium	221.0	208.4	176
Bulgaria	116.9	135.6	247
Cyprus	18.0	20.8	23
Czech Republic	239.1	225.4	286
Denmark	132.3	125.2	127
Estonia	36.7	35.9	60
Finland	166.5	153.6	170
France	1,067.1	1,000.8	810
Germany	1,328.1	1,293.6	1,051
Greece	318.8	296.0	344
Hungary	162.5	130.6	198
Ireland	76.7	69.0	65
Italy	963.6	929.9	990
Latvia	36.4	31.5	61
Lithuania	60.2	55.7	110
Luxembourg	17.9	17.7	11
Malta	8.1	7.9	8
Netherlands	271.9	257.3	260
Poland	862.1	845.9	879
Portugal	187.2	177.3	250
Romania	217.9	222.5	437
Slovakia	88.6	85.2	130
Slovenia	44.7	46.3	45
Spain	886.2	881.1	847
Sweden	148.0	138.8	148
United Kingdom	1,117.4	1,045.0	1,167
EU-27	8,942.1	8,581.5	9,003

Source: EEA (2014).

Note: The NEC directive and the EEA (2014) reported data does not cover "a) emissions from international maritime traffic; (b) aircraft emissions beyond the landing and take-off cycle; (c) for Spain, emissions in the Canary Islands; (d) for France, emissions in the overseas departments; (e) for Portugal, emissions in Madeira and the Azores" (EC, 2001, p. 23).

Table 2: Distribution of NO_X direct emission in 2000 and 2011 by source sector

	2000		2011	
	t	**%**	**t**	**%**
Combustion in energy production and transformation	340,308.6	23.5	198,505.2	19.8
Small combustion (Non-industrial combustion plants)	45,477.4	3.1	59,614.6	5.9
Combustion in industry	191,679.8	13.2	145,991.0	14.5
Production processes without combustion	10,445.3	0.7	8,993.7	0.9
Road transport	533,369.0	36.8	346,447.7	34.5
Other transport and mobile machinery	256,899.7	17.7	178,039.1	17.7
Waste treatment and disposal	4,984.2	0.3	4,600.9	0.5
Agriculture	22,057.7	1.5	21,734.9	2.2
Nature	45,718.7	3.2	40,504.1	4.0
TOTAL SOURCE SECTORS	1,450,940.5	100	1,004,431.2	100

Source: MAGRAMA (2016b).

Table 3: Output, value-added, and direct emissions of NO_X of economic sectors. Spain 2007

		Output		Value Added		NO_X	
	Sector	US$:	%	US$:	%	Tons.	%
1	Agriculture, Hunting, Forestry and Fishing	65,043.9	2.3%	37,279.0	2.9%	196,205.7	16.3%
2	Mining and Quarrying	9,175.5	0.3%	3,559.2	0.3%	7,543.1	0.6%
3	Food, Beverages and Tobacco	128,145.9	4.5%	26,708.3	2.1%	22,911.7	1.9%
4	Textiles and Textile Products	22,658.5	0.8%	6,701.7	0.5%	8,285.7	0.7%
5	Leather, Leather and Footwear	7,474.7	0.3%	1,985.9	0.2%	998.5	0.1%
6	Wood and Products of Wood and Cork	15,486.6	0.5%	4,433.6	0.3%	4,799.5	0.4%
7	Pulp, Paper, Paper , Printing and Publishing	47,053.4	1.7%	17,049.0	1.3%	14,921.7	1.2%
8	Coke, Refined Petroleum and Nuclear Fuel	47,171.2	1.7%	3,455.0	0.3%	45,445.5	3.8%
9	Chemicals and Chemical Products	65,116.6	2.3%	18,052.2	1.4%	21,870.9	1.8%
10	Rubber and Plastics	27,514.2	1.0%	7,826.9	0.6%	2,302.3	0.2%
11	Other Non-Metallic Mineral	52,455.9	1.8%	15,903.3	1.2%	114,627.9	9.5%
12	Basic Metals and Fabricated Metal	120,843.8	4.3%	34,762.7	2.7%	32,446.2	2.7%
13	Machinery, Nec	41,675.5	1.5%	14,269.6	1.1%	2,365.4	0.2%
14	Electrical and Optical Equipment	47,084.9	1.7%	12,052.2	0.9%	882.6	0.1%
15	Transport Equipment	104,715.8	3.7%	20,959.1	1.6%	5,651.3	0.5%
16	Manufacturing, Nec; Recycling	33,342.9	1.2%	9,485.2	0.7%	2,734.0	0.2%
17	Electricity, Gas and Water Supply	78,711.9	2.8%	27,118.1	2.1%	313,031.3	26.1%
18	Construction	443,732.3	15.6%	153,550.8	11.9%	69,042.7	5.7%
19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	52,054.3	1.8%	21,822.5	1.7%	8,207.9	0.7%
20	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	98,269.0	3.5%	53,797.6	4.2%	25,778.7	2.1%
21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	96,592.8	3.4%	60,659.7	4.7%	5,746.3	0.5%
22	Hotels and Restaurants	160,363.6	5.6%	93,361.2	7.2%	2,777.2	0.2%
23	Inland Transport	70,532.8	2.5%	30,593.7	2.4%	178,839.5	14.9%
24	Water Transport	4,388.3	0.2%	1,600.7	0.1%	65,040.8	5.4%
25	Air Transport	14,565.7	0.5%	4,628.2	0.4%	27,296.8	2.3%
26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	62,782.6	2.2%	22,514.6	1.7%	8,424.2	0.7%
27	Post and Telecommunications	59,487.9	2.1%	28,494.1	2.2%	2,056.0	0.2%
28	Financial Intermediation	107,410.2	3.8%	68,583.9	5.3%	399.9	0.0%
29	Real Estate Activities	160,303.3	5.6%	118,489.3	9.2%	71.5	0.0%
30	Renting of M&Eq and Other Business Activities	190,196.6	6.7%	104,983.0	8.1%	240.9	0.0%
31	Public Admin and Defence; Compulsory Social Security	114,523.1	4.0%	78,348.7	6.1%	579.0	0.0%
32	Education	70,989.2	2.5%	61,212.0	4.7%	38.4	0.0%
33	Health and Social Work	113,537.7	4.0%	72,754.4	5.6%	5,835.4	0.5%
34	Other Community, Social and Personal Services	105,546.3	3.7%	57,885.8	4.5%	3,742.2	0.3%
Total		2,838,946.8	100%	1,294,881.3	100%	1,201,140.7	100%

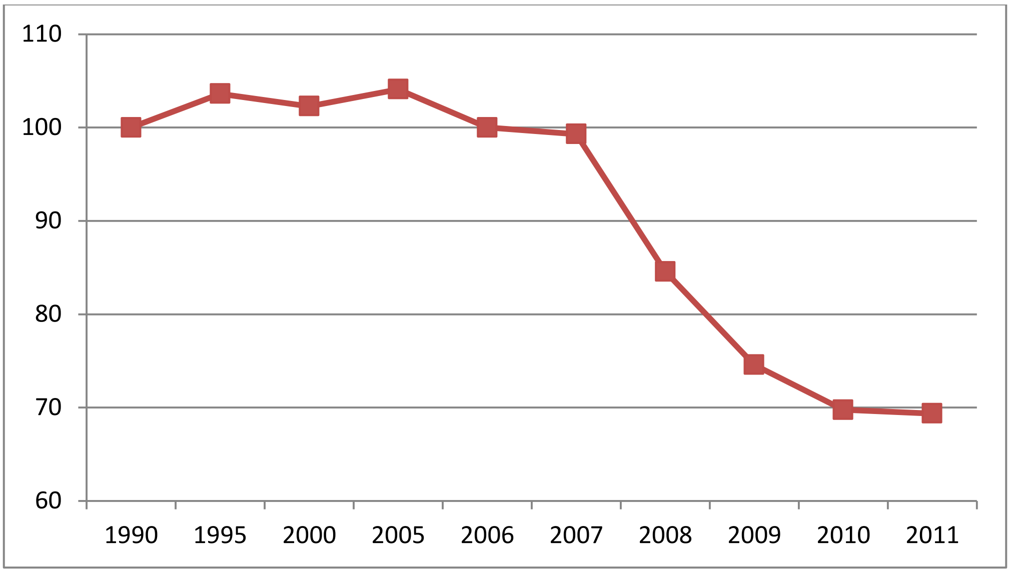
Source: Prepared by the authors with data from WIOD (Timmer et al., 2012).

Table 4: Decomposition of total NO_X emissions in Spain, 2007

		Scale		Own internal		Feed-back		Spillover		Total	
	Sector	**Tons.**	**%**	**Tons.**	**%**	**Tons.**	**%**	**Tons.**	**%**	**Tons.**	**%**
1	**Agriculture, Hunting, Forestry and Fishing**	99,815.66	85.3%	4164.9	3.6%	2414.13	2.1%	10674.99	9.1%	117069.7	9.7%
2	**Mining and Quarrying**	1,417.48	51.3%	12.2	0.4%	4.18	0.2%	1327.92	48.1%	2761.8	0.2%
3	**Food, Beverages and Tobacco**	13,693.11	13.0%	2465.3	2.3%	385.69	0.4%	88802.49	84.3%	105346.6	8.8%
4	**Textiles and Textile Products**	5,636.45	38.8%	836.6	5.8%	5.45	0.0%	8035.29	55.4%	14513.8	1.2%
5	**Leather, Leather and Footwear**	897.50	20.2%	75.9	1.7%	0.06	0.0%	3465.55	78.1%	4439.0	0.4%
6	**Wood and Products of Wood and Cork**	931.98	28.0%	277.8	8.4%	2.04	0.1%	2112.23	63.5%	3324.1	0.3%
7	**Pulp, Paper, Paper , Printing and Publishing**	5,524.06	33.7%	808.6	4.9%	48.26	0.3%	10002.36	61.1%	16383.3	1.4%
8	**Coke, Refined Petroleum and Nuclear Fuel**	27,734.03	83.7%	2314.2	7.0%	45.63	0.1%	3021.66	9.1%	33115.5	2.8%
9	**Chemicals and Chemical Products**	15,726.88	36.8%	1269.0	3.0%	54.54	0.1%	25699.38	60.1%	42749.8	3.6%
10	**Rubber and Plastics**	845.47	12.1%	115.9	1.7%	2.79	0.0%	6051.84	86.3%	7016.0	0.6%
11	**Other Non-Metallic Mineral**	21,812.97	67.5%	2542.9	7.9%	125.82	0.4%	7820.38	24.2%	32302.1	2.7%
12	**Basic Metals and Fabricated Metal**	9,951.32	33.1%	2473.1	8.2%	326.92	1.1%	17291.49	57.6%	30042.8	2.5%
13	**Machinery, Nec**	1,359.64	11.8%	74.4	0.6%	9.28	0.1%	10061.77	87.5%	11505.1	1.0%
14	**Electrical and Optical Equipment**	539.46	4.5%	55.7	0.5%	1.44	0.0%	11470.99	95.1%	12067.6	1.0%
15	**Transport Equipment**	4,447.82	12.8%	655.4	1.9%	16.66	0.0%	29570.45	85.2%	34690.3	2.9%
16	**Manufacturing, Nec; Recycling**	1,257.20	14.4%	39.0	0.4%	25.49	0.3%	7434.04	84.9%	8755.8	0.7%
17	**Electricity, Gas and Water Supply**	75,545.71	76.4%	19994.8	20.2%	799.45	0.8%	2528.32	2.6%	98868.3	8.2%
18	**Construction**	40,221.66	20.9%	18960.5	9.9%	590.37	0.3%	132347.47	68.9%	192120.0	16.0%
19	**Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel**	4,371.06	32.9%	111.8	0.8%	25.65	0.2%	8780.31	66.1%	13288.8	1.1%
20	**Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles**	11,370.22	33.4%	330.0	1.0%	90.46	0.3%	22226.26	65.3%	34016.9	2.8%
21	**Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods**	2,790.63	13.6%	12.7	0.1%	16.23	0.1%	17666.25	86.2%	20485.8	1.7%
22	**Hotels and Restaurants**	2,578.34	4.4%	2.4	0.0%	5.46	0.0%	56280.98	95.6%	58867.2	4.9%
23	**Inland Transport**	64,739.94	85.5%	1202.7	1.6%	2544.49	3.4%	7198.18	9.5%	75685.3	6.3%
24	**Water Transport**	44,616.97	96.3%	17.9	0.0%	73.80	0.2%	1608.66	3.5%	46317.3	3.9%
25	**Air Transport**	22,292.45	82.7%	417.0	1.5%	53.03	0.2%	4191.48	15.6%	26954.0	2.2%
26	**Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies**	2,740.72	12.5%	536.9	2.5%	131.56	0.6%	18448.33	84.4%	21857.5	1.8%
27	**Post and Telecommunications**	800.93	9.0%	116.8	1.3%	7.45	0.1%	8017.84	89.7%	8943.0	0.7%
28	**Financial Intermediation**	179.02	3.3%	35.3	0.7%	1.03	0.0%	5182.94	96.0%	5398.3	0.4%
29	**Real Estate Activities**	50.60	0.3%	0.3	0.0%	0.31	0.0%	14737.58	99.7%	14788.8	1.2%
30	**Renting of M&Eq and Other Business Activities**	96.42	0.5%	9.2	0.1%	2.29	0.0%	18096.80	99.4%	18204.7	1.5%
31	**Public Admin and Defence; Compulsory Social Security**	534.71	1.7%	1.8	0.0%	0.86	0.0%	30530.77	98.3%	31068.2	2.6%
32	**Education**	36.35	0.4%	0.1	0.0%	0.01	0.0%	8819.89	99.6%	8856.3	0.7%
33	**Health and Social Work**	5,293.51	21.1%	290.4	1.2%	4.13	0.0%	19505.95	77.7%	25094.0	2.1%
34	**Other Community, Social and Personal Services**	2,618.59	10.8%	358.8	1.5%	15.38	0.1%	21250.11	87.7%	24242.9	2.0%
Total		492,468.84	41.0%	60,580.60	5.0%	7,830.33	0.7%	640,260.96	53.3%	1,201,140.7	100%

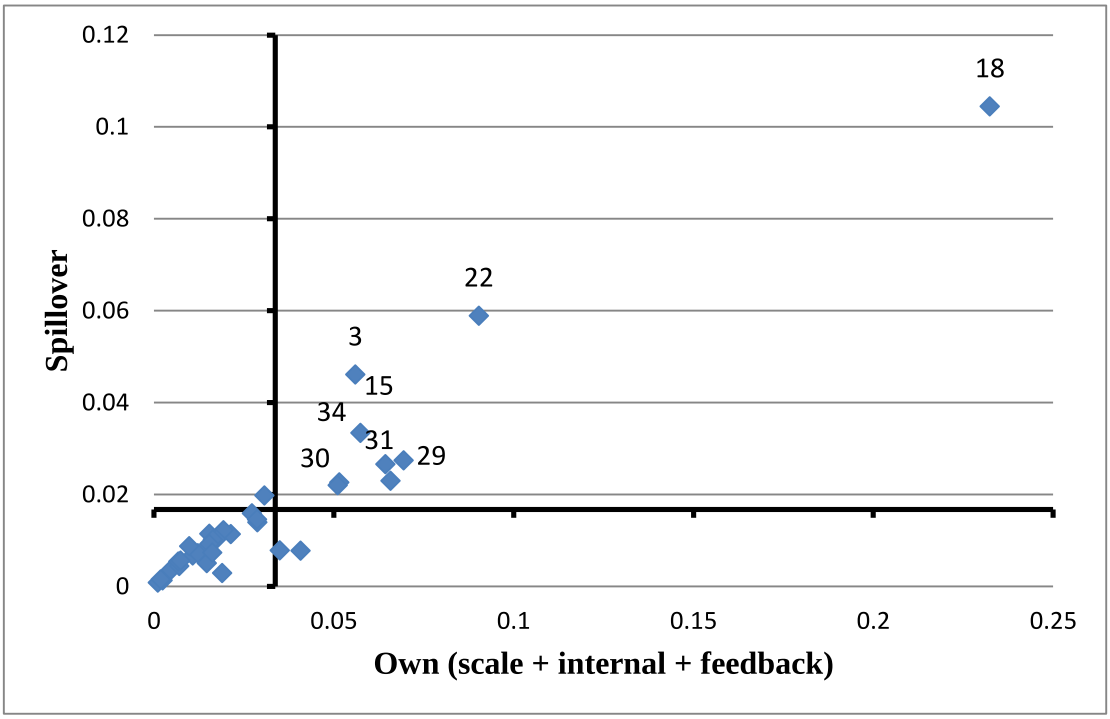
Source: Prepared by the authors with data from WIOD (Timmer et al., 2012).

Figure 1. NOx emissions in Spain 1990–2011 (Index 1990 = 100)



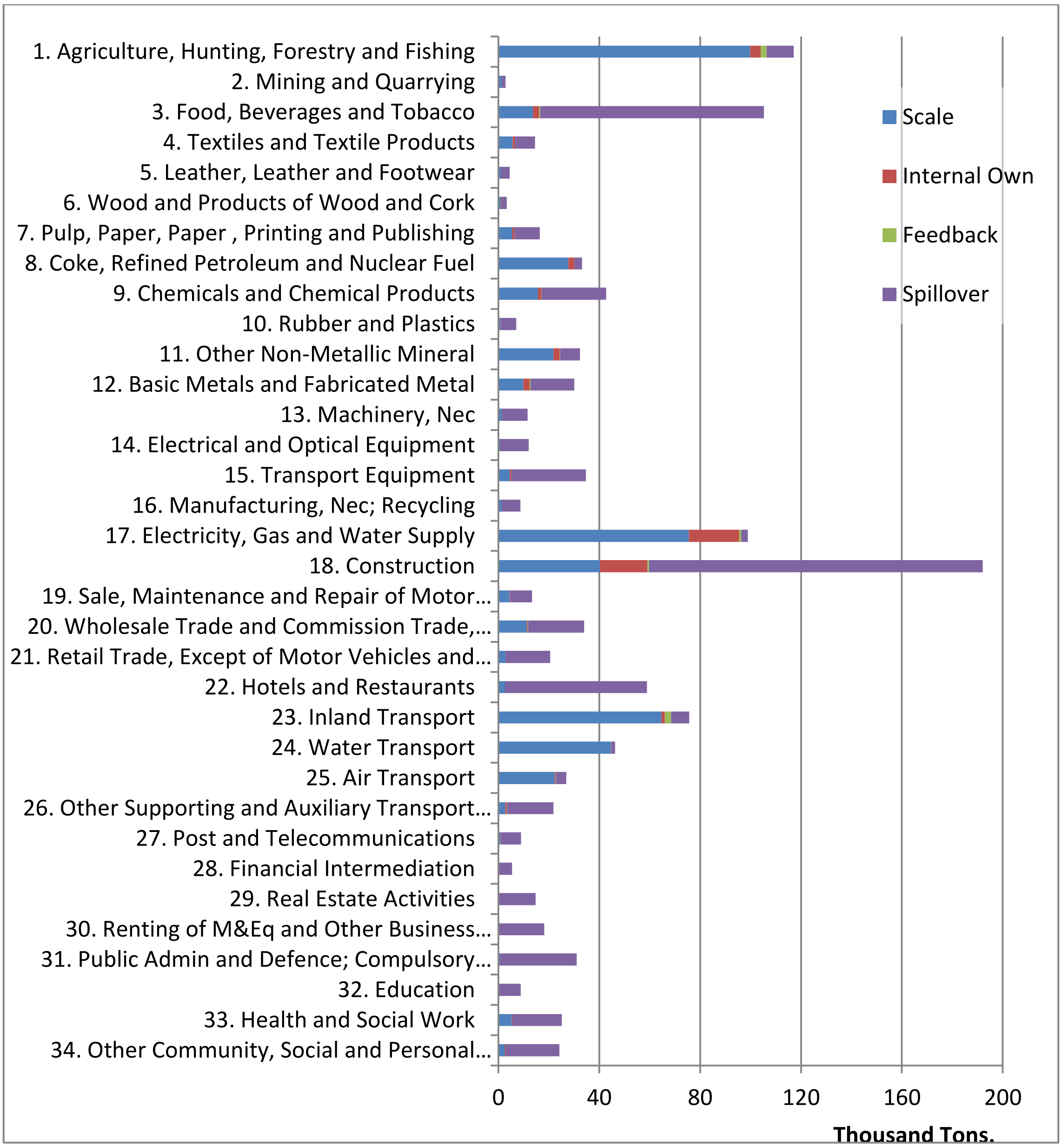
Source: EEA (2014).

Figure 2: Multipliers of the own (scale, internal, feed-back) and spillover components weighted by final demand (emissions per unit of final demand)



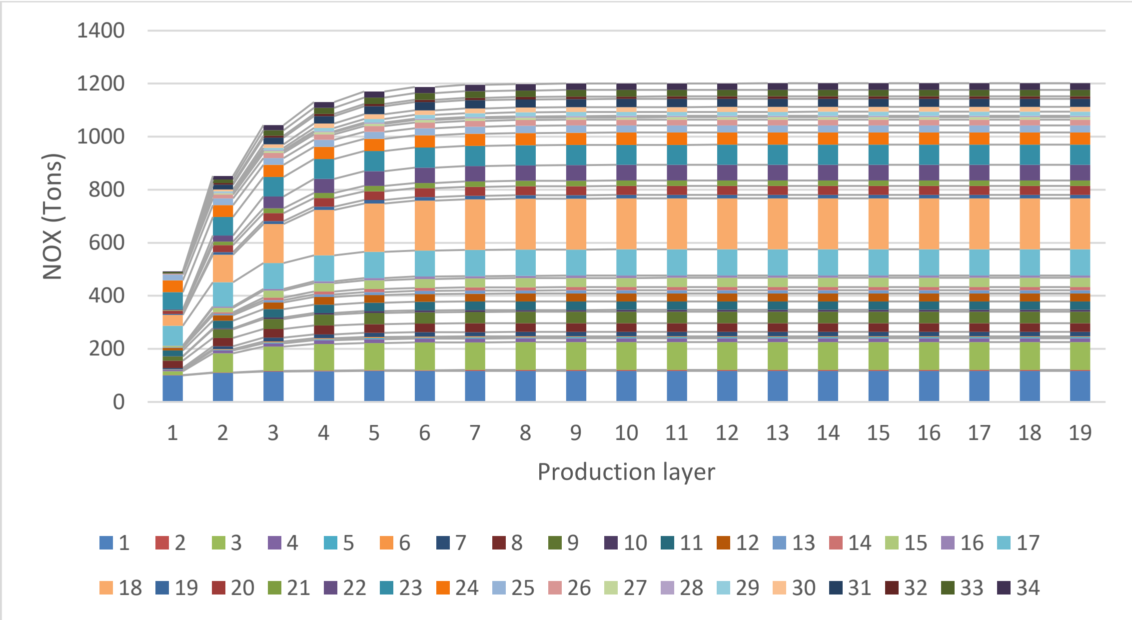
Source: Prepared by the authors with data from WIOD (Timmer et al., 2012).

Figure 3: Total sectoral emissions split by scale, own internal, feed-back and spillover components (thousand Tons.)



Source: Prepared by the authors with data from WIOD (Timmer et al., 2012).

Figure 4: Structural path analysis of sectoral NO_X direct and indirect emissions



Source: Prepared by the authors with data from WIOD (Timmer et al., 2012).