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On the aggregate and distributional effects of carbon taxation in Portugal

Zeina Hasna
University of Cambridge

Nuno Lourenço
Banco de Portugal

Cezar Santos
Banco de Portugal,
FGV EPGE and CEPR

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Abstract
Drawing on the model developed by Cavalcanti *et al.* (2021), we quantify the aggregate and distributional effects of a carbon tax in Portugal. Carbon taxation induces changes in relative prices and reallocation of inputs, including labour. We target a decline in emissions of a 30 to 40%, required for Portugal to achieve its original Paris Agreement pledge. This entails at most a 1.7% drop in output. As the Paris Agreement targets have been revised over time, we also estimate the carbon tax needed for Portugal to achieve a 70% decline in emissions, which stands at 80.4%. We find that the effects are asymmetric across sectors and individuals, with those workers with a comparative advantage in dirty energy sectors who do not reallocate being hit harder. (JEL: E13, H23, J24.)

1. Introduction

Triggered by a high concentration of carbon dioxide and other greenhouse gases (GHG) in the atmosphere, climate change is arguably the largest global negative externality in the world. It affects ecosystems worldwide by causing global warming, rising sea levels or more frequent extreme weather events. Its economic effects are surrounded by heightened uncertainty, and are long-lasting and heterogeneous across geographies.

The 2015 Paris Agreement set the stage for the international response to climate change by bringing several parties to adopt policies to limit global warming to well below 2, later revised to 1.5 degrees Celsius compared to pre-industrial levels. Countries have thus submitted their plans for climate action known as nationally determined contributions (NDCs), where they communicated the intended actions to reduce GHG

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E-mail: zh274@cam.ac.uk; nalourenco@bportugal.pt; cezarsantos.econ@gmail.com

emissions. Portugal was no exception. A long-term strategy for carbon neutrality by 2050 was designed, consisting of the identification of the main decarbonisation vectors in all sectors, the policy options and the emission reduction path to achieve this end across different socio-economic scenarios.[1]

Given that there is scientific consensus that global temperatures are rising, it is almost unanimous that governments lie at the root of the transition to a greener economy. In fact, one of the policy prescriptions to address climate change has been known for more than a century, since the work of Pigou (1920). By imposing a tax on GHG emissions at the source that must be equal to the total marginal damage the polluter is not paying for, it provides incentives to producers to shift their operations to a less carbon-intensive direction. A second policy prescription for climate change mitigation drawing on the work of Coase (1960) lies in the implementation of tradable carbon permits (e.g. European Union Emissions Trading System). As carbon dioxide spreads fast in the atmosphere, the damages are identical regardless of where pollution occurs.

In this paper, we assess the aggregate and distributional effects of a climate change mitigation policy in Portugal, in particular a tax on GHG emissions, inspired by the line of research highlighting the effectiveness of carbon taxes in reducing emissions (see for example, Golosov *et al.* (2014), Hassler *et al.* (2018) and Hassler *et al.* (2021)). The carbon tax will induce a change in factor prices that then spreads to the rest of the economy and causes sectoral reallocation of inputs, in particular labour. To do so, we resort to the model introduced in Cavalcanti *et al.* (2021) featuring heterogeneity in the workers' skill distribution and the economy's sectoral composition.

In our policy experiments, we analyse the economic impacts of introducing a carbon tax to the "dirty" energy producers.[2] Our model-based estimates needed for Portugal to achieve its Paris Agreement pledges of a 35 and a 70% reduction in emissions point to a 32.9 and an 80.4% carbon tax, respectively.[3] We find that the carbon tax is an effective tool for Portugal to reduce emissions and achieve its climate targets laid down in the Paris Agreement. We also show that the effects will be conditional on the magnitude of the tax and how the tax revenues are rebated back to the economy. For instance, we estimate that a 32.9% (80.4%) carbon tax costs the Portuguese economy at most a 1.7% (7.5%) drop in output, which is the worst-case scenario when the government does not rebate tax revenues back to the economy. Moreover, the carbon tax has non-trivial distributional effects at the sectoral and individual levels. Our analysis points to asymmetric effects across sectors and individuals; workers with a comparative advantage in dirty energy sectors who do not reallocate experience the largest welfare loss.

1. See `https://descarbonizar2050.apambiente.pt/en/documents/` for an overview of the documents that have been released following the Paris Agreement.

2. The "dirty" energy sectors refer to oil, coal and natural gas sectors, whereas the "non-dirty" energy sector refers to the green sector.

3. A reduction target of 30 to 40% by 2030, below 2005 levels was originally pledged by Portugal. Later on, Portugal assumed a reduction target of 65 to 75% by 2040, below 2005 levels. Hence, in our experiments we target the mid-points of these intervals, respectively, 35 and 70%. See `https://files.dre.pt/1s/2020/07/13300/0000200158.pdf` for details (in Portuguese only).

The remainder of the paper is structured as follows. Section 2 describes the model. Section 3 details the aggregate results and Section 4 presents the sectoral- and individual-level results of the policy scenarios. Section 5 concludes.

2. The model

We follow the multi-sectoral model developed by Cavalcanti *et al.* (2021), in which the workers' skill distribution is integrated with the economy's sectoral composition. As in Hsieh *et al.* (2019), the framework features endogenous occupational choice and human capital accumulation, where individuals live for two periods. In the first period, individuals take into account their sector-specific productivities to choose the sector they work for and their investment in human capital.[4] In the second period, individuals work and consume. The production side of the economy consists of sectors producing differentiated intermediate goods, including four energy types: oil, coal, natural gas and green. There is also a final good sector. A carbon tax is introduced to the dirty energy producers, which in turn affects their prices. Given the intersectoral linkages in the economy, these changes in relative prices induce reallocation of inputs across sectors, including labour. The model environment is described in what follows.

2.1. Households

Individuals work in each one of the J intermediate sectors and are endowed with two units of time: one unit when they are "young", which is allocated between leisure and schooling; and one unit when they are "old", when they supply their labour inelastically to one of the intermediate goods sectors. There is a continuum of measure one of those individuals.

Each individual derives utility from consumption, c, and leisure, $1-s$, according to the following function:

$$U = c^{\gamma}(1-s),\ \gamma > 0,$$

where s denotes time spent on schooling in the first period of life and γ controls the relative weight of consumption in the individual's utility.

Human capital for sector j depends on schooling time, s, and schooling resources (e.g. tuition fees), e, and is given by:

$$h_j(s,e) = s^{\varphi_j} e^{\eta}.$$

The elasticity of human capital with respect to time is sector-specific, φ_j, such that different sectors feature different returns to schooling.

The individual's labour income is the product of the wage per efficiency unit in sector j, w_j, their idiosyncratic ability draw, z_j, and their acquired human capital for sector j,

4. Ability, talent, comparative advantage and productivity are used interchangeably in the text.

$h(s, e)$:

$$I = w_j z_j h_j(s, e).$$

Individuals split income between consumption, c, and expenditures on schooling resources, e:

$$c = w_j z_j h_j(s, e) - e.$$

Given an occupational choice, wage, and idiosyncratic talent, z_j, the individual's utility maximisation problem is given by:

$$U_j(w_j, z_j) = \max_{c,s,e} c^{\gamma}(1-s) \text{ subject to } c = w_j z_j h_j(s, e) - e. \tag{1}$$

The solution of this problem reads as follows:

$$s_j^* = \frac{1}{1 + \frac{1-\eta}{\gamma\varphi_j}}, \tag{2}$$

$$e_j^*(z_j) = \left[\eta w_j z_j (s_j^*)^{\varphi_j}\right]^{\frac{1}{1-\eta}}. \tag{3}$$

After plugging in equations (2) and (3) into (1), the individual's indirect utility is given by:

$$U_j^* = \left[w_j z_j s_j^{\varphi_j}(1-s_j)^{\frac{1-\eta}{\gamma}} \eta^{\eta}(1-\eta)^{(1-\eta)}\right]^{\frac{\gamma}{1-\eta}}. \tag{4}$$

2.1.1. Occupational skills

We assume that each worker is endowed with a vector of idiosyncratic abilities $\{z_j\}_{j=1}^{J}$ drawn from a multivariate Fréchet distribution, such that:

$$F(z_1, ..., z_J) = \exp\left(-\sum_{j=1}^{J}(z_j)^{-\lambda}\right), \ \lambda > 1,$$

where the parameter λ measures the dispersion of individual productivity across sectors. When λ is small, workers' abilities are more dispersed, and hence a larger change in wages is needed to get workers to reallocate across sectors. And vice versa. However, when λ is larger, skills are less dispersed, and workers' occupational choices are more sensitive to changes in wages, which makes reallocation across sectors easier.

2.1.2. Occupational choice

Heterogeneous abilities interact with the endogenous components of an individual's utility in (4) and drive self-selection. As such, workers supply their labour to the sector which offers them the highest relative returns given their vector of ability, i.e. the highest utility $\max_j\{U_j\}$.

The share of workers in each sector can be derived using the tractability afforded by the Fréchet distribution, given the decision rule behind workers' occupational choice (see Cavalcanti *et al.* (2021) for details). Each worker's occupational choice is driven by *relative* returns instead of *absolute* returns. Having calculated the labour supply for each sector, we can compute the efficiency units of labour supplied (i.e. effective labour supply) in each sector.

Average worker quality in each sector can be computed by taking the ratio of efficiency units of labour supplied over the units of labour supplied. Average quality is therefore inversely related to the labour share in each sector, which captures a selection effect.

2.2. Production

As alluded before, the economy consists of J intermediate goods sectors and one final good sector. These are now described.

2.2.1. Intermediate goods

The production setup is similar to trade models such as Eaton and Kortum (2002). There are J sectors, each producing a differentiated intermediate good. Among these, there are four energy sectors (oil, coal, natural gas and green), from which the first three are polluting, i.e. dirty energy sectors. The fourth sector is the clean energy sector. The technology to produce each intermediate good $j \in \{1, 2, ..., J\}$ is represented by a Cobb-Douglas function with constant returns to scale:

$$Y_j = L_j^{\beta_j} \prod_{k=1}^{J} x_{jk}^{\nu_{jk}},\ \beta_j, \nu_{jk} \in [0, 1];\ \textit{and}\ \beta_j + \sum_{k=1}^{J} \nu_{jk} = 1,$$

where L_j corresponds to effective labour input and β_j is the labour share in sector j. The variable x_{jk} denotes the quantity of intermediate input k used in the production of good j. The parameter ν_{jk} determines the relative importance of good k in the production of sector j. The inclusion of intersectoral linkages allows for a more detailed analysis of the general equilibrium effects of adding a carbon tax (Jones 2011; Acemoglu *et al.* 2012; King *et al.* 2019).

The representative firm in the intermediate goods sector j chooses labour L_j and intermediate inputs $\{x_{jk}\}_{k=1}^{J}$ to maximise:

$$\pi_j = \max_{L_j, x_{jk}} \Big\{ P_j L_j^{\beta_j} \prod_{k=1}^{J} x_{jk}^{\nu_{jk}} - w_j L_j - \sum_{k=1}^{J} P_k x_{jk} \Big\}, \tag{5}$$

where P_j is the price of intermediate good j and w_j is the wage rate paid in sector j. Inputs are paid according to their marginal products, such that:

$$\beta_j P_j L_j^{\beta_j - 1} \prod_{k=1}^{J} x_{jk}^{\nu_{jk}} = w_j,$$

$$\nu_{jk} P_j L_j^{\beta_j} x_{jk}^{\nu_{jk}-1} \prod_{k \neq s} x_{js}^{\nu_{js}} = P_k,\ \forall x_{jk},\ k \in \{1, 2, ..., J\}.$$

2.2.2. *Final good*

A production function using differentiated intermediate goods, $\{Y_j^F\}_{j=1}^J$, yields the final good, Y_f, according to the following aggregator:

$$Y_f = \prod_{j=1} \left(Y_j^F\right)^{\sigma_j},\ \sigma_j \in [0,1) \text{ and } \sum_{j=1}^{J} \sigma_j = 1.$$

The final good is the numéraire, i.e. $P_f = 1$. The optimisation problem of the representative firm in the final good sector is to choose each input $\{Y_j^F\}_{j=1}^J$ to maximise:

$$\pi_f = \max_{Y_j} \left\{ \prod_{j=1} \left(Y_j^F\right)^{\sigma_j} - \sum_j P_j Y_j^F \right\}, \tag{6}$$

and the optimal demand for each input satisfies:

$$Y_j^F = \sigma_j \frac{Y_f}{P_j},\ \forall j \in \{1, 2, ..., J\}.$$

2.3. *Equilibrium*

The stationary competitive equilibrium consists of individual choices $\{c, s, e\}$, individual occupational choices, efficiency units of labour input in each sector $\{L_j\}_{j=1}^J$, intermediate goods $\{Y_j\}_{j=1}^J$, final output Y_f, wages $\{w_j\}_{j=1}^J$ and prices of intermediate goods $\{P_j\}_{j=1}^J$. In the economy, individuals maximise their utility and supply labour to the sector that provides them the highest income according to their abilities. Firms producing intermediate goods and the representative firm of the final good are profit-maximisers. Finally, all markets clear.

2.4. *Carbon taxation*

A carbon tax affects the prices of energy inputs, particularly the more polluting types. Therefore, the burden of the tax on the price of each energy type should depend on the carbon content of that particular energy type. Following Golosov *et al.* (2014) and Hassler *et al.* (2018), we differentiate between the four energy inputs according to their carbon content (intensity of carbon emissions to the atmosphere). Denote this content by g_j, such that $g_j \in [0, 1]$. Green energy types (such as wind and solar) are not associated with any climate externality, so $g_{green} = 0$. The carbon tax rate on each energy type is given by $\tau_j = \tau g_j$, $\forall j$. Note that $\tau_{green} = 0$ since $g_{green} = 0$.

We introduce the carbon tax as a sales tax to each energy type j, such that profits in energy type j, in the presence of such a tax, are given by:

$$\pi_j = (1 - \tau_j) P_j Y_j - w_j L_j - \sum_{k=1}^{J} P_k x_{jk}.$$

In our simulations, we consider different ways to rebate revenues raised with carbon taxes and adjust the equilibrium conditions accordingly. For instance, in one counterfactual experiment, we consider the use of tax revenues in dirty energy sectors to subsidise the green energy sector. In that experiment, the green subsidy is designed such that the carbon tax is revenue neutral (i.e. $\sum_{j=1}^{J} \tau_j P_j Y_j = 0$), which implies that $\tau_{green} < 0$.

The parameterisation of the model is conducted by disciplining the parameters with detailed micro-data for Portugal. Some of the model parameters can be directly observed in the data (e.g. the relative importance of each input in the production of intermediate goods). Others will be estimated to match key moments of the data. For example, the expenditure shares in the final good (σ_j) are estimated to map sectoral value added. Returns of schooling in sector j (φ_j) are calibrated to target average relative wages, whereas the dispersion of productivities (λ) are calibrated to map the coefficient of variation in earnings. A detailed discussion of the data sources used and on how the model parameters are disciplined is provided in the Appendix.

3. The aggregate effects of a carbon tax

We assess how the economy reacts to a climate change mitigation policy by introducing a carbon tax to the dirty energy producers. In the analysis, four different revenue-recycling schemes are considered, where revenues are either:

1) wastefully spent, i.e. not rebated back to the economy ("Wasteful spending");
2) used to subsidise green energy, for example wind energy projects ("Green subsidy");
3) used to subsidise all non-dirty sectors ("Useful spending") or;
4) used to subsidise education expenditures for all non-dirty sectors in the economy ("Education subsidy").[5]

Subsidies in the schemes 2 – 4 are designed such that the government budget balances.

Emissions do not affect production or consumption, so the model does not feature emissions as an externality (as in King *et al.* (2019)). We take a positive approach rather than normative, in the sense that our goal is not to derive the optimal policy but to understand the aggregate and distributional effects of imposing a carbon tax aimed at curbing emissions consistent with the Paris Agreement climate targets.

We consider two experiments in which we increase the tax rate on oil, coal and natural gas energy production sectors from $\tau = 0\%$ to $\tau = 32.9\%$ and from $\tau = 0\%$ to $\tau = 80.4\%$.[6] In its original Paris Agreement pledge, Portugal's intended NDCs entailed an emissions reduction target of 30 to 40% by 2030, below 2005 levels. A tax rate of 32.9% yields the mid-point of the interval (a 35% reduction). NDCs have been revised over time, thus we also consider a 70% emissions reduction, for which a tax rate of 80.4% is needed.

5. The subsidy in the useful spending scenario and in the education subsidy scenario applies to all non-dirty sectors, which include the 14 non-energy intermediate goods and the green energy sector.

6. Adding a 32.9% (80.4%) value added tax translates into a tax $\tau_{oil} = 27.8\%$ (68%) on oil sales, $\tau_{coal} = 23.6\%$ (57.6%) on coal sales, and $\tau_{gas} = 24.1\%$ (59%) on natural gas sales upon adjusting for the carbon content of each energy input. This tax rate is equivalent to 53 (129.5) euros per ton of CO_2 in Portugal.

The main aggregate results for these analyses are displayed in Table 1. Panel A reports the results on emissions (total and fossil), GDP, consumption and welfare of introducing a 32.9% carbon tax.[7] Panel B displays the results for a 80.4% carbon tax. Welfare includes everything that individuals value, that is, consumption and leisure and is measured by a consumption equivalent variation from adding the carbon tax relative to the baseline. We detail the results for the different types of revenue-recycling schemes.

Panel A: 32.9% carbon tax					
Scenario	Total emissions	Fossil emissions	GDP	Consumption	Cons. Equiv.
Wasteful spending	-35.0	-37.7	-1.7	-4.0	-3.3
Green subsidy	-26.2	-28.4	-0.9	-0.9	-1.0
Useful spending	-33.6	-36.3	-1.5	-1.5	-0.7
Education subsidy	-35.0	-37.7	0.4	-2.0	-1.1
Panel B: 80.4% carbon tax					
Scenario	Total emissions	Fossil emissions	GDP	Consumption	Cons. Equiv.
Wasteful spending	-70.0	-75.5	-7.5	-11.6	-10.7
Green subsidy	-61.8	-66.8	-5.8	-5.8	-6.6
Useful spending	-68.8	-74.4	-7.1	-7.1	-6.0
Education subsidy	-70.0	-75.5	-4.1	-8.4	-7.1

TABLE 1. The effects of a carbon tax under all recycling schemes (% change).

By construction, the model yields a 35% reduction in total emissions (Panel A) in the wasteful spending scenario. Since the dirty energy sectors pollute more than the other activities, the drop in fossil emissions is larger (37.7%). A detailed breakdown of emissions by fossil fuel type is presented in Table 2. As energy becomes more expensive, the economy contracts and GDP falls by 1.7%. With the tax, reallocation of resources and fall in output, aggregate welfare decreases.

Panel A: 32.9% carbon tax							
Scenario	%Δ oil emissions	%Δ coal emissions	%Δ natural gas emissions	%Δ green emissions	%Δ non-energy emissions	%Δ total fossil fuel emissions	%Δ total emissions
Wasteful spending	-32.3	-51.0	-43.3	-	-2.0	-37.7	-35.0
Green subsidy	-28.6	-28.4	-27.5	-	-0.4	-28.4	-26.2
Useful spending	-31.0	-49.4	-41.5	-	-0.3	-36.3	-33.6
Education subsidy	-32.3	-51.0	-43.3	-	-2.0	-37.7	-35.0
Panel B: 80.4% carbon tax							
Scenario	%Δ oil emissions	%Δ coal emissions	%Δ natural gas emissions	%Δ green emissions	%Δ non-energy emissions	%Δ total fossil fuel emissions	%Δ total emissions
Wasteful spending	-71.7	-85.9	-78.2	-	-3.8	-75.5	-70.0
Green subsidy	-68.8	-63.6	-63.1	-	-0.8	-66.8	-61.8
Useful spending	-70.7	-84.8	-76.8	-	-0.6	-74.4	-68.8
Education subsidy	-71.7	-85.9	-78.2	-	-3.8	-75.5	-70.0

TABLE 2. Percentage change in CO_2 emissions by source and recycling scheme.

7. Total emissions in the economy include emissions from fossil fuel sectors plus emissions from non-energy sectors. The effects on GDP and consumption are "long-run" effects. There is no dynamics in the model and comparisons are made across two steady states.

If the government uses the carbon tax revenue to subsidise the green sector, the fall in GDP is dampened to only 0.9%. With more economic activity, emissions actually decline by less than with wasteful spending even with subsidies to the clean sector. An alternative is to subsidise all non-dirty sectors ("Useful spending"). Again, the fall in GDP is dampened relative to the wasteful spending scenario, but emissions do not fall by as much.

When tax revenues are used to finance education subsidies, Portugal GDP rises by 0.4%. Individuals invest more in education with this policy, increasing individual productivity and therefore aggregate output.

The estimated effects of a 32.9% carbon tax on aggregate output are not sizeable. This happens because the dirty energy sectors constitute a small fraction of the gross output in the economy (see Table B.1 in the Appendix for details). Panel B of Table 1 also displays the results for a higher tax rate (80.4%). The results are qualitatively similar, but amplified.[8] In order to achieve a 70% emissions reduction, GDP is expected to decline at most 7.5%. In this scenario, welfare losses can be sizeable.

3.1. Cross-country analysis

Given that economies differ in their production structures and labour force characteristics, the impact of carbon taxes is likely to vary across countries. Cavalcanti *et al.* (2021) find that for the United States to achieve its original Paris Agreement pledge of 26% reduction in emissions, it will need a 32.3% carbon tax and it will suffer at most a 0.6% drop in GDP (Table 3). In the case of China, their results indicate that to achieve a similar emission reduction target, it would need a 25.4% carbon tax and it would come with at most a 1.5% reduction in GDP. This is due to the fact that China is more reliant on dirty energy than the United States (see Cavalcanti *et al.* (2021) for details).

Applying the same emission reduction target of 26% for Portugal, we find that Portugal would need a 23.2% carbon tax and it will come with at most a 1% drop in GDP. In Portugal, the non-energy sectors contribute relatively more to national emissions than in the United States and China. Hence, to achieve the same emission reduction target, a lower carbon tax must be implemented in Portugal.

Meanwhile, the GDP losses of the United States, Portugal, and China associated with a 26% drop in emissions are in line with the relative shares of dirty energy sectors in each economy's total sales: 2.4%, 3.3% and 5.1%, respectively.

8. The amplification effect of increasing the tax rate to 80.4% is highly non-linear. This results from the law of diminishing returns, whereby the marginal product increases as the input quantity declines.

Panel A: 23.2% carbon tax					
Portugal	Total emissions	Fossil emissions	GDP	Consumption	Cons. Equiv.
Wasteful spending	-26.0	-28.0	-1.0	-2.8	-2.2
Green subsidy	-18.6	-20.2	-0.4	-0.4	-0.5
Useful spending	-24.7	-26.8	-0.9	-0.9	-0.3
Education subsidy	-26.0	-28.0	0.6	-1.2	-0.5
Panel B: 32.3% carbon tax					
United States	Total emissions	Fossil emissions	GDP	Consumption	Cons. Equiv.
Wasteful spending	-26.0	-26.8	-0.6	-1.7	-1.1
Green subsidy	-24.3	-25.0	-0.3	-0.3	-0.3
Useful spending	-25.3	-26.1	-0.5	-0.5	0.1
Education subsidy	-26.0	-26.8	0.4	-0.7	0.1
Panel C: 25.4% carbon tax					
China	Total emissions	Fossil emissions	GDP	Consumption	Cons. Equiv.
Wasteful spending	-26.0	-27.5	-1.5	-4.7	-3.6
Green subsidy	-20.6	-21.8	-0.7	-0.7	-1.2
Useful spending	-23.4	-24.8	-1.3	-1.3	-0.1
Education subsidy	-26.0	-27.5	1.0	-2.2	-1.0

TABLE 3. Effects of a carbon tax targeting a 26% reduction in emissions by country (% change).

4. The distributional effects of a carbon tax

Carbon taxes have non-trivial distributional effects at the sectoral and individual levels. These are now documented.[9]

4.1. *Sectoral-level analysis*

Introducing a carbon tax on oil, coal and natural gas energy sectors makes them more expensive relative to other sectors. As a result, these sectors shrink and labour demand and wages fall. Workers reoptimise their occupational decisions and some switch sectors. Figure 1 shows the changes in equilibrium labour by sectors. Employment in the oil, coal and natural gas sectors drops, with losses ranging from 20 to 40%, depending on the revenue-recycling scheme. With the subsidy to clean energy, inputs are reallocated from the dirty energy sectors to the green sector to equalise marginal returns. This yields an increase in employment in this sector of more than 30%. With an education subsidy, human capital rises because education becomes relatively cheaper, reinforcing the increase in effective labour to the sectors not directly affected by the carbon tax.

The occupational decision of workers is driven by their innate abilities and the wage in each occupation. Marginal workers with relatively low productivity in the dirty energy sectors reallocate to other sectors of the economy. Workers with a high

9. The results of this section are based on a comparison across two different steady states. We use terms like "switchers" and "stayers" when discussing the results for the sake of readability. But we emphasise that the comparisons are made across the steady states.

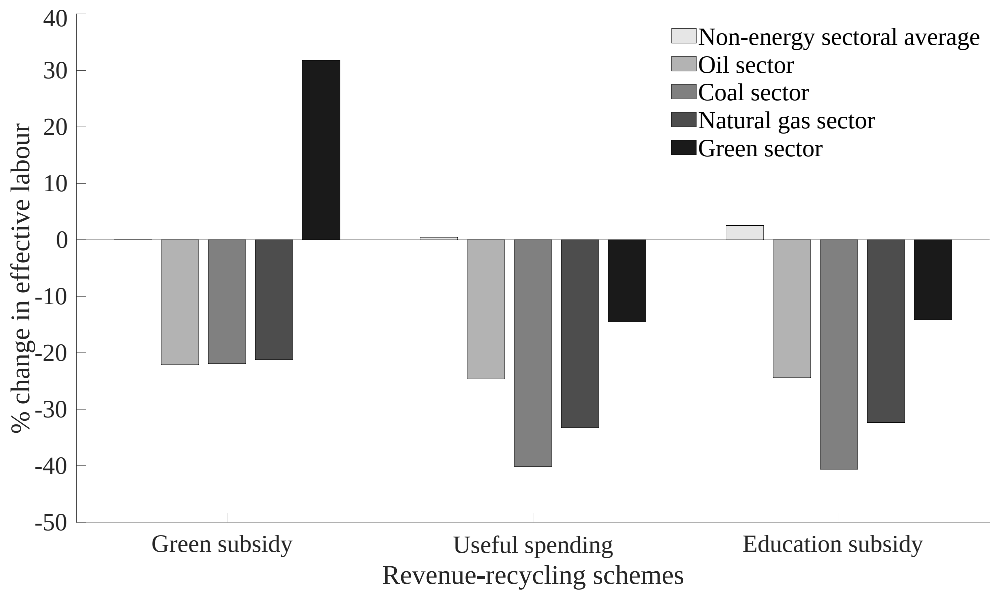

FIGURE 1: Percentage change in effective labour upon increasing the carbon tax from 0% (benchmark) to 32.9%.

comparative advantage in the dirty energy sectors remain in these sectors after the policy change. Therefore, due to a selection effect, the average productivity of workers in the taxed sectors rises (see Figure 2). In the green subsidy scenario, average productivity drops by 10% in the green sector due to the larger prevalence of workers in this sector, as depicted in Figure 1.[10]

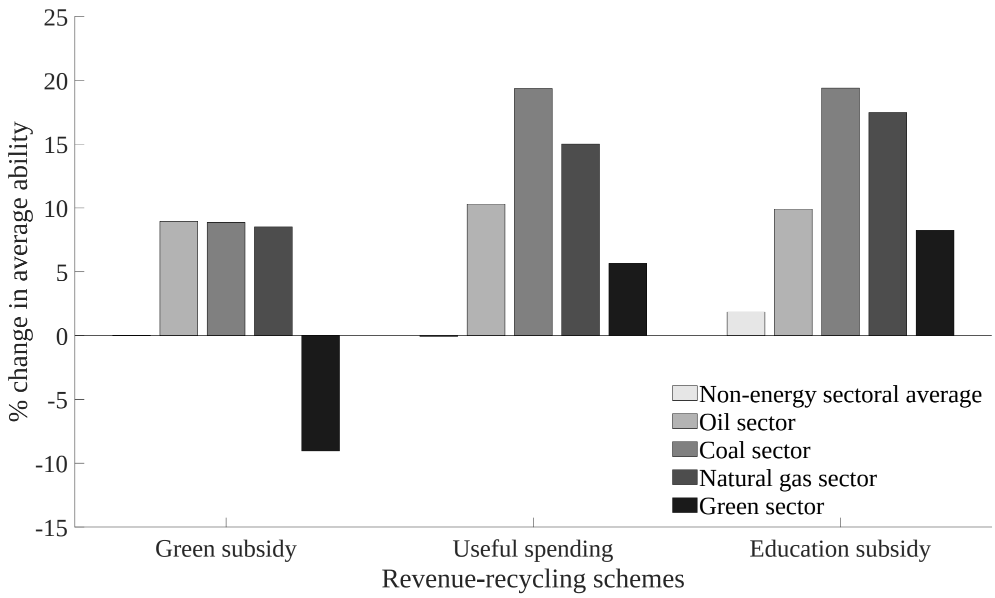

FIGURE 2: Percentage change in average productivity upon increasing the carbon tax from 0% (benchmark) to 32.9%.

10. For the sake of space, the figures for $\tau = 80.4\%$ are not reported but are available from the authors upon request. The effects across sectors and tax rebate schemes are qualitatively similar, but amplified.

4.2. *Individual-level analysis*

We now assess the distributional effects at the individual-level that arise after the introduction of a carbon tax. Workers are split into four categories: (i) those who remain in the non-dirty energy sectors; (ii) those who reallocate from non-dirty energy sectors; (iii) those who remain in dirty energy sectors; and (iv) those who reallocate from dirty energy sectors. We then track how their welfare changes after the implementation of the policy. As stated earlier, welfare is measured by the consumption equivalent variation from adding the carbon tax relative to the baseline.

Panel A: 32.9% carbon tax								
	Wasteful spending		Green subsidy		Useful spending		Education subsidy	
	CE (%)	LFP (%)	CE (%)	LFP (%)	CE (%)	LFP (%)	CE (%)	LFP (%)
Non-dirty sectors, stayers	-3.5	98.7	-0.3	98.8	-1.0	98.9	-1.3	98.7
Non-dirty sectors, switchers	-3.3	0.4	3.2	0.3	-0.7	0.3	-1.1	0.4
Dirty sectors, stayers	-16.8	0.5	-9.7	0.6	-14.5	0.5	-14.9	0.5
Dirty sectors, switchers	-9.7	0.3	-5.2	0.2	-7.3	0.3	-7.6	0.3
Aggregate	-3.3	100.0	-1.0	100.0	-0.7	100.0	-1.1	100.0
Panel B: 80.4% carbon tax								
	Wasteful spending		Green subsidy		Useful spending		Education subsidy	
	CE (%)	LFP (%)	CE (%)	LFP (%)	CE (%)	LFP (%)	CE (%)	LFP (%)
Non-dirty sectors, stayers	-11.1	98.4	-5.2	98.4	-6.5	98.7	-7.6	98.4
Non-dirty sectors, switchers	-10.7	0.8	1.2	0.8	-6.0	0.5	-7.1	0.8
Dirty sectors, stayers	-41.8	0.2	-30.3	0.3	-38.6	0.2	-39.4	0.2
Dirty sectors, switchers	-23.4	0.6	-17.0	0.6	-19.3	0.6	-20.3	0.6
Aggregate	-10.7	100.0	-6.6	100.0	-6.0	100.0	-7.1	100.0

TABLE 4. Welfare analysis. | CE denotes consumption equivalent variation; LFP stands for labour force participation.

Table 4 shows that workers who remain in the dirty sectors (oil, coal and natural gas) experience the largest decline in welfare. Take Panel A as an example. In the wasteful spending scenario, the welfare of stayers in the dirty sectors declines by 16.8%. This loss is almost twice as much as the one experienced by those who managed to switch from the dirty sectors (9.7%) and almost five times the loss witnessed by non-dirty workers (stayers and switchers). However, these workers who are most affected account for less than 0.5% of the Portuguese labour force. This decline in welfare is due to the reduction in labour demand and wages in the taxed sectors. Due to general equilibrium effects, labour reallocation also takes place in the non-dirty sectors.

In the face of a higher carbon tax (Panel B), workers who stay in the dirty sectors are hit harder and experience welfare losses ranging from 30 to 42%, compared to 17 to 23% welfare loss by workers who managed to reallocate out of the dirty sectors and -11 to 1.2% by workers not in the dirty energy sectors. As such, workers with a comparative advantage in dirty energy production are still the hardest hit, but now constitute only 0.2% of the Portuguese labour force.

5. Concluding remarks

As the economic effects of climate change unfold, there is a growing pressure for governments to adopt more aggressive environmental policies. In fact, the costs of delayed action can be substantial. In this paper, we unveil the aggregate and distributional effects of the carbon tax Portugal needs to meet its Paris Agreement pledges.

We estimate that a carbon tax of 32.9% is needed for Portugal to achieve its original Paris Agreement pledge of 35% emissions reduction. This carbon tax costs the Portuguese economy at most a 1.7% drop in GDP, which is the worst-case scenario when the government does not rebate tax revenues back to the economy. Despite the small impact on GDP and welfare, carbon taxes have non-trivial distributional effects at the sectoral and individual levels. Workers with a comparative advantage in dirty energy sectors who do not reallocate suffer a welfare loss five times higher than workers in non-dirty sectors, but constitute less than 0.5% of the labour force.

As NDCs have been adjusted over time, we also target the carbon tax needed for Portugal to achieve a 70% decline in emissions. The results point to a 80.4% carbon tax, with the effects being qualitatively similar to those leading to a 35% emissions reduction, but amplified. Under this policy experiment, workers with a comparative advantage in dirty energy production experience the largest welfare loss, but now constitute only 0.2% of the Portuguese labour force.

While the experiments in this study have focused on Portugal, the framework outlined here can be easily replicated to other countries to inform policy responses. This is of particular interest as climate change mitigation policies have heterogeneous responses across individuals, sectors, as well as geographies.

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Appendix A: Data and calibration

This section outlines the data sources used in the model calibration to assess the aggregate and distributional effects of a carbon tax policy. Table A.1 lists the two main data sources used: the World Input-Output Database (WIOD) and the Labour Force Survey (LFS). We also resort to the World Development Indicators (WDI).

Data	Year	Source
Input-Output table	2014	WIOD
Environmental Accounts	2009	WIOD
CO_2 emissions	2009	WIOD
Sectoral labour force participation	2014	WIOD
Sectoral labour compensation	2014	WIOD
Income earnings	2019	LFS
Education attainment by sector	2019	LFS
Public expenditure on education (% GDP)	2018	WDI
Total labour force participation rate (%)	2018	LFS

TABLE A.1. Data sources.

Although we have prior information about some of the model parameters (e.g. importance of each input in the production of intermediate goods), others will be estimated internally to match key moments of the data. Table A.2 lists all model parameters.

Parameter	Externally calibrated parameters	Data source
J	Number of sectors	WIOD
ν_{jk}	Input-output shares	WIOD
β_j^L	Labour shares	WIOD
$g_{\text{oil}} = 84.6\%$	Carbon intensity of oil	Golosov *et al.* (2014)
$g_{\text{coal}} = 71.6\%$	Carbon intensity of coal	Golosov *et al.* (2014)
$g_{\text{natural gas}} = 73.4\%$	Carbon intensity of natural gas	Garg *et al.* (2006)
$g_{\text{green}} = 0\%$	Carbon intensity of green	Golosov *et al.* (2014)
γ	Consumption weight in the utility function	Mincerian estimate using LFS data
η	Expenditure on education (% GDP)	WDI
	Internally calibrated parameters	**Moment(s) targeted**
σ_j	Expenditure shares in final good	Sectoral value added from WIOD data
φ_j	Returns of schooling in sector j	Average relative wages using WIOD data
λ	Fréchet dispersion parameter	Coefficient of variation in earnings from LFS data

TABLE A.2. List of parameters.

External Calibration. To set values for J, β_j, and ν_{jk}, we use data from the WIOD. This is a comprehensive database containing national input-output tables, data on sectoral labour force participation rates, labour compensation and environmental accounts. We use data on inter-sectoral sales to compute ν_{jk} and set $\beta_j = 1 - \sum_{k=1}^{J} \nu_{jk}$. First, we collapse the 35 sectors in the WIOD tables to the top-level International Standard Industrial Classification (ISIC) Rev. 4 classification as outlined in the first column of Table A.3. Second, we aggregate these 21 sectors into the 15 sectors presented in the LFS database. Since the focus is on taxing dirty energy producing sectors in the economy, we create an aggregate energy sector by merging "Mining and quarrying" and "Electricity" sectors (second column of Table A.3). Third, we split the aggregate energy sector (Total energy: B, D) into oil, coal, natural gas and green energy production based on the energy input mix of each of the intermediate sectors, according to the WIOD environmental accounts on energy use by sector and energy type. This yields 18 intermediate goods sectors overall. To save on space, the 18 sectors are not included in Table A.3.

	Sectors ($J = 21$) **ISIC Rev. 4: Top-level aggregation**		**Sectors ($J = 15$)** **LFS aggregation**
A	Agriculture, hunting, forestry and fishing	A	Agriculture, hunting, forestry and fishing
B	Mining and quarrying	C	Manufacturing
C	Manufacturing	E	Water supply
D	Electricity, gas, steam and air conditioning supply	F	Construction
E	Water supply; sewerage, waste management and remediation activities	G	Wholesale and retail trade
F	Construction	H, J	Transport, storage and communications
G	Wholesale and retail trade; repair of motor vehicles and motorcycles	I	Accommodation and food service activities
H	Transportation and storage	K	Financial and insurance activities
I	Accommodation and food services activities	L, M, N	Real estate, renting and business activities
J	Information and communication	O	Public administration and defence
K	Financial and insurance activities	P	Education
L	Real estate activities	Q	Health and social work
M	Professional, scientific and technical activities	R, S, U	Arts and other service activities
N	Administrative and support service activities	T	Private household services
O	Public administration and defence; compulsory social security	B, D	Total energy
P	Education		
Q	Human health and social work activities		
R	Arts, entertainment and recreation		
S	Other service activities		
T	Activities of households as employers; undifferentiated goods - and services-producing activities of households for own use		
U	Activities of extraterritorial organisations and bodies		

TABLE A.3. Intermediate goods sectors.

We then calculate the input-output matrix ν which represents intersectoral elasticities, such that each entry ν_{jk}:

$$\nu_{jk} = \frac{\text{Input of sector } k \text{ into sector } j}{\text{Sales of sector } j}$$

β_j^L is calculated by adhering to the constant returns to scale characteristic of the production function, such that $\beta_j^L + \sum_{k=1}^{J} \nu_{jk} = 1$.

With the environmental accounts data on CO_2 emissions by sector and energy type we calculate the effect of taxes on emissions. Note that the model abstracts from the feedback effects of emissions on the economy. In order to discipline the magnitude of the carbon tax we compute the change in CO_2 emissions.

The sectoral carbon content, g_j, is based on Golosov *et al.* (2014): $g_{oil} = 0.846$ and $g_{coal} = 0.716$. We replicate their methodology and calculate $g_{gas} = 0.734$ using estimates from Garg *et al.* (2006).

We follow Hsieh *et al.* (2019) to calibrate η and γ. From the WDI, we compute η, which is the public expenditure on education (as a percentage of GDP) normalised by labour force participation. To calibrate γ, we take average earnings in sector j, $\bar{w}_j = w_j \mathbb{E}[h_j z_j] = (1-s)^{\frac{-1}{\gamma}} \eta^{\frac{\eta}{1-\eta}} \Gamma(1 - \frac{1}{\lambda}\frac{1}{1-\eta})$. Drawing on the micro-data from the LFS for Portugal, we calculate the average years of schooling divided by a pre-work time endowment of 25 years, $\bar{s}$, and estimate the Mincerian return to schooling across sectors, ξ, from a regression of log average wages on average schooling across sectors. With $\bar{s}$ and ξ, we calculate $\gamma = \frac{1}{\xi(1-\bar{s})}$. The values for η and γ are 0.080 and 0.645, respectively.

Internal Calibration. The remaining parameters σ_j, φ_j and λ are disciplined by solving the model and targeting certain data moments. In particular, we calibrate the expenditure shares σ_j such that the sectoral value added shares in the model match those in the data (Table A.4).

Sector	VA$_j$ (%)	σ_j
1. Agriculture, hunting, forestry and fishing	2.3	0.020
2. Manufacturing	13.2	0.231
3. Water supply	1.2	0.007
4. Construction	4.5	0.066
5. Wholesale and retail trade	14.7	0.097
6. Transport, storage and communications	8.2	0.056
7. Accommodation and food service activities	5.1	0.070
8. Financial and insurance activities	5.2	0.036
9. Real estate, renting and business activities	19.6	0.119
10. Public administration and defence	7.9	0.091
11. Education	6.2	0.063
12. Health and social work	6.0	0.087
13. Arts and other service activities	2.1	0.029
14. Private household services	0.8	0.007
15. Oil energy production	1.4	0.010
16. Coal energy production	0.1	0.000
17. Natural gas energy production	0.2	0.001
18. Green energy production	1.2	0.008

TABLE A.4. Intermediate goods sectors: Value-added and final expenditure shares.

We follow the methodology in Hsieh *et al.* (2019) to estimate φ_j and λ. To estimate φ_j, we use data from WIOD on the number of persons engaged and labour compensation to calculate the average wage in each sector. This yields the relative sectoral wages, which determine the relative values for φ_j. To find the absolute values of φ_j, we take the ratio of the average wages relative to Agriculture. We calculate average schooling in Agriculture, s_{Agri}, and then use equation (2) to solve for φ_{Agri}. With this, we pin down the remaining φ_j by targeting the ratio of each sectoral wage relative to Agriculture.[11] Data on the relative ratios of sectoral wages and the values for φ are presented in Table A.5.

11. Given the lack of information on the individual energy sectors, we target the ratio of average wage in the aggregate energy sector relative to Agriculture.

Sector	$\frac{w_j}{w_{Agri}}$	φ_j
1. Agriculture, hunting, forestry and fishing	1.0	0.580
2. Manufacturing	1.8	0.740
3. Water supply	2.0	1.968
4. Construction	1.8	1.073
5. Wholesale and retail trade	1.8	0.694
6. Transport, storage and communications	3.1	1.770
7. Accommodation and food service activities	1.7	0.934
8. Financial and insurance activities	5.1	3.583
9. Real estate, renting and business activities	2.0	0.727
10. Public administration and defence	3.4	2.044
11. Education	2.9	1.815
12. Health and social work	2.4	1.400
13. Arts and other service activities	2.0	1.599
14. Private household services	1.0	0.852
15. Energy average (weighted by LFP)	3.7	3.698

TABLE A.5. Relative sectoral wages and sector-specific elasticity of human capital accumulation to schooling years.

Finally, to estimate λ, we use micro-data on individual wages to fit the distribution of residuals from a cross-sectional regression of log income earned on age-industry dummies. We then match the coefficient of variation of sectoral residual wages. The values of the estimated Fréchet parameter and model's estimate of the coefficient of variation of wages are 3.915 and 0.247, respectively.

Appendix B: Additional statistics

Sector	**Sales (%)**	**VA$_j$ (%)**	**Int. Cons. (%)**	**LFP (%)**
1. Agriculture, hunting, forestry and fishing	2.6	2.3	2.7	11.3
2. Manufacturing	26.1	13.2	38.2	15.3
3. Water supply	1.3	1.2	1.4	0.9
4. Construction	5.9	4.5	7.3	6.3
5. Wholesale and retail trade	11.5	14.7	8.5	14.7
6. Transport, storage and communications	9.5	8.2	10.4	5.2
7. Accommodation and food service activities	4.4	5.1	3.5	6.0
8. Financial and insurance activities	4.7	5.2	4.3	1.9
9. Real estate, renting and business activities	12.9	19.6	6.5	10.8
10. Public administration and defence	5.4	7.9	3.0	6.4
11. Education	3.5	6.2	1.0	6.8
12. Health and social work	5.0	6.0	4.0	7.7
13. Arts and other service activities	1.9	2.1	1.7	3.3
14. Private household services	0.4	0.8	0.0	2.9
15. Oil energy production	2.1	1.4	2.8	0.2
16. Coal energy production	0.5	0.1	0.9	0.0
17. Natural gas energy production	0.7	0.2	1.2	0.1
18. Green energy production	1.7	1.2	2.3	0.2

TABLE B.1. Sectoral breakdown of output, value-added (VA), intermediate consumption and labour force participation (LFP) in the zero-tax benchmark.