CATALIST: A NEW, BIGGER, BETTER MODEL FOR EVALUATING CLIMATE CHANGE TRANSITION RISKS AT BANCO DE ESPAÑA

2025

BANCO DE ESPAÑA
Eurosistema

Documentos de Trabajo
N.º 2504

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Documentos de Trabajo. N.º 2504
January 2025

https://doi.org/10.53479/38921

ISSN: 1579-8666 (on line)

Abstract

This paper introduces CATALIST, a production network model developed to evaluate the economic effects of energy transition risks. Building upon Aguilar, González and Hurtado (2022) and Izquierdo, Moral-Benito, Prades and Quintana (2023), CATALIST incorporates a multi-country setting and an investment network and models greenhouse gas emissions and carbon taxes. The model places special emphasis on energy inputs by accounting for renewables and energy commodities and by differentiating their use from other intermediates in production and final consumption. Our findings reveal substantial heterogeneity in the impact of regulatory shocks relating to emissions across sectors and under different schemes. Specifically, a shock to the price of emissions and an expansion of the ETS system yield similar aggregate impacts, but the latter results in greater electrification, which can be further accelerated with increased renewable energy capacity. We also find that the aggregate impact is significantly influenced by how the additional revenues from carbon taxes are utilized, with recycling through a reduction in labor taxes proving more beneficial than through lump-sum transfers. Finally, while some sectors may respond to regulatory shocks with notable declines in investment, our simulations indicate a low risk of stranded assets, at least for shocks of a size compatible with the current medium-term emissions targets.

Keywords: climate change, transition risks, stress test, production networks, input-output, carbon tax, energy transition.

JEL classification: Q43, Q48, Q52, Q54, C67.

Resumen

Este documento presenta CATALIST, un modelo de red de producción desarrollado para evaluar los efectos económicos de los riesgos de transición asociados con la transición energética. Basándose en Aguilar, González y Hurtado (2022) e Izquierdo, Moral-Benito, Prades y Quintana (2023), CATALIST incorpora un entorno multinacional, una red de inversión, los modelos de emisiones de gases de efecto invernadero y sus impuestos asociados. El modelo pone un énfasis especial en los insumos energéticos al considerar las energías renovables y las materias primas energéticas, y diferencia su uso de otros intermediarios en la producción y el consumo final. Los resultados revelan una importante heterogeneidad sectorial en el impacto de los cambios regulatorios relacionados con las emisiones. Específicamente, un aumento en el precio de las emisiones y una expansión del sistema ETS producen impactos agregados similares, pero esta da como resultado una mayor electrificación, que puede acelerarse aún más con un aumento de la capacidad de generación renovable. También encontramos que el impacto agregado está significativamente influido por cómo se utilizan los ingresos adicionales de los impuestos a las emisiones, siendo más beneficiosa una reducción en los impuestos laborales que su transferencia directa. Finalmente, aunque algunos sectores pueden responder a los cambios regulatorios con notables disminuciones en su inversión, nuestras simulaciones indican un bajo riesgo de activos varados, al menos para cambios regulatorios de un tamaño compatible con los actuales objetivos de emisiones a medio plazo.

Palabras clave: cambio climático, riesgos de transición, test de estrés, redes de producción, *input-output,* impuestos a las emisiones, transición energética.

Códigos JEL: Q43, Q48, Q52, Q54, C67.

1 Introduction

Climate change, if left unaddressed, poses monumental physical risks, related to rising temperatures, extreme weather events, rising sea levels, and biodiversity loss. All of these risks threaten substantial disruptions to the economy. As global efforts intensify to mitigate these physical risks through comprehensive policies, transition risks can begin to appear. They manifest themselves in various forms: impacting household purchasing power, affecting corporate profitability, destabilizing financial markets, and influencing public finances. Further complicating matters, uncertainties in the ambition and pace of policy implementation can negatively impact economic decision making. In addition, the impacts of these policies are not uniform: they vary significantly across industries and countries. In this intricate context, academically rigorous and precise models become indispensable, offering vital insights into the varied implications of transition policies and aiding in devising strategies that balance ecological objectives with economic stability.

In this paper, we introduce CATALIST (Carbon Tax Labor Investment Sectoral Trade), a sectoral general equilibrium model designed to deepen our understanding of the economic impacts of climate policy transitions. Building on the sectoral detail of the CATS model Aguilar et al. (2022), CATALIST expands the analysis to a multi-country framework following Baqaee and Farhi (2024), and in particular incorporating international trade elements as specified in Izquierdo et al. (2023). This expansion allows for a comprehensive tracking of transition risks across international production networks and enables a detailed assessment of policy impacts at a sectoral level. The adoption of a multi-country framework in CATALIST is notable, as transition policies and the market for emissions operate at the European level and production networks span across borders. Although the results of this paper focus on Spain and the rest of the EU, it can easily be re-calibrated for other regions.

CATALIST also incorporates an investment network, drawing on the approach of Lehn and Winberry (2021), adding a crucial dimension to the flows of intermediate goods. By combining the two networks and capturing the general equilibrium interactions, CATALIST can more accurately predict the economic consequences of transition risks. Furthermore, investment decisions of industries become particularly valuable in identifying sectors prone to stranded assets (those for which the response to a shock leads to a sharp fall in the optimal level of capital) or likely to have higher financing needs (if their optimal capital level increases).

Building on what was already implemented in CATS, CATALIST places special emphasis on the role of energy inputs. This allows CATALIST to deal with shocks to the price of fossil fuels, which is instrumental to our calibration strategy. Additionally, we have divided the electricity sector into fossil and clean energy sources, which will be of great importance when estimating the impact of regulatory shocks that affect the relative prices of energy inputs and generate an electrification response.

Our focus among transition policies is on the pricing of emissions, which is one of the most efficient public policies for reducing them, as it allows economic agents to incorporate the social cost arising from the environmental impact into the private cost of their emission-generating actions. In Europe, the main tool in this regard is the Emission Trading System (ETS), operational since 2005[1]. This system sets a maximum amount of greenhouse gas emissions for a specific period and requires companies in sectors subject to this system to obtain permits for emissions. Thus, reductions tend to concentrate on companies that can more easily transition to less polluting technologies, minimizing the cost of transition. Currently, this mechanism covers approximately 45% of total emissions.

Going forward, the European Commission will expand the coverage of this framework to include transport, construction and other industries starting in 2027.[2] Besides, the ETS will be gradually complemented by the Carbon Border Adjustment Mechanism (CBAM), a tariff system that will charge different imported goods according to their emission footprint. [3] While the scope of the emissions market has been expanding, the price of emission permits has been increasing dramatically in recent years, going from around 5€/(ton of CO_2) in 2017 to more than 100€ in March 2023. This dynamic could continue in the coming years, as meeting the most ambitious goals of emissions set by the EU will require further increases in the price of emissions.

The characteristics of CATALIST make it particularly suited to evaluate the economic impact of policies in the context of the ETS framework, as it relies on rich installation level data on the surrendered ETS permits and sectoral verified emissions to incorporate these costs into the energy

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[1] See European Comission (2023) for details.

[2] See European Parliament and Council of the European Union (2023a) for details.

[3] See European Parliament and Council of the European Union (2023b).

purchases decisions of agents. Our setting allows us to differentiate between shocks on the price of emissions and changes in the coverage of emissions permits on different activities. The model is calibrated for a horizon of three years using ICIO tables and KLEMS data. We use the oil shock of 2014-2016 to calibrate energy-related elasticities and follow standard literature values for the rest.

The results presented in this paper show great heterogeneity across sectors for both types of shocks. Although the differences are mostly explained by the direct impact of the increase in emissions costs, the relations between industries in the production network play a significant role that our model brings to light. Crucially, an expansion of coverage favors the electrification of the economy to a bigger extent than an increase in the price that affects only the sectors currently covered by the system. This electrification effect is amplified by the installation of more renewable capacity and is slowed by improvements in the emissions intensity of fuel use. We also find that the economic effects can differ strongly depending on the use given to the extra revenues coming from the price charged for emissions; if they are rebated to households through reductions in distortionary taxes, the macroeconomic cost of the carbon tax can be reduced, and additional growth can even be fostered. Finally, we find that investment in some sectors can be severely impacted, although in our simulations no sector shows falls in optimal capital levels that are faster than what a standard rate of depreciation would generate, which indicates a low risk of stranded assets appearing as a result of these shocks.

Similarly to CATS, we do not incorporate physical damages in CATALIST, for two main reasons. First, our focus is on the short term, where the transition risks are concentrated and the physical damage has not fully materialized. However, we acknowledge that the costs of climate change already have a great impact, particularly those associated with acute events such as heat waves, flooding, and other extreme events. These costs can have consequences for financial stability (see European Central Bank (2022)), fiscal sustainability (see European Commission. (2022)) or on natural services (see Network for Greening the Financial System (NGFS) (2022)). Second, there is a trade-off between integrating different types of risk with their interaction and how granular the characterization of the economy is. Integrated Assessment Models (IAMs), a popular approach in the economic literature, tend to focus their attention more toward the former, which allows them to make a cost-benefit analysis of climate goals and policies at the cost of relying on a more simplified representation of the economy. In contrast, our objective here is to quantify with a higher sectoral detail the spread of regulatory shocks through the production network. This approach makes CATALIST a convenient framework for simulating stress test of transition risks with high sectoral resolution. The issues related to physical risks are still left for other work, using different types of models.

Many other recent studies have adopted production network approaches to examine transition risks. In addition to Aguilar et al. (2023), Campiglio et al. (2022) compares different international carbon pricing schemes; Krivorotov (2022) evaluates the impact of carbon taxes and green subsidies for the US; Frankovic (2022) and Devulder and Lisack (2020) develop similar models focused on the German and French economies, respectively. Other works explore different dimensions of the consequences of carbon markets. For example, Känzig (2023) evaluates the distributional effect of carbon pricing using a high-frequency econometric model, finding that a tighter regime can disproportionately harm poorer households.

Another related strand in the literature comprises DSGE models that include climate modules, though these naturally tend to focus on the long term. For example, Ernst et al. (2023) develop a multi-country model with reduced sectoral decomposition and abatement technology, tailored to study climate policies from a medium to long-term international perspective. Meanwhile, Matsumura et al. (2024) looks at the effect of carbon taxation on the Japan economy with a multi-sectoral New-Keynesian DSGE model.

The remainder of the paper is organized as follows. In Section 2 we describe the model in detail, and Section 3 discusses the data sources used and the calibration strategy. Section 4 presents the results of various exercises and Section 5 concludes.

2 Model

CATALIST combines features of the CATS model by Aguilar et al. (2022) and the production network model by Quintana (2022), both of which are based on Baqaee and Farhi (2024). It is a multi-country static general equilibrium model with a detailed two-digit sectoral production network. Although intermediate goods networks are widespread in the recent literature on production networks, our framework also includes a capital goods network à la Lehn and Winberry (2021), which allows us to characterize the impact of shocks on investment at the sectoral level.

The structure of production chosen for the model is of a nested CES of the (KL-E)-M form, where KL is a combination of labor and capital that forms value added, E is a mix of energy inputs, and M is a composite of intermediate materials. We work with this structure over others following Werf (2008) and Lagomarsino (2020), who, among others, find evidence supporting a (KL)-E structure over (LE)-K or (KE)-L. [4]

In the case of the energy composite, we assume that producers combine a fuel aggregate and electricity, while some specific industries (electric and refinery sectors) can substitute across different types of fuel. We also differentiate between green (renewables but also nuclear) and brown (fossil) production of electricity, by calibrating exogenously the share and growth of non-fossil generation, while allowing electricity production based on fossil fuels to react endogenously to shocks. Although buyers do not distinguish the source of electricity, the composition of electric production is relevant for prices, emissions, investment, and the propagation of shocks.

For each type of basic input, industries can buy them domestically or from other countries, also replacing them with a CES function. A schematic representation of the production process is shown in Figure 1.

Regarding emissions, we assume that there are two sources: those generated when industries and households use fuels and those produced by the brown electricity sector. Accordingly, firms and consumers may have to pay a carbon tax when they generate emissions through purchases of fuel (calibrating using the ETS data and each agents' fuel spending). When buying electricity, they have to pay a different carbon tax that is calibrated using the ETS surrendered by the electricity sector (which does not pay carbon tax directly in the model).

Domestic revenues from the carbon tax are fully rebated to local households through a lump-sum transfer. This is a pessimistic assumption, as those resources could be better spent, for example, in reducing distortionary taxes. In Section 4.3.1 we explore this alternative assumption and find more positive economic effects[5]. In any case, our focus is on generating scenarios for transition risk stress tests, and therefore the baseline setup of lump-sum transfers is more parsimonious and appropriate to our purpose of generating sizable impact from the shocks considered.

In each region, a representative consumer provides elastic labor and rents all the domestic capital, then purchases final goods using their income from labor and capital. We also assume a CES nested structure for their consumption. First, it combines regional varieties (with high elasticity), then it combines energy-related goods and non-energy goods separately (with medium elasticities), and finally it combines the two composites into aggregate consumption (with low elasticity). See a schematic representation in Figure 2.

Finally, we allow for wedges in prices that depend on sector and country destination. This gives us flexibility to introduce a wide range of shocks to the system, including carbon price shocks, trade tariffs, currency devaluation, etc.

There are C countries, each consisting of S sectors. In every country $c \in C$, there is a representative firm that produces the local variety of sector $s \in S$. We refer to each pair of sector-country as an industry, so the total number of industries is $N = C \times S$.

The entire model is described using exact hat algebra[6], which implies that the variables are expressed as deviations from their value in the absence of shocks. The notation $\widehat{x} = \frac{x}{\bar{x}}$ shows that $\widehat{x}$ is the deviation of variable x with respect to its initial equilibrium value $\bar{x}$. The new equilibrium of the model consists of the deviations of the variables that clear the conditions of the goods market and the labor market.

2.1 Firms

For each country-sector variety, there is a representative firm that produces competitively. Firms produce using a 5-layer nested CES function (see Fig 1). From top to bottom:

1. In the first layer, the industry i combines a mix of Value Added and energy $a|E_i$ with a composite of materials M_i with a CES aggregator with elasticity θ.

2. In the second layer, the mix $a|E_i$ is obtained from the combination of value added a_i and an energy composite E_i.

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[4] Nevertheless, we perform robustness checks with (KL-M)-E and (KL)-M-E structures. See Appendix E

[5] Other papers have looked at this question. For example, Hinterlang et al. (2022) and Maksym et al. (2022)

[6] See Appendix A for the basics of a CES aggregator in exact hat algebra. Dekle et al. (2007) is seminal reference for the use of exact-hat algebra. Barrot et al. (2021) apply hat algebra to a production network model.

3. In the third layer, value added combines a capital composite K_i and labor L_i, the energy composite E_i is a mix of fuels F_i and electricity EL_i, and materials composite M_i combines the rest of intermediate goods $x_{i,j}$ composites, where $j \in (S - F - EL)$.
4. Finally, in the fourth layer, sector varieties are aggregated from country varieties with trade elasticity ξ_j.

Notice that this setting is more flexible than appears. For example, by setting $\epsilon_{a|E} = \theta$, value added and energy may enter production in the first layer. In the following subsections, we describe in detail each step of the production. Expressions for prices and demand functions are given in appendix B

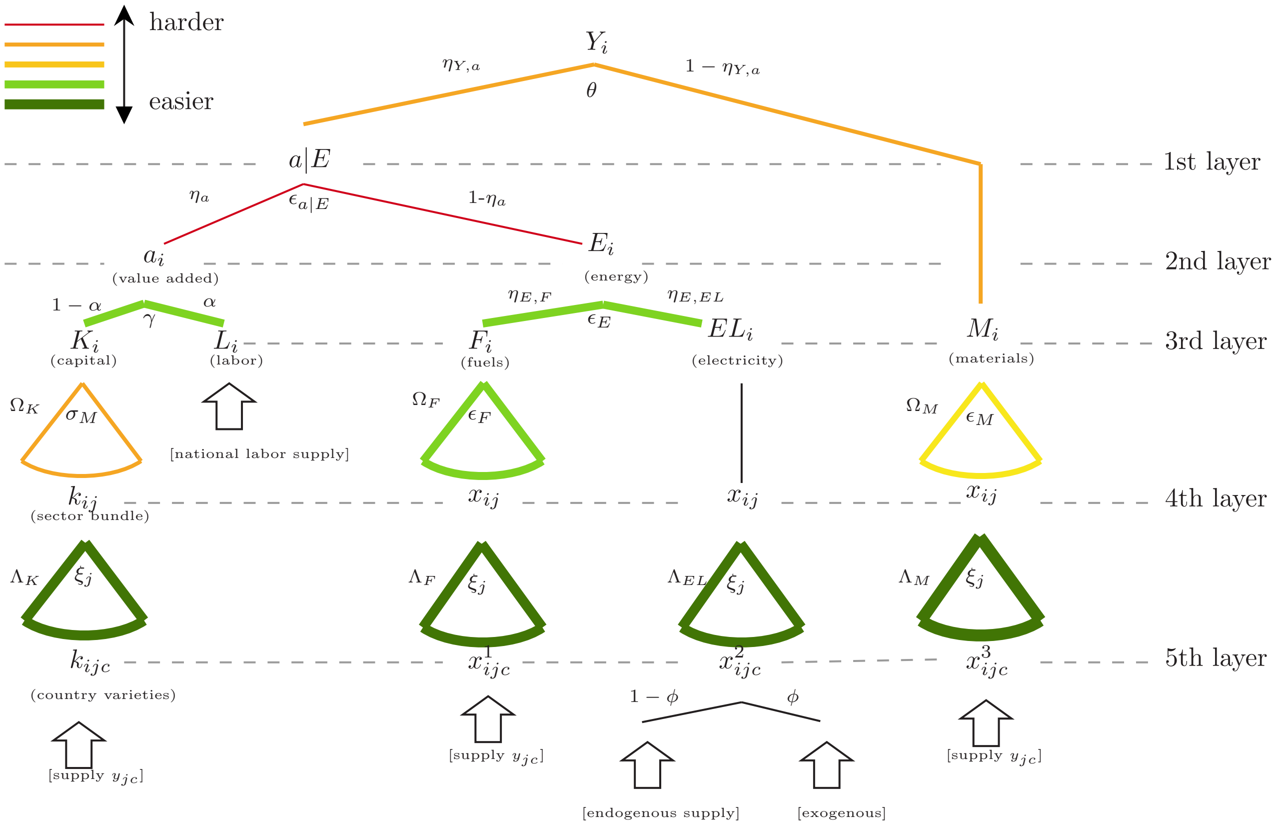

Figure 1: Structure of production

Let us begin with the first layer. Each industry i only produces one final good y_i using the CES production function:

$$\widehat{y}_i = \widehat{z}_i \left(\left(1-\eta_i^M\right) \widehat{a|E}_i^{\frac{\theta-1}{\theta}} + \eta_i^M \widehat{M}_i^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}} \tag{2.1}$$

where z_i is a Hicks neutral productivity shifter, θ is the elasticity of substitution between the value added—Energy mix $\widehat{a|E}_i$ and materials composite M_i. η_i^M is the share of expenditure on the materials composite, that can be recovered from I-O tables:

$$\eta_i^M = \frac{\overline{P}_i^M \overline{M}_i}{\overline{p}_i \overline{y}_i} \tag{2.2}$$

where $\overline{P}_i^M$ is the price of materials composite M that industry i needs and p_i is the price of the output of industry i.

Value added and energy In a second layer of production, firms aggregate value added a_i and energy with an elasticity $\epsilon_{a|E}$.

$$\widehat{a|E}_i = \left(\eta_i^a \widehat{a}_i^{\frac{\epsilon_{a|E}-1}{\epsilon_{a|E}}} + \left(1-\eta_i^a\right) \widehat{E}_i^{\frac{\epsilon_{a|E}-1}{\epsilon_{a|E}}} \right)^{\frac{\epsilon_{a|E}}{\epsilon_{a|E}-1}} \tag{2.3}$$

Again, shares of each component can be calibrated with IO data.

Intermediates Intermediates enter production in two different ways: (1) as an energy composite E_i that is combined with value added, and (2) as materials M_i combined with the value added-energy mix in the first layer. In the case of energy, the composite E_i is nested as a combination of fuels[7] F_i and electricity EL_i:

$$\widehat{E}_i = \left(\eta_i^F \widehat{F}_i^{\frac{\epsilon_E - 1}{\epsilon_E}} + \left(1 - \eta_i^F\right) \widehat{EL}_i^{\frac{\epsilon_E - 1}{\epsilon_E}} \right)^{\frac{\epsilon_E}{\epsilon_E - 1}} \tag{2.4}$$

On the other side, the materials composite is defined as:

$$\widehat{M}_i = \left(\sum_{j=1}^{S^M} \Omega_{ij}^M \widehat{x}_{i,j}^{\frac{\epsilon_M - 1}{\epsilon_M}} \right)^{\frac{\epsilon_M}{\epsilon_M - 1}} \tag{2.5}$$

where S^M is the subset of intermediates defined as materials (in our case, all goods except electricity and fuels), ϵ^M is the elasticity of substitution across intermediate inputs, and Ω_{ij}^M equals, for each industry i, the average share of expenditure on each sector j (over the total expenditure on inputs of composite X). This value comes from ICIO tables:

$$\Omega_{ij}^M = \frac{\overline{p_{ij} x_{ij}}}{\sum_{j=1}^{S^X} \overline{p_{ij} x_{ij}}} \tag{2.6}$$

Country varieties In the fourth layer, for each intermediate good $j \in S^x$, producers combines the different country varieties of that good:

$$\widehat{x}_{i,j} = \left(\sum_{c=1}^{C} \lambda_{i,j,c} \cdot \widehat{x}_{i,j,c}^{\frac{\xi_j - 1}{\xi_j}} \right)^{\frac{\xi_j}{\xi_j - 1}} \tag{2.7}$$

where ξ_j is the elasticity of substitution across country varieties of the same good (trade elasticity) and $\lambda_{i,j,c}$ is the share of expenditure on the national variety c over the total expenditure of industry i on inputs from sector j:

$$\lambda_{i,j,c} = \frac{\bar{p}_{j,c} \bar{x}_{i,j,c}}{\sum_{c \in C} \bar{p}_{i,j,c} \bar{x}_{i,j,c}} \tag{2.8}$$

2.2 Value Added Component

Firms create value added using labor (l_i) and capital (k_i) remunerated by w_i and r_i, respectively.

$$\widehat{a}_i = \widehat{d}_i \left(\alpha_i \widehat{l}_i^{\frac{\gamma - 1}{\gamma}} + (1 - \alpha_i) \widehat{k}_i^{\frac{\gamma - 1}{\gamma}} \right)^{\frac{\gamma}{1 - \gamma}} \tag{2.9}$$

where $\widehat{d}_i$ is a Hicks neutral productivity shifter and α_i equals the share of payments to labor in each sector.

Capital Firms rent capital from capital agencies at a rate r_i. For capital, we follow Lehn and Winberry (2021) and implement an investment network for investment[8]. In this way, capital goods have a similar structure to intermediates in this model. The accumulation over time of each type of capital is driven by new investments, $\widehat{I}_{i,t}$, and the depreciation of the existing stock.[9]

$$k_{i,t} = I_{i,t} + (1 - \delta) k_{i,t-1} \tag{2.10}$$

In deviations, the law of motion is:

$$\hat{k}_{i,t} = \delta_j \widehat{I}_{i,t} + (1 - \delta) \hat{k}_{i,t-1} \tag{2.11}$$

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[7] For most sectors, there is only one fuel input, produced by sector C19. Only C19 and D35 have access to other types of fuel, namely crude oil and natural gas. These two sectors aggregate different fuels using another CES with elasticity ϵ_F.

[8] See details on how we construct an IO database for capital in calibration subsection 3.1.

[9] $I_{i,t}$ represents the investment of industry i at time t. This value is normalized by the initial stock of such capital goods in the industry

It is important to notice that in the steady state:

$$I_{i,ss} = \delta_j k_{i,ss} \implies \hat{I}_{i,ss} = \hat{k}_{i,ss} \tag{2.12}$$

The capital stock of each industry is made up of different investment goods $j \in S_K$. The importance of each type of capital good j is captured by $\Omega^K_{i,j}$. We assume that Firms can substitute across different types of investment goods with an elasticity ϵ_k:

$$\hat{I}_i = \left(\sum_{j \in S_K} \Omega^K_{i,j} \cdot \widehat{I}_{i,j}^{\frac{\epsilon_k - 1}{\epsilon_k}} \right)^{\frac{\epsilon_k}{\epsilon_k - 1}} \tag{2.13}$$

Similarly to materials, industries source their capital supplies from different countries. Thus, industries demand different national varieties of each of the capital goods with an elasticity of substitution between national varieties equal to ξ_j.

$$\hat{I}_{i,j} = \left(\sum_{c \in C} \lambda^K_{i,j,c} \cdot \widehat{I}_{i,j,c}^{\frac{\xi_j - 1}{\xi_j}} \right)^{\frac{\xi_j}{\xi_j - 1}} \tag{2.14}$$

where ξ_j is assumed here to be the same as for intermediates. This can easily be relaxed to allow a different elasticity for capital goods.

Notice that in the steady state, the Euler equation implies that the rental price of capital r_i is proportional to the price of investment composite P^I_i . In deviations, this simplifies to $\hat{r}_i = \hat{P}^I_i$. [10]

In the results presented in this paper we consider two alternative settings: (1) short-run, in which capital is fixed but rental rates are allowed to move, and (2) long-run, in which capital can be adjusted and the deviation of rental rates is equal to the deviation of the price of investment.

Labor Labor is perfectly mobile across sectors and household receive a wage w_c. Total labor demanded in country c is given by:

$$\hat{L}_c = \sum_{i \in S} \nu_{i,c} \widehat{l}_{ic} \tag{2.15}$$

where ν_i is the average share of employment in sector i (over total employment of country c).

2.3 Households

The representative consumer $c \in C$ provides labor and spends her labor and capital income[11] on consumption goods. Similarly to firms, she aggregates country varieties into sector varieties using a CES function:

$$\widehat{c}_{ij} = \left(\sum_{h=1}^{C} \lambda^{\text{cons}}_{ijh} \, \widehat{c}_{ijh}^{\frac{\xi_j - 1}{\xi_j}} \right)^{\frac{\xi_j}{\xi_j - 1}} \tag{2.16}$$

and then aggregates energy and materials goods into two different composites with elasticities ϵ^c_E and ϵ^c_M, see Figure 2. In the first layer, they combine an energy composite and a materials composite with elasticity ϵ^c, which is lower than the elasticity for materials (ϵ^c_M) and the one for energy goods (ϵ^c_E).

We assume homothetic utility function for consumption composite and labor:

$$U(C, L) = \frac{C^{1-\eta_c} - 1}{1 - \eta_c} - \alpha \frac{L^{1+1/\eta_L}}{1 + 1/\eta_L} \tag{2.17}$$

where η_c is the degree of relative risk aversion and η_l is the Frisch elasticity. Using exact hat algebra, the labor supply is given by:

$$\hat{L} = (\hat{w}_r \hat{C}^{-\eta_c} / \alpha)^{\eta_L} \tag{2.18}$$

where w_r is the wage in real terms, i.e. adjusted by PCI (see eq B.10).

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[10] See the expression $\hat{P}^I_i$ for in equation B.5 in the appendix.

[11] We assume that labor is not mobile across countries and that capital is domestically owned.

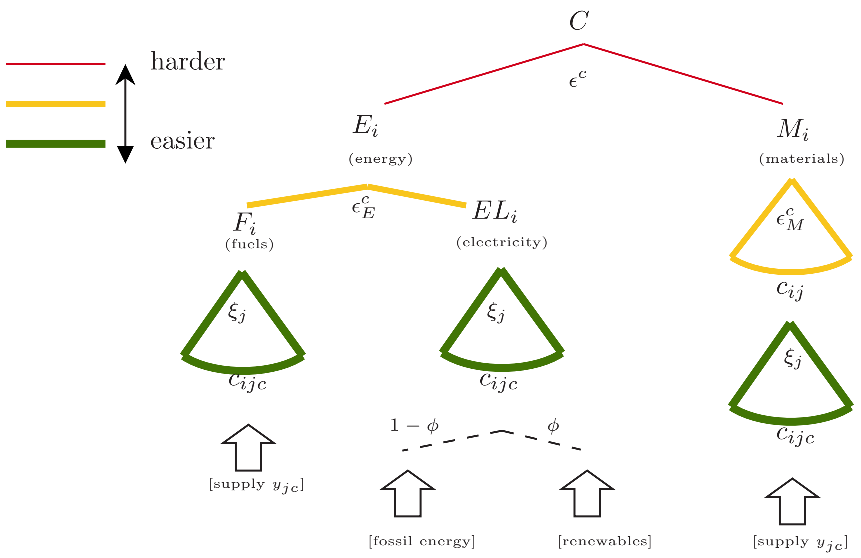

Figure 2: Consumption aggregation

2.4 Market clearing

Production of each firm is used for the final consumption of households in each country (c_j), as intermediate inputs ($x_{j,i}$) or investment goods $\left(\widehat{I}_{j,i}\right)$ by every other industry j, or as public expenditure by any country (G). Given that we are outlining the model in percentage deviations, we need to weight the change of each of the demand elements.

$$\widehat{y}_i = \sum_{j \in C} \Delta^C_{i,j} \cdot \widehat{c}_j + \sum_{j \in N} \Delta^X_{j,i} \cdot \widehat{x}_{j,i} + \sum_{j \in N} \Delta^k_{j,i} \cdot \widehat{I}_{j,i} \tag{2.19}$$

where:

- $\Delta^C_{i,j}$ shows the weight of the final consumption of households from country j on the total demand of sector i.
$$\Delta^C_{i,j} = \frac{\overline{p}^{cons}_{ji}\overline{c}_{ji}}{\overline{p}_i\overline{y}_i}$$
- Matrix Δ^X shows the share of the sales of sector i that are sold as intermediate input for sector j
$$\Delta^X_{i,j} = \frac{\overline{p}_{ji}\overline{x}_{ji}}{\overline{p}_i\overline{y}_i}$$
- Matrix Δ^K shows how much the demand of sector i changes when sector j increases its capital stock. The values of matrix Δ^K are the result of two components. First, it takes into account the type of capital that sector j demands and, second, whether sector i is a supplier of that type of capital goods.

2.5 Renewable energy

Since the IO tables do not differentiate between different sources of electricity, we use electricity source data (from EMBER) to separate the electricity sector into two: fossil and non-fossil. The later subsector is different in two ways: it does not generate greenhouse emissions directly and it is assumed that it has no intermediate inputs. [12].

We modify the market clearing condition for electricity by introducing a non-fossil term in the i equation of (2.19) corresponding to the electricity sector $i = e$.

$$(1 - s_f)\widehat{A} + s_f\widehat{y}_e = \sum_{j \in C} \Delta^C_{j,e} \cdot \widehat{c}_j + \sum_{j \in N} \Delta^X_{j,e} \cdot \widehat{x}_{j,e} \tag{2.20}$$

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[12] We think this is a good assumption for renewables and a reasonable one for nuclear. According to US Energy Information Administration (2022) estimates, variable costs for nuclear are around 10-15%, compared with 70% for combined cycle.

where s_f is the initial share of fossil generation in the electricity sector, $\widehat{A}$ is the deviation of non-fossil production (i.e. $A = 1.1$ means 10% more renewable/nuclear production in the next period). $\widehat{y}_e$ should be interpreted as the deviation of the dirty electricity sector.

For the rest of market clearing conditions, we must adjust the investment term. In particular, $\Delta^k_{j,i}$ should be multiplied by s_f for $j = e$. That is, we assume that only the dirty part of electricity production continues to invest endogenously in the model. Meanwhile, investment in renewables has to be added by an extra term. Then, the MC condition for industries $i \neq e$:

$$\widehat{y}_i = \sum_{j\in C} \Delta^C_{i,j} \cdot \widehat{c}_j + \sum_{j\in N} \Delta^X_{j,i} \cdot \widehat{x}_{j,i} + \sum_{j\neq e\in N} \Delta^k_{j,i} \cdot \widehat{I}_{j,i} + s_f \Delta^k_{e,i} \cdot \widehat{I}_{e,i} + (1 - s_f)\Delta^k_{e,i} \cdot \widehat{I}_{ren,i} \tag{2.21}$$

where we assume that $\widehat{I}_{ren,i} = \widehat{A}$, i.e. that investment in renewables deviates in the same rate as the production capacity. We are also assuming that the renewable sector is not buying any intermediate goods (which is a good assumption for solar/wind/hydro). Regarding capital, we are assuming that the share of sales of good i as capital destined to non-fossil electricity is proportional to the share of green energy : $(1 - s_f)\Delta^k_{e,i}$. Actually, we expect that in reality this is more biased towards renewables, since they are more capital intensive. We are also implicitly assuming that the composition by type of capital is the same for the two kinds of electricity.

The assumption of exogenous growth in renewables within the model is a significant simplification, as the composition of electricity generation does not respond to changes in the price of emissions. Additionally, the transition policies discussed in this paper can indirectly influence the installation of renewables. For instance, some industries may find more opportunities to substitute energy inputs with renewable generation, although this is partially captured by the elasticity between fuels and electricity.

In our baseline scenario, we assume that the proportion of non-fossil electricity generation remains constant. This is a conservative assumption, considering the current rapid pace of renewable installations. Nonetheless, we recognize that the rate of renewable deployment is a policy decision. In alternative simulations, we assume a 10% increase in non-fossil generation (see section 4.3.2), which significantly reduces transition costs. It is important to note that while the expansion rate is exogenous, its capital requirements are accounted for within the model through the capital network.

Another assumption of the meodel is that the price of electricity is marginalistic. That is, the price of electricity is equal to the price of the non-fossil electricity generation. This is a good approximation for electricity markets, but is becoming less so as the share of renewables increases. See Quintana (2024) for a detailed analysis of the deviation of the price of electricity from the price of non-fossil generation.

2.6 Prices

The price paid by producer $i \in N$ for an intermediate good $j \in S$ from country $c \in C$ is given by

$$\widehat{q}_{j,c,i} = (\tau_{j,c,i}\widehat{p}_{j,c}) \tag{2.22}$$

where $\widehat{p}_{j,c}$ is the selling price of producer of good j of country $c \in$ and $\tau_{j,c,i}$ is the wedge faced by producers. Similarly, for consumers:

$$\widehat{q}^C_{j,c,i} = \left(\tau^c_{j,c,i}\widehat{p}_{j,c}\right) \tag{2.23}$$

where $\tau^c_{j,c,i}$ is the wedge faced by consumers. This setting is very flexible and allows us to accommodate various shocks. In Section 3.3 we show how to implement different shocks on prices.

2.7 Aggregate variables

The nominal GDP of each country can be obtained by adding up the value added of all sectors and the taxes paid on factors:

$$\widehat{GDP}_c = \sum_{i\in S_c} \gamma_i \widehat{p}^a_i \widehat{a}_i + T_c \tag{2.24}$$

where γ_i represents the share of value added of sector i in country c (over the total VA in country c).

For emissions, we assume that each sector and households generate emissions proportional to their fuel intermediate consumption, except for electricity that emits proportionally to non-renewable generation. This is a good assumption in the sort term, but it is reasonable to think that in the long run technological improvement can weaken this relation. For country c, the deviations of emissions are given by:

$$\widehat{EM}_c = \frac{1}{\overline{EM}_c}\left[\sum_{i\in S_c-\{D35\}} \left(\overline{EM}_i \widehat{F}_i\right) + \overline{EM}_{D35}\widehat{y_{D35}} + \overline{EM}_{cons}\widehat{F_{cons}}\right] \tag{2.25}$$

3 Data and calibration

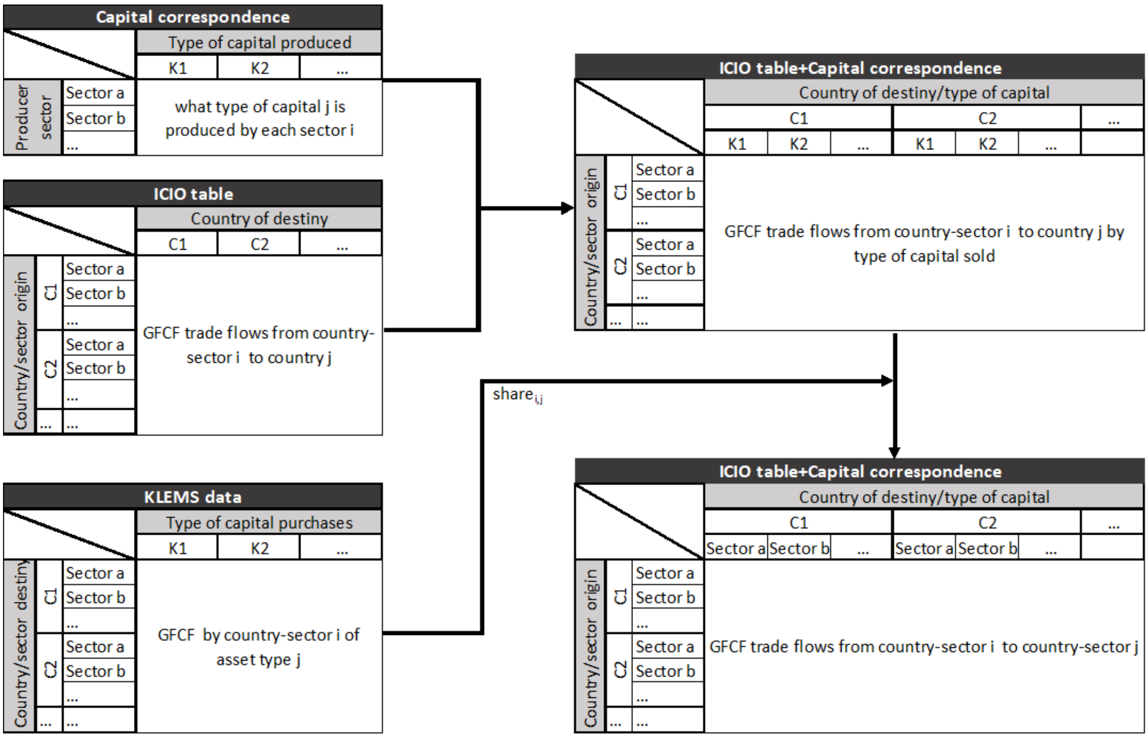
To calibrate the model and the shocks in the different simulations, we use several data sources. As in any production network model, the main source of data are input-output tables, which in our case come from OECD (2021). Unlike other IO tables (such as WIOD or FIGARO), ICIO offers a finer disaggregation of mining sectors, which facilitates our modeling of fuel input sectors (see Section 3.1). This means that we work with 46 sectors (the 44 defined in ICIO plus the two mining sectors that we artificially separate). A list of sectors and codes can be found in Appendix G. For the purpose of this paper, we aggregate data in three regions: Spain, rest of the EU and Rest of the World. That means that the total number of industries is $N = 132$.

3.1 Production

We use the last available release of the ICIO tables, which relates to 2019, to calibrate the shares of expenditures at each level of production for intermediate goods. For example, to calibrate the country weight at the lowest level of the CES aggregator, we use expression 2.8. We proceed similarly for sector varieties shares (eq 2.6 and shares of composites (eq 2.2. For labor and capital shares, we rely on WIOD SEA data[13].

Capital network ICIO tables only provide sector sales destined to gross fixed capital formation (GFCF) by sector of origin and country of destiny. Following Quintana González (2024), to calibrate the network of capital goods, we combine this information with KLEMS data[14] using Lehn and Winberry (2021) methodology, which we describe briefly here:

Figure 3: Construction of capital IO matrix



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[13] See WIOD (2021).

[14] See Bontadini et al. (2023).

1. We take the KLEMS data that show the purchases made by each sector of 9 types of capital[15]. We calculate the share of each type of capital in the total investment for each buying sector.

$$weight_{i,k} = \frac{I_{i,k}}{I_{i,GFCF}}$$

   where i is a capital-buying industry and k is one of the 13 types of capital[16]

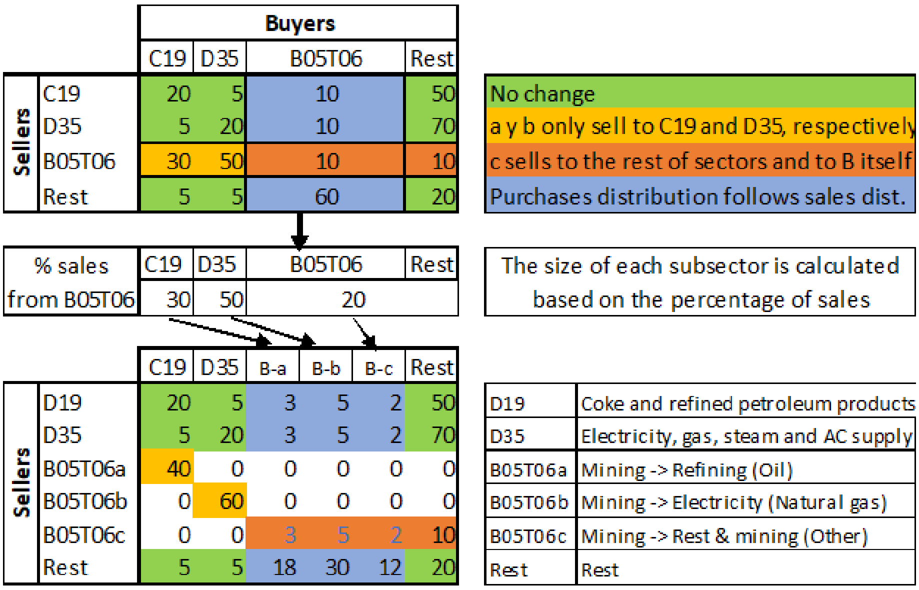
2. On the other hand, we establish a correspondence between types of capital and seller sectors. For example, sector C21 only sells Pharmaceutical IP and agriculture sectors only produce cultivated assets. Retail and warehousing sectors sell a distribution of types that reflects the distribution of purchased assets.

3. We assign each GFCF data from ICIO tables to the types of capital each sector produces according to the aforementioned correspondence. That way, we have the sales of capital of each sector by country of destiny and per type of capital.

4. Finally, we combine it with the KLEMS weights to break down the flows columns by sector destination, generating separate IO tables for each type of capital. Keep in mind that these matrices have many zeros, since most sectors only produce one or two types of capital. We then consolidate this tables into one IO matrix for capital.

Mining sectors We enlarge the input-output tables provided by ICIO by artificially separating the sector B05T06 (Mining and quarrying, energy producing products) into three subsectors, with the methodology illustrated in Figure 4. With this approach, we end up with a Crude Oil sector (B05T06A) that only sells to Refinery (C19), a Natural Gas sector (B05T06B) that only sells to Electricity (D35) and a residual sector that sells to the rest of sectors. This structure is particularly useful for analyzing shocks related to energy resources and carbon taxes, as it allows some of the simplifications regarding emissions that we use in order to approximate real-world structures within a stylized framework.This change allows us to devote special attention to our simulations to the energy factors in the production network, and to use the shock in the price of oil observed during 2014-2017 (see section 3.2) to calibrate some elasticities of the model.

Figure 4: Fuel input sectors



		Buyers			
		C19	D35	B05T06	Rest
Sellers	C19	20	5	10	50
	D35	5	20	10	70
	B05T06	30	50	10	10
	Rest	5	5	60	20

🟩	No change
🟨	a y b only sell to C19 and D35, respectively
🟧	c sells to the rest of sectors and to B itself
🟦	Purchases distribution follows sales dist.

% sales from B05T06	C19	D35	B05T06	Rest
	30	50	20	

The size of each subsector is calculated based on the percentage of sales

		C19	D35	B-a	B-b	B-c	Rest
Sellers	D19	20	5	3	5	2	50
	D35	5	20	3	5	2	70
	B05T06a	40	0	0	0	0	0
	B05T06b	0	60	0	0	0	0
	B05T06c	0	0	3	5	2	10
	Rest	5	5	18	30	12	20

D19	Coke and refined petroleum products
D35	Electricity, gas, steam and AC supply
B05T06a	Mining -> Refining (Oil)
B05T06b	Mining -> Electricity (Natural gas)
B05T06c	Mining -> Rest & mining (Other)
Rest	Rest

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[15] For certain buying industries, we can artificially create three additional types of capital: -Aviation and ships=transport capital for aviation and naval sectors; Mining capital=0.25*non-residential equipment for mining sectors; and Pharmaceutical IP=IP for the pharmaceutical industry.

[16] The capital types are: Computing equipment, Communications equipment, Computer software and databases, Transport equipment, Other Machinery and Equipment, Total non-residential investment, Residential structures, Cultivated assets, Research and development, Other IP assets, Aviation and ships, mining assets, Pharmaceutical IP

3.2 Elasticities

As is common in production network models, the most difficult parameters to estimate are elasticities. While there is a rich literature that tries to estimate elasticities of substitution by sector[17], those estimates are highly sensitive to the nesting structure of production, the geographical scope and the period of the data. On the other side, a significant part of the literature in production networks sets sector-wide values for elasticities following broad ranges estimated by the empirical work.

In this paper, we follow a mixed approach by setting some of the elasticities following the values generally used in the literature and calibrating the energy-related ones by exploiting an observed oil price shock. Table 1 shows the values chosen, which we assume are constant across sectors and countries. In Figure 1 we show schematically the ordinality of elasticities that the literature finds. The specific values for θ and ϵ_M are consistent with Baqaee and Farhi (2024) and the consumption elasticity for non-energy goods is standard in the literature. For the elasticity of capital and labor, we adopt $\gamma = 1$, i.e. we assume a Cobb-Douglas for value added. This is common in the literature of production networks and is supported by some estimation evidence, such as Baccianti (2013). For trade elasticities, we rely on Caliendo and Parro (2014) sectoral estimates[18]. These elasticities are the highest in the model, with a range from 1 to 1.5.

Table 1: Calibrated elasticities of substitution

Parameter	**Value**	**Target/source**
Calibrated externally		
Trade elasticities	$\xi \in [1, 1.5]$	Caliendo and Parro (2014)
Materials	ϵ_M=0.4	Baqaee and Farhi (2024)
Top prod. elasticity	θ=0.2	Baqaee and Farhi (2024)
Capital-labor	$\gamma = 1$	Cobb-Douglas,Baccianti (2013)
Capital types	$\epsilon_k = 0.2$	$< \epsilon_M$
Consumption non-energy	$\epsilon^c_M = 0.9$	Standard
VA-Energy	$\epsilon_{VA\|E} = 0.1$	$< \theta$
Fuels	$\epsilon_F = 1$	$> \epsilon_E$
Frisch elasticity	$\eta_L = 1$	Standard
Relative risk aversion	$\eta_c = 1$	Standard
Calibrated using oil-shock 2014-2017		
Energy intermediates	$\epsilon_E = 0.6$	Relative fall in GO of C19 and D35
Energy goods consumption	$\epsilon^c_E = 0.6$	Equal to ϵ_E
Materials/energy consumption	$\epsilon^c = 0.1$	Mean fall in GO of C19 and D35

The remaining elasticities are calibrated by exploiting the 2014 shock on the oil price, following the approach of Aguilar et al. (2022). First, we assume that the consumption elasticity of substitution of energy goods (ϵ^c_E) is equal to that of intermediates (ϵ_E). We also assume that the substitution across fuels ϵ_F[19] is higher than ϵ_E. We select a lower elasticity of substitution between value added and the energy than θ, following the findings of Antoszewski (2019) and Okagawa and Ban (2008)[20]. Finally, we look for values of ϵ_E and ϵ_c for which the model predicts a fall in the nominal production of the refining and electricity sectors that is similar to the one observed in Spain in the period 2014-2017, following a similar oil price shock. Table 2 shows how the fall of nominal output in each sector varies with each elasticity and the values that minimize the distance between the two targets.

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[17] See, for example Okagawa and Ban (2008) and Antoszewski (2019), who estimates elasticities for a production structure similar to ours. Brockway et al. (2017) and Lagomarsino (2020) provide a detailed review of estimation techniques of elasticities for nested CES.

[18] Since those elasticities are estimated for a period of 12 years, we re-scale them to serve for our horizon of three years.

[19] Notice that this elasticity is only relevant for sectors C19 (refining) and D35 (electricity), that are the only ones that can substitute refined fuel with crude oil and natural gas respectively. The remaining sectors only use the output of C19 as fuel. See how we construct mining subsectors.

[20] Our choice for this parameter is in the lower bracket of the literature (See Dissou et al. (2015)), but our calibration strategy requires a low value to meet our targets.

Table 2: Simulation of 2014-2017 oil-shock

ϵ_c	ϵ_E	C19	D35	Distance
Observed:		-19.3	-18.8	-
0.1	**0.6**	**-18.68**	**-18.69**	0.45
0.05	0.6	-19.6	-19.9	0.81
0.2	0.6	-16.92	-16.38	2.4
0.3	0.6	-15.25	-14.23	4.32
0.4	0.6	-13.68	-12.22	6.12
0.1	0.3	-21.20	-10.26	6.19
0.1	0.4	-20.15	-13.72	3.64
0.1	0.5	-19.33	-16.47	1.65
0.1	0.7	-18.16	-20.52	1.46
0.1	0.8	-17.75	-22.05	2.54
0.1	0.9	-17.43	-23.34	3.47

The first row show the observed fall nominal output of refinery and electricity sectors in Spain in the period 2014-2017. The second row indicates the values of elasticities that get the closest to the data. The other rows show how different values ϵ_c and ϵ_E affect the target.

3.3 Emissions and ETS

We use Eurostat data[21] to account for sectoral emissions of greenhouse gases (in equivalent CO_2). For countries that are not present in this data set, we use WIOD Environmental accounts [22] and extrapolate to the year of reference using national emissions data from EDGAR [23]. We use EUETS[24] data to calibrate the ETS permits surrendered by each sector. This dataset offers information at the installation level, which can be tied to a NACE code, increasing the resolution compared with EEA[25] data, which is aggregated at the activity level.

We implement the ETS system in the production network as a carbon tax levied on the purchases of fuel and electricity, following the approach by Aguilar et al. (2022). For the tax on fuel, we first reallocate the ETS surrendered by sector C19 to the other sectors (and consumers) proportionally to their emissions. Then we assume that the emissions EM_i of each industry are proportional to fuel purchases F_i. This proportionality factor, which we call *technological component* is industry specific and we assume that it is constant[26]:

$$EM_i = \tau_i^{ts} F_i \tag{3.1}$$

Since not all emissions are covered by ETS permits, producers only have to pay for a fraction τ^{rs} (the *regulatory component*) of the total emissions, which is simply the fraction of surrendered ETS and verified emissions:

$$ETS_i = \tau_i^{rs} EM_i \tag{3.2}$$

Figure 5 displays the calculated technological component times the present price of emissions(left panel) and the regulatory component (right panel) for every sector in Spain. Notice that only some sectors have a coverage of their emissions close to 1 (some manufacturing, Electricity D35 and Air transport H51), while agriculture and services have a very low regulatory component. This reflects the limited scope of the present ETS system, which is expected to expand in the following years. For the technological component, we observe a great deal of heterogeneity, with Agriculture (A01T02), Paper and Printing (C17T18), Other non-metallic mineral products (C23) and Basic metals (C24) showing the highest emissions per unit of fuel.

Using the data of emissions, ETS and the purchases of fuel from the IO tables, we can compute the present fraction[27] of regulatory cost over the total cost of fuel as:

$$\bar{\tau}_i = 1 + \frac{\bar{\tau}_i^{rs} \bar{p}_{EM} EM_i}{\bar{p}_F \bar{F}_i} \tag{3.3}$$

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[21] Air emissions accounts by NACE Rev. 2 activity. Reference year: 2019

[22] See Corsatea et al. (2019)

[23] See Crippa et al. (2022).

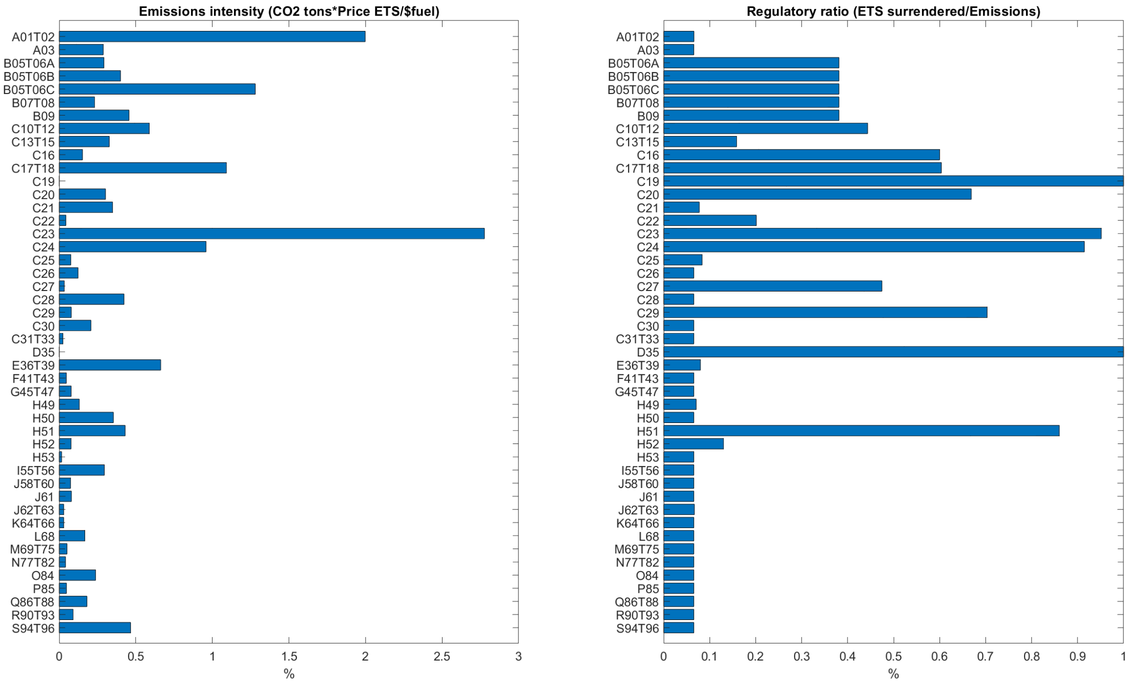
[24] European Union Emissions Trading System,https://www.euets.info/.

[25] European Environment Agency.

[26] In section 4.3.3 we explore how a reduction of this factor can mitigate the impact of regulatory shocks.

[27] Present values are indicated with $\bar{x}$, deviations as $\hat{x}$.

Figure 5: Technological and Regulatory component



Given the price of ton of CO_2 (P_{EM}), the total cost of fuel are:

$$\bar{p}_F\bar{F}_i + \bar{p}_{EM}\overline{ETS}_i = \bar{p}_F\bar{F}_i + \bar{p}_{EM}\tau_i^{ts}\bar{\tau}_i^{rs}\bar{F}_i = \underbrace{\bar{p}_F(\bar{\tau}_i)}_{\bar{q}_i}\bar{F}_i \tag{3.4}$$

where q_i represents the price observed by the buyer per unit of fuel. Now, a shock on the carbon price or the regulatory component (or both) impacts the tax following:

$$\hat{\tau}_i = \frac{1}{\bar{\tau}_i}\left(1 + (\bar{\tau}_i - 1)\hat{\tau}_i^{rs}\frac{\hat{p}_{EM}}{\hat{p}_F}\right) \tag{3.5}$$

Notice that an increase in the price of fuel decreases the size of the tax.

For electricity purchases, the calibration strategy is different. Here, the base of the tax is the output of the electricity producer industry (D35) and the tax paid is the same for all sectors and consumers. For the case of D35, the technological component is defined as:

$$EM_e = \tau_e^{ts} s_f y_e \tag{3.6}$$

where y_e is the output of the electricity sector and s_f is the fraction of the fossil electricity production. The fraction of regulatory costs over electricity input cost given by:

$$\bar{\tau}_e = 1 + \frac{\bar{\tau}_e^{rs}\bar{p}_{EM}E\bar{M}_e}{p_{\bar{e}}y_e} \tag{3.7}$$

The deviation of the observed price by buyers is:

$$\hat{\tau}_e = \frac{1}{\bar{\tau}_e}\left(1 + (\bar{\tau}_e - 1)\hat{s_f}\hat{\tau}_e^{rs}\frac{\hat{p}_{EM}}{\hat{p}_e}\right) \tag{3.8}$$

Compared with the tax on fuels, here the carbon tax on electricity also increases in the share of fossil electricity (an endogenous variable of the model) rises.

3.4 Renewables

To allow for renewable electricity generation as outlined in section 2.5, we rely on data from EMBER (Energy Institute Statistical Review of World Energy) for the fraction of non-fossil generation (renewables plus nuclear).

4 Results

We now present the results of three sets of simulations. First, we analyze the impact of three different regulatory shocks on the ETS framework. In a second set of results, we examine the possible implications in terms of stranded assets by removing the short-term restriction on investment. Finally, we explore three possible ways to mitigate the impact of regulatory shocks.

4.1 Simulations: emissions regulatory shocks

In this subsection we look at simulations of three different changes in the regulations regarding emissions: an increase in the price of emissions, an expansion of the ETS permits to cover all the verified emissions in the European economy, and a combination of the two. The size of the shocks for these exercises is large and serves as a stress test related to the transition risks associated with climate change. We evaluate the impact of these shocks over a period of three years (which was the time horizon used in the calibration of the model). Given the short horizon, we assume that capital stock is fixed (i.e. investment only replaces depreciation) and that the fraction of renewables in electricity production remains constant. The additional revenues of the carbon tax are rebated to households through lump sum transfers. We provide a comparison of the CATALIST results with those of CATS in Appendix F.

4.1.1 Increase in the price of emissions

Table 3: Regulatory shocks: summary statistics

	Price shock (x4)		Expansion coverage ETS		Both, lump sum rebate	
	Spain	EU	Spain	EU	Spain	EU
GDP	-0.16	-0.18	-0.13	-0.15	-0.57	-0.65
CPI	0.44	0.37	0.66	0.64	1.91	1.88
Consumption	-0.02	-0.04	-0.07	-0.08	-0.60	-0.75
Employment	-0.29	-0.36	-0.22	-0.24	-0.95	-1.06
Wages	0.13	-0.02	0.37	0.31	0.33	0.04
Fuel use	-2.21	-1.20	-3.35	-4.31	-11.61	-13.31
Elect. use	-0.35	-2.05	1.01	1.64	2.77	3.20
Emissions	-9.27	-5.68	-7.39	-6.26	-22.01	-17.84
Average carbon tax	11.78	13.44	6.70	7.39	23.66	29.64
Exports	-0.75	-0.56	-0.55	-0.62	-2.06	-1.90
Imports	-0.22	-0.11	-0.21	-0.07	-1.13	-0.71

Note: All results are expressed in deviations in real terms, except average carbon tax (new level) and CPI (deviations relative to deviations of the CPI of the rest of the world, that is the numeraire in the model and which impact under the shocks considered is small). Additional carbon tax revenues are rebated with a lump sum transfer to households. The initial average carbon tax is of 4% for the spanish economy.

In the first exercise, we simulate a fourfold increase on the carbon price in Europe (including Spain), from around 25€to 100€(similar to the increase that was observed between late 2020 and early 2023). Notice that this shock has a larger direct impact on sectors with a higher share of emissions covered by the ETS system, i.e. sectors with higher τ_{rs}, such as air transport, manufacturing sectors and electricity generation (see Figure 5, right panel). The first two columns of Table 3 show the aggregate impact in the short term (three years) of the price surge. The average rate of the carbon tax (that is, the total cost of ETS permits divided by the total intermediate energy costs) raises from 4% to around 12%. The use of fuels in Spain falls by 2.2%, while electricity falls by just 0.35% as its carbon intensity is smaller. This leads to a reduction in emissions of 9.3% and a contraction in GDP of 0. 16% [28]. A similar fall of GDP is observed for the rest of the EU. However, the reduction in fuel use and emissions is significantly smaller, while electricity use decreases around 2%. This is a consequence of the fact that electricity production in Spain is less emission-intensive than the European average. In terms of trade flows, the Spanish and European trade balances

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[28] Compared with a fall of 0.37% in CATS.

deteriorate, with real exports falling roughly three times as much as imports. Finally, inflation is almost half a point higher [29].

Figure 6 presents the impact on the value added by sector after this shock. The sector most affected is H51 (air transport), due to the high intensity and coverage of its emissions, and the weakness relative to EU competition. In a second tier, we find C19 (coke and refinery, that is, the sector that produces fuel), mining (B), chemical (C20), metal manufacturing sectors (C23, C24), wood and paper (C16-C18) and other transport sectors (H). As expected, sectors with a higher emissions cost as a proportion of total intermediate costs are generally more impacted (see Figure 7, left panel). Still, some sectors with low emission costs end up suffering a significant impact due to their position in the production network. For example, in the sector of fabricated metal products (C25), only 0.05% of the total costs are emission permits, but they buy a significant part of the input from the metal sectors, which are some of the most directly affected. On the other side, the sector C23 (other nonmetallic mineral products) has one of the highest emissions costs and performs relatively well, as the main buyer (construction) is not particularly affected by the shock.

Notice that for this type of shock, the amount of emissions over total intermediate costs is not a good predictor of being most impacted (see Figure 7, right panel). That is, even if a sector generates a lot of emissions, a shock on the price of carbon does not affect it much if the regulatory coverage of the ETS is low for that sector.

Compared to CATS (see orange bars in Figure 6) we can observe some differences in the sectoral distribution of the impact. This is not a surprise, since CATALIST is a richer model that includes international trade links, renewable electricity generation, and investment networks. However, we also identify a significant impact coming from the different data used to calibrate the models. First, the impact on aviation is much larger in CATALIST due to a revision in ETS permits data that significantly increases the regulatory coverage of this sector. Secondly, the fall in value added is more evenly distributed across manufacturing sectors in CATALIST, thanks to the use of a finer database on the ETS permits with installation/NACE code resolution (versus only disaggregated by activity in CATS). Other sources of data, such as the registered use of energy inputs from the IO tables, play a role. These differences lead to a generally lower present cost of emissions as a fraction of energy costs. All of this reflects the need for high-quality data and the sensitivity to sources and revisions of this type of exercise. Finally, the differences in the Refinery and Electricity sectors (C19 and D35) reflect the higher calibrated elasticity of substitution and the introduction of renewables in CATALIST.

4.1.2 Expansion of ETS coverage

The second shock that we evaluate is an expansion of ETS permits up to full coverage. In other words, what would happen if every sector had to pay the current price of carbon for all their verified emissions? This is, of course, a challenge from the point of view of implementation, as it may be very difficult to verify emissions by installation in some sectors. Nevertheless, the ETS framework continues to progress towards that goal [30] which makes this exercise also useful for climate transition stress tests.

In this scenario, the average country-wide rate of the carbon tax on energy increases from 4% to around 6.7% in Spain. The middle columns of Table3 show the aggregate impact of this shock. The fall in GDP is 0.13 points[31] for Spain and similar for Europe (-0.15%). Surprisingly, emissions fall by a lesser amount compared to the price shock in Spain (-7.39% vs -9.27%) while they fall slightly more in the rest of the EU (-6.26% vs 5.68%) [32]. Unlike the previous shock, electricity use increases by 1% as producers and consumers move away from fuel (-3.35 percentage points). This occurs as electricity becomes relatively cheaper as an energy input, as the electricity sector already has a coverage close to one. Meanwhile, the expansion of coverage makes the burning of fossil fuels more costly for industries in other sectors, especially those with a low initial coverage. Finally, the magnitude of the slowing of the trade flows is similar to that observed with the price shock.

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[29] The model needs to set a numéraire, which in our case is the CPI of the rest of the world. We expect that the impact of the shocks considered (which are European) over the prices abroad are of second order. Therefore, the CPI impact reported for Spain and EU should be a good approximation.

[30] Transport, construction and more manufacturing sectors will be included starting in 2027 (see European Parliament and Council of the European Union (2023a) and the European Commission is studying the inclusion of agriculture (see Commission et al. (2023)).

[31] Compared with a fall of 0.12% in CATS.

[32] Further simulations indicate that the price shock required to match the decrease in emissions in Spain observed with the expansion of coverage shock would be about a 3.2x rise in the price of ETS permits, and for the rest of the EU, a 4.1x increase would be necessary, bearing in mind that the ETS price is the same for Spain and the rest of the EU in these simulations

Figure 6: Increase of carbon price: fall in real value added by sector (Spain)

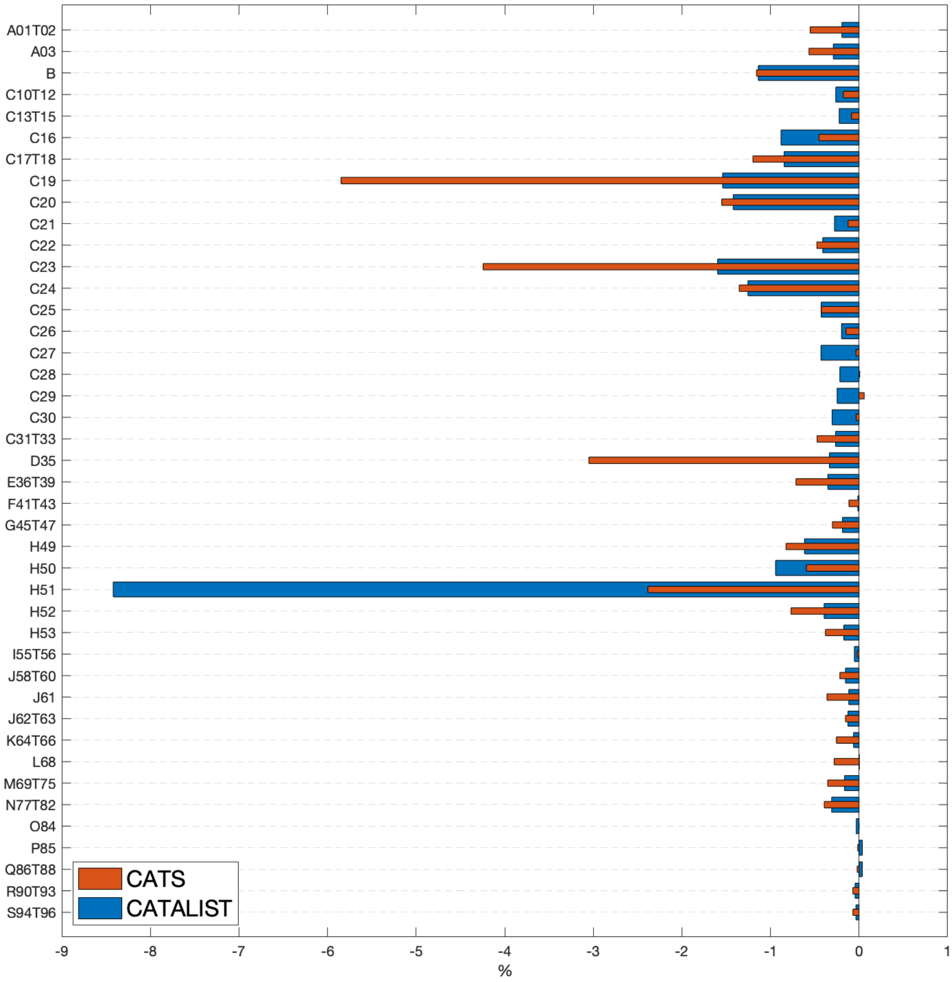


Figure 7: Increase of carbon price: fall in real value added vs fall in real value added vs share of emissions costs (left) and vs potential emissions costs (right)

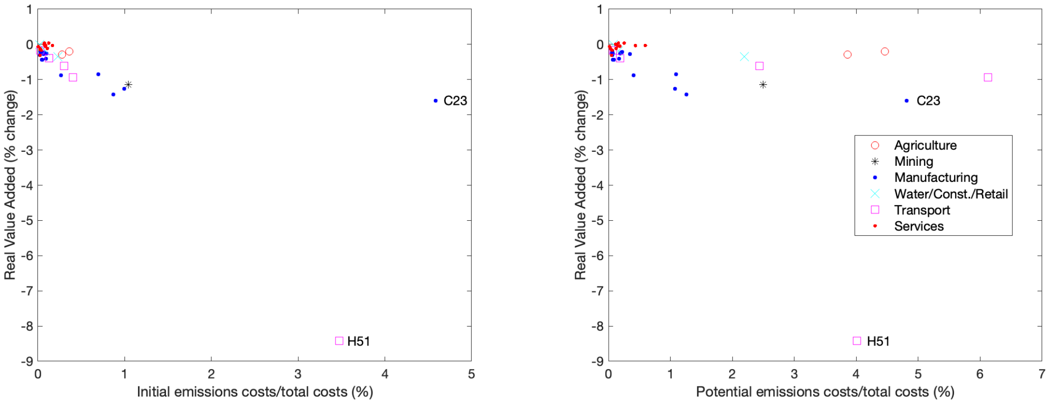


Figure 8 plots the fall in value added by sector in Spain and compares it with the shock on price to highlight the different impact distribution of the two shocks. The sector most affected in this case is Water Transport (H50) and Refinery and Coke (C19) with a fall ranging between 2% and 3% of value added. Other sectors significantly impacted are Land Transport (H49, -1.1%), Fishing and Aquaculture (A03, -1.3%), Water Supply and Waste Management (E36T39, -0.6%) and Air Transport (H51, -0.5%). The losses in manufacturing (C) range from 0.12% to 0.5% and are more homogeneous than in the case of a price shock. In the case of services, the impact is comparable. Figure 9 shows that, in general, sectors with more emissions per total cost tend to be more adversely affected under this shock. Again, the network exposure of some sectors makes them more vulnerable or resilient than expected. For example, while Agriculture (A01T02) is a sector

Figure 8: Expansion of ETS coverage: fall in real value added by sector (Spain)

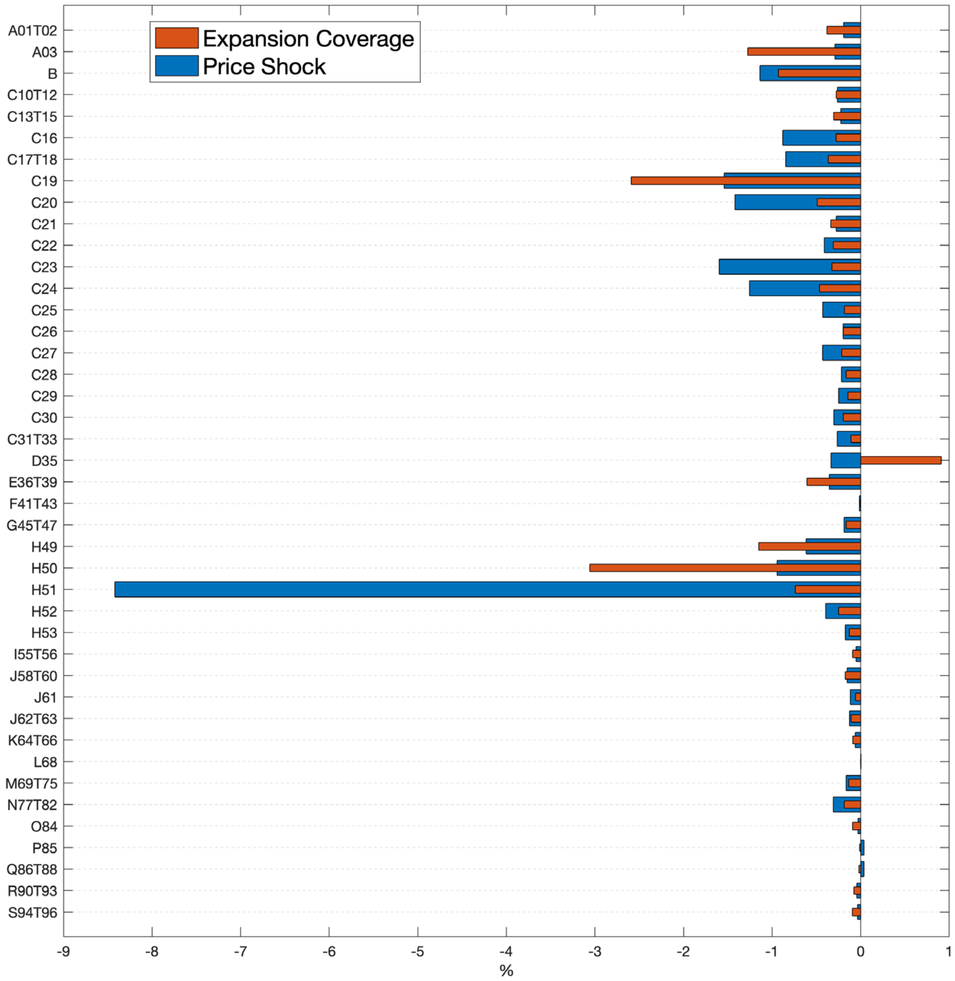
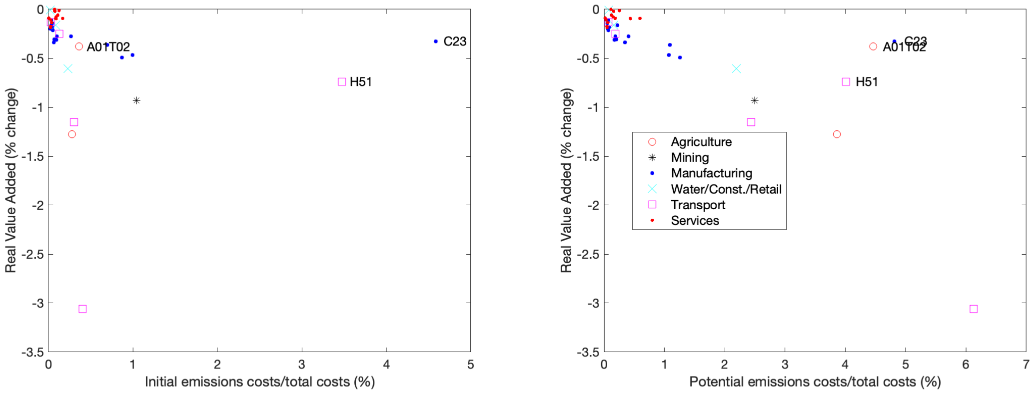


Figure 9: Expansion of ETS coverage: fall in real value added vs fall in real value added vs share of emissions costs (left) and vs potential emissions costs (right)



with one of the largest expansions of coverage, it sells mostly to the Food industry (C10T12) and Retail (G), which are not as directly impacted by this shock. As mentioned above, one of the most notable effects of this shock is the resulting electrification of the economy, with an uptick of 1% in the value added in the Electricity sector (D35).

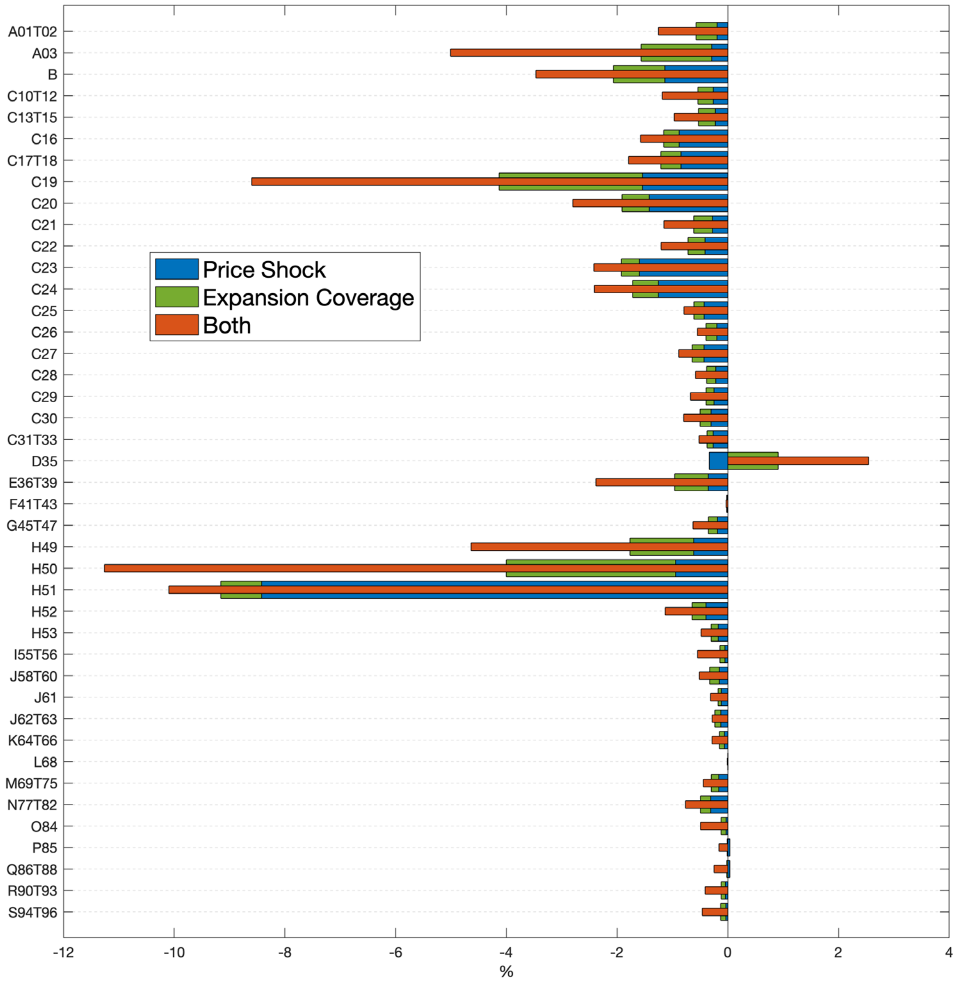
Compared with CATS, the value added impact on nonenergy sectors is larger overall, while the impact on energy sectors is smaller (or even positive for the case of electricity). We believe that some factors behind this are the revision of verified emissions in many sectors and the updated distribution of ETS permits. Furthermore, the higher elasticity of substitution of energy inputs in CATALIST leads to stronger electrification.

4.1.3 Combined shock (increase of carbon price and expansion of ETS coverage)

Now, we combine the two previous shocks, resulting in an average carbon tax on energy of 23%. The aggregate impact by region is shown in the last two columns of Table 3. Emissions decrease by 22% due to a reduction in fuel use by nearly 12% and an intensified electrification with an increase of almost 3% in real electricity purchases. The combined shock exacerbates the hit on activity, reaching -0.57% for Spain and -0.65 percent for the rest of the EU. Again, exports fall nearly twice as much as imports, worsening Spanish and European trade balances, although the size of the impact roughly maintains its proportion to the fall in GDP.

In Figure 10, we depict the sectoral impact of the combined shock and compare it with the sum of the impacts of the other two shocks separately. This illustrates the compounding effect that this shock generates on the value added across industries. Among the sectors most affected are Refinery (C19), transport sectors (H49-51), Fishing (A03), Mining (B), and Water supply (E). The hit on manufactures ranges from just over 0.75% for C30-C33 to more than 2% falls for the chemical industry (C20) and metal manufacturing (C24). Services are not exempt from this shock and suffer losses between 0.5% and 1% of real value added. Figure 11 (right panel) shows that the relationship between value added loss and potential emissions costs is stronger with the combined shock. Again, some sectors are less affected than others, like Other non-metallic mineral products (C23), which has a more secure position in the network than other manufacturing industries and only loses around 2% of value added[33].

Figure 10: Combined shock: fall in real value added by sector (Spain)



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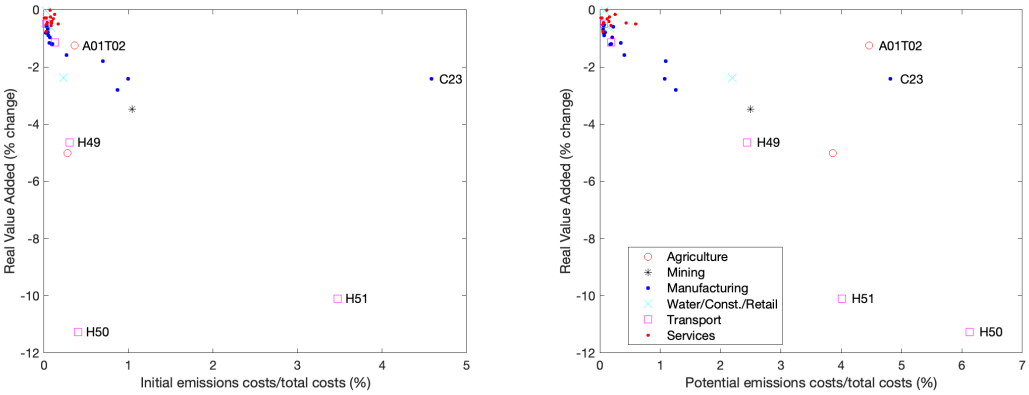
[33] Other sector that fares relatively well is Agriculture (A01T02). In this case, another factor contributing to the relatively low impact is the way emissions are taxed in this model (over purchases of fuel). However, a significant part of the emissions in this sector are not caused by the burning of fossil fuels. This suggests that regulatory shocks in this sector could have a bigger impact in reality

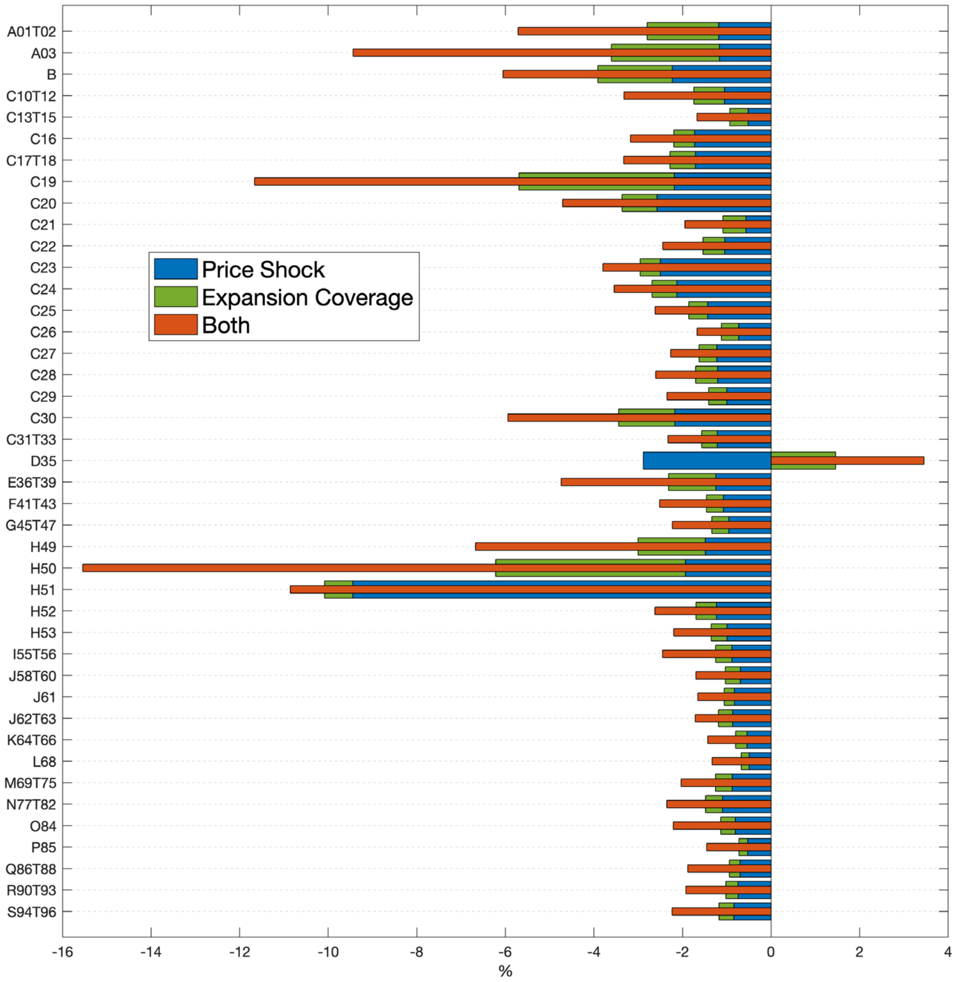
Figure 11: Combined shock: fall in real value added vs fall in real value added vs share of emissions costs (left) and vs potential emissions costs (right)



In Figure 17 in the Appendix D.4we represent how relative consumer prices [34]of the different sector varieties change for the three shocks. The greatest increase corresponds to fuel (the output of C19), followed by electricity and transports. All services experience falls in their consumer prices.

4.2 Investment

Figure 12: Combined shock with capital adjustment: fall in investment by sector (Spain)



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[34] Notice that all simulations of the model need to fix one price. We set the Consumer Price Index (PCI) of Spain to stay constant.

Up to now, we have simulated scenarios with a short-term assumption on investment, namely that investment only replaces depreciation over the period considered. This makes sense as the horizon (3 years) is too short for adapting the capital structure to the regulatory shocks assumed. However, our model allows for investment decisions and their impact through the capital network. In this section, we repeat the previous simulations with a long-run assumption, i.e., we let the capital be freely adjusted. This results in a higher fall in value added and allows us to observe the desired disinvestment by sector. Evaluating these results could help us assess the risks of stranded assets in the economy.

Figure 12 displays the projected disinvestment by sector. Most industries would like to reduce their investment by less than 4%, which indicates a low probability of stranded assets among them. The sectors with the highest drop are Transport (H49-H51), Refinery (C19), Primary sectors (A), Mining (B), Other Transport equipment (C30) and Water Supply and wast Management (E). Still, the magnitudes are not higher than the mean depreciation for capital over the three year period. In conclusion, the transition shocks considered in this paper do not seem to imply widespread risks of stranded assets.

4.3 Mitigation

4.3.1 Rebate as labor tax reduction

In the previous simulations, we have rebated the additional tax revenues from the carbon tax as a lump sum transfer to households. This is a parsimonious assumption for a model that focuses on the transition risks of regulatory shocks. However, compensation through a reduction of distortionary taxes can be more efficient. Thus, in an additional exercise, we rebate the extra revenues as a reduction to labor tax. This generates incentives to expand the labor supply of households (see equation 2.18), which in turn increases value added and output compared to the lump sum transfer scenario. Since the model is written in deviations, we need to calibrate an initial income tax, which we assume is at 30% in the steady state. In Appendix C, it is detailed how the additional revenues translate into a reduction of labor tax.

The second set of columns in Table 4 show the results for a scenario with the combined shock of a price increase and expansion of coverage with a rebate as labor tax. The GDP expands by 0.82% compared with the economy with no shocks. This growth is possible thanks to the boom in the labor supply and leads to a smaller reduction in fuel use. Still, electrification is significantly accelerated, and the reduction in emissions is only slightly behind the case with lump sum transfers. This suggests that smart use of public resources can fuel growth while maintaining the objectives of a green transition. [35]

In Appendix D.1 we compare the sectoral impact of the scenario with lump sum transfers with the one of labor tax reduction. The sectors most affected in the former case still suffer important value added losses (Transport sectors, refinery, Metal Manufacturing, Refinery, etc.). However, the

Table 4: Combined shock (price ETS x4 and expansion of ETS) with mitigation alternatives, summary statistics

	Baseline		Labor tax rebate		+10% Renewables		-10% Tech. component	
	Spain	EU	Spain	EU	Spain	EU	Spain	EU
GDP	-0.57	-0.65	0.82	0.78	-0.42	-0.55	-0.52	-0.61
IPC	1.91	1.88	3.35	5.92	2.31	2.06	1.76	1.74
Consumption	-0.60	-0.75	0.59	3.35	-0.09	-0.31	-0.54	-0.69
Employment	-0.95	-1.06	1.41	1.29	-0.96	-1.13	-0.88	-0.99
Wages	0.33	0.04	0.33	3.17	1.23	0.60	0.32	0.05
Fuel Use	-11.61	-13.31	-9.99	-10.61	-13.24	-14.91	-10.68	-12.18
Electricity Use	2.77	3.20	3.72	4.96	4.57	3.62	2.41	2.66
Emissions	-22.01	-17.84	-20.62	-15.82	-23.81	-20.37	-20.80	-16.79
Average carbon tax	23.66	29.64	23.28	28.68	24.88	31.26	22.21	27.86
Exports	-2.06	-1.90	-0.17	-5.66	-2.21	-2.06	-1.89	-1.75
Imports	-1.13	-0.71	-0.44	4.56	-1.02	-0.78	-1.04	-0.65

Note: All results are in real terms.

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[35] From a different perspective and with a long term horizon, Hinterlang et al. (2022) find a labor tax reduction is best financed with a tax on final consumption of brown energy.

manufacturing sectors that experienced smaller falls with transfers are now able to maintain their value added. In the case of services, they do not only not contract, but they expand up to 2%. Since these sectors have a relative higher use of electricity as energy input, their growth impulse the electrification of the economy with an uptick of clost to 4% in the Electricity generation (D35).

4.3.2 Renewables

The results of previous simulations show that the economy undergoes electrification, especially with an expansion of the ETS coverage, even as we assumed that the fraction of renewable electricity generation remained constant. In this section, we evaluate how an increase of 10% of the renewable generation can reduce the emissions of the electricity sector and accelerate electrification as a result. We assume that this additional capacity is achieved with an increase in the investment of the electricity sector (maintaining the same distribution of types of capital) and no new use of intermediates. Regarding the size of the expansion of renewables, a 10% growth in production in three years is actually conservative. For example, the last published plan by the Spanish government (Ministerio para la Transición Ecológica y el Reto Demográfico (2023)) anticipates an increase of 40% in renewable capacity for 2025 compared with 2019 [36].

Table 4 shows that the installation of renewables reduces the impact of the most adverse regulatory shock (price x4 and expansion of the ETS coverage) from 0.57% of GDP to just 0.42% for the Spanish economy. The fall in private consumption is four times smaller and the electrification of the economy accelerates, with the fuel use decrease in an additional 1.5% and the electricity use rises from +2.8% to +4.5%. All this leads to a further reduction in emissions up to -23.8%. By sectors, Figure 15 shows that all industries except mining an refinery are benefited by the renewable expansion with the biggest gains being concentrated in services and, not surprisingly, in the electricity sector D35. Notice that inflation is higher in this scenario, which is a side effect of the increase in the demand of electricity and the marginal price of electricity. We expect that in reality, the acceleration of renewable deployment will make the market less marginalistic and the price of electricity will fall, reducing inflation. Therefore, the results of this simulation should be interpreted as a lower bound of the potential benefits of renewables. [37]

All in all, this simulation shows that greening electricity production can significantly mitigate the transition risks of regulatory shocks.

4.3.3 Technological component

One of the limitations of CATALIST is that it does not include the possibility of producers endogenously reducing their emission intensity by assuming some abatement costs [38]. To assess how a reduction in emissions intensity can dampen the costs of regulatory shocks, we apply a negative shock of 10% to the technological component τ_{ts} (see eq. 3.1) of fuel use along with the combined ETS shock. We therefore assume that the emission intensity reduction is homogeneous across sectors. Although this is a simplistic choice, it is not very realistic since in some activities, it is harder (or more costly) to reduce the ratio of emissions to fuel. In addition, it is uncertain how successful technologies like Carbon Capture and Storage (CCS) will be. According to the EEA (European Environment Agency. (2022)), the intensity of emissions has been reduced by up to 6% in road transport between 2000 and 2019, in part due to the transition to biofuels. Given this, an improvement in the intensity of the emissions of 10% over three years seems an optimistic scenario.

The last columns of Table 4 display the macroeconomic impact of this scenario. The fall in output only shrinks by 0.05 percentage points. In contrast to the expansion of renewables, fuel use decreases less in this scenario, while electrification is slowed. As a result, emissions do not fall as much as in the baseline case (-20.8 vs -22 %). By sectors, we can see in Figure 16 that, unsurprisingly, those with higher dependency on fuel as energy (transport, refinery, mining, some manufactures) are the most benefited by the general improvement of the intensity of emissions.

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[36] Of course, installed capacity is not the same as production, but an increase of 10% (or more) in generation from renewables in the next three years seems like a safe bet.

[37] Quintana (2024) estimates that the price of electricity in Spain would fall by 50% by 2050 under the deployment plans of the National Energy and Climate Plan (Ministerio para la Transición Ecológica y el Reto Demográfico (2023)).

[38] For example, Hinterlang (2023) develops a model with abatement technology that is suitable for studying the international dynamics of the green transition. CATALIST, on the other hand, has more sectoral resolution and detail in the ETS framework, which makes it more appropriate for stress test scenarios.

5 Conclusions

The need to deepen our understanding of the transitional risks associated with the policies needed to mitigate the worst effects of climate change will only grow in the next few years. In particular, models with high sectoral detail are crucial to calibrate the design of carbon pricing policies and gauge the impact on financial stability. In this paper, we contribute to this endeavor by introducing a rich sectoral model focused on the Spanish economy. By building upon the sectoral detail of the CATS model and expanding it into a multi-country framework with investment, our model stands out in its ability to trace transition risks across international production networks and scrutinize the sector-specific impacts of various carbon tax policies.

The results obtained from CATALIST highlight considerable heterogeneity in sectoral responses to changes in emissions pricing. Although the aggregate effects that we find are small considering that the shocks considered would likely be implemented over a longer horizon, some sectors may experience significant losses in value added, which in turn could have more severe consequences through mechanisms that are outside the scope of this model. For example, if financial institutions are overly exposed to the most vulnerable industries, the economic losses could be amplified. On the other hand, we also find that a smart use of the public revenues of the carbon taxes could not only reduce the hit but actually be an engine for growth and the electrification of the economy.

Beyond its current applications, CATALIST presents a versatile platform for exploring a range of scenarios and policy interventions. It could be effectively employed to simulate the impact of energy input shocks, such as variations in fossil fuel prices, or to assess the implications of other carbon pricing mechanisms like the Carbon Border Adjustment Mechanism (CBAM).

Looking ahead, several extensions of the model are feasible and would further enhance its utility. These include incorporating sector-specific elasticities to refine our understanding of industry responses, expanding the scope to include other greenhouse gas emissions beyond those resulting from fuel use, and integrating a more sophisticated representation of the ETS market, particularly with regard to freely allocated permits. Additionally, extending the model's horizon would allow for a more comprehensive assessment of medium-term impacts, and an endogenous modeling of renewable energy sources would offer deeper insights into the transition towards a greener economy.

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A Hat algebra

In this appendix we derive the basics of hat algebra expressions in a CES economy. For a more datailed overview, see Dekle et al. (2007) and Barrot et al. (2021). Consider the following CES aggregator:

$$\widehat{y} = \hat{z}\left(\sum_{i=1}^{N} \lambda_i \cdot \widehat{x}_i^{\frac{\theta-1}{\theta}}\right)^{\frac{\theta}{\theta-1}} \tag{A.1}$$

where $\hat{y} = y/\overline{y}$ indicates deviation from the equilibrium value $\overline{y}$. The problem of the firm is:

$$\text{Max}\pi = \text{Max}Py - \sum_i w_i x_i \tag{A.2}$$

The first order conditions are:

$$[x_i] : \frac{\lambda_i}{\lambda_k}\left(\frac{\overline{x}_k}{\overline{x}_i}\right)^{\frac{\theta-1}{\theta}}\left(\frac{x_k}{x_i}\right)^{\frac{1}{\theta}} = \frac{w_i}{w_k} \tag{A.3}$$

Using the fact that the equation above is true for $x_i = \overline{x_i}$, we obtain that:

$$\overline{x_i} = \frac{\overline{w_k}}{\overline{w_i}}\frac{\lambda_i}{\lambda_k}\overline{x_k} \tag{A.4}$$

and that:

$$\lambda_i = \frac{\overline{w_i x_i}}{\sum_k \overline{w_k x_k}} \tag{A.5}$$

Writing A.3 in deviations, we can prove that:

$$\widehat{x_i} = \left(\frac{w_k}{w_i}\right)^{\theta} \widehat{x_k} \tag{A.6}$$

Under perfect competition, $\pi = 0$. Then:

$$P = \frac{\sum_i w_i x_i}{y} \tag{A.7}$$

Using A.6 and A.1, we can demonstrate that:

$$\widehat{P} = \hat{z}\left[\sum_i \lambda_i \widehat{w_i}^{1-\theta}\right]^{\frac{1}{1-\theta}} \tag{A.8}$$

and

$$\widehat{x_i} = \hat{z}^{\theta-1}\left(\frac{\widehat{P}}{\widehat{w_i}}\right)^{\theta} \widehat{y} \tag{A.9}$$

$$\widehat{w_i} = \hat{z}^{\frac{\theta-1}{\theta}}\left(\frac{\widehat{y}}{\widehat{x_i}}\right)^{\frac{1}{\theta}} \widehat{P} \tag{A.10}$$

B Prices and demands

Using the hat algebra results shown in the appendix A we can recover prices and demands of composite goods sequentially. Following the algorithm that we use to solve the model, we present here the formulas for prices from the bottom to the top and, later, the demand functions from top to bottom.

B.1 Intermediate prices

From (A.8), the price that industry $i \in N$ pays for sector variety good $j \in S$ is given by:

$$\widehat{p}_{ij} = \left(\sum_{c\in C} \lambda_{ijc}\left(\tau_{ijc}\widehat{p}_{jc}\right)^{1-\xi_j}\right)^{\frac{1}{1-\xi_j}} \tag{B.1}$$

Similarly, the price that industry $i \in N$ pays for the $X \in \{F, EL\}$ composite is:

$$\widehat{p}_i^x = \left(\sum_{j \in S^x} \Omega_{ij}^X \widehat{p}_{ij}^{1-\epsilon_x} \right)^{\frac{1}{1-\epsilon_x}} \tag{B.2}$$

Now, the price of energy and materials composites are:

$$\widehat{p}_i^z = \left(\sum_{x \in X_z} \eta_{ix}^z \left(\widehat{p}_i^x\right)^{1-\epsilon_z} \right)^{\frac{1}{1-\epsilon_z}} \tag{B.3}$$

where $z \in \{E, M\}$ and X_z are the composites that form each one.

B.2 Value added prices

In a similar way, the prices for capital goods are aggregated from the bottom up:

$$\widehat{p}_{ij}^I = \left(\sum_{c \in C} \lambda_{ijc}^K \left(\tau_{ijc} \widehat{p}_{jc}^I\right)^{1-\xi_j} \right)^{\frac{1}{1-\xi_j}} \tag{B.4}$$

and the composite:

$$\widehat{P}_i^I = \left(\sum_{j \in G} \Omega_{ij}^K (\widehat{p}_{ij}^I)^{1-\epsilon_k} \right)^{\frac{1}{1-\epsilon_k}} \tag{B.5}$$

In the long-run this has to be equal to r_i, but this is not true in the sort run, where the amount of capital is fixed and the rental price is determined as an equilibrium object.

Then, the price of value added by industry i

$$\widehat{p}_i^a = \widehat{z}_i^{-1} \left[\alpha_i \widehat{w}_i^{1-\gamma_i} + (1-\alpha_i) \widehat{r}_i^{1-\gamma_i} \right]^{\frac{1}{1-\gamma_i}} \tag{B.6}$$

B.3 a—E composite price

The price of the a—E mix is:

$$\widehat{p}_i^{a|E} = \left[\eta_i^a \left(\widehat{p}_i^a\right)^{1-\epsilon_{a|E}} + (1-\eta_i^a) \left(\widehat{p}_i^E\right)^{1-\epsilon_{a|E}} \right]^{\frac{1}{1-\epsilon_{a|E}}} \tag{B.7}$$

B.4 Price of output

The final price of good i can be recovered using hat algebra results from (A.8):

$$\widehat{p}_i = \widehat{z}_i^{1-\theta} \left((1-\eta_i^m-\eta_i^e) (\widehat{p}_i^a)^{1-\theta} + (1-\eta_i^m) (\widehat{p}_i^M)^{1-\theta} + (1-\eta_i^e) (\widehat{p}_i^E)^{1-\theta} \right)^{\frac{1}{1-\theta}} \tag{B.8}$$

B.5 Consumers' prices and demands

The price that consumer in country $i \in C$ pays for sector variety good j can be recovered from the country-sector variety using:

$$\widehat{p}_{ij}^{cons} = \left(\sum_{c \in C} \lambda_{ijc}^{\text{cons}} \left(\tau_{ijc} \cdot \widehat{p}_{jc}\right)^{1-\xi_j} \right)^{\frac{1}{1-\xi_j}} \tag{B.9}$$

And the aggregate price level that consumer in country $i \in C$ pays for aggregate good:

$$\widehat{p}_i^{cons} = \left(\sum_{j \in S} \Omega_{ij}^C (\widehat{p}_{ij}^{cons})^{1-\epsilon_c} \right)^{\frac{1}{1-\epsilon_c}} \tag{B.10}$$

B.6 Demand of consumers

The consumption of composite good j by consumer in country i

$$\widehat{c}_{ij} = \widehat{\beta}_{ij} \left(\frac{\widehat{p}_{ij}^{cons}}{\widehat{p}_i^{cons}} \right)^{-\epsilon_c} C_i \tag{B.11}$$

where $\widehat{\beta}_{ij}$ is the taste shock of good j for consumer in country i.

Finally, consumption of variety c of composite good j by consumer in country c

$$\widehat{c}_{ijc} = \left(\frac{\widehat{p}_{jc}}{\widehat{p}_{ij}^{cons}} \right)^{-\xi_j} \widehat{c}_{ij} \tag{B.12}$$

B.7 Demand of materials, a—E and energy

Given the supplied quantity y_i and prices, the demand of the $a|E$ mix is:

$$\widehat{a|E}_i = \widehat{z}_i^{\theta-1} \left(\frac{\widehat{p}_i^{a|E}}{\widehat{p}_i} \right)^{-\theta} \widehat{y}_i \tag{B.13}$$

and the demand of materials is:

$$\widehat{M}_i = \widehat{z}_i^{\theta-1} \left(\frac{\widehat{p}_i^{M}}{\widehat{p}_i} \right)^{-\theta} \widehat{y}_i \tag{B.14}$$

The demand of energy super-composite is:

$$\widehat{E}_i = \left(\frac{\widehat{p}_i^{E}}{\widehat{p}^{a|E}} \right)^{-\epsilon_{a|E}} \widehat{a|E}_i \tag{B.15}$$

B.8 Demand of value added, capital and labor

The demand for added value is:

$$\widehat{a}_i^{dem} = \left(\frac{\widehat{p}_i^{a}}{\widehat{p}^{a|E}} \right)^{-\epsilon_{a|E}} \widehat{a|E}_i \tag{B.16}$$

while the demand of capital composite is

$$\widehat{k}_i = \widehat{d}_i^{\gamma_i-1} \left(\frac{\widehat{r}_i}{\widehat{p}_i^{a}} \right)^{-\gamma_i} \widehat{a}_i \tag{B.17}$$

and the demand of each capital good:

$$\widehat{k}_{ij} = \left(\frac{\widehat{p}_{ij}^{I}}{\widehat{r}_i} \right)^{-\epsilon_k} \widehat{k}_i \tag{B.18}$$

Finally, the demand of country variety c of capital good j by industry i

$$\widehat{k}_{ijc} = \left(\frac{\widehat{p}_{jc}}{\widehat{p}_{ij}^{I}} \right)^{-\xi_j} \widehat{k}_{ij} \tag{B.19}$$

The demand of labor is

$$\widehat{l}_i = \widehat{d}_i^{\gamma_i-1} \left(\frac{\widehat{w}_i}{\widehat{p}_i^{a}} \right)^{-\gamma_i} \widehat{a}_i \tag{B.20}$$

B.9 Demand of intermediates

Using the hat algebra result (A.9), the demand of material composite input by industry $i \in N$

$$\widehat{X}_i = \left(\frac{\widehat{p}_i^{X}}{\widehat{p}_i^{M}} \right)^{-\theta} \widehat{M}_i \tag{B.21}$$

and similarly with energy composites. The demand of sector variety $j \in S^m$ good by industry i:

$$\widehat{x}_{ij} = \left(\frac{\widehat{p}_{ij}}{\widehat{p}_i^X}\right)^{-\epsilon_x} \widehat{X}_i \tag{B.22}$$

Finally, the demand of country variety c of good j by industry i

$$\widehat{x}_{ijc} = \left(\frac{\widehat{p}_{jc}}{\widehat{p}_{ij}}\right)^{-\xi_j} \widehat{x}_{ij} \tag{B.23}$$

C Rebate of ETS

C.1 As lump sum transfer

If ETS revenue is rebated as a lump sum tax $T = ETS_{rev}$ to consumers:

$$C = (wL + T)/P_C \tag{C.1}$$

In deviations:

$$\widehat{P_C}\widehat{C} = \widehat{wL}\left(\frac{\bar{C} - \bar{T}}{\bar{C}}\right) + \widehat{T}\frac{\bar{T}}{\bar{C}} \tag{C.2}$$

C.2 As labor tax reduction

With labor taxes, the final consumption is:

$$C = wL(1 - \tau_l)/P_C \tag{C.3}$$

If we assume that ETS extra revenues are rebated as a reduction in labor taxes, the extra revenue of ETS should be equal to the reduction in revenue from labor taxes:

$$\Delta wL\tau_l = -\Delta ETS_{rev} \tag{C.4}$$

which implies in deviations that:

$$\widehat{\tau_l} = \frac{1}{\widehat{wL}}\left[1 - \frac{\Delta ETS_{rev}}{\overline{wL\tau_l}}\right] \tag{C.5}$$

and the consumption deviation is

$$\widehat{C} = \frac{\widehat{wL}}{\widehat{P_C}}\left(\frac{1 - \bar{\tau}_l\widehat{\tau_l}}{1 - \bar{\tau_l}}\right) \tag{C.6}$$

D Additional figures

D.1 Labor tax rebate

Figure 13: Combined shock with labor tax rebate vs lump sum transfers: fall in real value added by sector (Spain)

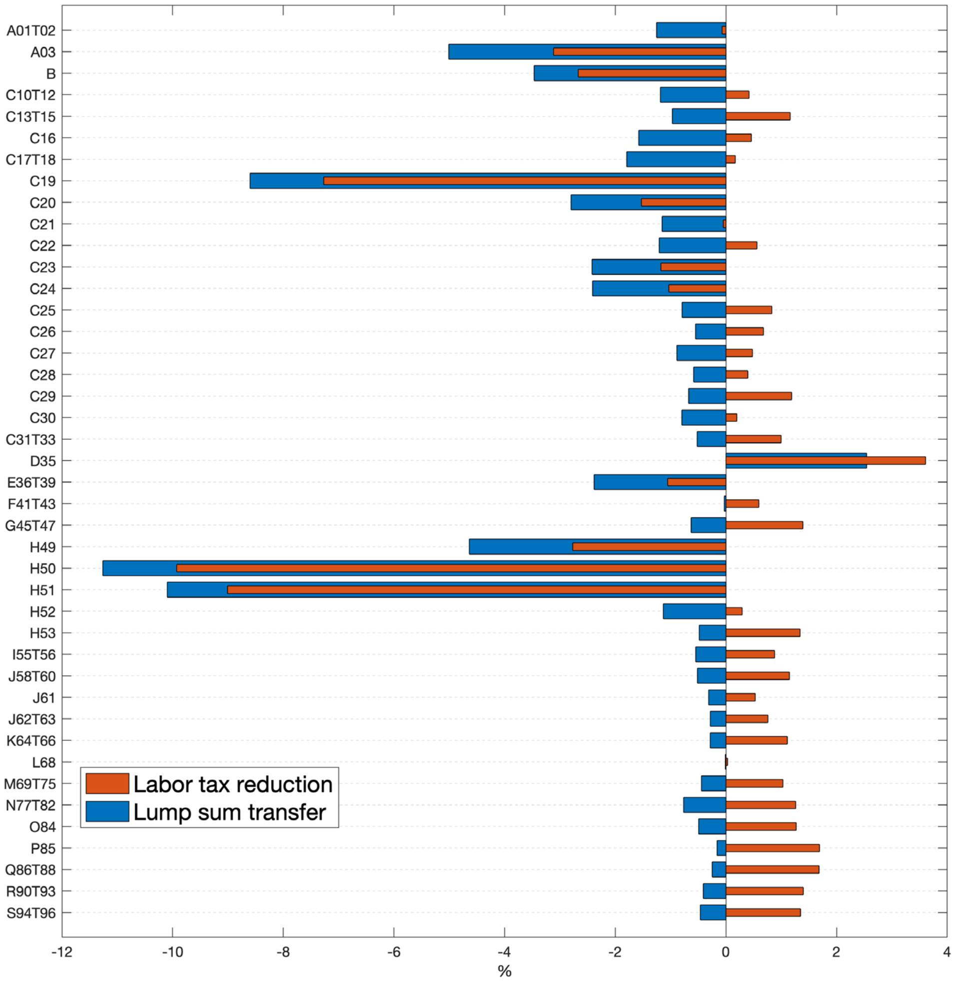
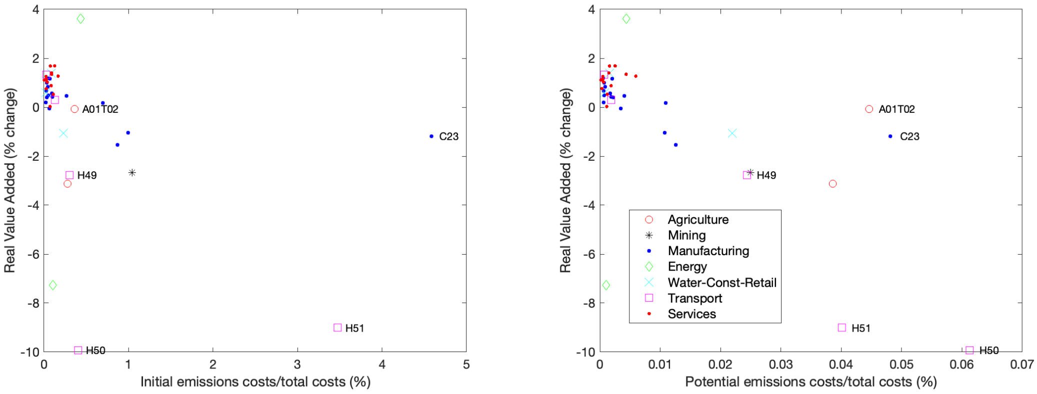
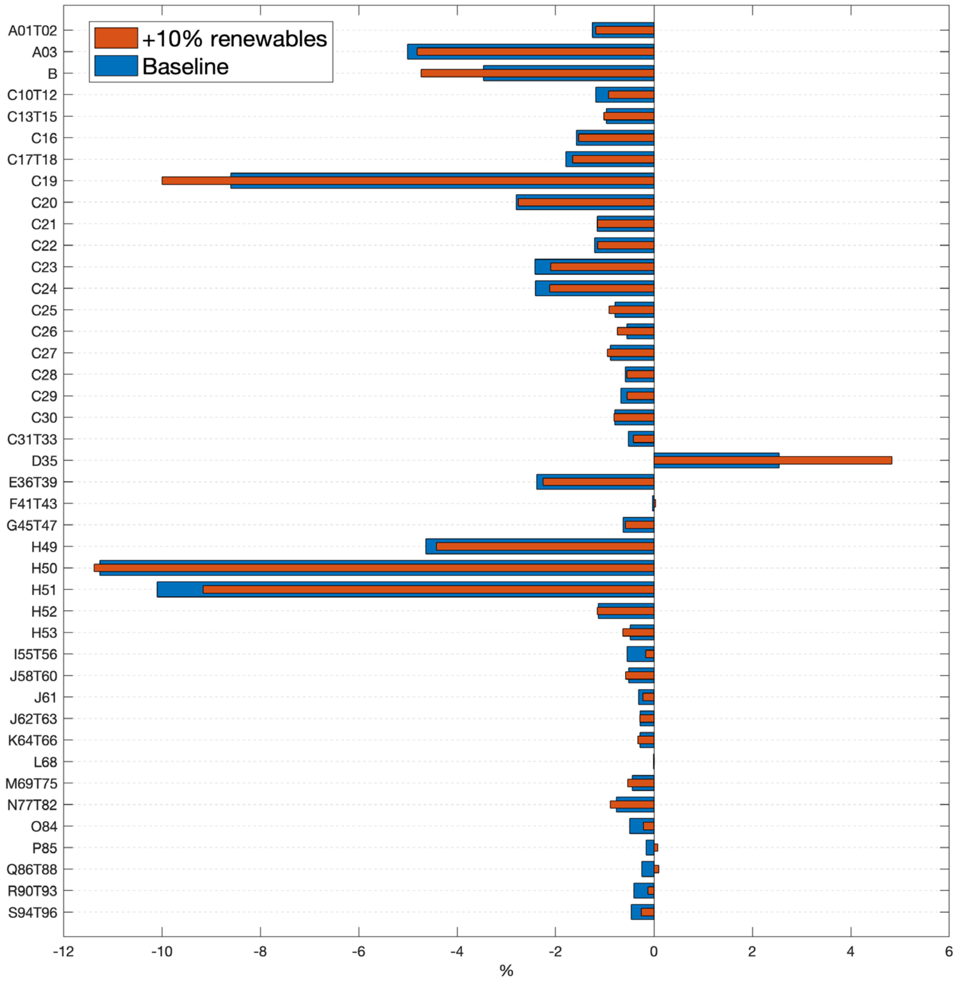


Figure 14: Combined shock with labor tax rebate: fall in real value added vs fall in real value added vs share of emissions costs (left) and vs potential emissions costs (right)



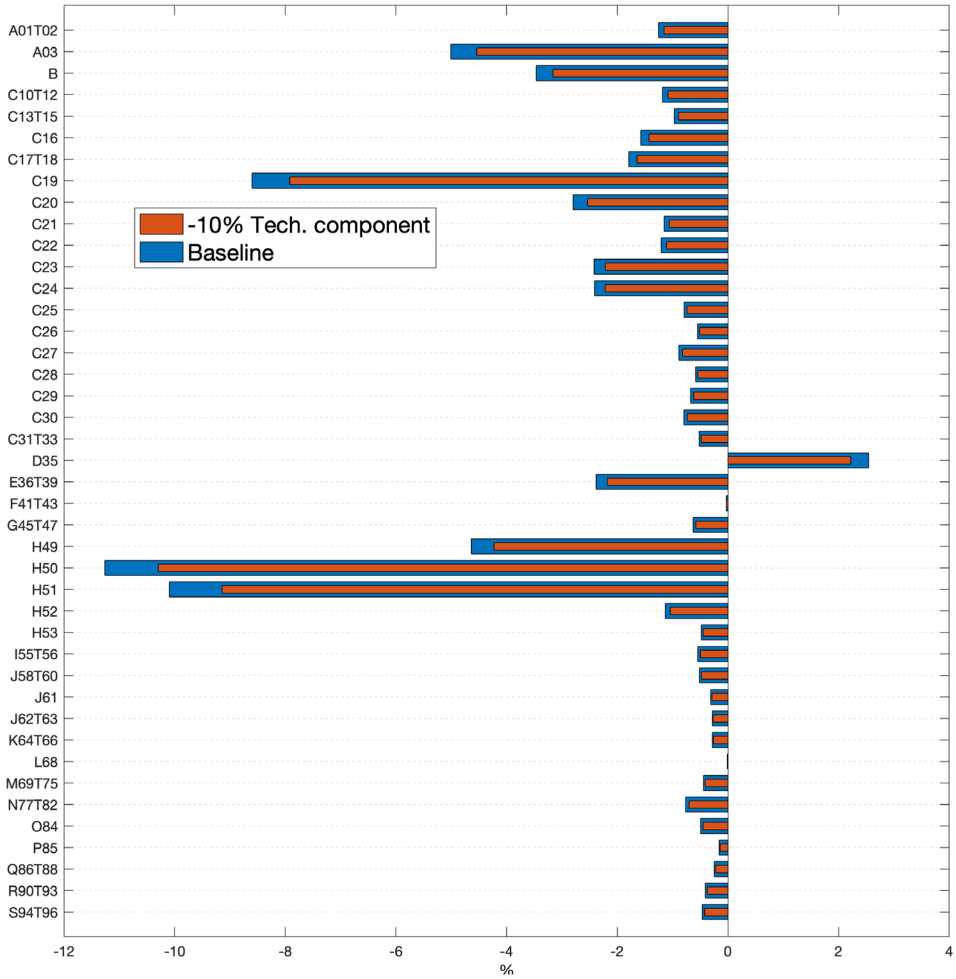
D.2 Mitigation with renewables

Figure 15: Combined shock with and without expansion of renewables production: fall in real value added by sector (Spain)



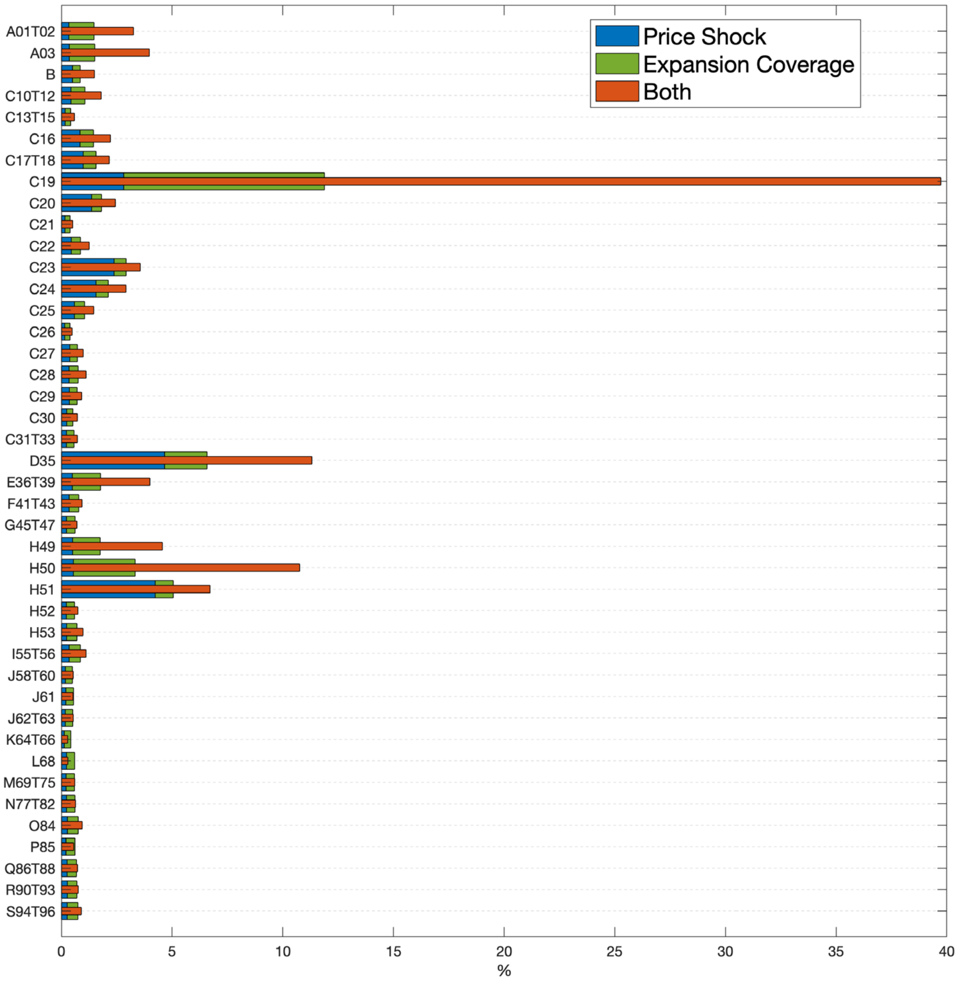
D.3 Mitigation with technological component

Figure 16: Combined shock with and without a reduction of 10% in the technological component: fall in real value added by sector (Spain)



D.4 Prices

Figure 17: ETS shocks compared: basic prices for domestic output



E Production structure robustness

In this section, we evaluate the importance of the assumption of (KL-E)M nesting on the results. We compare the aggregate and sectoral results against the ones obtained with two alternative nesting structures: (KL-M)-E and (KL)-M-E-F. We maintain the same elasticities as in the original structure, although there is one elasticity less in the (KL)-M-E-F structure. In the latter, materials, fuel, and electricity enter at the same level with elasiticity of substitution equal to θ.

In table 5 we show how the aggregate results for the combined shock change with the alternative nesting settings. The differences are relatively small for most variables. However, the use of fuel and electricity is particularly affected by the position of energy in production. In the (KL-M)-E structure, energy use is lower than in the baseline model because the elasticity between energy and the KL-M mix is greater ($= \theta$) than with VA in the baseline setting. The biggest change is with the (KL)-M-E-F structure. Here, fuel and electric power are substituted at the same level with VA and M. Therefore, fuel use falls less and electricification does not occur as a result.

Sectoral impact is also not greatly affected by the nesting structure, but transport sectors are significantly less affected with the alternative structures (e.g. water transport observes a fall of close to 12% in the baseline model, while this goes down to around 8% with the alternatives).

Table 5: Combined shock (price ETS x4 and expansion of ETS) with different nesting alternatives, summary statistics

	Baseline		(VA-M)E		(VA)-M-E-F	
	Spain	EU	Spain	EU	Spain	EU
GDP	-0.57	-0.65	-0.55	-0.63	-0.56	-0.64
IPC	1.91	1.88	2.08	2.05	1.87	1.85
Consumption	-0.60	-0.75	-0.56	-0.72	-0.52	-0.67
Employment	-0.95	-1.06	-0.92	-1.02	-0.93	-1.06
Wages	0.33	0.04	0.57	0.28	0.39	0.10
Fuel Use	-11.61	-13.31	-12.44	-14.67	-10.34	-12.30
Electricity Use	2.77	3.20	1.95	2.03	-0.17	-0.72
Emissions	-22.01	-17.84	-23.56	-19.91	-15.25	-14.79
Average carbon tax	23.66	29.64	23.39	29.28	28.97	34.04
Exports	-2.06	-1.90	-2.18	-2.07	-2.11	-2.00
Imports	-1.13	-0.71	-1.20	-0.80	-1.20	-0.88

F Comparison with CATS

The results of the simulations above can be compared with those provided by CATS (see table 6. In terms of aggregate effects, the impact of price shocks on GDP is around half in CATALIST. The biggest difference is that CATS gives a bigger fall for consumption and energy use in all simulations and does not predict electrification of the economy. Emissions reductions are also larger as a result of lower fuel use. Although the sector composition of the price shock is similar to CATS (see figure 6), is quite different for the coberture shock (figure 18). Almost all sectors suffer a bigger loss in CATALIST, except for the energy ones, balancing out the aggregate impact on GDP. As shown in table 7, using the same implied rates on energy purchases as in CATS leads to an even higher aggregate impact. However, the smaller calibrated rates in CATALIST reduce the transition costs significantly. Notice that the effect of the capital network also is to reduce the aggregate impact of the shocks.

Table 6: Regulatory shocks: comparison with CATS. Spain.

	Price ETS x4		Exp. Coverage		Pricex4 & exp cov	
	CATS	CATALIST	CATS	CATALIST	CATS	CATALIST
GDP	-0.37	-0.16	-0.12	-0.13	-0.90	-0.57
Consumption	-0.63	-0.02	-0.24	-0.07	-1.52	-0.60
Employment	-0.58	-0.29	-0.19	-0.22	-1.27	-0.95
Wages	-0.94	-0.31	-0.35	-0.29	-2.27	-1.54
Use fuel	-5.85	-2.21	-4.45	-3.35	-15.85	-11.61
Use Electricity	-3.05	-0.35	-0.49	1.01	-4.82	2.77
Emissions	-9.75	-9.27	-14.54	-7.39	-31.10	-22.01

Table 7: Combined shock: comparison with CATS

	CATS	OLD ETS-NO K	OLD ETS	CATALIST
GDP	-0.90	-1.90	-1.29	-0.57
Consumption	-1.52	-1.91	-1.48	-0.60
Employment	-1.27	-1.89	-2.10	-0.95
Wages	-2.27	-1.87	-1.08	-1.54
Use fuel	-15.85	-24.49	-21.95	-11.61
Use Electricity	-4.82	10.49	7.32	2.77
Emissions	-31.10	-30.87	-29.38	-22.01

Note: All results are in real terms. The first column show the output of CATS, the second one are the impacts of CATALIST calibrated with estimated carbon taxes of CATS and with no investment network. The third adds capital and the last one is the baseline result of CATALIST.

Figure 18: Expansion of ETS coverage: fall in real value added by sector (Spain)

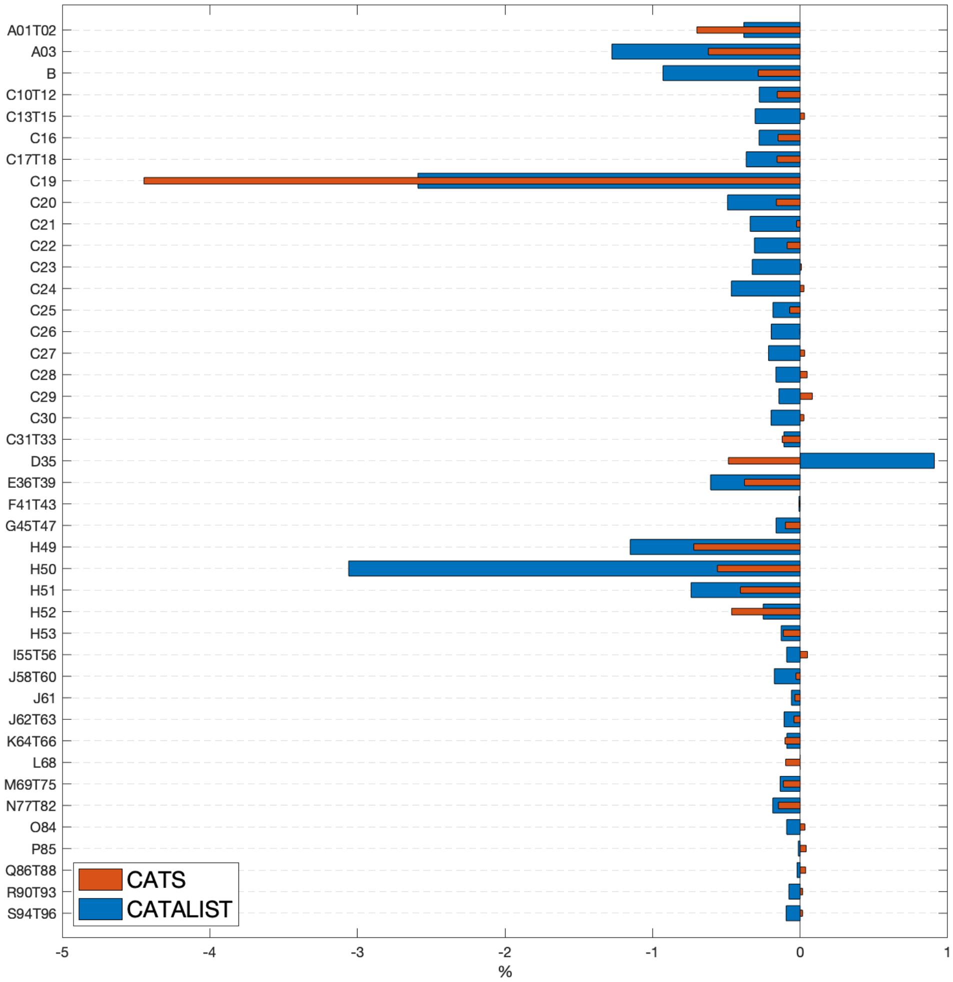
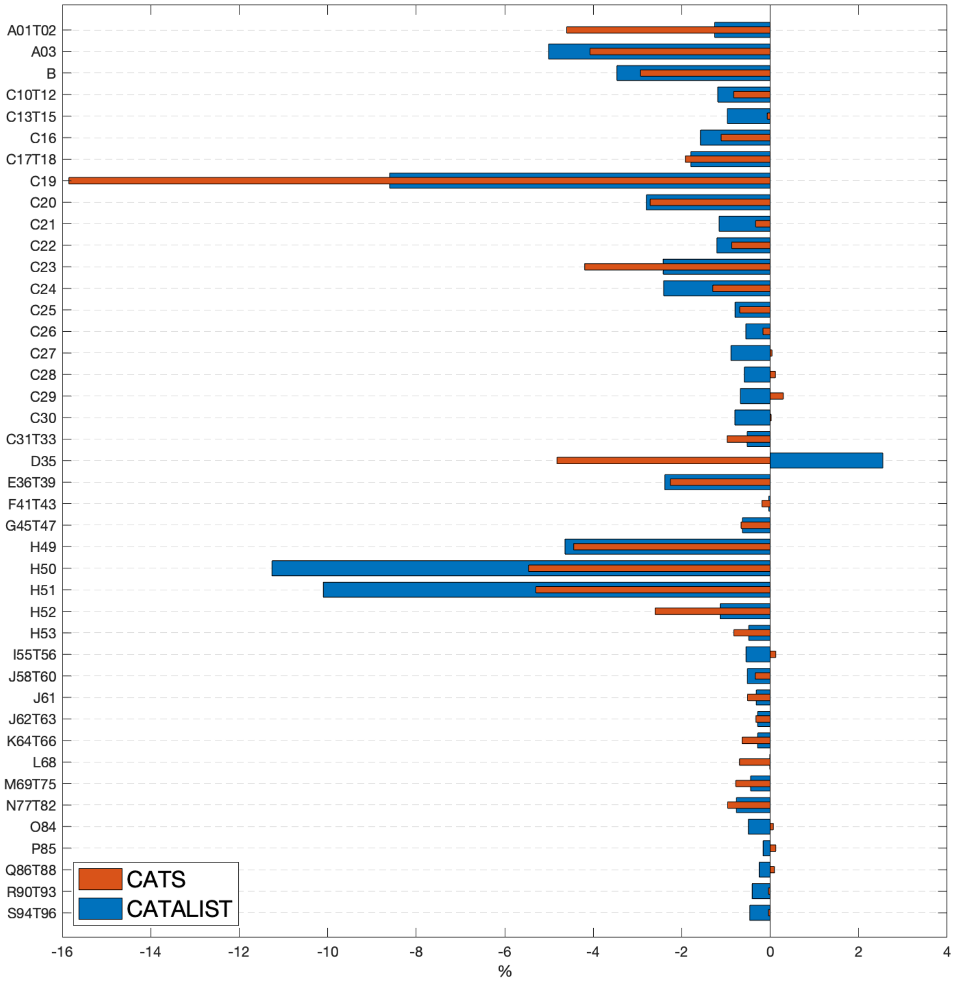


Figure 19: Combined shock: fall in real value added by sector (Spain)



G Sector glossary

Table 8: Sector Codes and Descriptions (ICIO)

Category	**Code**	**Sector**
Primary	A01T02	Agriculture, hunting, forestry
	A03	Fishing and aquaculture
Mining	B05T06	Mining and quarrying, energy producing products
	B07T08	Mining and quarrying, non-energy producing products
	B09	Mining support service activities
Manufactures	C10T12	Food products, beverages and tobacco
	C13T15	Textiles, textile products, leather and footwear
	C16	Wood and products of wood and cork
	C17T18	Paper products and printing
	C19	Coke and refined petroleum products
	C20	Chemical and chemical products
	C21	Pharmaceuticals, medicinal chemical and botanical products
	C22	Rubber and plastics products
	C23	Other non-metallic mineral products
	C24	Basic metals
	C25	Fabricated metal products
	C26	Computer, electronic and optical equipment
	C27	Electrical equipment
	C28	Machinery and equipment, nec
	C29	Motor vehicles, trailers and semi-trailers
	C30	Other transport equipment
	C31T33	Manufacturing nec; repair and installation of machinery
Electricity	D35	Electricity, gas, steam and air conditioning supply
Water	E36T39	Water supply; sewerage, waste management
Construction	F41T43	Construction
Retail	G45T47	Wholesale and retail trade; repair of motor vehicles
Transport	H49	Land transport and transport via pipelines
	H50	Water transport
	H51	Air transport
	H52	Warehousing and support activities for transportation
	H53	Postal and courier activities
Services	I55T56	Accommodation and food service activities
	J58T60	Publishing, audiovisual and broadcasting activities
	J61	Telecommunications
	J62T63	IT and other information services
	K64T66	Financial and insurance activities
	L68	Real estate activities
	M69T75	Professional, scientific and technical activities
	N77T82	Administrative and support services
	O84	Public administration and defense; social security
	P85	Education
	Q86T88	Human health and social work activities
	R90T93	Arts, entertainment and recreation
	S94T96	Other service activities

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