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Technology determinants of carbon emissions from demand and supply perspectives

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Abstract: We study the role that the productive structure plays in determining carbon dioxide (CO_2) emissions by industry. Specifically, we distinguish and isolate the interdependencies originating from the structure of the demand for inputs from those resulting from the supply structure. This separation has the advantage of enabling a better identification of the causal origin of emissions and allows the establishment of a catalog of industries based on their characteristics as demanders or suppliers of inputs. This information, linked to the different nature of demand or supply, can be relevant for designing more effective emission containment measures. The empirical basis of the analysis utilizes input-output data for Spain in 2020, while the methodological platform is an adaptation of the hypothetical extraction method (HEM).

Keywords: Demand-induced emissions, Supply-induced emissions, Selective extractions.

JEL Classification : C67, D57, Q51

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1. Introduction

The control of anthropogenic emissions of carbon dioxide (CO_2) into the atmosphere has become one of the most relevant concerns of our times. The evidence that carbon emissions are the main cause of the global increase in temperatures is increasingly conclusive (IPCC, 2023). Since carbon emissions, on the other hand, are a byproduct of the production activity that is carried out to satisfy final demand needs by households, firms, government, and external agents; it is natural to ask what type of policy interventions on economic activity can contribute to the mitigation of carbon emissions (Stern, 2006).

Direct government regulation turns out to be costly and inefficient and ends up generating excessive organizational costs (Fullerton and Muehlegger, 2019). For their part, market-directed measures, such as environmental taxes and trade permits, transfer cost incentives associated to carbon emissions to agents in order to modify their behavior in a way that is conducive to promote effective reductions in emissions.

The analysis of market measures of this type is typically conducted using economic models that capture the production and emissions structure at a specific point in time. Using input-output analysis, Labandeira and Labeaga (2013) demonstrate how to compute carbon intensities and explore the resulting implications for alternative fiscal policies, while Gemechu et al. (2014) investigate the potential effect of an eco-tax on carbon emissions using the input-output price model. Extending standard input-output analysis to the trade field, Su and Ang (2013) calculate embodied emissions under different trade assumptions and Hasan et al (2022) study the distribution of carbon emissions within a trade area. Integrating linear programming with input-output analysis, Barreiro et al. (2016) and Guerra and Sancho (2018) evaluate the optimality of possible policies directed at achieving specific CO_2 mitigation objectives.

When using computable general equilibrium models, the focus has often been on exploring second and third round effects related to the possible benefits (employment and/or welfare) of carbon abatement policies based on eco-taxation. See Jorgenson and Wilcoxen (1993), Conrad and Loschel (2005), and Moosavian et al (2020) for examples of specific applications and Patuelli (2005) and Maxim (2020) for descriptive surveys.

The effect of these mitigation policies is then studied by comparing the system without and with the policy. The estimated differences are attributed to the role that those policy measures can potentially play. In a temporal perspective, however, the incentive to adopt less polluting technologies is a third line of action for governments. In this case, it would be about establishing an action framework that makes it possible to directly influence the production structure via, for example, the development and adoption of new production techniques aligned with government set goals.

In all cases, current technology serves as the baseline upon which policies need to be considered and eventually evaluated. A line of inquiry that has not been sufficiently explored and deserves more attention concerns the identification of the various circuits of economic influence affecting the volume of emissions. Specifically, more attention should have been given to distinguishing between the subsets of influence attributable to firms' demand for inputs and those attributable to the supply role that those same firms play.

This type of interconnection, concerning the demand for and supply of goods and services by firms, finds its natural framework of analysis in input-output economics (Leontief, 1936; Miller and Blair, 2022). In this analytical approach, each firm in an economy belongs to a specific industry defined, with a certain degree of aggregation, by all those firms that are sufficiently similar. This perspective simplifies the analysis, allowing us to shift the focus to industries rather than directly on their individual firms.

Industries demand inputs, which are produced and delivered by other industries, to carry out their production. Simultaneously, industries deliver their output to other industries, which require it as an input, as well as to final demand. This dual role of industries as both demanders and suppliers is what will enable us to distinguish the respective circuits of influence and determine the magnitude of their effects on carbon emissions. The key concept here is magnitude. Since individual industries use sector-specific technologies, the resulting effects will in fact depend on the particularities of each industry's interconnection with the rest of industries.

The investigation of these effects and their scale has commonly been carried out using the Hypothetical Extraction Method (HEM) (Miller and Lahr, 2001; Dietzenbacher and Lahr, 2013; Dietzenbacher et al., 2019). This method estimates the role that an industry plays within the economic framework by hypothetically removing it. When an industry ceases to interact with others, input-output analysis is particularly suited for assessing the resulting consequences. The contrast between the initial scenario, where all industries are operational, and the simulated scenario, where an industry is extracted, indicates the significance of that industry within the network. Typically, the extraction method computes the global impact of the simultaneous cessation of all upstream and downstream interactions of an industry with other industries.

The simultaneous cessation of all interactions at the same time does not allow us to distinguish the differences attributable to the fact that the circuits of interdependence based on the structure of demand respond to different economic needs than those based on the structure of supply. From the perspective of demand the determining factor is the technology of the extracted industry, while from the point of view of supply the determining factor is the distribution of output, which, in turn, depends on the requirements across the rest of the industries.

The separation of effects arising from these different influence circuits would enable us to discern the underlying causality in the generation of emissions, providing more robust economic information that could be useful in the design of mitigation measures. An example could be the design of an eco-tax with the consequent clarification of who the main recipient of the tax signal should be. This tax can be levied either on the buyer of inputs (if the importance lies mainly in demand) or on the seller (if it lies mainly in supply). Hence the relevance of considering this demand/supply distinction from the perspective of the extraction method.

In Section 2 we describe the essentials of the analytical approach while in Section 3 we outline and comment on the numerical results that the model produces. Section 4 briefly concludes.

2. Methodology

In input-output economics, the available technology is described by a $n \times n$ nonnegative square matrix $\mathbf{A}=(a_{ij})$, with n being the number of industries and a_{ij} the technical coefficient that captures the required amount of good i used as input in the production of one unit of good j. In terms of interpretation, the first column of matrix $\mathbf{A}$ indicates industry 1 demand for inputs from itself and the rest of industries whereas the first row indicates the deliveries of industry 1 to itself and the rest of industries, and so on.

If $\mathbf{x}=(x_i)$ denotes the column vector of total output in the economy and $\mathbf{d}=(d_i)$ the column vector of final demand, the basic input-output equation (Miller and Blair, 2022) states that total output comprises intermediate and final deliveries:

$$\mathbf{x} = \mathbf{A} \cdot \mathbf{x} + \mathbf{d} \tag{1}$$

Solving this equation:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{d} \tag{2}$$

Let $\mathbf{e}=(e_i)$ be the vector of carbon emissions per unit of output. Then, total carbon emissions E in the economy will be driven by the levels in the vector of final demand:

$$E = \sum_{i=1}^{n} e_i \cdot x_i = \mathbf{e}' \cdot \mathbf{x} = \mathbf{e}' \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{d} \tag{3}$$

Now suppose for the sake of the argument that industry 1 ceases its purchases of inputs from the rest of the industries in the economy, i.e. $a_{i1}=0$ for $i \neq 1$. In this case, the domestic input-output matrix after the extraction of industry 1's demand for inputs would become:

$$\mathbf{A}^{(-1)} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ 0 & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{4}$$

Implicitly, the production of industry 1 continues to need those same inputs although industry 1 would now acquire them abroad via imports (Dietzenbacher et al, 2019; Guerra and Sancho, 2023). The consequence would be a fall in domestic demand for inputs, which would lead to a downward readjustment in domestic production. This readjustment, in turn, would affect the volume of interior emissions, leading to a reduction in them. The magnitude of the reduction will indicate the importance of the demand links originating in industry 1. The reduced level of domestic emissions resulting from the cessation of these upstream links can be evaluated as:

$$E^{(-1)} = \mathbf{e}' \cdot (\mathbf{I} - \mathbf{A}^{(-1)})^{-1} \cdot \mathbf{d} \tag{5}$$

The difference $E - E^{(-1)}$ would show the relevance of the demand links of industry 1 on the generation of carbon emissions. This type of calculation can be repeated for all industries which would yield a vector indicating the demand role played by all industries.

Consider now the situation whereby industry 1 ceases its deliveries to the rest of industries, i.e. $a_{1j} = 0$ for $j \neq 1$. Under this supply extraction of industry 1 the domestic input-output matrix would now become:

$$\mathbf{A}_{(-1)} = \begin{bmatrix} a_{11} & 0 & \cdots & 0 \\ a_{12} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{1n} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{6}$$

The elimination of these domestic deliveries to the rest of the industries would be replaced, once again, by an increase in imports from these industries, with the consequent drop in domestic production. The associated fall in the level of domestic emissions following the cessation of these downstream links can be calculated as:

$$E_{(-1)} = \mathbf{e}' \cdot (\mathbf{I} - \mathbf{A}_{(-1)})^{-1} \cdot \mathbf{d} \tag{7}$$

The estimated difference $E - E_{(-1)}$ reveals the significance of the supply links of industry 1 in the generation of carbon emissions.

Since industry 1 is just an industry in the system, these demand and supply extraction exercises can be repeated for any of the other industries. We would then obtain vectors $E–E^{(-i)}$ for i=1, 2,…,n and $E–E_{(-j)}$ for j=1, 2,…,n incorporating information, respectively, on the underlying strength of demand and supply links in the overall generation of domestic carbon emissions.

3. Data and results

We use the recently published Spanish input-output data for 2020 (INE, 2023) with 62 distinct industries. We hypothetically extract each of the 62 industries repeatedly solving equations (5) for demand extractions and (7) for supply extractions, comprising a total of 124 cases. The corresponding vector of emissions has been extracted for 2020 (INE, 2023b). For each of these extractions, we calculate the associated reductions in emissions.

In Table 1 we present the list of industries and the potential decrease in carbon emissions via demand for and supply of inputs. Furthermore, Graph A-1 in the Appendix provides a visual display of the same results for all the activity sectors.

[**Table 1 around here**]

The two industries with the higher percentage change in potential reduction of CO_2 emissions from the demand side are Foodstuffs, beverages, and tobacco (5) with an 18.30 percent and Construction (27) with a 13.98 percent. Both stand for a percentage change significantly above a 10 percent. Furthermore, Wholesale commercial services except for vehicles (29) with a 6.87 percent, Coke and petroleum refining (10) with a 5.34 percent, Hostelry services (36) with a 4.85 percent, Motor vehicles (20) with a 4.83 percent, Metallic products except machinery (16) with a 4.78 percent, Energy (24) with a 4.31 percent and Agriculture (1) with a 4.13 percent register each one more than a 4 percent contribution to CO_2 emissions reduction.

On the opposite side, the top two worst-performing industries in demand emissions' cuts from the demand side are Forestry (2) with 0.03 percent and Employment-related services (51) with 0.05 percent. Moreover, the remaining industries with less capacity to reduce demand-side emissions when they cease purchases of inputs from the rest of the national sectors are, listed from lower to higher values: Home repair services (61) with 0.15 percent, Postal services (35) with 0.16 percent, Maritime transportation (32) with 0.22 percent, Informatic and electronic products (17) with 0.23 percent, and Fisheries

(3) with 0.27 percent, all of them below 0.3 percent. The reduction in emissions after demand extractions, ordered from higher to lower percentage for the 62 industries, can be consulted in Graph A-2 in the Appendix

When we look at the potential results from the supply side, the best performing industries with high percentages of reduction in emissions are Agriculture (1) with a 14.78 percent, Energy (24) with a 11.78 percent and Other nonmetallic products (14) with 10.97 percent; the three of then registering above a 10 percent of emissions cut. The rest of best performers from the supply side are Chemical products (11) with a 9.40 percent, Metallurgy (15) with an 8.85 percent, Land transportation (31) with 7.95 percent. Extractive industries (4) with a 7.33 percent, Coke and petroleum refining (10) with a 5.61 percent, Foodstuffs, beverages, and tobacco (5) with a 5.31 percent and Metallic products except machinery (16) with a 4.38 percent, all of them marking reductions above a 4 percent.

Focusing on the supply worse performing industries, we highlight the cases of Research and development (47) and Social services (57) both with no reduction of emissions encountered. These industries are followed by Travel agencies and tourist operators (52) with a 0.01 percent, Fisheries (3) with a 0.02 percent, Agriculture (2) and (58) with a 0.03 percent, Other personal services (62) with a 0.04 percent, Education (55) and Employment related services (51) with a 0.06 percent, Home repair services (61) with a 0.08 percent and finally Public Administration services (54) with an 0.10 percent; all of them being equal or below 0.10 percent. The reduction in carbon emissions after supply extractions, ordered once again from higher to lower percentage, can be consulted in Graph A-3 in the Appendix.

In interpretive terms, these figures reveal that the degree of emissions reduction strongly depends on the ability to transfer input purchases to external suppliers. In this sense, the reduction in emissions would reveal the occurrence of a diversion of emissions to other territories. This diversion increases with the degree of vertical integration in domestic industries, leading to a considerable rise in substitute imports. On the other end of the spectrum, low levels of vertical integration would be evident when the reduction in emissions is minimal.

From the input supply side, the extraction of an industry entails substituting domestic inputs for imported ones across the rest of industries. A high emissions reduction figure would indicate an industry whose horizontal deliveries are directly and indirectly significant within the domestic production context. The discontinuation of such an industry as a supplier of inputs would inevitably result in a substantial reduction in emissions.

The selective extraction of industries from these two perspectives, as purchasers and deliverers of inputs, allows for the identification of specific properties for each industry in each dimension within the economic framework. For the purpose of designing possible mitigation policies associated with limiting emissions, it may be interesting to compare the reduction capacities from both perspectives. In Graph 1, we present the distribution of industries by terciles corresponding to the potential reduction of emissions from both demand and supply. Tercile 1 includes the top performers in each of the two extractions, and so forth. Thus, the block of both top deciles collects the industries with the highest reduction capacities in both demand and supply. The figures in the Graph correspond to the industries and their location on the coordinates of their numerical percentage reduction.

[**Graph 1 around here**]

From Graph 1, we can observe that the joint distribution of emissions reductions clearly illustrates an association between industries of the same type. Thus, the top industries in emissions reduction from both perspectives (box tercile 1-tercile 1) are mostly manufacturing industries, while the remaining ones are service industries auxiliary to manufacturing. In contrast, industries with a limited record of reductions (box tercile 3-tercile 3) consist mostly of administrative or social services sectors. This finding confirms the intuitive idea that industries associated with manufacturing contain broader and deeper interaction chains compared to service sectors. The selective hypothetical extraction method allows for their detection and quantification.

Finally, as additional confirmation, upon analyzing the table by columns, we observe that the column corresponding to tercile 1 (indicating high reductions from supply-side extractions) includes almost exclusively sectors associated with manufacturing, while the column of tercile 3 (indicating low reductions) contains mostly sectors associated with services. From the demand-side extractions, most manufacturing sectors appear in the top two terciles, i.e., the second and third rows. Overall, this set of results reveals the commonalities present in the classification of input-output industries and provides useful information regarding their underlying, though not straightforward to discover, technological properties.

4. Concluding remarks

The objective of this work has been to study and reveal the non-directly observable chains of mutual interaction between sectors of an economy and examine their potential repercussions on CO_2 emissions. The linear input-output model is particularly well-suited to be our chosen framework of analysis. To this end, we have used a simple adaptation of the hypothetical extraction method that allows us to distinguish the effects of the interaction chains depending on whether we consider the sectors as purchasers (demanders) or deliverers (suppliers) of inputs.

We have thus conducted two illustrative experiments. One consists in the extraction of industries as purchasers, and then we evaluate the associated reduction in emissions. This enables us to quantify and rank the industries in terms of their potential capacity for carbon emissions reduction. In the second hypothetical experiment, we repeat the extractions where industries cease delivering goods to other domestic industries. Once again, this provides numerical insights into the potentially different capacity of industries to reduce emissions from the supply side.

Based on these results, we proceed to visualize the joint distribution of possible reductions in order to categorize industries based on their double reduction capacity, either on the demand side or the supply side. The results show that manufacturing sectors, for the most part, would lead the greatest reductions from both perspectives. In contrast, service sectors would be on the opposite side of the spectrum with the lowest contributions to reductions. This information can be useful in the design of mitigation policies. For example, in the design of an ecotax and to promote efficiency in its execution, it would be advisable to concentrate it on manufacturing sectors. This would maximize the concentrated effects while minimizing the inevitable administration costs that, with a generalized ecotax, would fall on sectors with a relatively lower incidence in emissions. Similarly, policies aimed at increasing the efficiency of technology, hence lowering input use, should concentrate on those sectors with the greatest reducing capacity.

Finally, we should also highlight some of the limitations of the approach. One limitation is that the procedure is purely hypothetical. An actual cessation of activities would, in the medium term, lead to a change in the available production technology since input substitution would eventually take place. Therefore, we should interpret the findings herein as short-term results. Another limitation is the nature of the input-output model, particularly its linear structure. Real-world economic interactions are not linear. The assumed linearity is therefore an approximation that makes sense when considering small changes or, once again, short-term effects. While these limitations can be relaxed, it would require an altogether different type of model that would neither have the operational capacity nor the transparency in interpretation characteristic of the input-output model.

Disclosure statement

No potential conflict of interest was reported by the authors.

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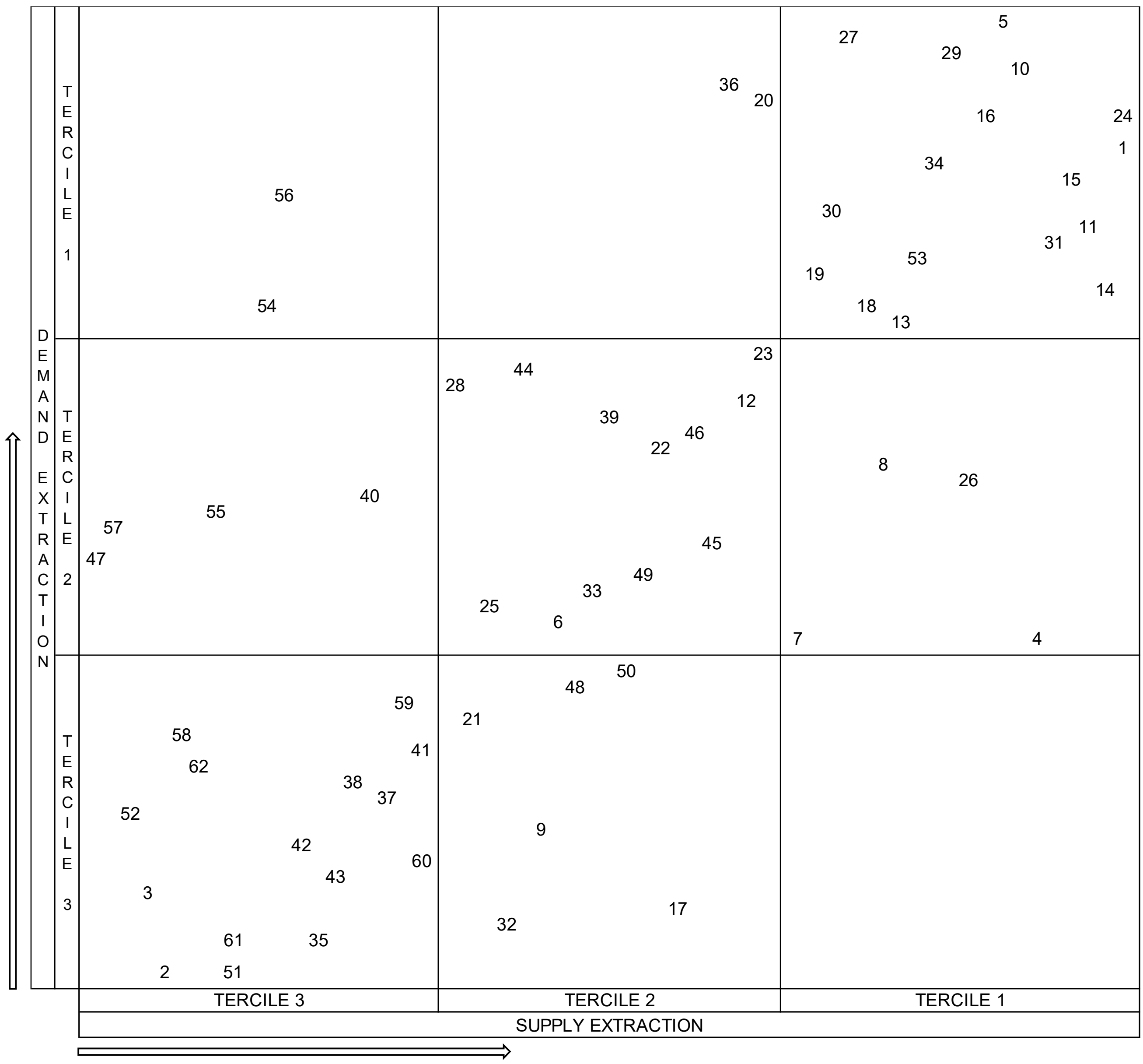
Table 1: Percentage change in CO_2 emissions after hypothetically removing demand and supply links.

	Demand	Supply
1. Agriculture	4,13	14,78
2. Forestry	0,03	0,03
3. Fisheries	0,27	0,02
4. Extractive industries	0,60	7,33
5. Foodstuffs, beverages, and tobacco	18,30	5,31
6. Textiles	0,66	0,54
7. Wood products	0,61	0,95
8. Paper products	1,14	2,24
9. Printing of recorded media	0,35	0,48
10. Coke and petroleum refining	5,34	5,61
11. Chemical products	3,02	9,40
12. Pharma products	1,33	0,84
13. Rubber and plastic products	1,88	2,42
14. Other nonmetallic products	2,06	10,97
15. Metallurgy	3,60	8,85
16. Metallic products except machinery	4,78	4,38
17. Informatic and electronic products	0,23	0,75
18. Electrical equipment	2,03	2,19
19. Machinery	2,14	1,39
20. Motor vehicles	4,83	0,94
21. Other transportation material	0,56	0,37
22. Furniture	1,20	0,71
23. Repair and installation of machinery	1,71	0,86
24. Energy	4,31	11,78
25. Water treatment and distribution	0,73	0,38
26. Waste management services	1,10	3,89
27. Construction	13,98	2,16
28. Motor vehicle commercial services	1,61	0,35
29. Wholesale commercial services except for vehicles	6,87	3,39
30. Retail commercial services except for vehicles	3,07	1,51
31. Land transportation	2,69	7,95
32. Maritime transportation	0,22	0,39
33. Air transportation	0,77	0,58
34. Auxiliary transportation services	3,82	2,94
35. Postal services	0,16	0,18
36. Hostelry services	4,85	0,78
37. Publishing services	0,36	0,20
38. Entertainment broadcasting services	0,36	0,19
39. Telecommunication services	1,33	0,63
40. Informatic services	1,02	0,20
41. Financial services	0,47	0,28
42. Insurance services	0,33	0,14
43. Auxiliary services to financial and insurance	0,31	0,19
44. Real estate services	1,61	0,45
45. Legal and accounting services	0,93	0,78
46. Engineering services	1,22	0,77
47. Research and development	0,90	0,00
48. Advertising and marketing	0,58	0,56

49. Other professional services	0,81	0,71
50. Rental services	0,60	0,69
51. Employment related services	0,05	0,06
52. Travel agencies and tourist operators	0,35	0,01
53. Auxiliary services to firms	2,47	2,65
54. Public Administration services	2,05	0,10
55. Education	1,01	0,06
56. Health services	3,29	0,13
57. Social services	0,98	0,00
58. Cultural services	0,48	0,03
59. Recreational services	0,57	0,25
60. Associational services	0,33	0,32
61. Home repair services	0,15	0,08
62. Other personal services	0,37	0,04

Source: Own elaboration.

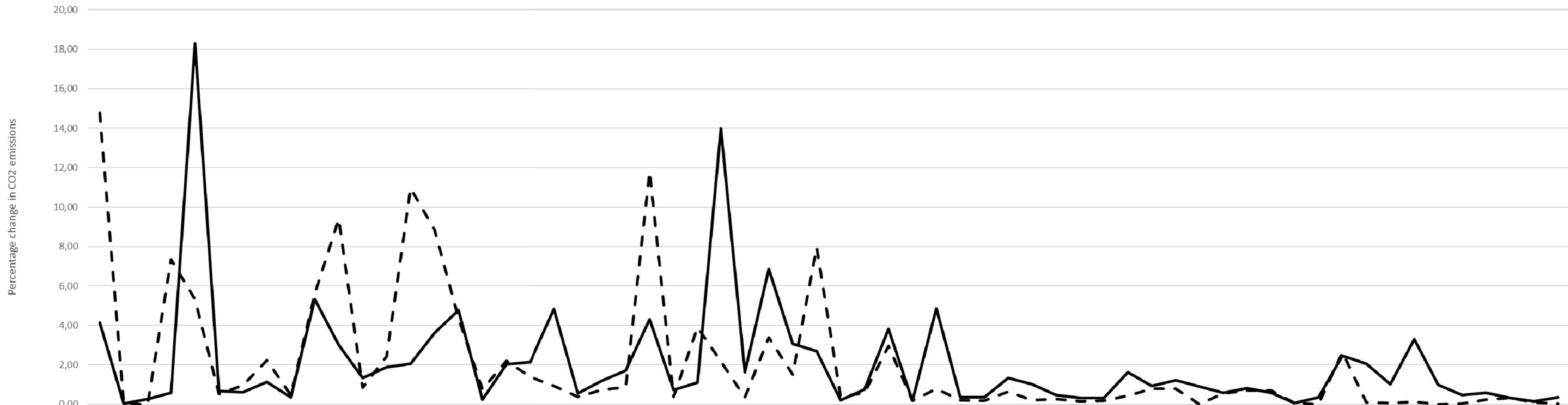
Graph 1: Distribution of CO_2 emission reductions by terciles



Source: Own elaboration.

Appendix:

Graph A-1: Demand and supply percentage change in CO_2 emissions.



Activity sectors	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Demand	4,13	0,03	0,27	0,60	18,3	0,66	0,61	1,14	0,35	5,34	3,02	1,33	1,88	2,06	3,60	4,78
Supply	14,7	0,03	0,02	7,33	5,31	0,54	0,95	2,24	0,48	5,61	9,40	0,84	2,42	10,9	8,85	4,38

Activity sectors	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Demand	0,23	2,03	2,14	4,83	0,56	1,20	1,71	4,31	0,73	1,10	13,9	1,61	6,87	3,07	2,69	0,22
Supply	0,75	2,19	1,39	0,94	0,37	0,71	0,86	11,7	0,38	3,89	2,16	0,35	3,39	1,51	7,95	0,39

Activity sectors	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
Demand	0,77	3,82	0,16	4,85	0,36	0,36	1,33	1,02	0,47	0,33	0,31	1,61	0,93	1,22	0,90
Supply	0,58	2,94	0,18	0,78	0,20	0,19	0,63	0,20	0,28	0,14	0,19	0,45	0,78	0,77	0,00

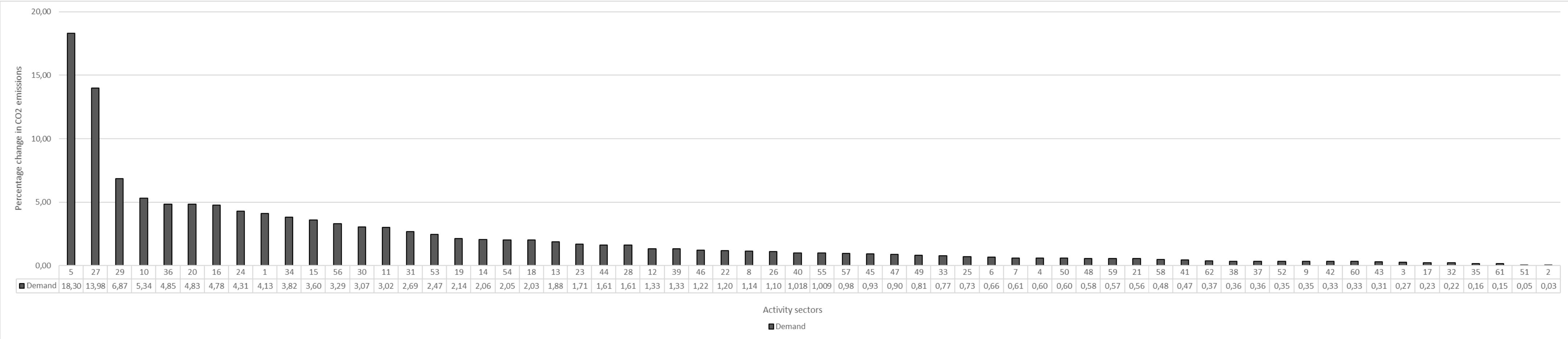
Activity sectors	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62
Demand	0,58	0,81	0,60	0,05	0,35	2,47	2,05	1,01	3,29	0,98	0,48	0,57	0,33	0,15	0,37
Supply	0,56	0,71	0,69	0,06	0,01	2,65	0,10	0,06	0,13	0,00	0,03	0,25	0,32	0,08	0,04

Activity sectors

Demand — Supply

Source: Own elaboration.

Graph A-2: Percentage change in emissions ordered from higher to lower under demand side extraction.



	5	27	29	10	36	20	16	24	1	34	15	56	30	11	31	53
Demand	18,30	13,98	6,87	5,34	4,85	4,83	4,78	4,31	4,13	3,82	3,60	3,29	3,07	3,02	2,69	2,47

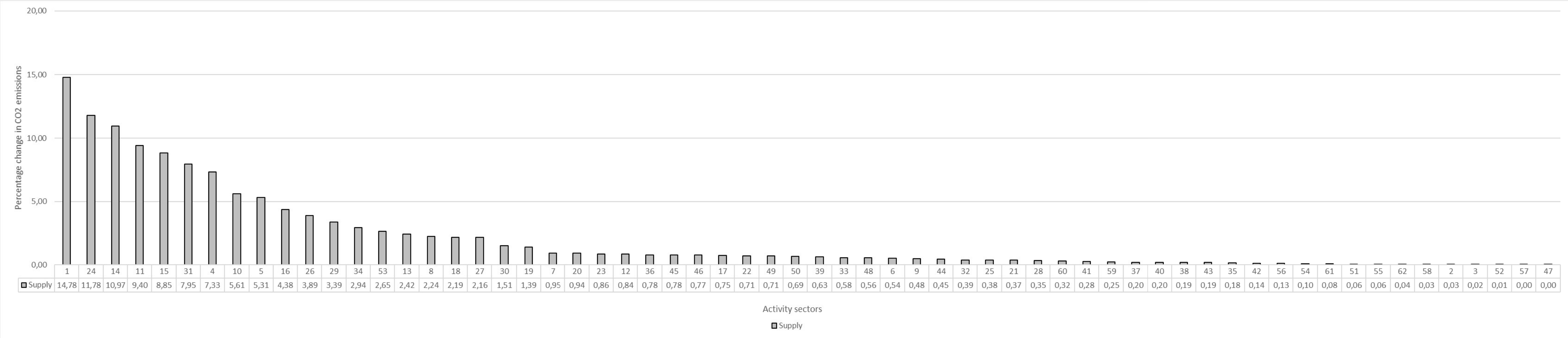
	19	14	54	18	13	23	44	28	12	39	46	22	8	26	40	55
Demand	2,14	2,06	2,05	2,03	1,88	1,71	1,61	1,61	1,33	1,33	1,22	1,20	1,14	1,10	1,018	1,009

	57	45	47	49	33	25	6	7	4	50	48	59	21	58	41
Demand	0,98	0,93	0,90	0,81	0,77	0,73	0,66	0,61	0,60	0,60	0,58	0,57	0,56	0,48	0,47

	62	38	37	52	9	42	60	43	3	17	32	35	61	51	2
Demand	0,37	0,36	0,36	0,35	0,35	0,33	0,33	0,31	0,27	0,23	0,22	0,16	0,15	0,05	0,03

Source: Own elaboration.

Graph A-3: Percentage change in emissions ordered from higher to lower under supply side extraction.



Source: Own elaboration.