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The undersigned Elisa Lanzi, in her quality of doctoral candidate for a Ph.D. degree in Economics and Organization granted by the University of Venice, attests that the research exposed in this dissertation is original and that it has not been and it will not be used to pursue or attain any other academic degree of any level at any other academic institution, be it foreign or Italian.

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Contents

Introduction

Increasing focus on climate change in the political arena raises the need to better analyze the mechanisms thanks to which it is possible to reduce greenhouse gases (GHGs) emissions in the most efficient way. In the past decades, we have seen a quick acceleration of international negotiations and efforts to address the problems of climate change mitigation. Starting with the establishment of the United Nations Framework on Climate Change Convention (UNFCCC) in 1992, to the adoption of the Kyoto Protocol in 1997, and more recently to the negotiations of the 15th Conference of the Parties (COP-15) that was aimed at achieving an international agreement on climate change. While there has been scarce success in the political arena and international negotiations have been hard to achieve, there is a wide agreement on the need to move towards a "greener" economy. This need calls for further investigation on the possibilities to achieve a more efficient economy in two main ways. Firstly, by reallocating capital from "dirty" to "clean" sectors, so as to produce output in a cleaner way. Secondly, by inventing new technologies that can lead to higher efficiency in production. Technical change has been given increasing importance as the main mitigation option, as the rigidities in the markets and production limit the possibilities to reduce GHG emissions.

The economic literature has addressed this problem by setting up clean-dirty industry models, in which there are two sectors one of which is polluting. This simple basic framework has been used in several contexts with the purpose to study the effects of a tax imposed on the polluting good on the economy, on welfare, and on the two sectors. This framework was used in models aimed at studying tax incidence, such as in Fullerton and Metcalf [37], in which a two-sector static general-equilibrium model based on the work by Harberger [44] is used to examine the incidence of carbon taxes. More complex dynamic models have also added a focus on R&D and technical change. There is wide agreement that a carbon tax will reduce output in the dirty sector and increase it in the clean sector, but results not so straightforward for R&D investments and innovation. This framework was used in models such as Smulders and de Nooij [84], van Zon and Yetkiner [95], who use an endogenous technological change model with energy to demonstrate there can be a change in the direction of technological change toward energy-saving due to increasing energy prices or constrained energy quantities. Sue Wing [88] uses the clean-dirty intermediate inputs framework to set up a model of R&D investment and directed technical change. He shows that an environmental tax always biases production away from the dirty good towards the clean good, but that it biases R&D only for certain levels of substitutability of the two intermediate goods.

A large literature on applied climate economy models also shares the structure of a clean-dirty input model. Energy is usually the dirty intermediate good. Examples are the works by Popp [78] on the ENTICE model, and Bosetti et al. [14] on the WITCH model. Despite the importance for the calibration of these models, there are only a few examples of empirical works that study the interactions between clean and dirty industries. Van der Werf [93], and De Cian [25] test the presence of input-specific technical change versus the hypothesis of homogenous technical change using capital, labor, and energy as inputs.

This literature still leaves space for further investigations and clarifications on the role of capital malleability, and possibilities to reallocate capital across sectors, and on the role of technical change and innovation. Furthermore, empirical analysis is needed to better explore these issues.

The dissertation is composed of four chapters in the form of self–contained papers that address the issues of climate change and technical change in different settings, and focusing on different aspects. They also combine theoretical, empirical, and modeling techniques. In the first part of the thesis theoretical models are used in combination with CGE models with the main purpose to address climate policy costs in function of characteristics of the economy such as the malleability of capital, the contribution of the polluting sector, the efficiency of the polluting sector, and the definition of the polluting good in terms of what sectors are considered to compose it. In the second part of the thesis instead, the feedbacks of climate policies to innovation are considered using theoretical and empirical models. The empirical analysis is based on the use of patent data as an indicator of innovation. Given the importance of the efficiency of the polluting sector in reducing the costs of mitigation of climate change, the focus is on the energy sector, whose carbon emissions account for a quarter of overall anthropogenic emissions.

The first chapter "Capital Malleability and the Macroeconomic Costs of Climate Policy", a joint work with Ian Sue Wing, addresses the issue of the role of capital malleability as a determinant of climate policy costs. While this issue has been previously addressed by Jacoby and Sue Wing [54], a thorough analysis is still missing in the literature. This chapter combines a theoretical analysis an application to an EU-wide CGE model, in which this issue is explored in the context of the European Union Emissions Trading Scheme (ETS). It is found that when capital is imperfectly malleable a climate policy is less effective. The relative size of the dirty sector, and its efficiency in terms of reliance on the polluting input influence its effect and the costs of climate policy.

In "Sectoral Extension of the EU ETS: a CGE Study" we illustrate that the definition of the polluting sector in terms of sectoral policy coverage influences the costs of climate policy. In particular, whilst the EU ETS has so far covered only energy and energy-intensive sectors, this chapter illustrates what factors may influence the choice of extending the ETS to other sector. This issue is addressed combining a theoretical analysis based on Marginal Abatement Cost Curves (MACCs) with an application to an EU-wise CGE model in which we consider the extension of the EU ETS to the air transport sector.

"Innovation in Electricity Generation Technologies: a Patent Data Analysis" is an empirical study of innovation in the energy sector. It illustrates that increasing fossil fuel prices lead to higher innovation in this sector, but that this effect does not apply to all types of electricity-generation technologies. Whereas we find that an increase in carbon-free technologies when considered in aggregate, there is a decrease in fossil-fuel technologies. This is an interesting result as it illustrates that the substitution effect is stronger than the efficiency effect. As prices increase there is more innovation in substitute intermediates as an effect of the substitutability. In absence of any substitution effect, the efficiency effect would lead to an increase in all types of technologies.

The last chapter, "Directed Technical Change in the Energy Sector: an Empirical Analysis of Induced Directed Innovation" applies a model of directed technical change to the energy sector. The aim is to study whether there is a change in the direction of innovation within the energy sector. A theoretical model of directed innovation is used to establish a long run relationship between relative innovation and relative input prices between fossil-fuel and renewable energy. This relationship is then estimated using a panel of OECD countries with data relative to R&D, energy prices, and patents. This paper contributes to clarify the role of induced innovation, and to show that within-sector dynamics can lead to higher efficiency in the production of the polluting energy sector.

This thesis contributes to the existing literature by further exploring the linkages between physical capital and climate policies, both in terms of the possibilities to reallocate capital, and the improvement of the existing capital (innovation). This is done both by considering the influence that capital malleability has on the costs of climate policies, and the feedback effect that climate policy has on the creation of new capital through innovation. This is crucial, as the generation of new technologies may lower mitigation costs. Secondly, it illustrates that the composition of the economy in the relative contribution of pollution-intensive sectors, and the efficiency of these sectors has a key role in the assessment of mitigation costs. Finally, it contributes to the literature on climate-economy models in generating results that are applicable to this literature. This work clarifies the role of capital malleability, and of induced innovation within the energy sector. These are both key factors in the assessment of climate costs, whose main tool for analysis are computable general equilibrium (CGE) and Integrated Assessment (IAM) models.

Chapter 1

Capital Malleability and the Macroeconomic Costs of Climate Policy

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The present chapter illustrates the results achieved and the discussions jointly had by my coauthor and me, but the final form as a chapter is due to me alone for the purpose of this thesis. This means that I am the only responsible for every linguistic or mathematical error and imprecision.

Abstract

This paper argues for introducing the role of capital malleability into the analysis of environmental policies. The issue is explored by means of a theoretical model, a numerical analysis and a computable general equilibrium (CGE) model. Considering the three approaches together is fundamental in obtaining theory-compatible policy-relevant results. The model outcomes reveal differences between results under separate assumptions regarding the malleability of capital. When capital is

imperfectly malleable a carbon policy is less effective than under the assumption of perfect malleability of capital. Therefore, it is important that, especially for the analysis of short-term environmental regulations, the issue of capital malleability is taken into consideration.

1.1 Introduction

Policies to limit emissions of greenhouse gases (GHG) have been the subject of extensive numerical analysis. The workhorse of such investigations has been computable general equilibrium (CGE) models, whose usefulness lies in their ability to combine economic accounts for a range of industries across different geographic regions within the Arrow-Debreu equilibrium framework of interacting markets. The result is a complete and theoretically consistent simulation which captures the full spectrum of economic feedback effects in response to an emission limit.

These advantageous characteristics have been particularly important for the study of the international policies such as the Kyoto Protocol. However, the majority of well-known CGE simulations (e.g., DART (Klepper, Peterson and Springer [59]), GEM-E3 (Capros et al. [21]), and the widely used GTAP-E (Burniaux and Truong [18])) have been constructed to examine long-run GHG emission-reduction scenarios, and a key assumption of their design is that physical capital is able to move among the economic sectors being modeled as its relative marginal productivities change. A decade ago Jacoby and Sue Wing [54] highlighted the adverse impact that imperfect "malleability" of capital can have on the short-run macroeconomic costs of U.S. compliance with its erstwhile Kyoto emission target. A more recent investigation by Sue Wing [89] in the context of the "technology substitution" commonly seen in bottom-up engineering simulations confirmed the crucial role played by imperfect malleability of capital among sectors and activities in determining the costs of carbon taxes. These studies raise two key questions:

- How malleable is capital likely to be over the time-frame that emission limits such as Kyoto are anticipated to bind? And,
- To what extent do various characteristics of abating economies influence the

magnitude of the short-run cost premium to which capital rigidities gives rise?

This paper is a preliminary attempt to answer the second question, and to assess the implications of our findings for the distribution of the costs of compliance with the European Union Emission Trading Scheme (EU-ETS).

Our approach draws on the theoretical literature arguing that capital, once invested in a sector, cannot be redeployed in other sectors of the economy and easily adjust to changes in relative prices. This view is supported by the works of Johansen [56], Bliss [11] and Gapinksi [38] who point out the difference between putty-putty capital, that is capital that can readjust between sectors, and putty-clay capital, that cannot readjust. The former is perfectly malleable capital, whereas the latter is imperfectly malleable.

We construct an analytical general equilibrium model of a simple two-sector economy following Harberger [44]. In the model, one sector only uses capital input (the "clean" sector), whereas the other sector uses capital as well as a polluting input (the "dirty" sector). We then adapt this simple "clean-dirty" sector model to the case of imperfect malleability of capital, which we use to compare the effects of a tax levied on the polluting input in the dirty industry. To gain insight into the likely magnitudes of these effects, we then use economic data from the EU member states to numerically parameterize the model, treating fossil fuels as the dirty input. Finally, we compare these results to the output of a CGE simulation of the EU-ETS.

Our results indicate that environmental taxation is more effective at reducing pollution when capital is perfectly malleable and can costlessly switch from the dirty to the clean sector. While the analytical model presents a general solution to this problem, which is based on parameter values, a numerical analysis using EU data yields determinate conclusions regarding the effects of a carbon tax on the main economic variables. We find that the imposition of a carbon tax is more effective in the reduction of pollution under conditions of perfect malleability of capital. Finally, the CGE model is used to perform a policy-relevant study and to identify secondary effects that cannot be seen in any of the previous analyses. Although the ETS target is met in both simulations related with the two scenarios of capital malleability, it is found that there is a much stronger carbon leakage effect under imperfect malleability of capital. This paper illustrates how the three levels of analysis can contribute to understand the influence of capital malleability on the effectiveness of carbon regulations. Thus, in evaluating short-run climate policies it is crucial to take into consideration the degree of malleability of capital.

The paper is organized as follows. Section 1.2 presents the theoretical models and their predictions. Section 1.3 shows the numerical application of the theoretical models. Section 1.4 illustrates the applied CGE model and its application to the EU-ETS. Section 1.5 concludes.

1.2 A Simple Theoretical Model

Our investigation of capital malleability begins with a simple two-sector tax incidence model in which capital is the only factor of production. In our test-bed economy, household are modeled as representative agent who derives utility (U) from consumption of a clean good (X_C) and a dirty good (X_D), which is offset by the disutility of exposure to pollution (Z). The sector which produces the clean good uses capital (K_C) exclusively, while the output of the dirty sector is produced using inputs of capital (K_D) and pollution (Z). The prices of the clean and dirty goods are given by P_C and P_D. The agent is endowed with a fixed stock of capital (K), which she rents out to the sectors in exchange for factor income. We examine the effects of a shock in the form of an exogenous pollution tax (τ_Z), and compare the economy's response when capital is intersectorally mobile and when it is fixed.[1]

1.2.1 Households

The representative agent's utility is increasing in consumption and decreasing in pollution, and can be written $U = U(X_C, X_D, Z)$, with $U_{X_C}, U_{X_D} > 0$ and $U_Z < 0$. The impact of the tax on households' welfare operates through two channels: the market effects of changes in goods consumption and the non-market effect of mitigating the disutility of pollution. To simplify the analysis we adopt Bovenberg and de Mooij's [15] assumption that consumption and pollution are separable. We

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[1] A more sophisticated model with two factors of production is developed in Appendix A. Its conclusions are similar to the ones we derive below.

assume that pollution negatively affects utility through an environmental damage function $\mathcal{E}(Z)$, where $\mathcal{E}_Z < 0$. This allows us to totally differentiate U to get

$$dU = [U_{X_C} dX_C + U_{X_D} dX_D] + U_Z \mathcal{E}_Z dZ.$$

The term in square braces as the market-mediated change in welfare due to the pollution tax, while the last term is the non-market impact.

The components of welfare change may be elaborated by examining the agent's optimal consumption decision. Letting M denote aggregate income, the agent's utility maximization problem is

$$\max_{X_C, X_D} \left\{ U(X_C, X_D, Z) \,|P_C X_C + P_D X_D \leq M \right\}.$$

The first order conditions equate the marginal utility of consumption of the two goods to the Lagrange multiplier (μ), whose natural interpretation is the marginal utility of income:

$$U_{X_C}/P_C = U_{X_D}/P_D = \mu.$$

Using this relation to substitute for the marginal utilities on the right-hand side of dU yields

$$dU = [\mu P_C dX_C + \mu P_D dX_D] + U_Z \mathcal{E}_Z dZ.$$

We simplify this by letting $U_Z \mathcal{E}_Z / \mu = -\delta$ denote the marginal disutility of environmental damage, dividing both sides by the level of income, and multiplying and dividing each differential on the right-hand side by its corresponding quantity level:

$$\frac{dU}{\mu M} = \left[\frac{P_C X_C}{M} \frac{dX_C}{X_C} + \frac{P_D X_D}{M} \frac{dX_D}{X_D} \right] - \delta \frac{Z}{M} \frac{dZ}{Z} = [(1-\phi)\hat{X}_C + \phi \hat{X}_D] - \delta \zeta \hat{Z}. \quad (1.1)$$

The left-hand side of this expression is the dollar value of the change in utility divided by initial income. This is a dimensionless index of the total welfare effect of the tax, which we denote $\hat{W}$. On the right-hand side, ϕ is the initial budget share of the dirty good, $\zeta = Z/M$ is the initial pollution intensity of GDP, and we follow Fullerton and Metcalf [37] in using a "hat" ($\wedge$) over a variable to indicate its logarithmic differential.[2]

Equation (1.1) provides insights into the welfare but has no bearing on the solution to the model. The latter requires us to make assumptions about households' preferences. We model the representative agent as having constant elasticity of substitution (CES) utility function in which the two goods substitute for one another with an elasticity of substitution, σ_U. Then, the definition of the elasticity implies the following relationship between the prices and quantities of commodities in log-differential form:

$$\hat{X}_C - \hat{X}_D = \sigma_U(\hat{P}_D - \hat{P}_C). \tag{1.2}$$

1.2.2 Producers

Turning to the supply side of the economy, we assume that each good is produced according to a homogeneous-of-degree-one technology, which we express using the production functions $X_C = f_C(K_C)$ and $X_D = f_D(K_D, Z)$. The assumptions of free entry and competitive markets for inputs and output then imply that each sector's revenue just equals its expenditures on inputs. We express this using the zero-profit conditions $P_C X_C = r_C K_C$ and $P_D X_D = r_D K_D + \tau_Z Z$, in which r_C and r_D are the rental rates of capital in each sector. Log-differentiation of the production functions and zero-profit conditions yields:

$$\hat{X}_C = \hat{K}_C \tag{1.3}$$

$$\hat{X}_D = \theta\hat{Z} + (1-\theta)\hat{K}_D, \tag{1.4}$$

$$\hat{P}_C + \hat{X}_C = \hat{r}_C + \hat{K}_C \tag{1.5}$$

$$\hat{P}_D + \hat{X}_D = \theta(\hat{\tau}_Z + \hat{Z}) + (1-\theta)(\hat{r}_D + \hat{K}_D) \tag{1.6}$$

where $\theta = \tau_Z Z/(P_D X_D) \in (0,1)$ is the share of pollution in the cost of dirty production. As well, we assume that the dirty sector employs CES production technology, treating capital and pollution as substitutes with an elasticity of substitution σ_D.

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[2] e.g., $\hat{z} = d\log z = dz/z$.

The definition of the elasticity yields the log-differential relationship:

$$\hat{K}_D - \hat{Z} = \sigma_D(\hat{\tau}_Z - \hat{r}). \tag{1.7}$$

Our model is closed through the specification of the factor market, which differs according to whether or not capital is malleable, in the sense of being intersectorally mobile, or sector-specific. In the malleable case the factor market clears ($K = K_C + K_D$) and the law of one price holds ($r_C = r_D = r$), while in the non-malleable case, sectors' endowments of capital are fixed. Letting $\lambda = K_D/K \in (0, 1)$ denote the share of malleable capital in the dirty sector, we may take the log-differential of the market clearance condition in each case to obtain

$$0 = \lambda\hat{K}_D + (1 - \lambda)\hat{K}_C, \tag{1.8a}$$

$$\hat{K}_i = 0 \quad i = C, D. \tag{1.8b}$$

The welfare index (1.1) must be appropriately normalized to accommodate the different capital market closures. Under malleable and sector-specific capital, aggregate factor income is rK and $r_C K_C + r_D K_D$, respectively. In each case, setting the initial values of the rental rates to unity ($r = r_C = r_D = 1$) allows us to equate GDP with the capital endowment ($M = K$) and treat ζ as the initial pollution-capital ratio.

In the malleable case, our model consists of equations (1.2)-(1.7) and (1.8a), along with the condition $r_C = r_D = r$, which yields a system of seven equations in eight unknowns ($\hat{P}_C$, $\hat{P}_D$, $\hat{r}$, $\hat{X}_C$, $\hat{X}_D$, $\hat{Z}$, $\hat{K}_C$, $\hat{K}_D$). In the sector-specific case, our model consists of equations (1.2)-(1.7) and (1.8b), which is a system of eight equations in nine unknowns ($\hat{P}_C$, $\hat{P}_D$, $\hat{r_C}$, $\hat{r_D}$, $\hat{X}_C$, $\hat{X}_D$, $\hat{Z}$, $\hat{K}_C$, $\hat{K}_D$). To solve the model we first designate X_C as the numeraire by setting $\hat{P}_C = 0$, and then find a solution to the system as a function of an increase in the pollution tax $\hat{\tau}_Z$. In each case, equation (1.1) is employed ex-post to evaluate the welfare effects of a small change in the tax.

Table 1.1: Results of the Theoretical Model

Variable	A. Malleable Capital	B. Non-Malleable Capital
$\hat{P}_C$	0	0
$\hat{P}_D$	$\theta\hat{\tau}_Z$	$\frac{\theta\sigma_D}{(\theta\sigma_D+(1-\theta)\sigma_U)}\hat{\tau}_Z$
$\hat{r}, \hat{r}_D, \hat{r}_C$	$\hat{r}=0$	$\hat{r}_D=-\frac{\theta(\sigma_U-\sigma_D)}{(\theta\sigma_D+(1-\theta)\sigma_U)}\hat{\tau}_Z, \hat{r}_C=0$
$\hat{X}_C$	$\theta\lambda(\sigma_U-\sigma_D)\hat{\tau}_Z$	0
$\hat{X}_D$	$-\theta(\lambda\sigma_D+(1-\lambda)\sigma_U)\hat{\tau}_Z$	$-\frac{\theta\sigma_D\sigma_U}{(\theta\sigma_D+(1-\theta)\sigma_U)}\hat{\tau}_Z$
$\hat{K}_C$	$\theta\lambda(\sigma_U-\sigma_D)\hat{\tau}_Z$	0
$\hat{K}_D$	$-\theta(1-\lambda)(\sigma_U-\sigma_D)\hat{\tau}_Z$	0
$\hat{Z}$	$-[\theta(1-\lambda)\sigma_U+(1-\theta(1-\lambda))\sigma_D]\hat{\tau}_Z$	$-\frac{\sigma_D\sigma_U}{(\theta\sigma_D+(1-\theta)\sigma_U)}\hat{\tau}_Z$
$\hat{W}$	$\hat{\tau}_Z\{\delta\zeta\sigma_D+\theta(\sigma_U-\sigma_D)$ $\times[\lambda(1-\phi)+(\delta\zeta-\phi)(1-\lambda)]\}$	$\frac{\sigma_D\sigma_U(\delta\zeta-\theta\phi)}{(\theta\sigma_D+(1-\theta)\sigma_U)}\hat{\tau}_Z$

1.2.3 Results

The solutions to both models are straightforward to obtain, and are summarized in Table 1.1[3]. The increase in the emission tax has an unambiguous effect on a few variables in the economy. Irrespective of capital malleability, the tax reduces pollution, raises the dirty good's price and reduces its production and consumption. For the remaining variables in the model, the effect of the tax depend on both the degree of capital malleability and the values of the parameters—in particular the difference between the elasticities of substitution for the consumer and for the dirty

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[3] We deal first with the malleable case. After price normalization, equations (1.3) and (1.5) imply that $\hat{r}=0$. Combining (1.4) and (1.6) yields $\hat{P}_D=\theta\hat{\tau}_Z$, which we plug into (1.2) to obtain $\hat{X}_D=\hat{K}_C-\sigma_U\theta\hat{\tau}_Z$. Substituting this result back into (1.4) yields $\hat{K}_C-\theta\hat{Z}-(1-\theta)\hat{K}_D=\sigma_U\theta\hat{\tau}_Z$, which we simplify by exploiting the fact that (1.8a) implies that $\hat{K}_C=\lambda/(\lambda-1)\hat{K}_D$. This leaves us with two equations, $(1-\theta+\lambda\theta)/(1-\lambda)\hat{K}_D+\theta\hat{Z}=-\sigma_U\theta\hat{\tau}_Z$ and equation (1.7), in two unknowns, $\hat{K}_D$ and $\hat{Z}$, the solution to which allows us to recover expressions for the remaining variables. Turning to the non-malleable case, (1.8b), (1.3) and (1.5) together imply that $\hat{K}_C=\hat{K}_D=\hat{X}_C=\hat{r}_C=0$, which collapses the system to simplified versions of equations (1.2), (1.4), (1.6) and (1.7). We use (1.7) to eliminate $\hat{Z}$ in (1.4) and (1.6). The former becomes $\hat{X}_D=\sigma_D\theta(\hat{r}_D-\hat{\tau}_Z)$, which we then plug into (1.2) and (1.6), leaving us with two equations, $\hat{P}_D=\theta\hat{\tau}_Z+(1-\theta)\hat{r}_D$ and $\sigma_D\theta(\hat{\tau}_Z-\hat{r}_D)=\sigma_U\hat{P}_D$, in two unknowns, $\hat{r}_D$ and $\hat{P}_D$, the solution to which allows us to recover expressions for the remaining variables.

producer. When $\sigma_U > \sigma_D$ the results are consistent with simple intuition, but it is less so when the opposite is true.

The clean good's production is unaffected when capital is sector-specific, and changes equivocally when it is malleable, increasing if $\sigma_U > \sigma_D$, and decreasing otherwise. Symmetrically, the capital rental rate is unaffected in the malleable case and in the clean sector in the sector-specific case. The rental rate in the dirty sector decreases if $\sigma_U > \sigma_D$, and increases otherwise. Capital mobility leads to induced changes of opposing signs in the two sectors' demands for capital, with the clean (dirty) sector's capital increasing (decreasing) if $\sigma_U > \sigma_D$, and vice versa.

The welfare effects of the tax turn out to be more transparent in the case where sectors have fixed capital stocks. Then, welfare improves so long as the dollar-denominated marginal environmental damage ($\delta\zeta$) exceeds the marginal benefit of pollution to households, which is indicated by the product of pollution's initial cost share in dirty production and the dirty good's initial share of household expenditure ($\theta\phi$). When capital is malleable the outcome is more complicated, with welfare increasing if marginal damage exceeds a threshold given by $\delta\zeta > \dfrac{\theta(\sigma_U - \sigma_D)(\phi - \lambda)}{\theta(1-\lambda)\sigma_U + (1-\theta(1-\lambda))\sigma_D}$, a condition which is satisfied if $\sigma_U \gtrless \sigma_D$ and $\lambda \gtrless \phi$.

The intuition behind the equivocal results is as follows. A low value of σ_U implies that households' commodity demands are relatively inelastic, with consumption of the dirty good declining only slowly as its price increases, while a high value of σ_D means that the level of production in the dirty sector can be easily maintained by substituting capital for pollution as the tax increases the latter's price. If capital is sector-specific, then the dirty sector's scope for input substitution is constrained by its perfectly inelastic capital supply, with the result that the fall in the quantity of pollution bids up the marginal product of capital. But if capital is intersectorally mobile, ease of input substitution in the dirty sector will increase the demand for capital, and will end up drawing capital away from the clean sector.

In the reverse situation with a high value of σ_U and a low value of σ_D, household demands for commodities are relatively elastic and the dirty sector's input demands are relatively inelastic. The tax-induced increase in the cost of pollution, combined with capital's limited substitutability, increases the dirty good's cost while leaving the unit demand for capital relatively unaffected. The price-sensitivity of the households' demand for the output of the dirty sector then causes the latter to decline, along with the demand for capital. This process releases capital to the clean sector, enabling its output to expand to substitute for the fall in households' dirty consumption.

Given these dynamics, a natural question is whether the impacts of the tax are larger—or, indeed, of the same sign—if capital is malleable rather than intersectorally immobile. The change in price of the dirty good is higher where capital is perfectly malleable. Furthermore, malleability results in larger declines in dirty production and pollution good if:

$$(\lambda\sigma_D + (1-\lambda)\sigma_U)(\theta\sigma_D + (1-\theta)\sigma_U) > \sigma_D\sigma_U,$$

and

$$[\theta(1-\lambda)\sigma_U + (1-\theta(1-\lambda))\sigma_D](\theta\sigma_D + (1-\theta)\sigma_U) > \sigma_D\sigma_U,$$

respectively. This solution is hard to interpret analytically, but it is possible to study it graphically by considering different combination of parameter values. In Figure 1.1 the white (gray) areas correspond to parameter values for which the effect on the variable is greater under perfect (imperfect) malleability of capital[4].

From Figure 1.1.A it is possible to see that the effect of a carbon tax on $\hat{X}_D$ depends mostly on the values of the elasticities of substitution. If $\sigma_U > \sigma_D$ ($\sigma_U < \sigma_D$) capital malleability results in larger (smaller) declines in dirty production if θ and λ are low (high). Thus, if in the economy it is easier to substitute production from the dirty good towards the clean good ($\sigma_U > \sigma_D$), production in the dirty sector declines more under perfect capital malleability unless the dirty sector is at the same time highly polluting and capital intensive. Given that the dirty sector is generally small, it is likely that the production if the dirty good decreases more when capital is perfectly malleable.

The effect on the pollution good is greater under perfect capital malleability mainly for high values of σ_U, as it is possible to see from 1.1.B. For low values it

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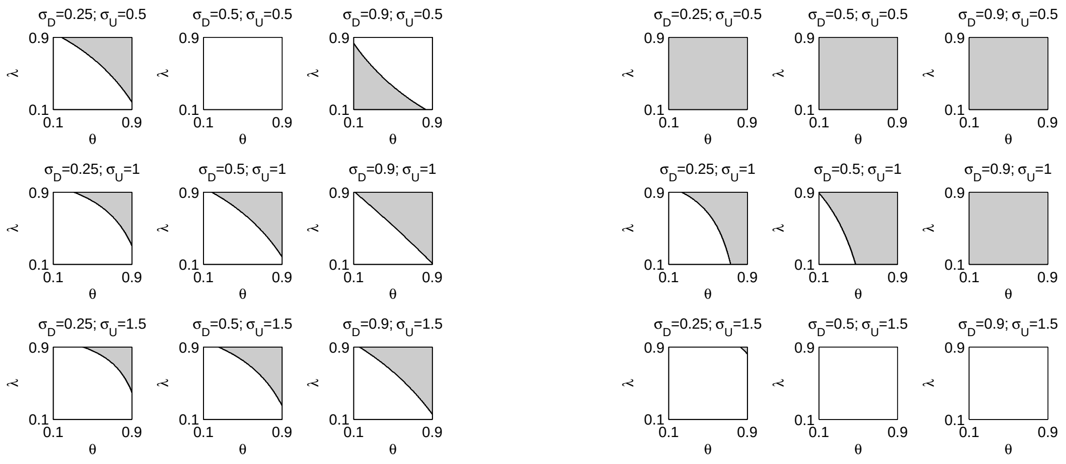
[4] The graphs are drawn considering the contours of the ratio of the absolute value of the variables under the two assumptions and determining where it is greater or smaller than one.

Figure 1.1: $\hat{X}_D$ and $\hat{Z}$ contours



A. $\hat{X}_D$ Contours

B. $\hat{Z}$ Contours

White: $\hat{X}_D$ larger w/. malleable capital
Gray: $\hat{X}_D$ larger w/. fixed capital

White: $\hat{Z}$ larger w/. malleable capital
Gray: $\hat{Z}$ larger w/. fixed capital

is always greater under imperfect capital malleability. For intermediate values of the elasticities, the decline in pollution is greater under perfect capital malleability if θ and λ are low. Again, the intuition is that production is reallocated to the clean sector if capital is mobile and at the same time the economy is elastic. Whereas, adjustment is made within the dirty sector if capital is not mobile and the elasticity of substitution between production factors in the dirty sector is high.

Finally, the impact on welfare is larger under perfect capital malleability if the following condition is satisfied:

$$\{\delta\zeta\sigma_D + \theta(\sigma_U - \sigma_D)[\lambda(1-\phi) + (\delta\zeta - \phi)(1-\lambda)]\}(\theta\sigma_D + (1-\theta)\sigma_U) > \sigma_D\sigma_U(\delta\zeta - \theta\phi).$$

This is complicated condition can be simplified considering that the environmental damage ($\delta\zeta$) is very small[5] and that it is likely offset by the environmental benefits gained from the reduction in pollution. By imposing $\delta\phi = 0$, we obtain a simpler condition:

$$\frac{\theta(\sigma_U - \sigma_D)(\lambda - \phi)(\theta\sigma_D + (1-\theta)\sigma_U)}{\sigma_D\sigma_U\theta\phi} > 0,$$

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[5] estimates by Newell and Pizer [72] give a value of approximatively 9.2*10^{-}13.

showing that welfare effects are higher under perfect capital malleability if $\sigma_U \gtrless \sigma_D$ and $\lambda \gtrless \phi$. This is the same condition under which the welfare impacts are positive under perfect malleability of capital.

In this simple model the results are highly dependent on the values of the elasticities of substitution and the shares describing the size and characteristics of the dirty sector. Where the economy is more flexible in the reallocation between the two sectors and where capital is malleable, a carbon tax results in the reduction of input investments in the production of the pollution goods, and thus in lower production of the good itself. This is with the exception of the instance in which the dirty sector is very large and very capital intensive, so that there is large scope for substitution between inputs in the dirty sector. Where the economy is less elastic but the production of the dirty good is elastic, then the effects on the economic variables are stronger under imperfect malleability of capital, which favors reallocation of inputs in the dirty sector.

1.3 Numerical analysis

The simple model illustrated achieves only parameter-dependent results. We now perform a numerical analysis in order to obtain conclusions on whether a carbon tax has a positive or negative impact on the key variables of the model, and on the difference in magnitude of these effects under the two assumptions on capital malleability [6]. This will be done using reliable parameter values[7].

The share parameters (θ, λ and ϕ) are calculated from the GTAP6 database[8] and are illustrated in Table 1.2. The dirty industry is represented by sectors covered by the EU ETS, namely refined coal and petroleum, pulp and paper, electric power, non-metallic mineral products and, iron and steel. All other sectors are considered to be part of the clean sector. Although no sector is fully clean, these sectors have a

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[6] A numerical analysis has been performed for the model with two production factors. Results are in Appendix I.

[7] Fullerton and Heutel [36] perform a similar analysis but for the US only.

[8] This is the database related to the Global Trade Analysis Project (Dimaranan and McDougall [30]) . It contains data related to 87 world countries/regions and 57 economic sectors. As the focus of this paper is on European countries the database has been aggregated to 25 regions, leaving European countries disaggregated while aggregating the rest of the world. Regional and sectoral aggregations will also be used in the CGE model in Section 1.4 and are described in Appendix II.

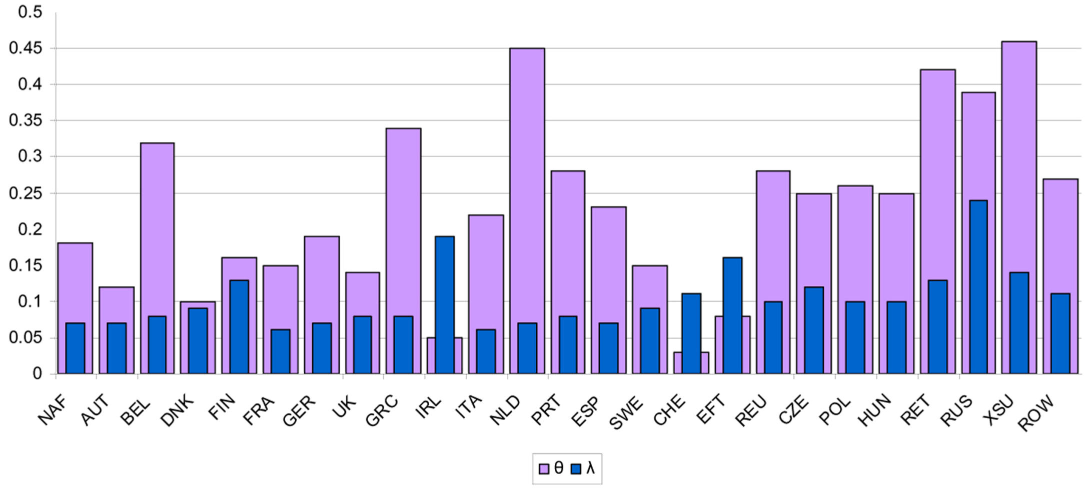
very small amount of dirty input Z, which can be disregarded and summed to the other inputs. The dirty inputs that correspond to the pollution good Z in the model, are fossil-fuel inputs (i.e. coal, gas and oil).

Table 1.2: Results from Numerical Analysis (*Perfect Capital Malleability, **Imperfect Capital Malleability)

REG	θ	λ	ϕ	**PCM***							**ICM****				
				$\hat{K}_D$	$\hat{K}_C$	$\hat{X}_D$	$\hat{X}_C$	$\hat{P}_D$	$\hat{Z}$	$\hat{W}$	$\hat{r}_D$	$\hat{X}_D$	$\hat{P}_D$	$\hat{Z}$	$\hat{W}$
NAF	0.18	0.07	0.04	-0.9	0.1	-1.9	0.1	1.9	-5.9	1.6	1.1	-1.1	1.1	-5.5	-4.6
AUT	0.12	0.07	0.02	-0.7	0.1	-1.5	0.1	1.5	-5.7	6.3	0.8	-0.8	0.8	-5.4	-1.9
BEL	0.32	0.08	0.03	-1.6	0.2	-3.5	0.2	3.6	-6.6	8.3	2.2	-2.2	2.2	-6.1	-7.0
DNK	0.1	0.09	0.03	-0.5	0.0	-1.0	0.0	1.0	-5.5	-3.4	0.5	-0.5	0.5	-5.3	-1.7
FIN	0.16	0.13	0.05	-0.7	0.1	-1.5	0.1	1.6	-5.7	2.6	0.9	-0.9	0.9	-5.4	-4.2
FRA	0.15	0.06	0.06	-0.9	0.1	-1.9	0.1	1.9	-5.9	-1.8	1.1	-1.1	1.1	-5.5	-6.5
GER	0.19	0.07	0.04	-1.0	0.1	-2.2	0.1	2.3	-6.0	1.3	1.3	-1.3	1.3	-5.6	-4.9
UK	0.14	0.08	0.03	-0.7	0.1	-1.4	0.1	1.5	-5.7	4.8	0.8	-0.8	0.8	-5.4	-2.8
GRC	0.34	0.08	0.05	-1.6	0.1	-3.3	0.1	3.4	-6.6	-6.5	2.1	-2.1	2.1	-6.0	-10.2
IRL	0.05	0.19	0.04	-0.2	0.1	-0.5	0.1	0.5	-5.2	7.8	0.3	-0.3	0.3	-5.1	-1.1
ITA	0.22	0.06	0.06	-1.2	0.1	-2.4	0.1	2.5	-6.2	-3.8	1.4	-1.4	1.4	-5.7	-7.7
NLD	0.45	0.07	0.04	-2.3	0.2	-4.7	0.2	5.0	-7.3	-0.3	3.3	-3.3	3.3	-6.6	-13.7
PRT	0.28	0.08	0.06	-1.4	0.1	-2.9	0.1	3.0	-6.4	-6.8	1.8	-1.8	1.8	-5.9	-10.1
ESP	0.23	0.07	0.04	-1.2	0.1	-2.5	0.1	2.6	-6.2	0.6	1.5	-1.5	1.5	-5.7	-5.5
SWE	0.15	0.09	0.04	-0.8	0.1	-1.6	0.1	1.7	-5.8	3.1	1.0	-1.0	1.0	-5.5	-4.1
CHE	0.03	0.11	0.02	-0.1	0.0	-0.3	0.0	0.3	-5.1	-0.7	0.2	-0.2	0.2	-5.1	-0.5
EFT	0.08	0.16	0.03	-0.4	0.1	-0.8	0.1	0.9	-5.4	7.2	0.5	-0.5	0.5	-5.2	-1.6
REU	0.28	0.1	0.04	-1.4	0.2	-2.9	0.2	3.1	-6.4	8.0	1.8	-1.8	1.8	-5.9	-7.0
CZE	0.25	0.12	0.05	-1.2	0.2	-2.6	0.2	2.8	-6.2	5.1	1.6	-1.6	1.6	-5.8	-8.5
POL	0.26	0.1	0.06	-1.3	0.2	-2.8	0.2	3.0	-6.3	2.7	1.8	-1.8	1.8	-5.9	-10.4
HUN	0.25	0.1	0.05	-1.2	0.2	-2.6	0.2	2.8	-6.2	4.6	1.6	-1.6	1.6	-5.8	-8.8
RET	0.42	0.13	0.06	-1.9	0.3	-4.0	0.3	4.3	-6.9	5.1	2.7	-2.7	2.7	-6.4	-15.6
RUS	0.39	0.24	0.08	-1.5	0.5	-3.5	0.5	4.0	-6.5	18.4	2.5	-2.5	2.5	-6.2	-19.8
XSU	0.46	0.14	0.11	-2.0	0.4	-4.4	0.4	4.8	-7.0	-10.6	3.1	-3.1	3.1	-6.6	-32.7
ROW	0.27	0.11	0.04	-1.2	0.2	-2.6	0.2	2.8	-6.2	8.2	1.6	-1.6	1.6	-5.8	-6.8

Results for the production and input variables depend on the values of the share parameter θ and λ, which are illustrated graphically in Figure 1.2. The share of polluting input in the production of the dirty good θ ranges from .03 to .46, while the share of capital invested in the dirty sector λ ranges from .06 to .24. Thus, the dirty sector usually represents a small share of the economy, and most capital is invested in the clean sector. Fullerton and Heutel [36] also perform a numerical analysis and calibrate their parameters according to stylized facts and data on the US economy. In fact, they assume that labor and capital invested in the clean industry is 0.8, and that the expenditure in pollution in the dirty industry is .25. These are similar to our results, as the share of capital invested in the clean industry in the NAFTA

Figure 1.2: Parameter values - θ and λ



region is .82, and the expenditure in pollution in the dirty industry is .07[9]. Figure 1.2 shows that for most countries/regions, the parameter θ has higher values than λ. The only countries for which this is not true are Ireland, Switzerland and the region Rest of Europe. These are the countries in which a relatively high percentage of capital is invested in the dirty sector and in which the share of the polluting input is particularly small.

For what regards the elasticities of substitution, following Fullerton and Metcalf [37], the substitution elasticity in consumption between the clean and dirty good is assumed to be 1 ($\sigma_U = 1$) and the elasticity of substitution between inputs in the dirty industry is assumed to be .5 ($\sigma_D = .5$). In the calculations the value of the tax increase is 10%, as in Fullerton and Heutel [36]. This is an arbitrary value that still allows us to study the different conclusions that the two models reach. Finally, estimates of marginal environmental benefits from CO_2 reduction by Newell and Pizer [72] are of around 9.2*10^{-13} \$/ton CO_2. This means that the value of $\delta\phi$ is very close to zero.

Table 1.2 illustrates results for the numerical analysis of the two models. Results reflect the predictions of the theoretical model for the case in which $\sigma_U > \sigma_D$. In

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[9] The fact that expenditure in pollution is lower can be explained by the difference in assumptions about the dirty inputs.

the case of perfect malleability of capital, as expected, production of the clean good increases, while that of the dirty good decreases. Pollution Z also decreases as a consequence of the carbon tax. Results on the reduction in pollution are similar to those obtained by Fullerton and Heutel [36]. They find that a 10% increase in the tax yields to approximately a 6% increase in pollution, which is in the range of the calculations for pollution changes illustrated in Table 1.2 . Countries with higher pollution intensity (higher θ), such as Russia and the rest of Former Soviet Union, the Netherlands and Belgium, achieve a bigger amount of pollution reduction. Countries with a large dirty sector instead (large λ), such as Ireland, tend to achieve a lower amount of emissions reductions. In the case of imperfect malleability of capital, results are also as expected, with no changes in the clean industry and a decrease in the production of the dirty good and in the use of the polluting input.

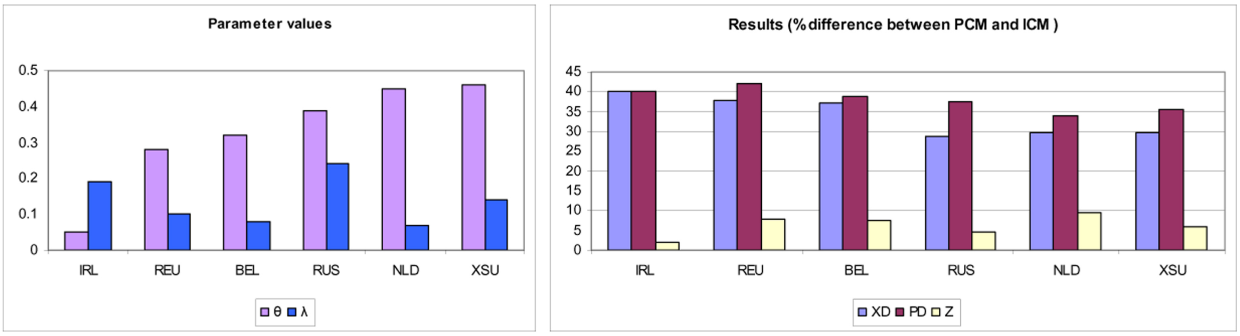
For what regards welfare, results depend also on the value of the parameter ϕ, namely the share of household expenditure in the dirty good. Where expenditure in the dirty good is very small welfare changes can be positive under perfect malleability of capital. Without capital mobility instead, the change in welfare is always negative.

Comparing results under the two assumptions it is possible to see that the carbon tax has a higher effect in the case of perfect capital malleability. In fact, in this case there is a more effective re-adjustment of production patterns and a higher reduction of pollution. Welfare increases in some cases under perfect capital malleability. With the exception of Denmark and Switzerland, welfare decreases more under imperfect malleability of capital. For most countries/regions, the same carbon tax is more effective in terms of emissions reductions, welfare and benefits from the improved environmental quality under perfect malleability of capital.

It is interesting to check the impact that the structure of the economy has on the results. This can be done by analyzing the relationship between the parameter values (λ and θ) and the difference in the variable changes between the case of perfect and imperfect malleability of capital, as illustrated in Figure 1.3.

Only a few countries with differing parameter values are presented in the graph. Ireland is the only country with a a high capital share invested in the dirty good and

Figure 1.3: Parameter values - θ and λ



a very low pollution intensity of the dirty sector. It is in fact the country in which the difference in pollution reduction between the two capital malleability scenarios is smaller. At the same time the difference in the decreases in the production and price of the dirty good is higher. Another interesting case is that of the Netherlands, where the dirty sector has a high level of pollution intensity and a low investment of capital. In this country the difference in pollution reduction is the highest while the difference in production and price is the between the lowest. This is because the high pollution intensity favors reallocation of capital to the clean sector, and this is not possible when capital is immobile. In general the higher the pollution intensity the higher the difference in the results between the two capital malleability scenarios. Also, the higher share of capital invested in the dirty sector, the lower the difference in the results. This is because in this case reallocation of inputs in the dirty sector is favored, and thus the immobility of capital has a lower effect on the results.

The results from the numerical analysis allow us to reach conclusions on a realistic outcome of the model presented in Section 1.2. Nonetheless, these results are limited for a number of reasons. First, it does not take into account adjustments taking place via international trade. Secondly, the dirty sector is in large part corresponding to inputs that are usually used to produce the clean good. Thus, a more complicated production structure would lead to a more realistic picture. Finally, the same carbon tax has been applied to all countries and world regions considered, even though a harmonized carbon tax is very hard to implement from the political point of view. A policy-relevant study would also include the possibility to study the effects of the imposition of asymmetric environmental regulations would have on the countries subject to the regulation as well as those that are not. It is not possible to capture these effect in a simplified model and in the numerical analysis of it. CGE models instead offer the possibility to take into account these issues, as they allow us to calculate the equilibrium of a multi-region and multi-sector model. The next section will explain the use of CGE models and give an example of a policy study.

1.4 CGE Application

1.4.1 Model Structure

The advantage of CGE models is that they make it possible to apply real data to multi-country and multi-sector general equilibrium models, so that it is possible to study the effects of policies, such as a carbon tax or carbon trading. In this section, a study of the EU ETS will be used to verify whether the assumption of perfect capital malleability influences policy conclusions. The model employed for the policy simulations is a static multiregion CGE based on Harrison, Rutherford and Tarr [46], outlined in Rutherford [83]. This model is a coherent and extended version of the model presented in Section 1.2. Thus, all policy results will be relevant for comparison to the theoretical model.

The model divides the world into 25 regional economies $r \in R$, each of which contains one representative agent, and 14 industries $j \in J$[10]. Agents are endowed with labor and capital, which are internationally immobile. They rent out these resources to domestic industries in return for factor income. Each industry produces a single homogenous output good $i \in I$, demanded by other sectors and the representative agent. The economies are linked by bilateral goods trade according to the Armington [7] assumption, whereby regions' exports of a given commodity are

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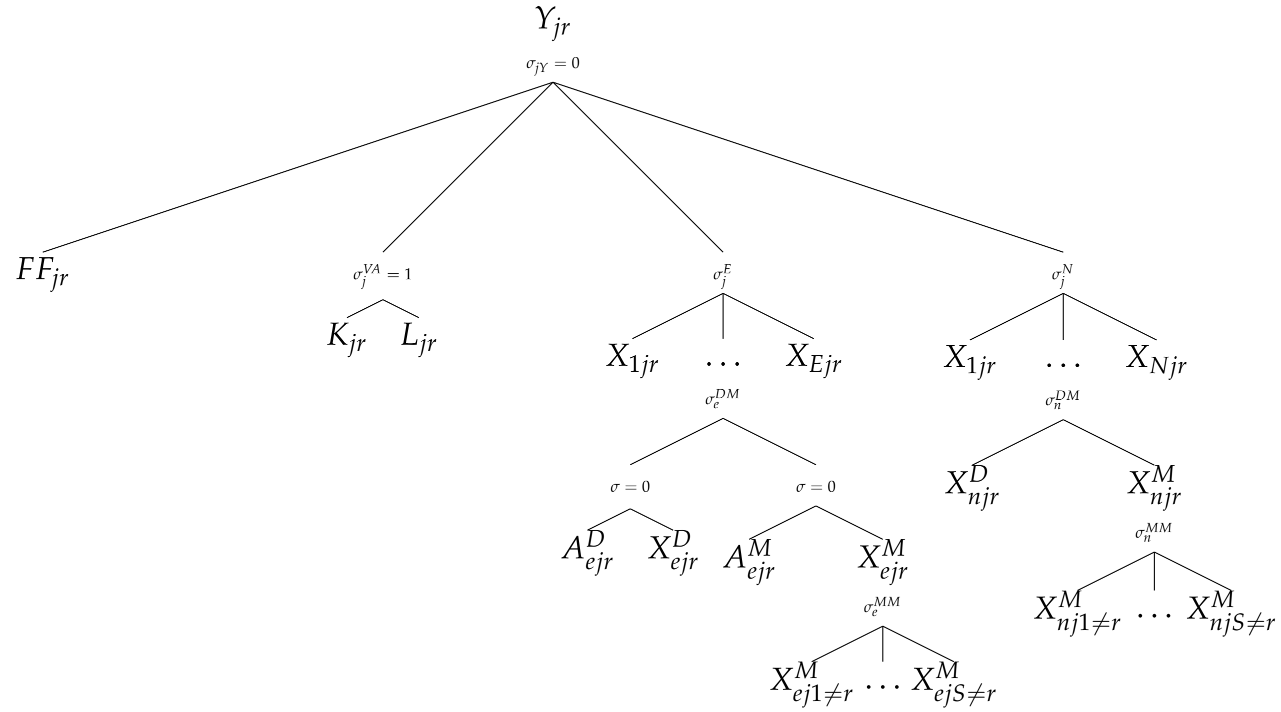
[10] See Appendix II for description of the regional and sectoral disaggregation

differentiated, and the use of each commodity is given by a constant elasticity of substitution (CES) composite of domestically-produced and imported varieties of that good.

Agents minimize expenditure and, as in the previous sections, are assumed to have a Cobb-Douglas utility function and a constant marginal propensity to save out of their income. The government is explicitly represented, though it has a passive role. It is modeled as a cost-minimizing firm using commodities to produce an aggregate government good. Industries are modeled as cost-minimizing representative firms whose technology is given as a nested CES production function. The production function parametrization differs across sectors, but it has the common structure illustrated in the diagram in Figure 1.4. The inverted tree represents the sub-production function. At the top level, output $Y_{j,r}$ is produced from materials, every value-added and a fixed resource factor according to a CES production function with an elasticity of substitution $\sigma_j^Y = .5$. Note that this is equivalent, though more complicated, to the elasticity of substitution σ_D used in the previous sections. In fact, σ_j^Y is the elasticity of substitution in production between clean inputs, such as value-added and some of the materials which derive from clean industries, and dirty inputs such as other materials deriving from dirty industries. This structure implies a limited capability of firms to substitute intermediate goods, labor and capital with natural resources, especially in the short-run. In the second level, the left nod represents the production of value-added from a Cobb-Douglas production function of inputs of capital $K_{j,r}$ and labor $L_{j,r}$. The intermediate nod represents the production of aggregate energy inputs to each sector j. These are generated by a CES sub-production function of intermediate energy commodities $X_{e,j,r}$ (energy sectors are indexed by $e \subset i$) and combined according to the interfuel elasticity of substitution σ_j^E. The right nod represents aggregate material input to each sector that is generated by a Leontief sub-production function of intermediate non-energy goods $X_{n,j,r}$ (non-energy sectors are indexed by $n \subset i$). The third and fourth levels of the diagram represent the two-level Armington aggregation process for each intermediate input. For the production of each good j, intermediate input $X_{i,j,r}$, is a CES composite of domestically-produced $X_{n,j,r}^D$ and imported varieties $X_{n,j,r}^M$ according to the Armington elasticity of substitution σ_i^{DM}. The imported component is itself a CES aggregate of r's imports of commodity i from other regions according to the interregional elasticity of substitution σ_i^{MM}.

Figure 1.4: Production Tree



The present model is particularly constructed for the analysis of carbon policies. In fact, the present hierarchical production function reflects the difficulty of substituting material inputs for energy and, to a lesser extent, low-carbon energy inputs such as natural gas for carbon-intensive fuels such as coal in the short-run. While data are not available on the technologies employed by covered sector installations and combustion units in the non-covered industries, it seems doubtful that a large fraction of these sources processes fuel-switching capability. On the other hand, there is ample evidence of fuel-switching capability (see Soderholm [85]). The parameter σ_j^E was thus set at a low value in all industries except the electricity sector.

A novel feature of this model is its ability to account for CO_2 emissions produced by the fossil fuel combustion installations which are regulated by the EU-ETS but are located in industries outside the program's covered sectors. In fact, for the policy simulations actual emissions of CO_2 will be linked to the use of energy. As illustrated in Figure 1.4, emissions associated with the intermediate use of each fossil fuel must be covered by allowances A, but this occurs only in the "covered" and "combustion" sectors (see sectoral aggregation in Table 1.5 in Appendix II). Denoting the set of covered industries by Z, for each industry $z \in Z$, the use of domestic and imported inputs of energy goods e are given by $A^D_{e,z,r} = \varepsilon_{e,z,r}\omega_{z,r}X^D_{e,z,r}$ and $A^M_{e,z,r} = \varepsilon_{e,z,r}\omega_{z,r}X^M_{e,z,r}$ respectively, where $\varepsilon_{e,z,r}$ is e's region- and sector-specific emission factor and $\omega_{z,r}$ is the fraction of that industry's emissions covered by policy. In the fully covered sectors $\omega_{z,r} = 1$, while in the combustion sectors, combustion installations account for less than the total quantity of emissions, so that $0 < \omega_{z,r} < 1$[11]. Each of these sectors' total emissions are thus given by the sum of domestic and imported emissions, $A^D_{e,z,r} + A^M_{e,z,r}$. The imposition of a cap to allowances across participating regions $s \in S \subseteq R$ and the set of covered and combustion sectors Z is given by the constraint:

$$\sum_{e}\sum_{z\in Z}\sum_{s\in S}[A^D_{e,z,s} + A^M_{e,z,s}] \leq \sum_{s\in S}\bar{A}_s$$

where $\bar{A}_s$ is the maximum amount of allowances assigned to region s. The dual to the expression above is the market clearing price of allowances.

1.4.2 Model Formulation and Calibration

The CGE model formulates the general equilibrium problem of equalizing demand and supply simultaneously across all markets as a mixed complementarity problem, or MCP (see Mathiesen [69], Rutherford [81]). Cost minimization by the industries and expenditure minimization by the representative agent in each region give rise to vectors of demands for commodities and factors. Demands are functions of domestic factor prices, domestic and international commodity prices, industries' activity levels, and the income levels of the regional representative agents. These demands are combined with the general equilibrium conditions of market clearance, zero-profit and income balance. This yields to a square system of non-linear inequalities that forms the aggregate excess demand correspondence of the world economy (cf. Sue Wing [87]). This system is numerically calibrated and expressed

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[11] Only a fraction of the combustion sector is covered by the EU ETS. This correspond to the Large Combustion Plants (LPC).

as an MPC using the MPSGE subsystem (Rutherford [82]) for GAMS (Brooke et al. [16]), and solve using the PATH solver (Dirkse and Ferris [32]).

The benchmark dataset, as in Section 1.4, is the GTAP6 database (Dimaranan and McDougall [30]). This database is a snapshot at the world economy in 2001. Data from bilateral trade, transport and protection data are combined with individual country social accounting matrices and energy balances in order to constitute an approximation of the world economy as if it were in a full economic equilibrium. The original dataset contains 87 world regions and countries, and 57 sectors, but it has been aggregated to the 25 regions and 14 sectors described in Appendix II. Elasticity of substitution between energy inputs is assumed to be .5, elasticities of substitution between domestic and imported intermediate products range from .3 to 11.0 according to the different products, and elasticities of substitution of intermediates across regions range from 3.8 to 33. These are adapted from from Dimaranan, McDougall and Hertel [31] and are assumed to be the same across regions. A baseline projection of economic activity in 2012 was prepared by scaling the endowments in each region according to the historical growth rates of GDP from 2001 to 2007, and forecasts of GDP growth for the period 2008-2012 from the 2009 IMF World Economic Outlook.

The emission coefficients that link CO_2 emissions to the model's projection of economic activity were computed by first estimating emissions by sector and fuel for each region based on the International Energy Agency (IEA) energy balances for 2001 following Lee[62], and then dividing quantities of emissions by the economic values of the corresponding flows of fossil fuels given in the GTAP6 database. The result is a consistent set of relationships between the economic quantities of the sectoral demand for fossil fuels and their associated CO_2 emissions for the benchmark year. It is assumed that this continues to hold throughout the period of operation of the EU ETS[12].

Some assumptions were required to estimate the sector coverage. For each combustion sector, it has been necessary to estimate the share of total CO_2 emissions that were attributable to large combustion installations. The only data available in

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[12] This is equivalent to assuming no autonomous energy efficiency improvement (AEEI) over period 2001-2012.

the regard were the 2001 IEA energy statistics on countries' emissions from "unallocated producers" (that is generators of electricity or heat for own consumption, as opposed to for sale) whose use of fossil fuels had not been apportioned between industrial and "other" sectors. Accordingly, unallocated producers have been treated as representing emissions of combustion installations in all of the combustion sectors in each country. The average proportion has been calculated for each country and used to assign the amount of emissions from unallocated producers. Although using the average value is not very realistic, the limitations of the data make it impossible to capture sectoral heterogeneity.

The final component of the calibration procedure is aimed at accounting for the high international crude oil and natural gas prices, which are expected to be a key factor in the abatement of emissions and in the trading of allowances. Preliminary runs of the models showed the prices of oil and gas in the European countries falling in real terms over the period 2001-2012, when world prices have been increasing. To remedy this situation supplies of the fixed factor in the oil and gas sectors in the NAFTA and Rest of the World regions have been reduced, and fixed factor supplies have been restricted in the remaining regions. As a result, import prices of these commodities in European countries are 90-100 percent higher than in the 2001 base year.

1.4.3 Policy Scenarios and Results

The chosen policy for simulation is the European Union (EU) Emissions Trading Scheme (ETS), as this is the most relevant carbon policy in Europe, and thus it has a high policy-relevance. The EU ETS has been designed to be divided into two phases. Phase I, started in 2004 and ended at the end of 2007, was designed as a kick off trial period to give a chance to the European companies to become confident with emission trading. The emission ceilings for all countries were relatively high and not all EU-27 countries were included, as some only recently entered the European Union. Phase II started at the beginning of 2008 and will last for a 4-year period up to 2012. The emission ceilings are lower than those of the previous phase and all EU Member States are now included in the trading system. In this section we will present the results from simulations on Phase II, comparing results in year 2012. Three different scenarios will be compared:

- Baseline: no policy
- ETS - PCM: Phase II ETS with perfect malleability of capital
- ETS - ICM: Phase II ETS with imperfect malleability of capital

Simulations related with imperfect capital malleability are done by imposing fixed and immobile capital between sectors (sluggish). Emissions ceilings $\bar{A}_r$ correspond to the amount of allowances established by the National Allocation Plans (NAP) of the regions included in the ETS (see Table 1.4). Results for the ETS scenario will be calculated under both assumptions on capital malleability, in order to compare the results. Results on emissions of CO_2 from the simulations are illustrated in Table 1.3.

From Table 1.3 it is possible to compare emissions from covered (Cov)[13] and non-covered (NCov) sectors, and for EU and non-EU countries in the three scenarios considered. Covered emissions are lower with ETS in EU countries, while non-covered emissions are higher. This shows that there there there is an increase in investment from the dirty to the clean sectors. Looking at the amount of carbon leakage, that is changes in emissions in countries that are not part of the ETS, emissions are higher than in the baseline case both for covered and non-covered sectors. This is because production shifts to places where there are no restrictions on pollution and input costs are lower. The presence of carbon leakage is stronger under the assumption of imperfect capital malleability. As it is not possible to reallocate capital between sectors, production is transferred to foreign countries. A large amount of carbon leakage may yield to an overall increase in world emissions, which would defeat the purpose of the imposition of climate policies. Furthermore, it may cause a strong decrease in the environmental quality of non-EU countries, which is of particular concern in the case of developing countries. In this countries the risk is to over-exploit the natural resources and thus to a development which is not sustainable over time. Emissions in non-covered sectors instead increase more under

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[13] Including combustion sector.

Table 1.3: Emission Results from Simulations - Mtoe CO_2

REG	**Baseline**		**ETS - PCM**		**ETS - ICM**	
	Cov	NCov	Cov	NCov	Cov	NCov
NAF	3591.2	2971.3	3626.7	2989.2	3679.2	2969.3
AUT	38.5	41.0	32.0	38.7	31.8	39.6
BEL	94.7	111.8	72.4	97.9	71.1	85.2
DNK	23.4	22.3	20.0	22.0	20.0	21.6
FIN	152.7	25.9	60.5	23.5	55.7	23.6
FRA	113.3	338.3	101.3	330.5	100.9	334.7
GER	529.6	442.7	431.1	405.6	456.5	473.9
UK	292.1	216.1	251.4	208.2	275.4	215.9
GRC	84.1	43.4	64.6	41.2	65.6	41.0
IRL	23.8	31.6	20.1	30.7	19.9	30.6
ITA	247.5	212.0	204.5	200.0	213.1	212.6
NLD	235.9	64.6	151.8	54.9	158.2	58.7
PRT	36.9	46.0	85.7	173.9	25.3	28.2
ESP	181.6	190.1	154.4	184.2	153.2	183.9
SWE	25.1	42.2	23.0	41.7	22.7	41.5
CHE	4.6	43.9	4.6	41.6	4.3	38.9
EFT	21.5	42.7	22.7	42.9	20.2	39.3
REU	107.9	79.6	87.1	79.4	88.1	83.6
CZE	119.0	54.1	85.0	50.0	88.6	60.3
POL	264.3	125.7	205.9	125.7	205.2	128.6
HUN	42.7	49.0	32.0	48.2	31.1	47.2
RET	222.2	113.2	227.2	113.6	228.9	113.1
RUS	1179.7	679.5	1203.2	682.3	1227.8	680.0
XSU	583.7	425.2	594.8	428.0	598.2	427.1
ROW	12531.8	9377.0	12643.3	9411.6	12849.4	9399.3
EU	2613.0	2136.5	2082.6	2156.6	2082.6	2110.6
Non-EU	18134.7	13652.7	18322.5	13709.1	18607.9	13666.9
TOT	20747.7	15789.2	20405.1	15865.7	20690.5	15777.5

perfect malleability of capital. This is coherent with the theoretical results and it reflects the fact that there is more possibility of intra-sectoral adjustment under perfect malleability of capital. Note that at world level emissions are reduced more under perfect malleability of capital (-0.7%) than imperfect malleability (-0.2%), thus considering both the side effects of increased non-covered and non-EU emissions ETS is more efficient when it is possible to reallocate capital across sectors.

It is also interesting to analyze the results within the emission trading area, as illustrated in Table 1.4. The price of emissions trading is 7.2% lower in the case of perfect capital malleability (€25.33) than then with imperfect capital malleability (€27.15). This means that costs of reducing the emissions of the amount determined by the ETS cap are higher in the case of imperfect malleability of capital.

This is coherent with the theoretical results[14]. Although the price under perfect malleability of capital is higher, it is worth pointing out that the difference is not very high. Therefore, given the many sources of uncertainty in the price of emission allowances, it appears that capital malleability only influences the carbon price to a relatively small extent. On the other hand, as the issue of capital malleability is known, contrarily to other factors, it should be taken into account in the evaluation of climate policies. The pattern of buyers and sellers is similar in the two cases. The main sellers of permits are countries belonging to the "REU" region, France and Germany. The main buyer instead is the Netherlands, followed by the UK, Finland and Belgium.

Table 1.4: ETS results

		Emissions PCM (Price=25.33€)	Emissions ICM (Price=27.15€)
AUT	31.0	32.0	31.8
BEL	59.0	72.4	71.1
DNK	25.0	20.0	20.0
FIN	38.0	60.5	55.7
FRA	133.0	101.3	100.9
GER	453.0	431.1	456.5
UK	246.0	251.4	275.4
GRC	69.0	64.6	65.6
IRL	22.0	20.1	19.9
ITA	196.0	204.5	213.1
NLD	86.0	151.8	158.2
PRT	35.0	85.7	25.3
ESP	152.0	154.4	153.2
SWE	23.0	23.0	22.7
REU	194.0	87.1	88.1
CZE	87.0	85.0	88.6
POL	209.0	205.9	205.2
HUN	27.0	32.0	31.1

This simple exercise with the applied model, has illustrated how CGE models can contribute to complement economic theory by quantifying the different results that the assumptions on capital may give. CGE can identify secondary-effects, such as carbon leakage, which could have not been calculated with a simple numerical analysis. This section illustrated how emissions trading is more efficient with perfect capital malleability, not only because more emissions are cut, but also because

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[14] Whereas in the theoretical model and numerical analysis we have compared the resulting emissions reduction given the same carbon price, here we are comparing carbon prices as resulting from the same emissions reductions. The conclusions reached are the same though, as in a general equilibrium setting price and quantity regulations are equivalent.

it leads to a more fair outcome, with a lower amount of carbon leakage.

1.5 Conclusions

This paper has presented a theoretical work on capital malleability in the context of a simple clean-dirty industry model in Harberger style [44], which is used to analyze the effect of climate policies. Results illustrate that a carbon tax is more efficient in reducing emissions under the assumption of perfect capital malleability, although results depend on parameter values. In order to get more determinate results, a numerical analysis has been performed using reliable parameter values. This confirms the expected results that the carbon tax is more efficient under perfect capital malleability. Even though this type of analysis is useful, it does not supply policy-relevant results as the value of the tax is imposed arbitrarily and there are no intra-country adjustments or layered production structure. Thus, a policy simulation has been performed using a Computable General Equilibrium model (CGE), based on the EU Emissions Trading System of carbon permits. This analysis also confirms that the environmental policy is more efficient under the assumption of perfect capital malleability.

The contribution of this paper is twofold. First of all, it offers a thorough analysis of the issue of capital malleability and brings to attention the need to consider the differences in results from carbon policy studies in the case of imperfect capital malleability. In fact, this could be particularly relevant in considering policies that are applied in too short a time span for capital to fully adjust between sectors. Secondly, this paper illustrated how CGE models can contribute to improving and completing a theoretical analysis in adding the possibility to conduct policy-relevant studies and take into consideration many of the several effects that affect the results of climate policies, such as international trade.

Appendix

I. Model with Labor and Capital

This section will present a more complete version of the model in which the production factors for both industries are capital K, a general production factor L that includes labor, natural resources and land, and pollution Z in the dirty industry. In the case of perfect capital malleability, the resource constraints, already formulated in Jones' algebra, can be stated as

$$\hat{K}_C \lambda_{KC} + \hat{K}_D \lambda_{KD} = 0$$
$$\hat{L}_C \lambda_{LC} + \hat{L}_D \lambda_{LD} = 0$$

Where $\lambda_j i$ is the share of factor $j \in K, L, Z$ invested in industry $i \in C, D$. It is again assumed that production factors are imperfect substitutes and can be substituted with elasticity of transformation σ_C and σ_D respectively in the clean and dirty sector. From the definition of elasticity we then have:

$$\hat{K}_C - \hat{L}_C = \sigma_C(\hat{w} - \hat{r})$$
$$\hat{K}_D - \hat{Z} = \sigma_D(\hat{\tau}_Z - \hat{r})$$
$$\hat{L}_D - \hat{Z} = \sigma_D(\hat{\tau}_Z - \hat{w})$$

From the assumptions of perfect competition and free entry we have:

$$\hat{P}_C + \hat{X}_C = \theta_{CK}(\hat{r} + \hat{K}_C) + \theta_{CL}(\hat{w} + \hat{L}_C)$$
$$\hat{P}_D + \hat{X}_D = \theta_{DK}(\hat{r} + \hat{K}_D) + \theta_{DL}(\hat{w} + \hat{L}_D) + \theta_{DZ}(\hat{\tau}_Z + \hat{Z})$$

Where $\theta_i j$ is the expenditure in sector j in industry i. From the firms cost minimization, we have that change in production of the two goods will depend from the changes in the production inputs, weighted by the shares of expenditure in the production factors:

$$\hat{X}_C = \theta_{CK}\hat{K}_C + \theta_{CL}\hat{L}_C$$
$$\hat{X}_D = \theta_{DK}\hat{K}_D + \theta_{DL}\hat{L}_D + \theta_{DZ}\hat{Z}$$

Finally, as before utility depends on the consumption of the two goods, with an elasticity of substitution of σ_U:

$$\hat{X}_C - \hat{X}_D = \sigma_U(\hat{p}_D - \hat{p}_C)$$

Setting $\hat{P}_C = 0$ and good X_C as the numeraire, it is possible to find the following solution to the system.

$$\begin{aligned}
\hat{w}^* =& \frac{\Delta_\Lambda \Delta_\sigma \theta_{CK}\theta_{DZ}\hat{\tau}_Z}{D} \\
\hat{r}^* =& -\frac{\Delta_\Lambda \Delta_\sigma \theta_{CL}\theta_{DZ}\hat{\tau}_Z}{D} \\
\hat{K}_D^* =& -\frac{\Delta_\sigma \theta_{DZ}(\sigma_C + \Lambda_L\sigma_D)\hat{\tau}_Z}{D} \\
\hat{L}_D^* =& -\frac{\Delta_\sigma \theta_{DZ}(\sigma_C + \Lambda_K\sigma_D)\hat{\tau}_Z}{D} \\
\hat{K}_C^* =& \frac{\Delta_\sigma \theta_{DZ}\Lambda_K(\sigma_C + \Lambda_L\sigma_D)\hat{\tau}_Z}{D} \\
\hat{L}_C^* =& \frac{\Delta_\sigma \theta_{DZ}\Lambda_L(\sigma_C + \Lambda_K\sigma_D)\hat{\tau}_Z}{D} \\
\hat{P}_D^* =& \frac{\theta_{DZ}((1 + \theta_{CK}\Lambda_K + \theta_{CL}\Lambda_L\sigma_C) + (\theta_{CL}\Lambda_K + (\theta_{CK} + \Lambda_K)\Lambda_L)\sigma_D)\hat{\tau}_Z}{D} \\
\hat{X}_C^* =& \frac{\Delta_\sigma \theta_{DZ}(\theta_{CL}\Lambda_L(\sigma_C + \Lambda_K\sigma_D) + \theta_{CK}\Lambda_K(\sigma_C + \Lambda_L\sigma_D))\hat{\tau}_Z}{D}
\end{aligned}$$

$$\begin{aligned}
\hat{X}_D^* =& -\frac{\theta_{DZ}(\sigma_D((1 + \theta_{CK}(\Lambda_K - 1) + \theta_{CL}(\Lambda_L - 1))\sigma_C + \Lambda_K\Lambda_L)\sigma_Y)\hat{\tau}_Z}{D} \\
& -\frac{(\sigma_D(\sigma_C + (\theta_{CL}\Lambda_K + \theta_{CK}\Lambda_L)\sigma_D))\hat{\tau}_Z}{D} \\
\hat{Z}^* =& -\frac{(\sigma_D((1 + \theta_{CK}\Lambda_K + \theta_{CL}\Lambda_L)\sigma_C + (\theta_{CL}\Lambda_K + (\theta_{CK} + \Lambda_K)\Lambda_L)\sigma_D))\hat{\tau}_Z}{D} \\
& -\frac{(\Delta_\sigma(\Delta_\Lambda(\theta_{CL}\theta_{DK} - \theta_{CK}\theta_{DL})\sigma_D + \theta_{DZ}(\sigma_C + (\theta_{CL}\Lambda_K + \theta_{CK}\Lambda_L)\sigma_D)))\hat{\tau}_Z}{D}
\end{aligned}$$

Where:

$$
\begin{aligned}
\Lambda_K &= \lambda_{KD}/\lambda_{KC} \\
\Lambda_L &= \lambda_{LD}/\lambda_{LC} \\
\Delta_\Lambda &= \Lambda_K - \Lambda_L \\
\Delta_\sigma &= \sigma_U - \sigma_D \\
D &= \sigma_C + \Lambda_K \Lambda_L \sigma_D + \theta_{CL}(\Lambda_L \sigma_C + \theta_{DK} \Delta_\Lambda \Delta_\sigma + \Lambda_K \sigma_D) + \theta_{CK}(\Lambda_K \sigma_C - \theta_{DL} \Delta_\Lambda \Delta_\sigma + \Lambda_L \sigma_D)
\end{aligned}
$$

For standard parameter values expression D is positive. The sign of coefficients are then only dependent on Δ_σ and Δ_Λ. Different conclusions can be reached from the model according to the parameter values. However, it is possible to notice that the price of the dirty good always increases, and that production of the dirty good and pollution always decrease. To check the results on the other variables it is necessary to consider the different cases of parameter values.

Case 1: $\sigma_U > \sigma_D$ **and** $\Lambda_K > \Lambda_L$

In this case both Δ_σ and Δ_Λ are positive, so that the quantity of both clean production factors invested will decrease in the dirty industry and increase in the clean industry. Production also increases in the clean industry. Finally, the prices of the production factors change consequently to the factor intensity. As Δ_Λ, which implies that the dirty sector is more capital intensive, the price of labor will increase and the price of capital will decrease. This is because if the dirty good is more capital intensive, when price of the good increases and the the production decreases due to an environmental tax, it will demand relatively less of the production inputs K_D and L_D, as well as less dirty input Z. As production is capital intensive, the fall in the demand for capital is greater than the fall in demand for the other clean factor L. Therefore, r falls relatively to w.

Case 2: $\sigma_U > \sigma_D$ **and** $\Lambda_K < \Lambda_L$

In this case Δ_σ is positive and Δ_Λ is negative. The results are very similar to the first case. In fact, the only differences concern the changes in prices of the production factors. These are exactly the opposite, as production is now less capital intensive, so that the price of K will increase, while the price of L will decrease.

Case 3: $\sigma_U < \sigma_D$ **and** $\Lambda_K > \Lambda_L$

In this case Δ_σ is negative and Δ_Λ is positive. In general, the elasticity of substitution between goods in consumption is always greater than the elasticity of substitution between inputs of production in the dirty industry, thus the conclusions from cases 3 and 4 are less realistic. In this case the conclusions are opposite to case 1. The quantity of both clean production factors invested will increase in the dirty industry and decrease in the clean industry. Production decreases in the clean industry, the price of K increases and the price of L decreases.

Case 4: $\sigma_U < \sigma_D$ **and** $\Lambda_K < \Lambda_L$

In this case both Δ_σ and Δ_Λ are negative. The results are very similar to case 3, except that the price of K decreases, while the price of L increases.

Note that the results are the same as in the version of the model without labor, only more complicated. Here the relative intensity of production factors can lead to different changes in the factor prices.

This model is easily modified to the case in which capital is imperfectly malleable. In this case, we have $\hat{K}_C = \hat{K}_D = 0$ and two different prices for the two types of capital, $\hat{r}_C$ and $\hat{r}_D$. This affects the following equations which become:

$$\begin{aligned}
\hat{L}_C &= -\sigma_C(\hat{w} - \hat{r}_C) \\
\hat{Z} &= -\sigma_D(\hat{\tau}_Z - \hat{r}) \\
\hat{X}_C &= \theta_{CK}\hat{r}_C + \theta_{CL}(\hat{w} + \hat{L}_C) \\
\hat{P}_D + \hat{X}_D &= \theta_{DK}\hat{r} + \theta_{DL}(\hat{w} + \hat{L}_D) + \theta_{DZ}(\hat{\tau}_Z + \hat{Z})
\end{aligned}$$

The new system of equations gives the following results:

$$
\begin{aligned}
\hat{w}^* &= -\frac{\Delta_\sigma \theta_{CK}\theta_{DZ}\Lambda_L\sigma_D\hat{\tau}_Z}{D} \\
\hat{r}_C^* &= \frac{\Delta_\sigma \theta_{CL}\theta_{DZ}\Lambda_L\sigma_D\hat{\tau}_Z}{D} \\
\hat{r}_D^* &= -\frac{\Delta_\sigma \theta_{DZ}(\sigma_C + \theta_{CK}\Lambda_L\sigma_D)\hat{\tau}_Z}{D} \\
\hat{L}_C^* &= \frac{\Delta_\sigma \theta_{DZ}\Lambda_L\sigma_C\sigma_D\hat{\tau}_Z}{D} \\
\hat{L}_D^* &= -\frac{\Delta_\sigma \theta_{DZ}\sigma_C\sigma_D\hat{\tau}_Z}{D} \\
\hat{P}_D^* &= \frac{\theta_{DZ}\sigma_D((1+\theta_{CL}\Lambda_L)\sigma_C + \theta_{CK}\Lambda_L\sigma_D)\hat{\tau}_Z}{D} \\
\hat{X}_C^* &= \frac{\Delta_\sigma \theta_{CL}\theta_{DZ}\Lambda_L\sigma_C\sigma_D\hat{\tau}_Z}{D} \\
\hat{X}_D^* &= -\frac{\theta_{DZ}\sigma_D(\sigma_U\sigma_C + \Lambda_L(\theta_{CK}\sigma_U + \theta_{CL}\sigma_C)\sigma_D)\hat{\tau}_Z}{D} \\
\hat{Z}^* &= -\sigma_D\left(D + \frac{\Delta_\sigma \theta_{CK}\theta_{DZ}\Lambda_L\sigma_D}{D}\right)\hat{\tau}_Z
\end{aligned}
$$

Where:

$$
\begin{aligned}
\Delta_\sigma &= \sigma_U - \sigma_D \\
D &= \theta_{DK}\sigma_U\sigma_C + (\theta_{CK}(\theta_{DK}+\theta_{DL})\Lambda_L\sigma_U + (\theta_{DL}+\theta_{DZ}+\theta_{CK}\Lambda_L)\sigma_C)\sigma_D + \theta_{CK}\theta_{DZ}\Lambda_L\sigma_D^2
\end{aligned}
$$

As before results depend on parameter values, but this time only on whether σ_U is greater than σ_D. In either case, pollution decreases, the price of the dirty good increases and production in the dirty sector decreases. If $\sigma_U > \sigma_D$, production and use of inputs in the clean sector increase and the price of L decreases. The prices of capital change in an opposite way in the two sectors. In the dirty sector, production decreases and less capital is demanded, so that the price of capital decreases. In the clean sector, production increases, so that more capital is demanded and the price of the clean capital increases. These are the expected conclusions from the model, and the ones related to the more realistic parameter values. If $\sigma_U < \sigma_D$, conclusions are the opposite for what concerns production in the clean sector, use of L and changes in the prices of the production inputs.

A numerical analysis is performed and parameters for several regions and countries are calculated from the GTAP database and reported in Table 1.5.

Table 1.5: Region-specific Parameters

REG	θ_{DZ}	θ_{DK}	θ_{DL}	θ_{CK}	θ_{CL}	λ_{KC}	λ_{KD}	λ_{LC}	λ_{LD}
NAF	0.17	0.20	0.63	0.21	0.79	0.94	0.06	0.95	0.05
AUT	0.08	0.17	0.75	0.25	0.75	0.94	0.06	0.92	0.08
BEL	0.23	0.10	0.67	0.17	0.83	0.95	0.05	0.93	0.07
DNK	0.10	0.16	0.74	0.17	0.83	0.94	0.06	0.94	0.06
FIN	0.09	0.20	0.72	0.20	0.80	0.85	0.15	0.86	0.14
FRA	0.10	0.19	0.72	0.25	0.75	0.94	0.06	0.93	0.07
GER	0.12	0.14	0.74	0.21	0.79	0.95	0.05	0.93	0.07
UK	0.12	0.14	0.73	0.18	0.82	0.95	0.05	0.94	0.06
GRC	0.28	0.10	0.61	0.18	0.82	0.96	0.04	0.95	0.05
IRL	0.12	0.13	0.75	0.19	0.81	0.97	0.03	0.96	0.04
ITA	0.15	0.15	0.70	0.28	0.72	0.96	0.04	0.92	0.08
NLD	0.36	0.14	0.49	0.19	0.81	0.94	0.06	0.95	0.05
PRT	0.16	0.13	0.71	0.12	0.88	0.91	0.09	0.94	0.06
ESP	0.16	0.20	0.64	0.24	0.76	0.94	0.06	0.93	0.07
SWE	0.08	0.15	0.77	0.14	0.86	0.89	0.11	0.91	0.09
CHE	0.03	0.18	0.79	0.19	0.81	0.93	0.07	0.93	0.07
EFT	0.10	0.17	0.73	0.22	0.78	0.94	0.06	0.93	0.07
REU	0.17	0.12	0.71	0.19	0.81	0.92	0.08	0.89	0.11
CZE	0.14	0.16	0.70	0.17	0.83	0.89	0.11	0.90	0.10
POL	0.19	0.15	0.66	0.21	0.79	0.93	0.07	0.92	0.08
HUN	0.21	0.14	0.65	0.21	0.79	0.94	0.06	0.93	0.07
RET	0.18	0.09	0.74	0.13	0.87	0.91	0.09	0.88	0.12
RUS	0.55	0.06	0.39	0.22	0.78	0.95	0.05	0.91	0.09
XSU	0.15	0.04	0.81	0.06	0.94	0.89	0.11	0.85	0.15
ROW	0.19	0.17	0.63	0.21	0.79	0.92	0.08	0.92	0.08

Comparing the values in Table 1.5 with those used by Fullerton and Heutel [36], which are based on stylized facts and on the US economy[15], it is possible to see that they indicate a very similar production structure. As in Fullerton Heutel [36], the values of the λ's show that the clean sector is bigger than the dirty one and that the clean inputs constitute the biggest share. The share of labor is the biggest in the dirty sector. For most countries capital is the second biggest input in the production of the dirty good. However, for some countries θ_{DZ} is smaller than θ_{DK}, showing that the dirty inputs can be a very small share in production even

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[15] Fullerton and Heutel [36] assume that the share of labor and capital invested in the clean industry is 0.8 ($\lambda_{LC} = \lambda_{LD} = .8$), that the input share of capital in the clean industry (θ_{KC}) is .4, and that the the inputs to the dirty industry contribute to production with shares $\theta_{KD} = .3$, $\theta_{LD} = .45$ and $\theta_{ZD} = .25$.

in the dirty industry. Despite differing from the general values used by Fullerton and Heutel [36], this is still plausible as the countries with these characteristics are mostly developing countries and transition economies such as the former Soviet Union area, in which energy inputs constitute a bigger share in the production of energy-intensive products.

For what regards the elasticities of substitution, it is not possible to obtain them from the GTAP database, thus it is necessary to make assumptions on them. Following Fullerton and Metcalf [37], a unity substitution elasticity in consumption between the clean and dirty good ($\sigma_U = 1$) is assumed. The elasticity of substitution between inputs in the clean industry is set to .7 instead ($\sigma_C = .7$), as in Pessoa et al. [76][16]. In the calculations the value of the tax increase is 10%, as in Fullerton and Heutel [36]. This is an arbitrary value used to study the different conclusions the two models reach.

Table 1.6 illustrates results for the numerical analysis of the model with perfect capital malleability. Results reflect the predictions of the theoretical model for the case in which $\sigma_U > \sigma_D$. As expected, production of the clean good increases, while that of the dirty good decreases. There is also an adjustment in the use of production factors in both industries. In fact, capital investments decrease in the dirty industry and move towards the clean industry. As production of the clean good grows, labor invested to produce it also increases, while decreasing in the dirty industry. Pollution Z also decreases as a consequence of the environmental tax imposed. These results apply to all countries and regions considered.

Results on the prices of the production factors instead vary between regions, as they depend on the relative factor intensities. In some regions the price of capital increases while the price of the other production factor decreases. Whereas in other regions the opposite situation is verified. This is because prices change according to the initial intensity of use of the input resources. In countries in which production is more capital intensive, that is $K_D/K_C > L_D/L_C$, as capital becomes more de-

---

[16] Fullerton and Heutel [36] assume a unity elasticity of substitution between capital and labor, based on estimates obtained by Lovell [66] and Corbo and Meller [23]. More recent estimates, such as by Pessoa et al. [76] and Collins and Williams [22] support a value of .7. Furthermore, these estimate are more relevant to the present work as they are based on OECD data rather than US data, as the previous studies.

manded it also becomes more expensive. Thus, the price of capital r grows. On the other hand, where production is less capital intensive, that is $K_D/K_C < L_D/L_C$, the price of capital decreases, while the price of L, w increases. Note how there are only a few countries that are relatively more capital intensive[17]. These are the NAFTA regions, Scandinavian countries, Switzerland, Czech Republic, the Netherlands and Portugal.

Table 1.6: Results with Perfect Malleability of Capital

REG	$\hat{w}$	$\hat{r}$	$\hat{K}_C$	$\hat{K}_D$	$\hat{L}_C$	$\hat{L}_D$	$\hat{X}_C$	$\hat{X}_D$	$\hat{P}_D$	$\hat{Z}$
NAF	0.0	0.0	-0.1	-0.8	0.0	-0.8	0.0	-0.2	2.4	-5.8
AUT	0.0	0.0	0.0	-0.4	0.0	-0.4	0.0	-0.2	1.1	-5.4
BEL	0.0	0.0	-0.1	-1.1	-0.1	-1.1	0.1	-0.2	3.2	-6.1
DNK	0.0	0.0	0.0	-0.5	0.0	-0.5	0.0	-0.2	1.4	-5.5
FIN	0.0	0.0	-0.1	-0.4	-0.1	-0.4	0.1	-0.4	1.2	-5.4
FRA	0.0	0.0	0.0	-0.5	0.0	-0.5	0.0	-0.2	1.4	-5.5
GER	0.0	0.0	0.0	-0.6	0.0	-0.6	0.0	-0.2	1.7	-5.6
UK	0.0	0.0	0.0	-0.6	0.0	-0.6	0.0	-0.1	1.7	-5.6
GRC	0.0	0.0	-0.1	-1.3	-0.1	-1.3	0.1	-0.1	3.9	-6.3
IRL	0.0	0.0	0.0	-0.6	0.0	-0.6	0.0	-0.1	1.7	-5.6
ITA	0.0	0.0	0.0	-0.7	-0.1	-0.7	0.1	-0.2	2.1	-5.7
NLD	0.0	0.0	-0.1	-1.7	-0.1	-1.7	0.1	-0.2	5.0	-6.7
PRT	0.0	0.0	-0.1	-0.7	-0.1	-0.8	0.1	-0.2	2.2	-5.7
ESP	0.0	0.0	-0.1	-0.8	-0.1	-0.7	0.1	-0.2	2.2	-5.7
SWE	0.0	0.0	0.0	-0.4	0.0	-0.4	0.0	-0.3	1.1	-5.4
CHE	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	-0.2	0.4	-5.1
EFT	0.0	0.0	0.0	-0.5	0.0	-0.5	0.0	-0.2	1.4	-5.5
REU	0.0	0.0	-0.1	-0.8	-0.1	-0.8	0.1	-0.3	2.3	-5.8
CZE	0.0	0.0	-0.1	-0.6	-0.1	-0.6	0.1	-0.3	1.9	-5.6
POL	0.0	0.0	-0.1	-0.9	-0.1	-0.9	0.1	-0.2	2.6	-5.9
HUN	0.0	0.0	-0.1	-1.0	-0.1	-1.0	0.1	-0.2	2.9	-6.0
RET	0.0	0.0	-0.1	-0.8	-0.1	-0.8	0.1	-0.3	2.4	-5.8
RUS	0.0	0.1	-0.1	-2.6	-0.3	-2.5	0.2	-0.3	7.6	-7.5
XSU	0.0	0.0	-0.1	-0.7	-0.1	-0.6	0.1	-0.3	2.0	-5.6
ROW	0.0	0.0	-0.1	-0.9	-0.1	-0.9	0.1	-0.2	2.6	-5.9

Results on the reduction in pollution are similar to those obtained by Fullerton and Heutel [36]. They find that a 10% increase in the tax yields to approximately a 6% increase in pollution. In the calculations in Table 1.6, pollution changes range from -7.5 in Russia to -5.1 in Switzerland.

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[17] This is also due to the fact that the production factor L includes different production factors, and is therefore a big share of the inputs

Welfare changes once again depend on $\hat{Z}$, so that they will be higher the greater the change in pollution. Thus, welfare improves more in the case of perfect malleability of capital.

Table 1.7 shows that results in the case of imperfect capital malleability follow the same pattern in all countries. As in the previous case, more of the production factor L is used in the clean industry, and less in the dirty industry, production increases in the clean industry and decreases in the dirty industry, pollution decreases and the price of the dirty good increases. Unlike the previous case however, the price of L always decreases. This is because L becomes relatively less scarce compared with the other production factors, and therefore it loses value. In the clean industry the price of capital increases. This is because, as production increases, more capital is demanded. The opposite happens in the dirty industry, where, as production decreases, capital becomes less demanded and thus less expensive. Welfare is also negatively affected by the carbon tax, even though less than in the case of perfect capital malleability.

By comparing the results, it is possible to see that the carbon tax has a higher effect in the case of perfect capital malleability. In fact, in this case there is a more effective re-adjustment of production patterns and a higher reduction of pollution. Welfare is also more affected in the case of capital malleability, as it is more expensive to offset the costs of the tax and of a higher pollution reduction. Although results are now dependent on relative factor intensities, the overall conclusions of the model are the same as the ones with a single production factor K.

Table 1.7: Results with Imperfect Malleability of Capital

REG	$\hat{w}$	$\hat{r}_C$	$\hat{r}_D$	$\hat{L}_C$	$\hat{L}_D$	$\hat{X}_C$	$\hat{X}_D$	$\hat{P}_D$	$\hat{Z}$
NAF	0.0	0.0	-1.5	0.0	-0.7	0.0	-13.8	14.4	-5.7
AUT	0.0	0.0	-0.8	0.0	-0.4	0.0	-7.7	8.5	-5.4
BEL	0.0	0.1	-1.7	0.1	-0.8	0.0	-10.8	11.7	-5.8
DNK	0.0	0.0	-1.0	0.0	-0.5	0.0	-9.9	10.5	-5.5
FIN	0.0	0.1	-0.9	0.1	-0.4	0.0	-4.0	4.6	-5.4
FRA	0.0	0.0	-1.0	0.0	-0.5	0.0	-9.2	9.9	-5.5
GER	0.0	0.0	-1.1	0.0	-0.5	0.0	-9.3	10.0	-5.5
UK	0.0	0.0	-1.1	0.0	-0.5	0.0	-10.4	11.1	-5.5
GRC	0.0	0.1	-1.9	0.1	-1.0	0.0	-16.6	17.5	-6.0
IRL	0.0	0.0	-1.1	0.0	-0.5	0.0	-16.3	17.0	-5.5
ITA	0.0	0.1	-1.3	0.1	-0.6	0.0	-9.2	10.2	-5.6
NLD	0.0	0.1	-2.3	0.1	-1.1	0.0	-18.4	19.2	-6.1
PRT	0.0	0.1	-1.3	0.0	-0.7	0.0	-10.7	11.2	-5.7
ESP	0.0	0.1	-1.4	0.1	-0.7	0.0	-9.9	10.6	-5.7
SWE	0.0	0.0	-0.8	0.0	-0.4	0.0	-6.1	6.6	-5.4
CHE	0.0	0.0	-0.3	0.0	-0.2	0.0	-7.3	7.9	-5.2
EFT	0.0	0.0	-1.0	0.0	-0.5	0.0	-8.9	9.6	-5.5
REU	0.0	0.1	-1.4	0.1	-0.7	0.1	-6.1	7.0	-5.7
CZE	0.0	0.1	-1.2	0.1	-0.6	0.0	-6.2	6.8	-5.6
POL	0.0	0.1	-1.5	0.1	-0.8	0.0	-9.0	9.8	-5.8
HUN	0.0	0.1	-1.6	0.1	-0.8	0.0	-10.8	11.6	-5.8
RET	0.0	0.1	-1.4	0.1	-0.7	0.1	-5.4	6.2	-5.7
RUS	0.0	0.1	-2.7	0.1	-1.3	0.1	-12.9	14.5	-6.3
XSU	0.0	0.1	-1.2	0.1	-0.6	0.1	-3.7	4.5	-5.6
ROW	0.0	0.1	-1.6	0.1	-0.8	0.0	-8.9	9.6	-5.8

II. Regional and sectoral aggregation

Table 1.8: Regional Aggregation

Code	Description	Participant to EU-ETS
NAF	North-American Free-Trade Area[a]	
AUT	Austria	√
BEL	Belgium	√
DNK	Denmark	√
FIN	Finland	√
FRA	France	√
GER	Germany	√
UK	Great Britain	√
GRC	Greece	√
IRL	Ireland	√
ITA	Italy	√
NLD	Netherlands	√
PRT	Portugal	√
ESP	Spain	√
SWE	Sweden	√
CHE	Switzerland	
EFT	European Free-Trade Area[b]	
REU	Rest of EU[c]	√
CZE	Czech Republic	√
POL	Poland	√
HUN	Hungary	√
RET	Rest of Eastern Europe	
RUS	Russian Feredation	
XSU	Rest of Former Soviet Union	
ROW	Rest of the World	

[a] USA, Canada, Mexico

[b] Norway and Iceland

[c] Cyprus, Estonia, Latvia, Lithuania, Luxembourg, Malta, Slovenia, Slovakia

Table 1.9: Sectoral Aggregation

EU-ETS Covered Sectors	Combustion Sectors	Non-Covered Sectors
Refined coal and petroleum[a]	Coal Mining[a]	Transportation
Pulp and paper	Crude oil and gas mining[a]	Rest of Economy Aggregate
Electric power	Gas production and distribution[a]	
Non-metallic mineral products	Non-ferrous metals	
Iron and steel	Chemical, rubber and misc. plastics	
	Durable manufactures	
	Non-durable manufactures	

[d] Sector producing a fossil fuel whose use generates emissions of CO_2

Chapter 2

Sectoral Extension of the EU ETS: a CGE Study

Abstract

This paper analyzes the sectoral extension of the European Union Emissions Trading Scheme (ETS) of CO_2. It underlines the main factors that influence the decision of including new sectors under the cap-and-trade system, namely the size of the sector in terms of emissions, the possibilities to reduce emissions in that sector, and the possibility to reallocate capital between sectors. The case of aviation is considered as an example and studied in an EU-wide Computable General Equilibrium (CGE) model. Thanks to the detailed regional and sectoral disaggregation of the model, sector- and region-specific costs of the inclusion of aviation in the EU ETS are also calculated. It is found that for what regards aviation, the European Union has chosen to allocate extra emissions in order to keep costs similar to the case in which aviation was not included.

2.1 Introduction

The European Union Emissions Trading Scheme (henceforth, EU ETS) is an EU-wide system for the trade of greenhouse gas emission permits covering emissions from energy and energy-intensive industries. The EU ETS started with Phase I, which lasted from 2005 to the end of 2007, and was followed by Phase II, which started in 2008 and will last till 2012. The first phase was designed as a kick-off trial period to give a chance to the European companies to become confident with emission trading. The emission ceilings for all countries were relatively high and not all EU countries were included, as some had entered the European Union only at a later stage. Verified emissions for the EU-25 area in 2005 and 2006, respectively 2.010 and 2.026 billion tonnes of CO_2, are both lower than the allowed yearly cap for Phase I, which was 2.152 billion tonnes of CO_2[1]. It has been argued that the emission cap has been respected mostly because the established cap was too high and not stringent enough, which was also the explanation for a low carbon price[2]. It is also important to underline that covered emissions in Phase I only accounted for around 41% of total EU greenhouse gases emissions[3]. This is both because only certain sectors were covered, of which only installations above a certain size, and because only CO_2 emissions, and not all greenhouse gases, were included. This is very limitative, especially when emissions in non-covered sectors are increasing, at the risk of offsetting any emission reduction obtained with the ETS.

Proposals for the sectoral expansion of the EU ETS have been made, particularly towards the chemical industry and transportation. In 2008, the EU accepted the proposal[4] to extend the EU ETS to the air transport sector, whose emissions have been increasing to the point of risking to offset the emission reductions from the ETS. The chosen target for emissions from aviation is equivalent to the 97% of the average 2004-2006 emissions. The decision has come in July 2008 after a long debate. In fact, whereas it is seen as too stringent by the industry, it is regarded as too loose by the environmental organizations. The determination of an appropriate target is important, as a high emission ceiling may lead once again to an abundance of emission rights which may lead to low carbon prices. In this case, the risk is to

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[1] European Commission, IP/07/776.

[2] Buchner and Ellerman [17] offer an analysis of Phase I trading prices and argue for the presence of over-allocation.

[3] Commission of the European Communities, SEC(2008) 52, Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC so as to improve and extend the EU greenhouse gas emission allowance trading system, COM(2008) 16 final.

[4] COM/2006/0818 final - COD 2006/0304: Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the Community {SEC(2006) 1684} {SEC(2006) 1685}.

achieve low emission reductions not only within the aviation sector, but also in the other sectors, which will be able to buy more emission permits.

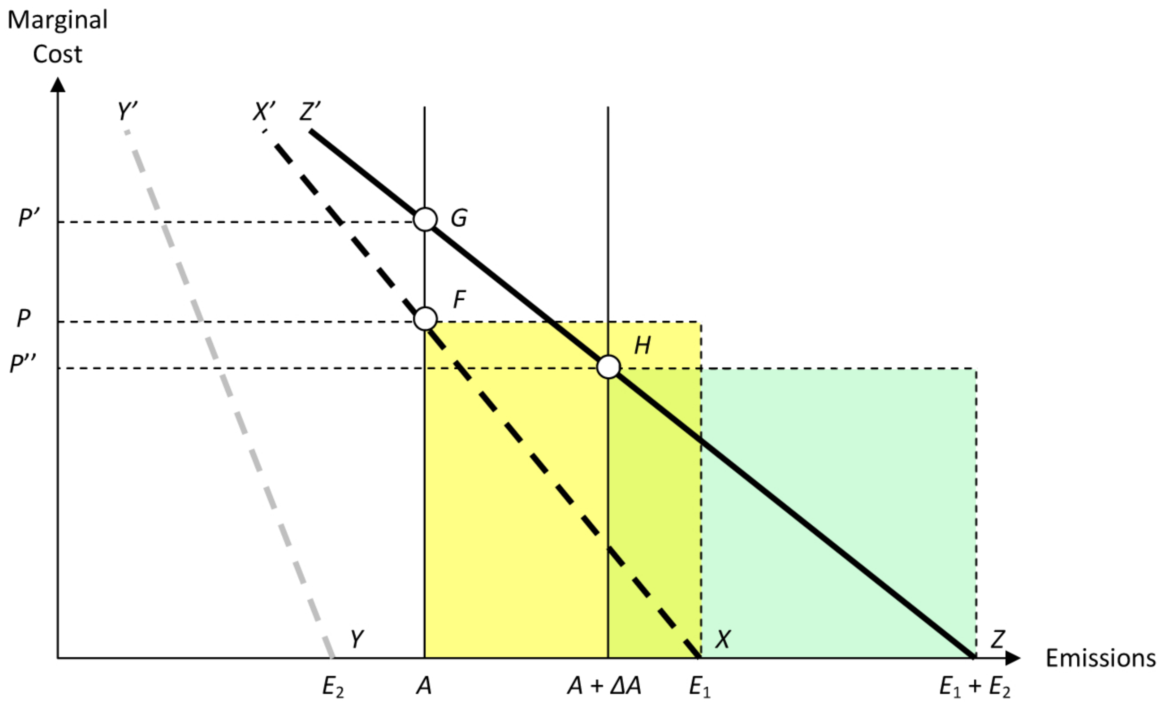
There have been a few examples of analysis of sectoral extension of the EU ETS. Abrell [1] compares welfare gains of adding the different transportation sectors, whereas Van der Laan [92] takes into consideration the costs under different levels of international cooperation. More attention has been given instead on regional enlargement (see Loeschel and Zhang [65], Bosetti et al. [13], and Blanchard, Criqui, and Kitous [10]). An economic analysis of the factors which influence the choice of sectoral extension of the EU ETS is still missing. This paper aims at analyzing this issue thoroughly. We combine a theoretical analysis of the sectoral enlargement of the EU ETS based on Marginal Abatement Cost Curves (MACCs), with an application to the aviation sector. The latter draws on the Computable General Equilibrium (CGE) literature, in which CGE models have been used to construct MAC curves and to study climate policy costs and possibilities (see Ellerman and Decaux [34], Criqui, Mima, and Viguir [24], and Morris, Paltsev, and Reilly [70]). We use an EU-wide CGE model whose disaggregation allows the study of sectoral and regional impacts of the extension of the EU ETS to aviation.

The paper is organized as follows. Section 2.2 presents a theoretical analysis of MAC curves and shows how they can be used to analyze the extension of the EU ETS to new sectors. Section 2.3 considers the case of aviation and uses a CGE analysis to assess the costs and the choice of emission allowances. Section 2.4 concludes.

2.2 An Analysis of the Sectoral Enlargement of the EU ETS

A common tool for the analysis of the impacts of emissions trading and carbon taxes is the use of marginal abatement cost curves (MACCs). These are determined by the permit prices and their corresponding emission reduction targets. Figure 2.1 illustrates how including a new sector in the ETS will change the MAC curves and thus the equilibrium market prices.

Figure 2.1: Marginal Abatement Cost Curves



Nomenclature:

XX′	MAC curve for original covered sectors with BAU emissions E_1
YY′	MAC curve for new sector with BAU emissions E_2
ZZ′	Aggregate MAC curve including aviation with BAU emissions $E_1 + E_2$
A	Original allowance allocation
ΔA	Incremental allowances issued by regulator to accommodate inclusion of new sector

With the original set of covered sectors, the MACC is given by the XX' curve, and allowance allocation in Phase II is given by A. The equilibrium of the permit market is at point F, which determines a market-clearing price P. The MAC for reducing emissions from the new sector is YY'. Given these results, when the ETS is enlarged to include the new sector, the aggregate MAC curve has an outward shift to curve ZZ', which is the horizontal sum of curves XX' and YY'. The new sector's abatement opportunities make the ZZ' curve more elastic (i.e. less steeply sloped) than the MAC curve of each of its two constituents XX' and YY'. Note that as long as the YY' does not intersect the vertical axis, ZZ' never intersects XX'. Therefore, if the total quantity of allowances remains unchanged, the new equilibrium will be at G, thus determining a higher market-clearing price $P' > P$. Total compliance costs will invariably rise. Symmetrically, generating a given quantity of abatement with an additional sector in the trading scheme will cost less at the margin if the new sector is excluded.

Cognizant of this fact, a regulator would likely issue additional allowances in order to moderate permit prices while at the same time generating larger amounts of real abatement. For example, relaxing the aggregate emission target by an amount ΔA will shift the allowance curve to $A + \Delta A$ and the equilibrium to H. The market-clearing price for carbon trading would thus lower to P'', increasing abatement ($\Delta A < E_2$), but keeping the total cost of compliance roughly constant. Compliance costs are illustrated by the shaded areas, which are approximately the same size for the ETS with and without the additional sector. Had the additional emission quotas (ΔA) been selected at a much lower level, the costs of the ETS with the inclusion of an additional sector would have been much greater than in the case of ETS without the new sector. Similarly, with a higher amount of additional permits, the costs would have been reduced and the stringency of the regulation would have been much lower. The results are dependent on the relevant elasticities, and with uncertain values of elasticities, it is easy to issue too many additional allowances.

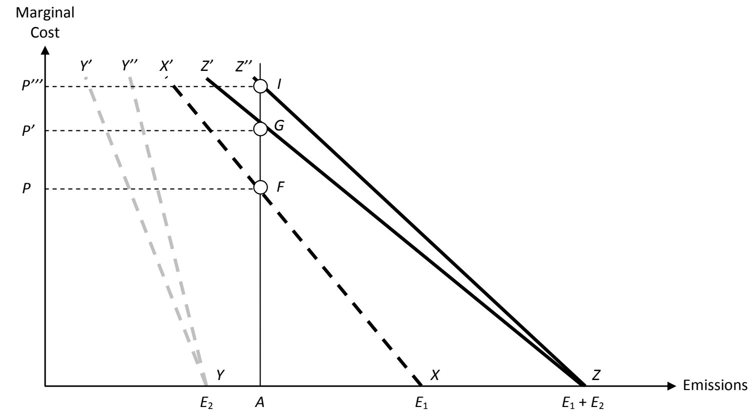
The decision of the policy maker in allowing extra permits, will depend on the characteristics of the new sector. Two factors are of main importance, namely the marginal abatement possibilities of the sector, and the size of the sector in terms of emissions.

Figure 2.2 illustrates the influence of the slope of the marginal abatement costs, and of the relative size of the sector in terms of emissions. The first figure illustrates that if the additional sector has a flat MACC, meaning that it has a high ability to reduce emissions, the additional costs of inclusion of this sector will be relatively low. When instead the MACC is steep (and vertical in the extreme case) and the sector is rigid in reducing emissions, the costs of including the sectors in the ETS will be high. In this case, the policy maker may decide to allocate additional allowances to keep costs low.

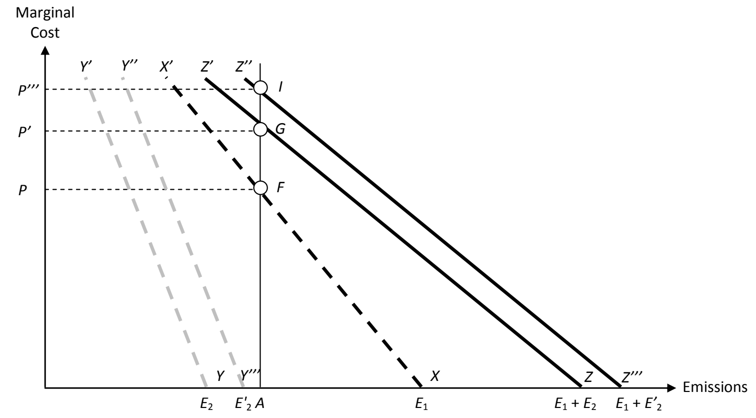
The second figure illustrates the relevance of the sector's emissions. The larger the size of the sector in terms of emissions, the higher the costs of including it in the ETS. Thus, once again, in the case of the inclusion of a particularly large sector, the decision maker may decide to issue additional allowances.

Figure 2.2: Factors influencing costs

1. DIFFERENT SLOPE OF MARGINAL COSTS



2. DIFFERENT QUANTITY OF EMISSIONS IN NEW SECTOR



Another factor that may influence the decision to sectorally enlarge the ETS, is the ability of capital to be reallocated within sectors. The degree of sectoral capital malleability, as highlighted by Jacoby and Sue Wing [54] has an adverse impact on the short-run macroeconomic costs of compliance with climate policies. In the case in which capital cannot easily be reallocated from the new sector to sectors with higher abatement capabilities, the costs of including the sector will be higher.

Finally, the sectoral and regional impacts that the inclusion of a new sector my have, should also be taken into consideration. In fact, even if the sector were characterized by high abatement possibilities and small relative amount of emissions, it would still be important to check the effects that including it in the ETS would have on other sectors, and on regional welfare.

2.3 The Case of Aviation

There are a number of issues involved with including aviation in the EU ETS. First, there are concerns with the effect that regulating emissions from aviation will have on the sector, especially given that, at least in an initial phase, only European countries will take part to the program. Second, allocation and distribution of allowances is likely to play a key role in the impacts the regulation will have on the individual airline companies. Third, flight prices are very likely to increase consistently, so that the burden of the emission trading regulation is going to be entirely on the consumers. The macroeconomic costs will depend on the reliance of each country on the aviation sector both in terms of intensity of trade and as opposed to other means of transport. Finally, there are concerns on the effectiveness of the extension of the EU ETS to include aviation with respect to the actual emission reduction achieved. This paper exploits the features of a multi-region and multi-sector CGE model to analyze the two last aspects, focusing on the macroeconomic aspects rather than on the strategic interactions and other microeconomic aspects.

After an initial proposal to include aviation in the ETS, which followed the EU Commission legislative proposal of December 2006, there have been wide debates on the actual implementation. The European Commission and Parliament have chosen as reference point the average emissions from aviation in the 2004-2006 period. These will then need to be cut by 3% in 2012 and 5% from 2013 onwards. This emission allowance is regarded as too stringent by the airlines and industrial associations, which proposed instead a cap equivalent to 110% of the 2007-2009 emissions. Finally, green associations argue that the cap is not stringent enough and that the EU has missed a chance in implementing a regulation which could have greatly limited greenhouse gases emissions. They supported a target equivalent to the 75% of the average 2004-2006 emissions.

In the simulations we will build MACC for the ETS with and without aviation. We will also compare the additional chosen cap on emissions from aviation (97% of average 2004-2006 emissions) with a baseline case in which aviation is not included in the ETS, and another scenario in which aviation is included but with no extra emissions allowance than in the baseline case. Comparing the two scenarios in which aviation is included with and without extra emission allowances, allows better understanding the impact that the inclusion of aviation has on the different sectors and countries, and the reasons for which extra emission quotas were necessary.Table2.1 summarizes the scenarios considered.

Table 2.1: EU ETS Scenarios (Phase II at 2012)

NoAir	Baseline EU ETS
Air	Inclusion of aviation with no extra emissions allowances
AirExtra	Inclusion of aviation with extra emissions allowances equivalent to -97% of average 2004-2006 emissions

2.3.1 Model Description

The model employed for policy simulations is a static multi-region CGE model based on Harrison, Rutherford and Tarr [46], and outlined in Rutherford [83]. The model divides the world into 25 regional economies, each of which contains one representative agent, and 15 industries (see the Appendix). Agents are endowed with labor and capital, which are internationally mobile. They rent out these resources to domestic industries in return for factor income. Each industry produces a single homogenous output good, demanded by other producer sectors and the representative agent. The economies are linked by bilateral trading according to the Armington [7] assumption whereby regions' exports of a given commodity are differentiated. The use of each commodity is given by a constant elasticity of substitution (CES) composite of domestically-produced and imported varieties of that good.

Agents minimize expenditure and are assumed to have a Cobb-Douglas utility function. Consumers also have a constant marginal propensity to save from their income. The government is explicitly represented, though it has a passive role. Industries are modeled as cost-minimizing representative firms where technology is given as a nested CES production function. Parameters differ across regions.

The CGE model formulates the general equilibrium problem of equalizing demand and supply simultaneously across all markets as a mixed complementarity problem, or MCP (see Mathiesen [69], Rutherford [81]). Cost minimization by the industries and expenditure minimization by the representative agent in each region give rise to vectors of demands for commodities and factors. Demands are functions of domestic factor prices, domestic and international commodity prices, industries' activity levels, and the income levels of the regional representative agents. These demands are combined with the general equilibrium conditions of market clearance, zero-profit, and income balance. This yields to a square system of non-linear inequalities that forms the aggregate excess demand correspondence of the world economy (cf. Sue Wing [87]).

The benchmark dataset is the GTAP6 database (Dimaranan and McDougall [30]). This database is a snapshot at the world economy in 2001. Data from bilateral trade, transport, and protection are combined with individual country social accounting matrices and energy balances to constitute an approximation of the world economy as if it were in a full economic equilibrium. The original dataset contains 87 world regions and countries, and 57 sectors, but it was aggregated to the 25 regions and 15 sectors described in the Appendix.

Transportation is modeled as trade margins, meaning that both profits and costs for transportation are on behalf of the exporter country. The model differentiates between air, sea and land transportation. Because the transportation is only accounted for if there is an international transaction, there is no account of emissions from transportation due to commuters or personal journeys. Though this is a limitation, especially given the increasing air traffic for private journeys in the EU, the model still allows us to see how much each sector and country relies on air transport for trade and thus the extent to which it is likely to be affected by the ETS.

Elasticity of substitution between energy inputs is assumed to be .5. Elasticities of substitution between domestic and imported intermediate products range from

.3 to 11.0 according to the different products. Elasticities of substitution of intermediates across regions range from 3.8 to 33. These are adapted from Dimaranan and McDougall [30] and are assumed to be the same across regions. A baseline projection of economic activity in 2012 was prepared by scaling the endowments in each region according to GDP growth rates. These were calculated using historical data from 2001 to 2008, and the 2007 IMF World Economic Outlook forecasts for the period 2009-2012.

The model also includes sector- and region-specific CO_2 emissions. The emission coefficients that link CO_2 emissions to the model's projection of economic activity were computed by first estimating emissions by sector and fuel for each region based on the International Energy Agency (IEA) energy balances for 2001 following Lee [62]. Then emissions quantities were divided by the economic values of the corresponding flows of fossil fuels given in the GTAP6 database. The result is a consistent set of relationships between the economic quantities of the sectoral demand for fossil fuels and their associated CO2 emissions for the benchmark year. It is assumed that this continues to hold through- out the period of operation of the EU ETS[5]. The implementation of the EU ETS is done by imposing an upper limit to CO_2 emissions for each participating countries. Countries are then free to allocate emissions between the covered sectors, to re-adjust their production patterns, and to trade between each other. When emission trading is extended to include the air transport sector, it is sufficient to extend the set of covered sectors.

Some assumptions were required to estimate the extent of the combustion sector coverage, as it is only partly covered by the EU ETS. For each combustion sector, it was necessary to estimate the share of total CO_2 emissions that were attributable to large combustion installations. The only data available were the 2001 IEA energy statistics on countries' emissions from "unallocated producers" (generators of electricity or heat for personal consumption) whose use of fossil fuels was not apportioned between industrial and "other" sectors. Accordingly, unallocated producers were treated as representing emissions of combustion installations in all of the combustion sectors in each country. The average proportion was calculated for each

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[5] This is equivalent to assuming no autonomous energy efficiency improvement (AEEI) over period 2001-2012.

country and used to assign the amount of emissions from unallocated producers. Although using the average value is not realistic, the limitations of the data make it impossible to capture sectoral heterogeneity.

The model is calibrated to account for the high international crude oil and natural gas prices, which are expected to be a key factor in the abatement of emissions and in the trading of allowances. Preliminary runs of the models showed the prices of oil and gas in the European countries falling in real terms over the period 2001-2012, when world prices were increasing. To resolve this situation, supplies of the fixed factor in the oil and gas sectors in the NAFTA and Rest of the World regions have been reduced, and fixed factor supplies have been restricted in the remaining regions. As a result, import prices of these commodities in European countries are 90-100 percent higher than in the 2001 base year.

There are a few shortcomings in using the GTAP model for this analysis. First of all, it cannot distinguish between the dimension of the airplanes. This is relevant as light aeroplanes[6] will be exempt from the regulation. This may lead to a wider diffusion of light planes in the future, and this switching could not be presented in the model. Similarly, airline companies with low emissions will not be included. This issue is part of the competitiveness concerns, as these small companies may gain market power. Finally, it is not possible to attribute intra-European flights to the EU if the transaction corresponding to the flight is originating from outside the EU[7]. This may be creating a bias and leading to lower carbon prices than expected, as the emissions accounted for are lower than the actual covered ones. However, these issues would need to be analyzed in a different framework, which may not permit an extensive macroeconomic study as the present one.

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[6] Under 5.7 tonnes.

[7] For example if somebody buys a flight in the US to go to China going through Europe. The model will account this as a transaction from the US to China and therefore will not account for it in the EU ETS.

2.3.2 Emissions from Aviation

The inclusion of aviation in the ETS increases total covered emissions by 5%. Covered emissions vary by country[8]. Table 2.2 shows the change in covered emissions for the ETS regions, as well as the percentage increase in emissions. The biggest increases in covered emissions are in Denmark (+27.7%), France (+23.3%), and Ireland (+16.06%). The lowest increases are in Poland (+0.4%) and Greece (+0.5%). We expect the countries that have an increase in emission allowances to result in higher final emissions. Table 2.2 also compares baseline (no policy) emissions with the extra emission allowances granted for aviation. These are very similar, although slightly superior to the baseline levels. Given that the increase in covered emissions is substantial especially in some countries, the choice to allocate extra emissions appears reasonable.

Table 2.2: Covered Emissions and Emissions from Aviation($MtCO_2$)

Region	NoAir	Air	%increase	Aviation Emissions	Aviation Permits
AUT	38.5	41.9	8.9	3.4	3.5
BEL	94.7	98.0	3.5	3.3	3.4
DNK	23.4	29.9	27.7	6.5	6.7
FIN	152.7	155.2	1.7	2.5	2.6
FRA	113.3	139.7	23.3	26.4	27.4
GER	529.6	547.4	3.3	17.7	18.4
UK	292.1	318.7	9.1	26.6	27.6
GRC	84.1	84.6	0.6	0.5	0.6
IRL	23.8	27.6	16.1	3.8	4.0
ITA	247.5	253.0	2.2	5.5	5.7
NLD	235.9	242.7	2.9	6.8	7.0
PRT	36.9	38.4	4.0	1.5	1.5
ESP	181.6	196.8	8.4	15.3	15.9
SWE	25.1	28.3	12.8	3.2	3.3
REU	107.9	111.5	3.3	3.6	3.7
CZE	119.0	120.2	1.0	1.2	1.2
POL	264.3	265.8	0.6	1.5	1.5
HUN	42.7	43.8	2.7	1.1	1.2
TOT	2613.1	2743.5		130.5	135.3

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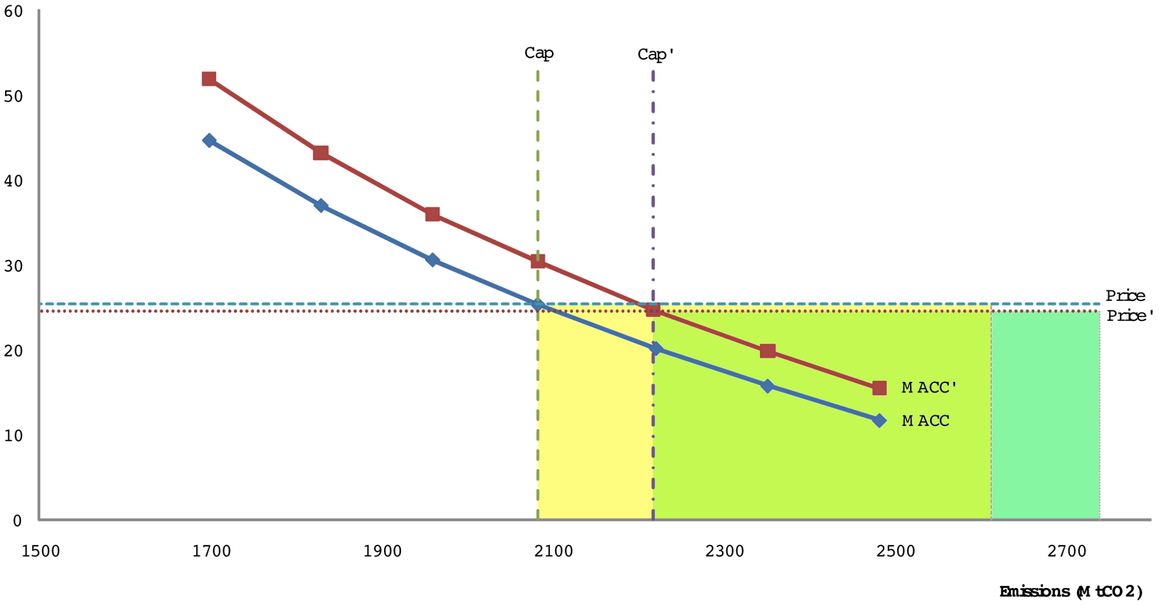
[8] Whereas the country-specific targets for the ETS are specified by the European Union, the additional quotas for aviation are not. However, the EU gave indications on wanting to give out permits according to historical emissions. Calculations have been made on the base of the size of the air transport sector in the 2001 GTAP Database.

2.3.3 Marginal Abatement Costs

Aviation is an inelastic sector, as it is necessary for transportation of goods and people. In the CGE model used, transportation is used as a marginal commodity to other goods, as it is necessary for international trade. This reflects the fact that it is an inelastic sector, necessary for the economy to carry on growing and expanding in terms of trade flows. Thus, we expect the marginal abatement costs for aviation to be steeply sloped, almost vertical.

Using the CGE model described, we simulated the ETS with different caps with and without aviation, so as to build MAC curves in both cases[9]. Figure 2.3 illustrates the MAC curves, the market clearing prices and the costs.

Figure 2.3: Simulated Marginal Abatement Cost Curves



We can see that the two curves are basically parallel. This shows that the aviation sector does not increase the abatement possibilities. This is coherent with the expected rigidity from the sector. This also supports the choice of policy makers to allocate extra emissions. Including aviation in the ETS increases the carbon price, and overall costs. This also supports the allocation of extra allowances for aviation.

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[9] The reference values used for the simulations correspond to a 5, 10, 15, 20, 25, 30, and 35% reduction compared to the baseline emissions.

In fact, when this is done costs are lowered back to the a level similar to the initial one before the inclusion of aviation (in the Figure costs for the cases of ETS with aviation without and with extra emission allowances correspond to the yellow and green areas respectively).

2.3.4 The Role of Capital Malleability

We expect that in the short run there is likely little capital malleability between sectors, especially in the case of aviation for which there is low possibilities of capital reallocation. Thus, it is interesting to see how results change in the case of assumption of no capital malleability. Table 2.3 shows the comparison of results with the case of imperfect malleability of capital, obtained by making capital sector-specific. It is found that costs are higher if capital is not assumed to be fully malleable. This also supports the choice of issuing extra emission allowances. Even in the case of imperfect malleability of capital, the costs of ETS with and without aviation and the extra allowances are similar. The market clearing price increases much more in the case in which no extra emissions are allowed. Without the possibility to reallocate capital it becomes more expensive to reduce emissions. Comparatively, the stricter the target is, the bigger the difference in price between the perfect and imperfect malleability of capital scenarios. Furthermore, the difference is larger in the case where aviation is included with extra permits than in the case with no aviation, even though these two scenarios have been shown to have similar costs. This is due to the fact that aviation is a rigid sector, making it more costly to re-allocate resources after the ETS.

Table 2.3: Capital Malleability

	Perfect Malleability	Imperfect Malleability	%change
NoAir	25.3	26.5	4.7
Air	30.2	32.4	7.3
AirExtra	24.6	26.2	6.5

2.3.5 The Choice of the Cap

The previous sections have shown that due to the characteristics of the aviation sectors, its inclusion in the ETS without extra allowances would lead to much higher costs.This supports the choice of the EU. The remaining question to be addressed is whether the chosen cap was reasonable.

Table 2.4: Simulation Results ($MtCO_2$)

	NoAir	Air	AirExtra
Initial covered emissions	2613.0	2743.6	2743.6
Initial aviation emissions	130.5	130.5	130.5
Final covered emissions	2083.6	2083.6	2217.9
Final aviation emissions	123.2	114.6	117.5
Final total emissions	2206.2	2083.6	2217.9
Price CO_2 (€/tCO_2)	25.3	30.2	24.6
Cost (€)	13409.9	19948.8	12932.2

The first step is to compare the outcome of the ETS without aviation with that of the ETS with aviation but without any additional allowances. In this case, emissions would be further reduced of the exact amount corresponding to overall emissions from the air transport sector. This would not only enlarge the scope of the ETS directive, but also reduce CO_2 emissions by a larger amount. It would lead to a 49% increase in costs due to the higher amount of emissions reduced and to the carbon price, which would be 19% higher than in the ETS without aviation.

If extra permits are distributed, both the costs and market clearing prices will become similar to the initial case without aviation. Emissions from aviation are reduced in all ETS cases, and more so in the cases where aviation is included in the emission trading. Total aviation emissions are lower in the case of aviation without extra emissions, and slightly greater when extra permits are distributed. Table 2.4 summarizes these results.

In the case where there are no extra emissions, or the reference level proposed by the green organizations had been allocated, the costs would have become higher, with both a higher price and emission reduction. Had the choice of the lobbies been implemented instead, the costs would have become lower, thus creating more hot air and lowering the effectiveness of the ETS. Table 2.5 compares the three targets proposed, demonstrating that the middle target , chosen by the EU, is the one where costs are similar to the initial costs.

Table 2.5: Simulation Results ($MtCO_2$)

	NoAir	Air_{Green}	Air_{EU}	$Air_{Lobbies}$
Emission quotas allowed	2082.9	2184.1	2217.9	2250.0
- of which extra for aviation	0.0	101.2	135.0	167.1
Initial emissions	2613.0	2613.0	2613.0	2613.0
- of which from aviation	130.5	130.5	130.5	130.5
- of which from other sectors	2613.0	2613.0	2613.0	2613.0
Final emissions	2206.1	2184.1	2217.9	2250.0
- of which from aviation	123.2	116.8	117.4	118.1
- of which from other sectors	2082.9	2067.4	2100.4	2131.9
Price CO_2 (€/tCO_2)	25.3	25.9	24.6	23.3
Cost (€)	13423.6	14485.2	12908.6	11511.6

The choice of the EU appears to have been aimed at keeping the costs similar to the ones they would have incurred without including aviation in the ETS, both in term of emissions and of CO_2 prices. These are consequent to the choice of distributing extra permits to a level that is similar to baseline emissions. As a first trial for the inclusion of a transportation sector in the ETS, bearing in mind that the cap on aviation will increase in the years following 2012, the choice of the EU seems reasonable. Given the problems that may arise on the aviation sector due to the fact that non-EU companies do not undergo the same restrictions on non-EU territory, and given the necessary re-organization within the air transport sector, the choice of keeping overall costs almost constant appears to be effective.

2.3.6 Sectoral and Regional Effects

Even once established that aviation could be included at no extra costs issuing more emission allowances, it is still important to study the sector- and region-specific costs. In fact it is important to check the consequences of sectoral enlargement in a more disaggregate way.

Table 2.6 illustrates that the inclusion of aviation in the ETS leads to even further emissions in the energy-related sectors (coal, oil, and electricity). More reductions are made in these sectors than in the aviation sectors. This is not surprising, as the aviation sector is inelastic, so that more emissions are reduced in other sectors.

Table 2.6: Sectoral output (M US$)

Sector	Baseline	NoAir	Air	AirExtra	%NoAir	%Air	%AirExtra
COAL	15.0	13.1	12.6	13.2	-12.3	-16.0	-11.7
OIL	19.8	19.7	19.7	19.7	-0.4	-0.5	-0.4
GAS	41.9	44.9	41.6	45.4	7.1	-0.8	8.2
REF	157.4	135.9	131.8	136.1	-13.7	-16.2	-13.5
PPP	445.7	442.4	441.9	442.5	-0.7	-0.9	-0.7
CRP	1052.2	1023.6	1019.5	1024.7	-2.7	-3.1	-2.6
NMM	293.2	286.8	285.9	287.1	-2.2	-2.5	-2.1
I_S	264.1	252.8	251.1	253.2	-4.3	-4.9	-4.1
NFM	148.9	143.6	143.0	143.9	-3.5	-4.0	-3.4
DUR	3025.6	3027.3	3029.6	3028.5	0.1	0.1	0.1
NDUR	1384.0	1382.7	1383.0	1383.0	-0.1	-0.1	-0.1
ELEC	333.0	309.3	304.9	310.0	-7.1	-8.4	-6.9
TRN	842.2	826.2	823.0	826.1	-1.9	-2.3	-1.9
AIR	137.5	132.2	125.2	127.1	-3.8	-8.9	-7.5
ROE	11251.5	11254.7	11254.5	11254.9	0.0	0.0	0.0

When extra allowances are granted for aviation, output changes are similar to the ETS case with no aviation. Although output declines in the aviation sector, there is still a larger amount of output reduction that occurs in the energy sectors. This shows that adding new sectors to the ETS does not change the pattern of emissions reduction as they still occur in the same sectors, especially in the case in which extra allowances are issued.

Finally, it interesting to see which countries are most affected from ETS and from the inclusion of aviation. Countries with particular reliance on aviation, such as Denmark or France, while having a positive effect due to the ETS, have a negative one once aviation is also included. In general, the changes in equivalent variation show that there is lower welfare when aviation is also included. However, then extra allowances are granted, the worsening in equivalent variation is limited.

Table 2.7: Regional Costs (Equivalent Variation)

Region	NoAir	Air	AirExtra
AUT	-0.12	-0.21	-0.12
BEL	-1.28	-1.55	-1.25
DNK	0.12	-0.09	0.01
FIN	-7.70	-8.19	-7.01
FRA	0.08	-0.09	0.04
GER	-0.56	-0.68	-0.63
UK	-0.30	-0.46	-0.39
GRC	0.01	0.07	0.10
IRL	0.26	0.11	0.34
ITA	-0.64	-0.77	-0.68
NLD	-2.49	-2.92	-2.32
PRT	5.87	4.83	6.11
ESP	-0.37	-0.60	-0.30
SWE	0.08	-0.04	0.00
REU	4.07	4.80	3.83
CZE	-1.63	-1.64	-1.24
POL	-0.59	-0.52	-0.58
HUN	-0.68	-0.87	-0.33

2.4 Conclusion

This paper presents an analysis of the factors that influence the decision of sectoral enlargement of the EU ETS. It is shown that the size of the sector in terms of emissions, the abatement possibilities, and the possibility to reallocate capital across sector all have an influence on the costs of including new sectors. It is also shown that when including new sectors may lead to much higher costs, it is possible to lower costs by issuing extra allowances. Given these results, the case of the extension of the EU ETS to the aviation sector is analyzed with the use of an EU-wide Computable General Equilibrium (CGE). We find that the choice of the EU in issuing extra allowances was supported by the characteristics of the aviation sector, both in terms of its rigidities and its influence on other sectors and on regional economies. The cap chosen by the EU has a value thanks to which costs and prices of the ETS were kept similar to the original ones before the inclusion of aviation. Considering that the aim of the EU is to further restrict emissions in the subsequent years, it appears to be a safe option as a first experiment of sectoral enlargement of the ETS.

Appendix

Regional and Sectoral Aggregation

The following tables illustrate the regional and sectoral aggregations used for the numerical analysis and the computable general equilibrium model.

Table 2.8: Regional Aggregation

Code	**Description**	**Participant to EU-ETS**
NAF	North-American Free-Trade Area[a]	
AUT	Austria	√
BEL	Belgium	√
DNK	Denmark	√
FIN	Finland	√
FRA	France	√
GER	Germany	√
UK	Great Britain	√
GRC	Greece	√
IRL	Ireland	√
ITA	Italy	√
NLD	Netherlands	√
PRT	Portugal	√
ESP	Spain	√
SWE	Sweden	√
CHE	Switzerland	
EFT	European Free-Trade Area[b]	
REU	Rest of EU[c]	√
CZE	Czech Republic	√
POL	Poland	√
HUN	Hungary	√
RET	Rest of Eastern Europe	
RUS	Russian Federation	
XSU	Rest of Former Soviet Union	
ROW	Rest of the World	

[a] USA, Canada, Mexico

[b] Norway and Iceland

[c] Cyprus, Estonia, Latvia, Lithuania, Luxembourg, Malta, Slovenia, Slovakia

Table 2.9: Sectoral Aggregation

EU-ETS Covered Sectors	**Combustion Sectors**	**Non-Covered Sectors**
Refined coal and petroleum[a]	Coal Mining[a]	Sea and Land Transportation
Pulp and paper	Crude oil and gas mining[a]	Rest of Economy Aggregate
Electric power	Gas production and distribution[a]	
Non-metallic mineral products	Non-ferrous metals	
Iron and steel	Chemical, rubber and misc. plastics	
Aviation	Durable manufactures	
	Non-durable manufactures	

[d] Sector producing a fossil fuel whose use generates emissions of CO_2

Chapter 3

Innovation in Electricity Generation Technologies: a Patent Data Analysis

Abstract

This paper focuses on innovation in energy-efficient electricity generation technologies. The evolution of different types of technologies - renewables, fossil fuel based, nuclear and fuel cells - is analyzed by considering patent data relative to 16 OECD countries over the period 1978-2006. Patent data is also used to study the determinants of innovation, particularly focusing on the role that fossil fuel prices play in inducing innovation in electricity generation. We find that although the effect of fossil fuel prices on aggregate energy-efficient technologies is positive, it varies according to the different types of technologies. The effect is negative on fossil fuel technologies, illustrating that there is a substitution effect from fossil fuel based towards carbon free technologies.

3.1 Introduction

In the past years we have seen increasing political efforts to tackle the problem of climate change. Nevertheless, the results of the policies chosen so far have been scarce. Furthermore, with rising emissions from developing economies, climate targets, such as the ones proposed by the International Panel on Climate Change Agreement (IPCC), appear hard to achieve. In this context, the importance of the development and use of new energy-efficient technologies for the production of electricity is crucial. The electricity production sector accounts for about a quarter of the overall anthropogenic CO_2 emissions, thus greatly contributing to the problem of climate change. Investment in new energy-efficient technologies for power generation, both fossil fuel based and carbon free, is essential for the realization of policy objectives.

Plants based on fossil fuel inputs are still more diffused. According to the International Energy Agency *Key World Energy Statistics 2006* (IEA [52]) total world total primary energy supply mostly relies on fossil fuels. In 2005, 35% of energy was produced with oil, 20.7% with gas and 25.3% with coal. Nuclear energy accounted for 6.3%, hydro for 2.2%, and renewables for 10%. In OECD countries the shares also show a strong reliance on fossil fuel energy. Renewable energy in 2005 accounter for only 3.5%, and hydro for 2%. A greater share was instead covered by nuclear with an 11% of total primary energy supply. Although there have been some changes and there exist differences between countries and regions, the greatest share of energy is still produced with fossil fuels. This causes problems of high emissions of greenhouse gases, as well as difficulties with energy security due to the uncertainties in the supplies of fossil fuels. Given the high reliance on fossil fuel energy, it is very important that new technologies for the combustion of fossil fuels are invented. It is also important that carbon free technologies are developed in order to increase their share of contribution to electricity production. It is crucial not just that energy-efficient technologies are invented and diffused, but that within these technologies there is a switching from fossil fuels based to carbon free technologies.

The present work attempts to analyze the dynamics of innovation in energy-efficient technologies using patent data. We focus on the effect of fossil fuel prices, as in indicator of the pressure on the electricity market also deriving from increasing attention on climate change. Fossil fuels are the most important input in the production of electricity in combustion plants. Increasing fossil fuel prices should stimulate investment in the development of new technologies that require less use of fossil fuel. As fossil fuel prices rise, we expect an efficiency effect that will induce innovation in all energy-efficiency technologies for electricity generation. However, there may also be a substitution effect driving away innovation from fossil fuel to carbon free technologies. This hypothesis is supported by recent works on directed technical change applied to the environmental sphere, such as Acemoglou et al. [3] and Sue Wing [88]. In these, it is found that the substitution between intermediate inputs is the crucial parameter in the determination of innovation in the two intermediates. Thus, if the substitution effect prevails over the efficiency effect, innovation in fossil fuel technologies should decline. In the other technologies instead, we expect a positive effect as both the efficiency and the substitution effects will induce more innovation. In the case in which the substitution effect is particulary strong, there may even be a decline in the overall amount of patents in the energy sector.

We also aim at finding out which economic variables lead to the production of more energy-efficient technologies. We use R&D expenditure as an indicator of the amount of investment that is made in the electricity sector. As underlined by Nemet and Kammen [71], R&D is an essential component of an innovation strategy to improve energy efficiency. The hypothesis for what regards R&D is that the higher is the R&D expenditure, the higher is the innovation in terms of patented technologies. Innovation also depends on the size of the sector and of the market it is serving. In a large and fast growing market there will be higher potential for inventive talent and stimulus to improve efficiency(see Popp [79]). We use electricity consumption to proxy for the growing size of markets and expect that it will have a positive sign. Finally, we expect countries that have a high propensity to patent and a large production of innovative output to produce more innovation. To control for this effect we also use total number of patents as an explanatory variable.

We draw on the literature on induced innovation and patents. Lanjouw and Mody [60] for example examined the relationship between patenting activity and stringency of environmental policy measured in terms of pollution abatement. They found that pollution abatement induces innovation by increasing the number of patents. Jaffe and Palmer [55] use R&D expenditure and patents to study whether changes in regulatory stringency lead to innovation. They do not find evidence that patenting activity responds to environmental regulation. More recently, studies such as Popp [79] focused on the effect that different policy instruments have on innovation. He finds that command-and-control policy instruments are less effective than market-based instruments. Instead of focusing on environmental regulation, Popp [77] considers the effect of energy prices on innovation in energy-efficient technologies. He shows that energy prices are a determinant of innovation. Most of these studies are country-specific or consider a limited number of countries. De Vries and Withagen [27] use cross-country data to investigate the relationship between environmental policy for limiting SO2 emissions and patenting activity. They find some evidence that stringency of environmental policies induces innovation. A recent study by Johnstone et al. [57] uses a panel of OECD countries, data on patents and R&D for different renewable technologies and on different types of environmental regulations, to check for the presence of induced innovation. They find that different types of policies are effective for different types of renewable technologies.

This paper applies the framework used in Johnstone et al. [57] to study the dynamics of innovation between different technology types induced by fossil fuel prices, using a panel of patent data relative to 16 OECD countries over the period 1978-2006. This is a very relevant point for a number of reason. First, it contributes to the literature on directed innovation in the environmental arena by giving some insights on the substitutability between different types of energy. Second, it illustrates that fossil fuel prices drive innovation in energy-efficient electricity generation technologies, although they have a negative effect on innovation in fossil fuel based technologies. Thinking of patents as a leading indicator for capacity, this is an interesting policy message. It supports the use of increasing costs on the use of fossil fuels as an incentive to reallocate production towards carbon free technologies. We also find that R&D expenditure, and the general propensity to patent drive innovation.

The paper is organized as follows. Section 3.2 describes the data used with a particular focus on patent data, which are analyzed to understand the innovation dynamics. Section 3.3 illustrates the empirical analysis by specifying the model, the estimation method used, and the empirical results. Section 3.4 concludes.

3.2 Data Description and Analysis

3.2.1 Patent Data

Patents have emerged as one of the main indicators used for measuring innovation. They are a measure of the output of innovation, and as such reflect the innovative performance of firms and economies (Griliches, 1990). They are a useful indicator as they can be distinguished by the nature of the applicant, and of the invention. This allows dividing patents by country and by technological field. Although not all inventions are patented, as underlined in Dernis and Guellec [28] there are few examples of economically significant inventions that have not been patented. Patents are issued by national offices and answer the necessity to protect new technologies with property rights which exclude others from the production for a defined number of years, which varies upon the nature of innovation and the rules of the national offices. In order to be patented, an innovation needs to be novel, non-obvious, and commercially viable (Dernis and Guellec [28]).

Although very useful, patents are an imperfect measure of innovation. First of all, it is difficult to identify the value of a patent. Some patents may have a higher impact on the market than others. For this reason patents are usually weighted to account for their difference in value. The most common procedure to weight patents is to use citations[1] (Popp [77]). As an alternative methodology, instead of taking all patent applications we only count the 'claimed priorities'[2]. Previous research has shown that the number of additional patent applications (other than the priority application) is a good indicator of patent value (see Guellec and van Pottelsberghe [43]; Harhoff et al. [45]). The second shortcoming in the use of patents is that the propensity to patent, patent regimes, and the innovative activity change across countries. We address this problem by including country fixed effects and controlling for the total number of claimed priorities in all technological fields.

Patent data can be disaggregated by technology, which proves useful for the se-

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[1] The number of times the patent has been cited in other patent applications. This is an indicator on the importance of the innovation in the technological field.

[2] Patents that have only been registered in one patent office are referred to as singulars. Patents that have been registered in multiple offices are instead referred to as claimed priorities. A patent that is registered in an office but that had already been registered before is referred to as a duplicate.

lection of the technological areas of interest. The International Patent Office (IPO) supplies patent classification codes developed by the World Intellectual Property Organization (WIPO), thanks to which patents are classified into different technological areas and at several hierarchical levels. The International Patent Classification (IPC) (WIPO [74]) is application-based, thus facilitating the identification of specific technology classes, and particularly for the scope of the present work, of classes including energy-efficiency patents.

Relevant patent classes have been selected after a careful and extensive review of technological developments in the area of energy-efficient technologies. Thanks to this review a set of technology-specific keywords has been identified. These were then used to determine the appropriate IPC codes related to each of the technologies considered. The fossil fuel technologies are gas turbines, compressed ignition engines, cogeneration, combined cycles, fuel cells, superheaters, steam engines, boilers, burners and fluidized beds[3]. Technology classes for the renewable technologies have been taken from previous selections (Johnstone et al. [57]) which provide codes for the relevant renewable electricity generation technologies. These include wind, solar, geothermal, ocean, biomass and waste. Finally, IPC classes have been selected for fuel cells, and both nuclear fusion and fission[4].

With the use of the selected IPC classifications and using the EPO/OECD Worldwide Patent Statistical Database (usually referred to as PATSTAT) we have created a database for energy-efficient technologies. The PATSTAT database includes patent data from 73 offices world-wide and post-grant data from about 40 offices. It is an extensive and comprehensive database that answers the needs of researchers and policy-makers to combine different data sets for patent-related information. Claimed priority counts are generated separately for the different types of technologies, in order to be able to study their dynamics separately.

3.2.2 Patents in Electricity Generation Technologies

The patent selection process allowed us to create a database of patent data for the different types of technologies, which can be used to study innovation in this sector.

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[3] A full description of the fossil fuel technologies is in Appendix I.

[4] These are described in Appendix II

Figure 3.1: Trends for claimed priorities in energy-efficiency patents

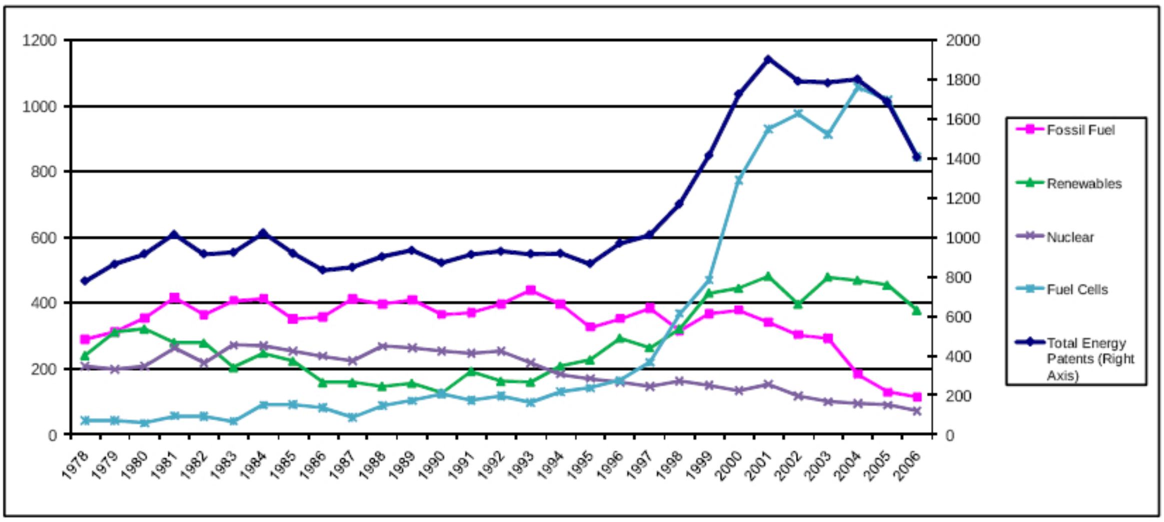
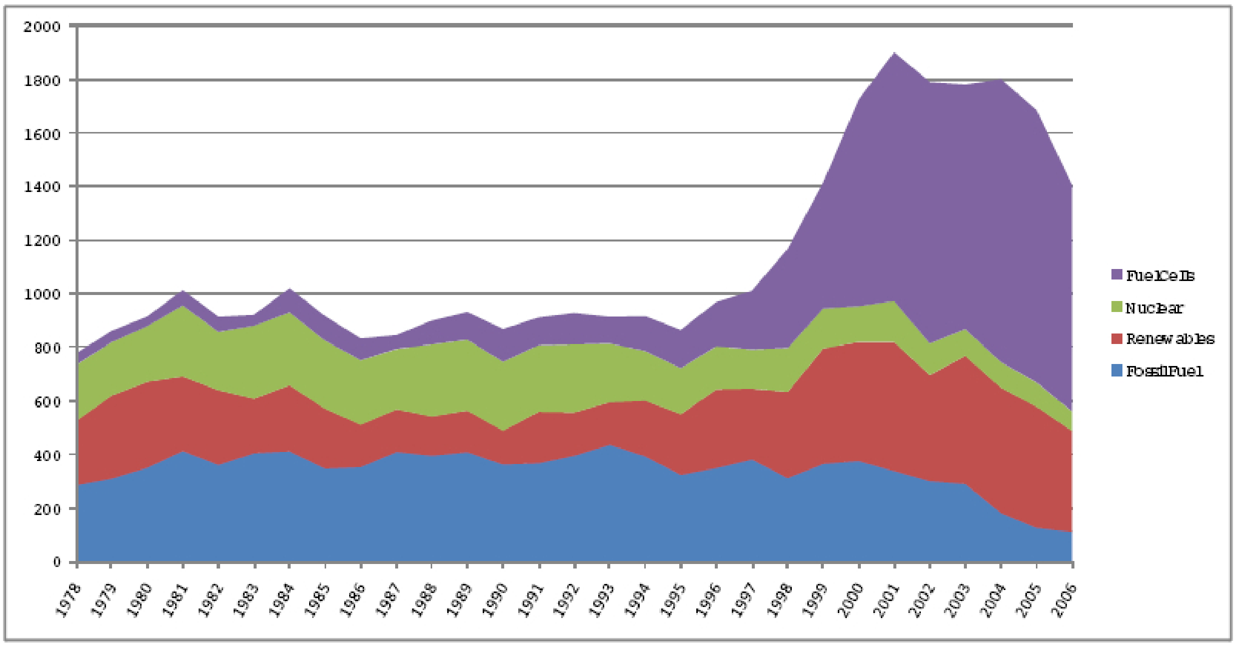


Figure 3.1 shows the time line for the world sum of claimed priority counts for energy-efficiency patents in aggregate and by technology type for the period 1978-2006. The aggregate number of patents was rather stable until 1997, when it started growing consistently. Interestingly energy patents start to increase rapidly after 1997, the year of ratification of the Kyoto Protocol. This is likely to be due to the increasing political attention given to the problem of greenhouse gases emissions, which encourages the development of energy-efficient technologies for electricity generation.

Looking at the different types of technologies aimed at improving energy efficiency it is possible to see that the technologies behave in different ways. Whereas some technologies increase in recent years, other ones appear to be declining. Renewables had a peak in the late 70ies and early 80ies, and then were stable until late 90ies where they started growing more rapidly. Fuel cells increased rapidly in the last decade after a slow start. Fossil fuel based technologies instead, though being stable over time; appear to have declined in the past decade. Finally, patents relative to nuclear show a slow decline starting from the early 90ies. Thus, the dynamics of the aggregate patent data are mostly driven by the behavior of renewable and fuel cells.

Figure 3.2 illustrates the number of claimed priorities in an area graph that helps understanding the relative increase in the different types of patents over time. With patents being a research output, this shows how the investments have changed and how some technologies are now given increasing priority.

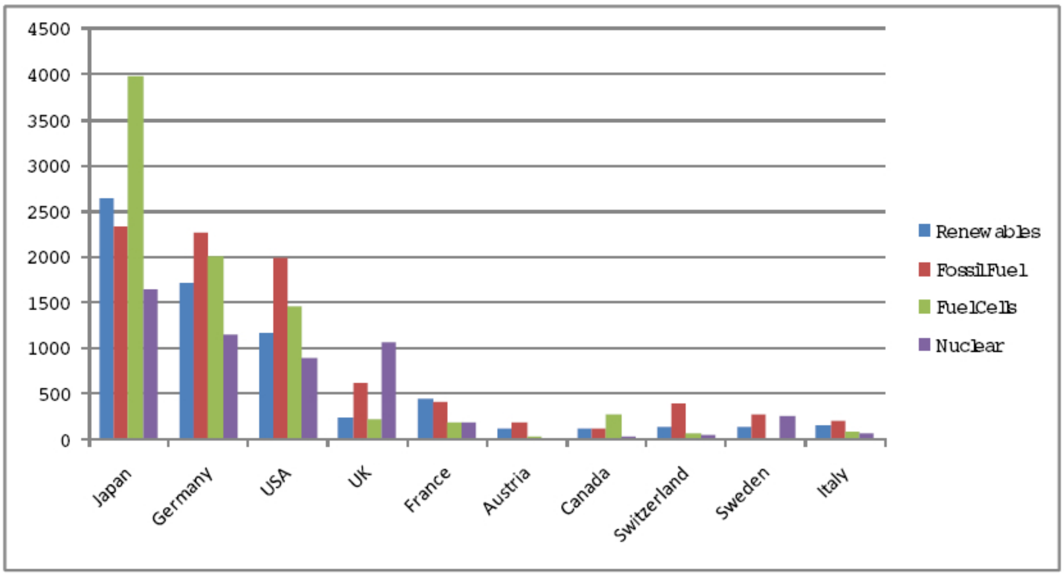
Figure 3.2: Relative importance of different technologies



The graph illustrates that renewables and fuel cells have been increasing more than fossil fuels and nuclear. From the data it is possible to see that fuel cells have had a very rapid increase in the last decade. This is mostly due to the fact that it is a new technology so that more inventions are created. The number of patents in fuel cells is also much higher than in the other technologies. This is because fuel cells are applicable also to sectors other than electricity generation, so that there is more investment in them. Finally, differences may also be due to the fact that differently from the other technologies, fuel cells are mostly financed by private investments in R&D. With the exception of fuel cells, looking at all technologies together, it is possible to see that the overall investments have been stable while the internal dynamics have slightly changed. In particular, if we consider patents as a proxy for research expenditure, we can hypothesize a certain level of crowding out from fossil fuel based and nuclear technologies to renewable.

It is also interesting to check where innovation takes place. Figure 3.3 shows the aggregate amount of patents over the time period 1978-2006 for the countries with highest number of patents in electricity generation. Main innovating countries are the same for the different types of technologies, although it is possible to see that there is a certain level of specialization. For example Japan has a particularly high number of patents in fuel cells. For Germany and the USA instead the prevailing technology fossil fuels, while the UK has the highest number of patents in nuclear technologies.

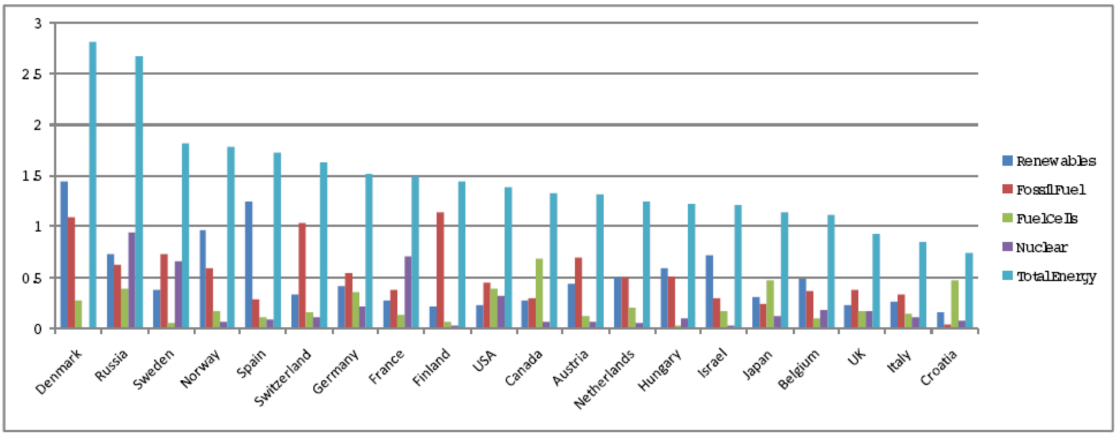
Figure 3.3: Main innovating countries



It is important to bear in mind that these values do not consider the size of the countries, nor their general ability to innovate and propensity to innovate. In order to verify the relative amount of innovation in these technologies, Figure 3.4 illustrates the number of claimed priorities in electricity generation normalized over the total number of patents.

Here it is possible to see that the countries with the highest relative number of patents in electricity generation are Denmark, Russia, and Sweden. It is also interesting to see that some countries have a high number of patents in all technologies, like Russia, Germany, or the UK, while for other countries there is a clear bias towards a certain type of technology, like renewable in Denmark and Spain, or fossil

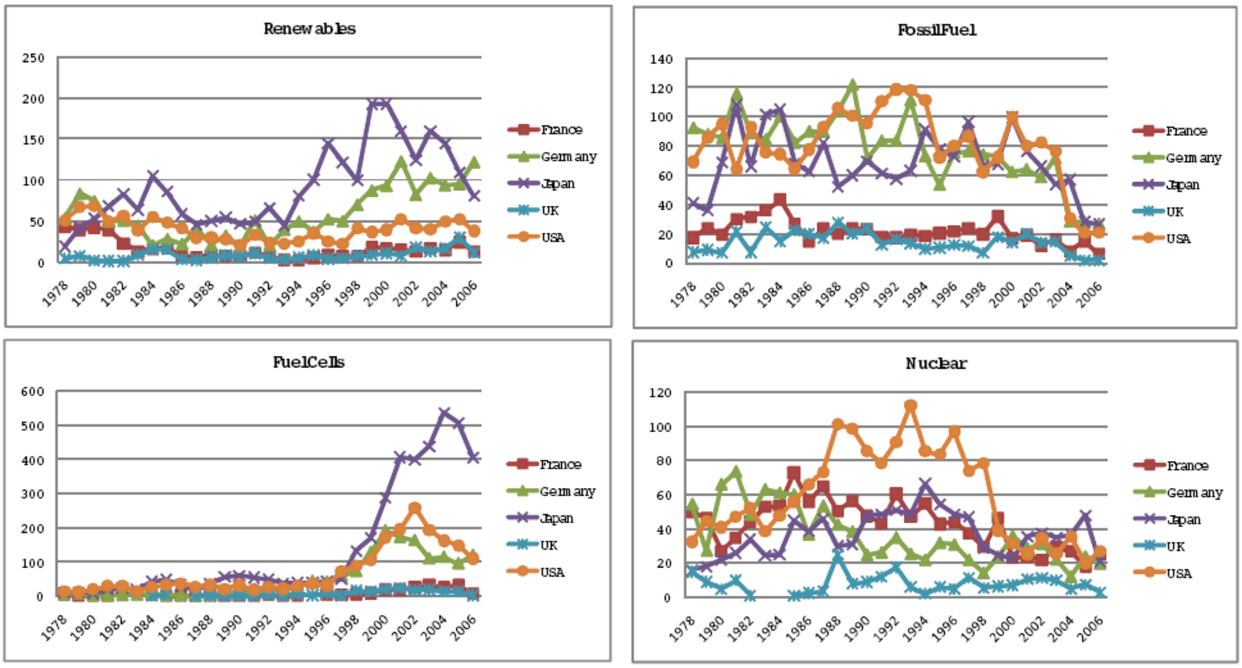
Figure 3.4: Relative importance of electricity generation technologies



fuels in Switzerland and Finland. The different outcome of the highest innovator with and without formalization by the total number of patents highlights the importance of taking into consideration the propensity to patent and the country-specific characteristics caused by the different approaches to the regulation of property rights.

If we consider instead the time development of the technologies by country, as illustrated in Figure 3.5, it is possible to see that there is a common path across countries. For example renewables and fuel cells are increasing in the last decade, fossil fuels declining, and nuclear has a peak in the middle of the time period considered. This shows that there are common paths across countries for the different types of technologies, and thus that a general relationship can be sought between the variables determining innovation and the number of claimed priorities. This is why the estimations done in the next section will be done for the whole panel and not for the single country-specific time series.

Figure 3.5: Time development by country



3.2.3 Other Data

Given the characteristics of the patent data, we explore through an empirical analysis the possible variables that may induce the development of the technologies considered. Two main explanatory variables are used, that is R&D investments and fuel input prices. The former is the input investment necessary to obtain new technologies; therefore in this case the number of patents also represents the returns from R&D investments. The latter is a measure of induced innovation. In fact, higher fuel prices are expected to induce innovation in energy efficiency as more energy efficient technologies would reduce the fuel input requirements lowering the firms' production costs. They are considered as an indicator and response factor of the pressure on the electricity sector coming from climate policies and the scarcity of fossil fuels.

The R&D measure used here is from the International Energy Agency (IEA)'s Energy Technology Research Development Database (IEA [51]). This database collects data on national public sector expenditures on energy R&D, which can also be obtained disaggregated by type of technology. Therefore, it is possible to create separate measures for the different technology types. It is generally expected that the sign on this variable is positive, as more investment in R&D should lead to higher technology output, and thus to more inventions. Having only private R&D data is a limitation. However, as found by Nemet and KammenčiteNemet who study R&D trends in the United States, the private R&D in the energy sector has been decreasing and public R&D has been the main source of funding. Fuel cells is an exception, as for this technology most funding comes from the private sector. This is mostly due to the fact that there is a large number of entrepreneurial firms who aim at developing this new technology. The input fuel prices have been constructed using the IEA Energy prices and taxes database (IEA [50]). The fuel prices have been obtained for the three fossil fuel inputs, namely coal, oil and gas. They have been constructed as a combination of the fuel input price index for the industry and the input prices to industry which are used to attribute a monetary value to the price index[5].

Finally, to control for the electricity market size, which can influence the potential market for innovation, percentage changes in electricity consumption are also included as an explanatory variable. Data on household and industry sector electricity consumption are obtained from the IEA's Energy Balances Database (IEA [49]).

Table 3.1 summarizes the descriptive statistics for the explanatory variables included in the panel. For what regards the patent data, interestingly the mean of the variables are rather similar between all technology types, but the standard deviations differ consistently. There is a higher variation in fossil fuels and fuel cells than in renewable and nuclear. For R&D investment instead, the highest variation is in nuclear.

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[5] Prices of oil and gas are highly correlated, thus only price of oil is included. The price of coal is not correlated to the other two fuel input prices, and it is rather stable over time. The coal prices data are scarce in terms of number of countries covered and they consistently lower the number of observations in the sample. Thus, as coal price is never found significant in the regressions, and as its omissions does not significantly change the results, it is omitted from the regressions, leaving the price of oil to be the unique measure of fuel input prices.

Table 3.1: Descriptive statistics (1978-2006)

Variable	Unit of Measure	Obs	Mean	Std.Dev
Claimed Priorities Fossil Fuels	Number of claimed priorities	986	10.72	43.212
Claimed Priorities Renewables	Number of claimed priorities	986	8.87	21.6
Claimed Priorities Fuel Cells	Number of claimed priorities	986	9.65	43.21
Claimed Priorities Nuclear	Number of claimed priorities	986	6.3	15.74
Claimed Priorities Total Energy	Number of claimed priorities	986	35.54	85.21
Claimed Priorities Total	Number of claimed priorities (th.)	986	2.7	6.59
Oil price	2000 US$/tonne - using PPP	870	24.82	12.35
Electricity Consumption (%change)	Thousand TWh	849	3.27	3.49
R&D Fossil Fuels	Bl 2000 US$ - Constant prices and PPP	576	0.07	0.17
R&D Renewables	Bl 2000 US$ - Constant prices and PPP	621	0.04	0.11
R&D Fuel Cells	Bl 2000 US$ - Constant prices and PPP	884	0.03	0.02
R&D Nuclear	Bl 2000 US$ - Constant prices and PPP	952	0.21	0.56
R&D Total Energy	Bl 2000 US$ - Constant prices and PPP	527	3.56	0.71

3.3 Empirical Analysis

3.3.1 Model Specification

The model we would like to test is a reduced form equation which is estimated both for all energy technologies and separately for the different technologies:

$$CP_{it} = \beta_1 RD_{it} + \beta_2 P_{it} + \beta_3 CONS_{it} + \beta_4 CPT_{it} + \alpha_i + \epsilon_{it} \tag{3.1}$$

where $i = 1, ..., 18$ indexes the cross-sectional unit (country) and $t = 1978, ..., 2006$ indexes time. The dependent variable, patenting activity $CP_{i,t}$, is measured by the number of patent claimed priorities in the relevant technology areas. The explanatory variables include specific R&D expenditures ($RD_{i,t}$), fossil fuel prices ($P_{i,t}$), electricity consumption ($CONS_{i,t}$) and total patent counts ($CPT_{i,t}$). Fixed effects (α_i) are introduced in order to capture unobservable country-specific heterogeneity. All residual variation is captured by the error term ($\epsilon_{i,t}$).

The model applies the framework used in Johnstone et al. [57] to explore the effect that fossil fuel prices have on energy-efficient technologies for electricity generation for the single technology types and in aggregate. As fossil fuels are an input for one of the main technology types, they will not only influence innovation in this sector but also in the substitute ones. interpret fossil fuel prices as an indicator of the attention given

3.3.2 Estimation Method

Patent data are usually estimated with techniques for count data models, namely data for which the dependent variable is non-negative[6].

The classical approach to count data is to use the Poisson regression thus assuming that the conditional distribution of the dependent variable follows a Poisson distribution, as in El Sayyad [33] and Maddala [67]. However, the Poisson regression is based on the strong assumption of variance-mean equality, which has been rejected in numerous application. A relaxed version of this assumption is allowed by the Poisson quasi-maximum likelihood estimator (QMLE), which allows the variance-mean ratio to be any positive constant σ^2. When $\sigma^2 < 1$, the mean of the distribution is greater than the variance, and there is underdispersion in the sample. When instead $\sigma^2 > 1$, the mean of the distribution is smaller than the variance, and there is overdispersion. In the latter case, the distribution corresponds to a Negative Binomial I, which is a particular parameterizations of the negative binomial distribution, as explained in Cameron and Trivedi [19]. Given that our sample has a high number of zero counts, it is likely to be overdispersed, and thus the negative binomial estimation is preferable to the Poisson.

Whilst count data models were initially designed for cross-sectional data, extensions have been developed for panel data model, starting with the pioneering work by Hausman, Hall and Griliches [47], who studied patent application by firms in terms of R&D spending. We follow their work in using a fixed effect negative binomial estimation technique.

A further problem with the data is that, it is not just heteroscedastic because of its count data nature, but it is also heteroscedastic across countries. In fact, because most innovation takes place in a limited number of countries (as it is possible to see from Figure 3.3), there is a further problem of heteroscedasticity. This is corrected for by applying a robust estimation.

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[6] For an overview of count data models see Cameron and Trivedi [20] or Woolridge [97].

3.3.3 Empirical Results

The model is first estimated in aggregate for all the energy-efficient electricity generation technologies, and then for each of the single technologies. Table 3.2 illustrates the results. Oil price has a positive effect on claimed priorities in electricity generation. This positive and strongly significant relationship between fossil fuel prices and innovative activity measured as patent counts shows that higher fuel prices can be an incentive to develop energy-efficient technologies. However, this relationship is not the same across the different types of technologies. The positive and significant effect still holds for renewable and fuel cells. However, the effect of increasing fossil fuel prices on fossil fuel based technologies is negative and significant. There is no significant effect of fossil fuel prices on patents relative to nuclear technologies. The negative effect on fossil fuel technologies demonstrates that the substitution effect is greater than the efficiency effect. Therefore, for fossil fuel prices changes it is preferable to substitute between technology types and to innovate in carbon free technologies than to invest in high-efficiency fossil fuel technologies. Nonetheless the effect on the technologies in aggregate is positive. This illustrates that the decline in fossil fuel technologies is offset by the growth in the other technological fields.

The results of fossil fuel prices on the disaggregated technologies can be interpreted in the context of the findings of Sue Wing [88]. These show in a model of directed technical change between a clean and a dirty input that increasing relative prices of the dirty input will lead to a decrease in innovation in the dirty input, and an increase in the clean input when these are close substitute. In the current case we are considering different electricity generation technologies, which can be considered almost as perfect substitutes given the homogeneity characteristics of electricity. Thus, these explanatory results reflect the findings of the theoretical model. Intuitively, despite the fact that all technologies considered are aimed at improving the efficiency of using fossil fuels for electricity generation, with increasing prices, political pressure on actions to mitigate climate change, and uncertainty about prices and supply of fossil fuels, innovation decreases in fossil fuels while increasing in carbon free technologies.

Table 3.2: Estimation Results

	Total Electricity	Fossil Fuels	Renewables	Nuclear	Fuel Cells
Oil price	.0172**	-0.0337***	.0168**	-0.0103	0.565***
	(0.002)	(0.000)	(0.009)	(0.108)	(0.000)
R&D Electricity Total	0.0886**				
	(0.003)				
R&D Fossil Fuels		5.5114***			
		(0.000)			
R&D Renewables			4.5382***		
			(0.001)		
R&D Nuclear				.001***	
				(0.000)	
R&D Fuel Cells					0.001
					(0.636)
Electricity consumption	-3.8176	-2.292	-3.5838	39.5254*	-36.1248*
	(0.900)	(0.989)	(0.828)	(0.038)	(0.048)
Total patents	.0472***	.1044***	.1204***	.1500**	.0879**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Fixed Effect	Yes	Yes	Yes	Yes	Yes
Observations	472	518	547	979	737
Log-likelihood	-1610.6	-1433.68	-1461.32	-103.87	-1256.34
Wald Chi2	9186.05	1846.74	1224.73	50451.84	12464.15
(Prob>chi2)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

Significance levels : $*$: 10% $**$: 5% $***$: 1%

For what regards nuclear, it appears that fossil fuel prices do not have an influence on this technology type. Innovation in this sector has more likely been influenced by other factors such as problems of security, disposal of nuclear discharges, and domestic political decisions.

Research and development expenditures have a positive and significant effect on innovation in aggregate and in the single technologies, with the exception of fuel cells for which there is no significant relationship. The positive effect found reflects the expectations that higher R&D investments correspond to higher innovation. The non-significant effect of R&D on fuel cells may be explained by the fact that the data on R&D in this sector is mostly comes from the private sector, as illustrated in Nemet and Kammen [71]. Thus, the non-significant result of R&D on fuel cells should be interpreted as a lack of private funding rather than as a problem of productivity of R&D in the sector.

Electricity consumption is negative and non-significant for the technologies in aggregate, fossil fuel, and renewables. It is positive and significant for nuclear and negative and significant for fuel cells. This result can be explained by the importance of the different technology types on the electricity grid. An increase in electricity consumption will lead to higher production of the technologies which are most connected to the grid, namely nuclear. On the contrary, it will have a negative effect on technologies that are completely disconnected to the grid, i.e. fuel cells. The effect on the other types of technologies is mixed, and thus turns out to be non-significant. This is an interesting results as it shows that the demand side also has an influence on the direction of innovation on the production side. The estimated coefficient of the total number of patents is positive and statistically significant for the technologies in aggregate and in specific. This suggests that part of the variation in patenting activity is due to the general propensity to patent and the structure of the patent system in the different countries.

Fixed effects are included to control for country-specific heterogeneities. The US is chosen as reference country. Most country dummies are negative and significant, showing that most countries have a lower production of energy-efficient technologies than the US when controlling for fuel prices, electricity consumption, R&D expenditure, and propensity to patent. This does not apply to the other top technology producers, such as Japan and Germany, for which the country dummies are non-significant[7].

For all regressions, values of the likelihood ratio chi-squared test with three degrees of freedom are given and show that all models are statistically significant. Estimate of the log of the overdispersion parameter alpha are also obtained in order to check whether the negative binomial estimation is appropriate. The likelihood ratio chi-square tests support the use of negative binomial[8].

3.4 Conclusion

This paper analyzes the behavior of patents in energy-efficient electricity generation technologies, as a source for mitigation of climate change in the energy sector.

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[7] Results on country dummies change according to the reference country. Choosing the US as a reference and checking results shows that the fixed effects are relevant and that it is important to control for country-specific heterogeneities.

[8] The test is used to verify whether the overdispersion parameter alpha is statistically significant from zero. If alpha equals zero, then there is no overdispersion. If the test is significant zero-truncated negative binomial is preferred to zero-truncated Poisson. In all estimated models the test is significant supporting the choice of estimating with negative binomial.

From the data analysis we find that it is possible to hypothesize a certain amount of crowding out from carbon-based to carbon free technologies. A panel of OECD countries for the period 1978-2006 is used for an empirical analysis of the determinants of innovation in these technologies in aggregate and separately. Patent counts, of which we only consider claimed priorities in order to select the patents with a higher value, are used to proxy for innovation.

The empirical results show that fossil fuel prices induce innovation in energy-efficient electricity generation technologies. We find that the effect is not so straightforward when the technologies are analyzed separately. That they have a positive effect on renewable and fuel cells, but a negative effect on fossil fuel technologies and no significant effect on nuclear. This results illustrates that there is a substitution effect between fossil fuel and carbon free technologies.

This paper shows that there are long-run internal dynamics, which could lead to a change in the technology mix for electricity production. An initial analysis of the effect of fossil fuel prices on innovation shows that increasing costs of fossil fuels is likely to induce such a change in the energy mix. This is encouraging as it shows that political pressure and price mechanisms such as emissions trading, and carbon taxes are likely going to lead to a direction in the change of innovation towards carbon free technologies. This empirical analysis contributes to the literature by combining and comparing information on innovation in different types of technologies. Whereas this is usually done with applied climate-economy models, the empirical literature analyzing the changes in the direction of innovation is not yet well developed. This paper underlines the need to further explore this topic by combining empirical analysis with more structural models of directed technical change and crowding out.

Appendix

I. Fossil Fuel Technologies

This appendix provides an overview of the selected energy-efficient fossil fuel technologies for power generation[9]. Whilst renewable, nuclear and fuel cells are all energy efficient, only a subset of fossil fuel technologies for power generation have been selected. The aim of the selection was to identify only technologies that are aimed at the improvement of efficiency in production and in the use of fossil fuels.

FUEL PREPARATION TECHNOLOGIES

Coal Gasification

In coal gasification, solid coal is reacted with either air or oxygen and steam to create a combustible gaseous mixture of carbon monoxide and hydrogen. The coal gasification process can produce substitute natural gas (SNG); synthesis gas, which can be converted to liquid fuels or used to manufacture chemicals; and electricity, which is generated in gasification combined cycle systems. As with coal liquefaction, emissions of sulphur and nitrogen compounds are reduced. In addition, the basic technology can be applied to other fossil energy feedstock, such as wood and biomass. During the 1970's, concerns over the supply of natural gas led to much R&D in coal gasification. Many of the R&D projects of the 1970's have been discontinued as concerns over the supply of energy have weakened.

C10J 3/00-86 - Production of producer gas, water-gas, synthesis gas from solid carbonaceous material, or mixtures containing these gases; carburetting air or other gases Production of combustible gases containing carbon monoxide from solid carbonaceous fuels

Coal Pulverization

Coal dust is a fine powdered form of coal, which is created by the crushing, grinding, or pulverizing of coal. Because of the brittle nature of coal, coal dust can be created during mining, transportation, or by mechanically handling coal. Coal dust

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[9] The patent selection is the result of a collaboration with Nick Johnstone and Ivan Hascic at the OECD, and a joint work with Elena Verdolini (Catholic University of Milan, and Fondazione ENI Enrico Mattei).

suspended in air is explosive. Coal dust has far more surface area per unit weight than chunks of coal, and is more susceptible to spontaneous combustion pulverization. Pulverized-coal is the main input in the electric power industry and provides steam to large turbines. Below, we report the general IPC classes that were identified for powdered coal mills. The IPC classification, however, does not allow distinguishing between mills specifically dealing with coals as opposed to other kinds of material. For this reason, therefore, this technology was excluded from the empirical studies.

B02C - Crushing, pulverizing, or disintegrating in general; milling grain

Coal Drying

Low rank fuels such as sub-bituminous coals and lignite contain relatively large amounts of moisture compared to higher rank coals. High fuel moisture results in fuel handling problems, and it affects station service power, heat rate, and stack gas emissions. By reducing the fuel moisture through coal drying, it is possible to reduce water consumption by evaporative cooling towers, improve boiler performance and unit heat rate, and reduce emissions. Below we report the selection of general classes identified for drying methods and machines. However, IPC classes do not allow isolating solely those patents that are specifically applied to coal drying, as opposed to drying material in general. Therefore, the selected classes include a great number of innovations that are not related to coal drying specifically. For this reason, this technology will not be included in the empirical research.

F26B - Drying solid materials or objects by removing liquid therefrom

FURNACES AND BURNERS

The process to convert fossil fuels into electricity is similar for all types of fuels. The first step, right after loading the fuels into the power plant, is that to burn the fuels in giant burners or furnaces in order to release heat energy. The combustion of the fuel can take place in more or less conventional burners, such as in fluidized beds, but the aim of this step is common to all the technologies selected. Fluidized beds are in per se an energy-efficient technology. As for the burners we have selected only those types of burners which aim at improvements in energy efficiency.

Burners

Burners are mechanical devices that burn fossil fuels in a controlled manner so as to create heat energy. Whereas this is a conventional step, burners aimed at improving the energy efficiency of the plant can also be used with different fuels or combinations of fuels. In other cases additional liquids are used to improve the heating process.

Excluding combinations with B60, B68, F24, F27:
F23C 1/00-12 - Combustion apparatus especially adapted for combustion of two or more kinds of fuel simultaneously or alternately, at least one kind of fuel being fluent
F23C 5/24 - Combustion apparatus characterized by the arrangement or mounting of burners. Disposition of burners. To obtain a loop flame
F23C 6/00-04 - Combustion apparatus characterized by the combination of two or more combustion chambers
F23B 10/00 - Combustion apparatus characterized by the combination of two or more combustion chambers
F23B30/00-10 - Combustion apparatus with driven means for agitating the burning fuel; Combustion apparatus with driven means for advancing the burning fuel through the combustion chamber
F23B 70/00 - Combustion apparatus characterized by means for returning solid combustion residues to the combustion chamber
F23B 80/00-04 - Combustion apparatus characterized by means creating a distinct flow path for flue gases or for non-combusted gases given off by the fuel
F23D 1/00-6 - Burners for combustion of pulverulent fuel
F23D 7/00 - Burners in which drops of liquid fuel impinge on a surface
F23D 17/00 - Burners for combustion simultaneously or alternatively of gaseous or liquid or pulverulent fuel

Fluidized beds

Fluidized beds suspend solid fuels on upward-blowing jets of air during the combustion process. The result is a turbulent mixing of gas and solids. The tumbling action, much like a bubbling fluid, provides more effective chemical reactions and heat transfer.

B01J 8 /20 - Chemical or physical processes in general, conducted in the presence of fluids and solid particles; Apparatus for such processes
. . moved by stirrers or by rotary drums or rotary receptacles
B01J 8 / 24-30 - Chemical or physical processes in general, conducted in the presence of fluids and solid particles; Apparatus for such processes
. . according to "fluidized-bed" technique (B01J 8/20 takes precedence; combustion apparatus in which combustion takes place in a fluidized bed of fuel or other particles F23C 10/00)
F27B 15/00-20 - Fluidized-bed furnaces; Other furnaces using or treating finely-divided materials in dispersion (combustion apparatus in which combustion takes place in a fluidises bed of fuel or other particles F23C 10/00)
F23C10/00-32 - Apparatus in which combustion takes place in a fluidises bed of fuel or other particles

BOILERS, TURBINES, AND ENGINES

Once the heat from the furnace has been created, the next step is to convert the heat power into mechanical power. The heat power is usually used to generate steam by means of a boiler. In the boiler the heat from the furnace flows around pipes, so that the water boils and it turns into steam. Once steam has been created, gas turbines are used to create kinetic energy out of the steam. Plants can have single engines or combined engines, which are more efficient as they can exploit the steam in different ways.

Boilers for steam generation

In energy-efficient boilers, to achieve a homogeneous combustion, fine aerosol droplets are sprayed into the boiler by a mechanical process, or through the action of an auxiliary fluid (air or steam) under pressure, or even through a combination of both.

When heavy fuel oil is used, low viscosity is needed at the burner, in order to ensure correct atomization of the fuel. Additives are used to improve the combustion of heavy fuel oil.

F22B 31/00-08 - Modifications of boiler construction, or of tube systems, dependent on installation of combustion apparatus
F22B 33/14-16 - Steam generation plants, with boilers of different types in mutual association

Steam engines

This category refers to energy-efficient steam engines in which a particular pressure is applied to the steam so as to better exploit the movement of the steam and thus to increase energy efficiency.

F01K 3/00-26 - Plants characterized by the use of steam or heat accumulators, or intermediate steam heaters, therein
F01K 5/00+ - Plants characterized by use of means for storing steam in an alkali to increase steam pressure, e.g. of Honigmann or Koenemann type
F01K 23/00-18 - Plants characterized by more than one engine delivering power external to the plant, the engines being driven by different fossil fuels

Superheaters

Process heaters and superheaters are sometimes referred to as process furnaces or direct fired heaters. They are heat transfer units designed to heat petroleum products, chemicals, and other liquids and gases flowing through tubes. The liquids or gases flow through an array of tubes located inside a furnace or heater. The tubes are heated by direct fired burners that use standard specified fuels such as HFO, LFO, and natural gas, or the by-products from processes in the plant, although these may vary widely in composition. Vertical furnaces could be oil-fired with a reduced number of air forced burners. This combustion system allows good air control, reduces excess air, improves the energy efficiency and lowers pollutant emissions. Air combustion could be preheated in a way which decreases energy consumption.

F22G 1/00-16 - Steam superheating characterized by heating method
F22G 3/00 - Steam superheaters characterized by constructional features
F22G 5/00-20 - Controlling superheat temperature
F22G 7/00-14 - Steam superheaters characterized by location, arrangement, or disposition

Gas turbines

Gas turbines are used to create mechanical energy from steam or gases. By means of an axial compressor, pressurized air is driven, into the combustion chambers, where the fuel injectors are connected. During the combustion reaction, the gas temperature rises, and at between 1000 and 1350 °C it is introduced into the turbine. These hot gases are depressurized in the turbine, which simultaneously drives both the air compressor and the alternator, which in turn generates electricity. In the ′open cycle′ configuration, the combustion gases are released directly into the atmosphere at a temperature of >450 °C. The thermal efficiency is then between 30 and 40 %. The energy efficiency of gas turbines can also be improved with the use of extra liquids.

F02C 7/08-105 - Heating air supply before combustion, e.g. by exhaust gases
F02C 7/12-143 - Cooling of plants
F02C 7/30 - Preventing corrosion in gas-swept spaces

Combines cycles

Combined cycle combustion plants are made up of:

- Gas turbine (GT), where combustion of natural gas takes place. The expansion of gas products rotates a first turbine and then the first electric generator connected to it.
- Steam generator, where the steam from the gas turbine is used to produce high pressure steam.
- Steam turbine (TV), in which steam produced by the recycled-steam generator expands, rotating another turbine and then a second electric generator, with production of additional electricity.

- Condenser, in which the exhausted steam from the steam turbine is condensed using air from the outside.

In practice, starting from a certain volume of fuel, electricity is produced with two systems: the gas cycle and the steam cycle, thereby optimizing the use of the initial energy resource. Water is not used for the steam condensation or machinery cooling: being located in an area that historically has little water; the plant has been equipped with special facilities (air exchangers and condensers) that allow for an almost complete saving of the water resource. The exhaust gases are also channeled into the atmosphere through a dedicated chimney and are constantly monitored.

F01K 23/00-10 - Plants characterized by more than one engine
F02C 3/20-36 - Gas turbine plants characterized by the use of combustion products as the working fuel
F02C 6/10 - Plural gas-turbine plants; Combinations of gas-turbine plants with other apparatus. Supplying working fluid to a user, e.g. a chemical process, which returns working fluid to a turbine of the plant

Compressed-ignition engines

A Compressed ignition (diesel) engine is an internal combustion engine which operates using the Diesel cycle; it was based on the hot bulb engine design and patented on February 23, 1893. Diesel engines use compression ignition, a process by which fuel is injected after the air is compressed in the combustion chamber leading the fuel to self ignition. By contrast, a gasoline engine utilizes the Otto cycle, in which fuel and air are mixed before ignition is initiated by a spark plug. Most diesel engines have large pistons, therefore drawing more air and fuel which results in a bigger and more powerful combustion. This was originally implemented in very large vehicles such as trucks, locomotives and ships, (and also as a stationary engine), as more efficient replacement for the steam engine.

Excluding combinations with B60, B68, F24, F27:

F02B 1/12-14 - Engines characterized by fuel-air mixture compression. with compression ignition

F02B 3/06-10 - Engines characterized by air compression and subsequent fuel addition. With compression ignition. With intermittent fuel introduction

F02B 7/00-04 - Engines with fuel-air charge ignited by compression of an additional fuel

F02B 11/00-02 - Engines with both fuel-air mixture compression and air compression, or with both positive ignition and compression ignition, e.g. in different cylinders.

F02B 13/02-04 - Engines characterized by the introduction of liquid fuel into cylinders by use of auxiliary fluid. Compression ignition engines using air or gas for blowing fuel into compressed air in cylinder

F02B 49/00 - Methods of operating air-compressing compression-ignition engines involving introduction of small quantities of fuel in the form of a fine mist into the air in the engine's intake

GENERATORS OF ELECTRICITY AND HEAT

Electricity is generated from the kinetic energy which origins from the movement of the turbines. A major progress in energy-efficiency relative to the electricity generation step is that to exploit the heat generated in the process in order to "recycle" it for other uses. This is usually referred to as cogeneration or the 'combined generation of heat and power' (CHP). Co-generation uses a single process to generate both electricity and usable heat. Co-generation is a proven technology and is mainly applied to industrial plants where both electricity and heat (hot water or steam) are needed. In addition to cost savings, cogeneration also yields environmental benefits through using fossil fuels more efficiently. Steam turbines driven by any fossil fuel-fired boilers have been used for industrial cogeneration systems for many years. High pressure steam raised in a conventional boiler is expended within a turbine to generate mechanical energy, which can then be used to drive an electric generator. Gas turbines could be used in specialized cogeneration plants, as above.

F01K 17/06 - Returning energy of steam, in exchanged form, to process, e.g. use of exhaust

F01K 27/00-02 - Plants for converting heat or fluid energy into mechanical energy, not otherwise provided for

F02C 6/18 - Using the waste heat of gas-turbine plants outside the plants themselves, e.g. gas-turbine power heat plants (using waste heat as source of energy for refrigeration plants)

F02G 5/00-04 - Profiting from waste heat of combustion engines, not otherwise provided for

F25B 27/02 - Machines, plant, or systems, using particular sources of energy - using waste heat, e.g. from internal-combustion engines

II. Fuel Cells and Nuclear Technologies Description

STATIONARY FUEL CELLS

Fuel cells are electrochemical conversion devices. They produce electricity from fuel (on the anode side) and an oxidant (on the cathode side), which react in the presence of an electrolyte. The reactants flow into the cell, and the reaction products flow out of it, while the electrolyte remains within it. Fuel cells can operate virtually continuously as long as the necessary flows are maintained. The general class for fuel cells is reported below. The IPC classification, however, does not allow us to distinguish between stationary and non-stationary fuel cells, nor to make a distinction based on fuel cell capacity, application or relevance to the power generation sector. For this reason, therefore, this technology was not included in the empirical studies.

H01M8/00-24 - Fuel cells

NUCLEAR

Nuclear energy is released either splitting or merging together of the nuclei of atom(s). We refer to the former as fission, and to the latter as fusion.

G21B - Fusion reactors

G21D - Nuclear power plant

G21C -

Except

G21C 9/00-06 - Emergency protection arrangements structurally associated with the reactor

G21C 17/00-14 - Monitoring; Testing

DATA SOURCES FOR THE TECHNOLOGY SELECTION:

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Chapter 4

Directed Technical Change in the Energy Sector: an Empirical Analysis of Induced Directed Innovation

Abstract

In this paper we investigate directed technical change in the energy sector. We develop a dynamic model in which energy demand is satisfied with production derived from renewable and fossil-fuel energy. The firm invests in technology-specific R&D. This directed-technical change framework allows us to establish a long-run relationship between relative energy prices and relative innovation in the two sectors. This relationship is estimated using a panel of 23 OECD countries and 28 years (1978-2006). We find that a raise in the relative price of fossil-fuel energy leads to an increase in the relative amount of innovation in renewable technologies. We also find that whether this is due to an actual decrease in innovation in the fossil-fuel sector or to renewables increasing at a faster pace depends on the values of the elasticity of substitution between the two energy types and on the price elasticity of the demand for energy.

4.1 Introduction

Endogenous technical change has been recognized to be one of the most important engines of economic growth. In early contributions technological progress as a result of R&D was a determinant of productivity growth (see Romer [80], Grossman and Helpman [42], and Aghion and Howitt [4]). More recently, a very important contribution by Acemoglu [2] was to develop models of directed technical change, where the final output is obtained by intermediate goods, and technical progress is input-specific. The direction of technical change is endogenously determined following the relative profitability of developing factor-specific innovations. This framework offers the opportunity to study Hick's [48] original intuition that a change in relative prices leads to innovation directed at economizing the use of the factor that has become relative more expensive.

Whereas Acemoglu's framework [2] considers labor and capital as intermediate inputs, there have been some application of the directed technical change framework in the field of environmental and resource economics. This framework is ideal to explore the response of the firm to regulatory constraints deriving from environmental policies. The aim is to understand whether technical progress is resource-augmenting, as this would lead to a more efficient and sustainable economy. There are a few applications of the directed technical change framework to this field. These are usually based on a two sector model in which one input is "clean" and the other is "dirty". Smulders and de Nooij [84] use this setting to demonstrate that quantitative limits on the dirty input induce a pollution-saving bias in technical change. Sue Wing [88] demonstrates in a simplified framework that firm's innovate in response to changes in relative prices of inputs as a consequence of environmental regulation. Di Maria and van der Werf [29] analyze carbon leakage effects under directed technical change. More recently, Acemoglu et al. [3] use the directed technical change framework in a two sector model with a polluting input to analyze optimal climate policies when natural resources are limited or when there is a policy restricting the use of the polluting good.

Technology-specific innovation has been investigated also in the context of climate-economy models with endogenous technical change. Some of these, such as Goulder [40], and Popp [78], assume that a general stock of knowledge is linked to climate policy by imposing exogenous links between innovation and energy-efficiency. Other works model sector-specific knowledge stocks, such as in the cases of Goulder and Schneider [41], Sue Wing [86], Gerlagh [39], and Massetti et al. [68]. These mostly focus on energy- versus non-energy R&D to investigate on the level of crowding out caused by climate policies.

Despite the rapid development of this literature and its policy relevance, empirical evidence is limited. Furthermore, the applications of this theory are bound to parameter values for which there are only a few empirical estimates. The only two examples of empirical applications are both based on a directed technical change framework with three inputs, namely capital, labor, and energy. Van der Werf [93] estimates elasticities of substitution and technological parameters to find what specification best fits the data. De Cian [25] tests the presence of input-specific technical change versus the hypothesis of homogenous technical change.

The present study aims at contributing to the empirical literature on directed technical change applied to the environmental arena. We start from the theoretical framework by Sue Wing [88]. This is chosen over the other models as it underlines the importance of R&D as source of innovation, while leading to an equilibrium solution illustrating the long-run relationship between relative innovation and relative prices. We apply Sue Wing's framework to the energy sector. This is an interesting application in the field of climate change economics, as it allows us to test on the presence of innovation between dirty (based on fossil fuels) and clean energy (renewables). Given the current attention on the energy sector due to its consistent contribution to greenhouse gases emissions, it is crucial that technological progress in this sector leads to improvements in efficiency as well as that it is mostly directed towards carbon-free technologies. In particular, we focus on energy-efficient electricity generation technologies both for fossil fuel and renewable energy. By focusing only on the most efficient technologies, we can study the changes in the direction of innovation in these two types of electricity generation avoiding the bias that may arise from considering technologies with more difference in the levels of maturity.

The main contribution of this paper is to propose a different estimation methodology respect to the previous empirical works. We apply a direct test of the steady state relationship between relative innovation and relative prices. We correct for short-run effects by using an Error Correction Model (ECM), drawing on induced innovation studies such as Thirtle et al. [90]. Finally, the results allow us to obtain estimates for the elasticity of substitution between fossil fuel and renewable energy. This is a crucial parameter as the conclusion from climate-economy models with a disaggregated energy sector (see Bosetti et al. [14] for the WITCH model, Popp [78] for the ENTICE model) are based on the value of the elasticity between fossil and carbon-free energy.

Using a panel of 23 OECD countries over the period 1978-2006 and data relative to patents, production, R&D expenditures, and energy prices, we find that changes in relative prices induce changes in the relative amount of innovation between fossil-fuel based and renewable technologies. Fossil fuel and renewable energies are found to be substitutable with an elasticity of 1.64, which shows a high level of substitutability. In order to further explore the crowding out hypothesis, we also estimate the model's parameter values and use them to evaluate how changes in relative prices affect technology-specific innovation. We find that innovation is expected to increase in renewables. In the fossil fuel sector innovation will increase initially but decrease above a threshold level of the relative prices.

The remaining of the paper is organized as follows. Section 4.2 outlines the theoretical model and its conclusions. Section 4.3 illustrates the empirical model, describes the data, estimation method, and the results. Section 4.4 concludes.

4.2 Theoretical Framework

The starting point of our analysis is the directed technical change framework proposed by Sue Wing [88]. This model considers the optimization problem of a firm facing a downward sloping demand curve, and producing with a clean and a dirty input. The firm augments inputs investing in input-specific R&D. Changes in relative input prices due to regulatory constraints on the firm create a tradeoff between the two R&D investments, leading to different levels of innovation.

We apply the model by Sue Wing [88] to study the changes in the direction of innovation in renewable and fossil fuel energy technologies. The clean industry is represented by renewables, and the dirty industry by fossil-fuel electricity production. Final demand for energy is satisfied by the energy produced with the two technology types[1]. In such a framework, both types of energy are treated as substitutable intermediate goods. This is a common assumption in the literature on energy and it is coherent with the work by Baker and Shittu [8] who also focus on energy-efficient electricity-generation technologies. As both intermediate goods produce energy, they are close substitutes and therefore the elasticity of substitution between them is expected to be greater than unity.

In the model a firm produces output E using quantities X_i of two goods, indexed by $i \in \{REN, FF\}$: the clean renewables X_{REN}, and the dirty fossil-fuel energy X_{FF}. Input markets are assumed to be competitive and inputs to be in perfectly elastic supply with prices p_{REN} and p_{FF}. Production at each point in time assumes that the two goods are substitutes with a constant elasticity of substitution σ, so that the production function is:

$$E(t) = \left[\theta_{REN}(A_{REN}(t)X_{REN}(t))^{\frac{\sigma-1}{\sigma}} + \theta_{FF}(A_{FF}(t)X_{FF}(t))^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{4.1}$$

where for each type of energy, θ_i are the input cost shares ($\sum_i \theta_i = 1$), and A_i are augmentation coefficients indicating the state of input-augmenting technology. The firms instantaneous net profit $\pi(t)$ is given by the difference between variable profits and research expenditure:

$$\pi(t) = V(t) - \Phi(t) \tag{4.2}$$

where $V(t) = p_E(t)E(t) - \sum_i p_i(t)X_i(t)$ are the firms variable profits given by the difference between the revenues and the expenditure in the intermediate goods. Research expenditure is given by $\Phi(t) = \frac{1}{2}\sum_i R_i^2(t)$, where R&D exhibit increasing costs and are modeled using a separable quadratic function following Parry

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[1] In this sense we can think of fossil fuel and renewable energy as two intermediate goods representing electricity which is supplied into the electricity grid. The final energy good instead is what is taken out of the grid for consumption and use by households.

and Fischer [75][2]. R&D is modeled heterogeneously, by splitting it into renewable-augmenting and fossil fuel-augmenting research. In this way the growth of the productivity parameters A_i can be modeled as directly dependent from its relative R&D expenditure R_i. The input augmentation coefficients represent the state of technological knowledge of the firm. Knowledge is the result of cumulated ideas resulting from the research activity, with the value of these ideas decaying over time. The augmentation coefficients are stocks of input-augmenting knowledge and they are modeled following the linear perpetual inventory model:

$$\dot{A}_i = \eta_i R_i(t) - \delta A_i(t) \tag{4.3}$$

in which the parameter δ reflects the decay of knowledge, and η_i the input-specific productivity of R&D. With knowledge decaying over time, the firm must continue to invest in R&D.

The demand for the firm's overall electricity output is modeled with a downward-sloping demand curve for the firm's product, with price elasticity $\gamma > 0$[3]:

$$E(t) = M p_E(t)^{-\gamma}. \tag{4.4}$$

Taking prices as exogenous, the intertemporal profit maximization problem of the

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[2] Sue Wing [88] uses the same function but adding weight parameters on the different types of technology so as to differentiate the expenditure between the two sectors. This does not change the overall results of the model. In order to simplify and also find variables which are estimable, we have simplified the framework and used the original function in Parry and Fischer [75] without the weights. The choice of the exponential function responds to various critiques of previous works that use functions with increasing returns in the R&D sector. The chosen function is consistent with the literature's findings that identified diminishing returns in the R&D sector (Jones [58], Popp [77]). Considering other types of research cost functions, for instance non-convex ones, could lead to increasing returns that have been criticized in works aiming at showing the possibilities of win-win situations such as the Porter Hypothesis. This states that a pollution tax can lead to lower pollution levels as well as higher profits. But this results is highly dependent on the assumption of increasing returns to R&D. Assuming decreasing returns is more coherent with empirical findings.

[3] Whereas Sue Wing [88] assumes the value of the elasticity to be greater than 1, we assume that it can also take values in the interval between 0 and 1. The model by Sue Wing addresses the case of a final good for which it is reasonable to assume an elasticity greater than 1. However, as we consider energy as our final good, it is more reasonable to assume that the market can be rigid and the elasticity can have lower values.

firm, subject to (4.1), (4.2), (4.3), and (4.4), is[4]:

$$\max_{E(t),X_{REN}(t),X_{FF}(t),R_{REN}(t),R_{FF}(t)} \int_0^{\infty} \pi(t)e^{-rt}dt \tag{4.5}$$

where r is the firm's discount rate. The solution to the model is shown in the Appendix. It is found that the control variables for the firm's research expenditure are given by the linear equation:

$$\dot{R}_i = (r+\delta)R_i - \eta_i \theta_i^{\sigma} A_i^{\sigma-2} p_i^{1-\sigma} \chi^{\sigma-\gamma} \tag{4.6}$$

where $\chi = \left(\theta_{REN}^{\sigma} A_{REN}^{\sigma-1} p_{REN}^{1-\sigma} + \theta_{FF}^{\sigma} A_{FF}^{\sigma-1} p_{FF}^{1-\sigma}\right)^{\frac{1}{1-\sigma}}$ is the CES unit cost function with input-augmenting technical change. The steady state results for research R_i^* are derived from the equilibrium condition $\dot{R}_i = 0$ and are given by:

$$R_i^* = \frac{\eta_i \theta_i^{\sigma} (A_i^*)^{\sigma-1} p_i^{1-\sigma} \chi^{\sigma-\gamma}}{(r+\delta)} \tag{4.7}$$

where A_i^* is the equilibrium level for the input-augmenting technological factors, also derived from the steady-state condition $\dot{A}_i = 0$:

$$A_i^* = \frac{\eta_i R_i^*}{\delta}. \tag{4.8}$$

From these equations we can see that the higher the input-specific R&D productivity η_i, the higher the R&D expenditure will be. R&D expenditures also positively depend on the cost share of the input θ_i. The effect of the input prices on R&D is less straightforward and it depends on the value of the elasticity of substitution σ. When the two goods are substitutes ($\sigma > 1$), an increase in price leads to a decrease in R&D expenditure. This is because there will be a change in production and R&D towards the substitute good. Conversely, when substitution between the two goods is not possible, it will be more convenient for the firm to invest in R&D in the same sector in order achieve lower costs by increasing the augmentation factor. The effect of the unit cost function for energy χ depends on the values of the elasticity

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[4] While variables continue to be in function of time, the time indication is omitted from now on for the sake of clarity.

of substitution and of the price elasticity of demand γ. When the energy market is elastic and demand responds to price changes, an increase in price will lead to a decrease in demand and a consequent fall in R&D expenditures for both inputs. If instead the market is rigid, it will be necessary for the firm to invest in R&D to reduce production costs. There is a tradeoff between the substitution effect and the demand effect. For high substitution levels between inputs, R&D expenditures will increase for any price elasticity of demand. Similarly, for very high price elasticities of demand R&D will decrease for any substitution elasticity.

We assume that the units of the θ_i can be chosen to normalize pre-tax input prices to unity, so that $p_{REN} = p_{FF} = 1$. Once the environmental regulation is imposed in the fossil fuel sector we then have that $\tau = p_{FF}/p_{REN} > 1$, where τ can be thought of as a carbon tax on the energy sector. Combining equations (4.7) and (4.8) we can derive the steady-state relative quantity of innovation in fossil fuel technologies A^*:

$$A^* = \left(\eta^2 \theta^\sigma \tau^{1-\sigma}\right)^{\frac{1}{3-\sigma}} \tag{4.9}$$

where $\eta = \eta_{FF}/\eta_{REN}$, and $\theta = \theta_{FF}/\theta_{REN}$ denote respectively the relative efficiency parameters, and the relative importance of energy produced by fossil fuels in overall energy production. Equation (4.9) establishes a steady state relationship between the direction of innovation and relative energy price[5]. This expression shows that the degree of crowding out depends on the carbon tax and on country-specific characteristics of the firms. When R&D is relatively more productive in the fossil-fuel sector, there will also be more innovation in this sector[6]. The higher the relative production cost share of fossil fuel energy, the higher the level of innovation in the sector. It illustrates that the effect of a change in relative prices on the direction of innovation depends on the elasticity of substitution. The larger the value of σ, the smaller the denominator of the exponent, and the greater the influence of prices on α^*. If the level of substitutability between the two goods is high, then there will be a decrease in the relative amount of innovation in fossil fuel technologies. Vice versa,

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[5] Note that this expression is equivalent to the findings in Acemoglu [2] who finds that the ratio of capital and labor augmenting innovation is a function of the relative magnitude of the capital and labor coefficients in production, the relative factor abundance, and the elasticity of substitution between capital and labor.

[6] Except in the case of a very high elasticity of substitution $\sigma > 3$.

with a low level of substitutability, relative innovation will decrease. The intuition behind the effect of relative prices is simple. As the price of fossil fuel energy increases, the demand for this type of energy will decrease, fossil fuel augmenting research generates a smaller increase in output and profit compared to renewable energy augmenting R&D. Thus, if it is easy for the firm to substitute between the two goods ($\sigma > 1$), it will be more convenient for the firm to invest in research the untaxed good. In this case, all else equal, α^* decreases showing a change in the direction of innovation from fossil fuels towards renewables. In instead there are limited possibilities of substitution ($\sigma < 1$), the firm will invest more in fossil fuel energy R&D to carry on having the same production levels of the input whose relative price is now higher. In this case the direction of innovation will change in favor of fossil fuels and there will be an increase in α^*.

Results so far do not show the effect of a carbon tax on the technology-specific innovation. Thus, it is not possible to say whether there is an actual decrease in innovation in fossil fuels. This is also interesting to explore as innovation will result into installed capacity in the long run. A change in the focus of innovation will thus influence the environmental impact of a country in term of carbon emissions. Equations (4.7), (4.8), and (4.9) combined lead to formulation of technology-specific expressions for the augmentation coefficients in function of relative prices:

$$
\begin{aligned}
A^*_{FF} &= k_1 \omega^{\frac{\sigma-\gamma}{(1-\sigma)(3-\gamma)}} && (4.10)\\
A^*_{REN} &= k_2 \omega^{\frac{\sigma-\gamma}{(1-\sigma)(3-\gamma)}} \tau^{\frac{1-\sigma}{3-\sigma}} && (4.11)
\end{aligned}
$$

Where $\omega = 1 + (\overline{\omega} - 1)\, \tau^{\frac{2(\sigma-1)}{3-\sigma}}$, and $\overline{\theta}$, k_1, and k_2 are positive constant depending on the firms parameters[7]. Studying the sign of these expressions tells us whether an increase in the carbon tax τ would lead to an increase in innovation in the single sectors. For what regards the renewable sector, innovation is monotone in relative prices and whether it is increasing or decreasing depends on the values of the elas-

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[7] $\overline{\omega} = 1 + \eta^{2\frac{\sigma-1}{3-\sigma}} \omega^{\frac{2\sigma}{3-\sigma}}$, $k_1 = \eta_{REN}^{\frac{2}{3-\gamma}} [\delta(r+\delta)]^{-\frac{1}{3-\gamma}} \omega^{\frac{\sigma(1-\gamma)}{(1-\sigma)(3-\gamma)}}$, and $k_2 = [1 + 1/\eta_{REN}^2]^{\frac{\gamma-\sigma}{(3-\sigma)(3-\gamma)}} [\delta(r + \delta)/\eta_{FF}^2]^{-\frac{1}{3-\gamma}} \omega_{REN}^{\frac{2\sigma(1-\gamma)}{(1-\sigma)(3-\gamma)}} \omega_{FF}^{\frac{\sigma}{3-\sigma}}$.

ticities. We have that:

$$\operatorname{sgn}\left[\frac{\partial A^*_{REN}}{\partial \tau}\right] = \operatorname{sgn}\left[\frac{\sigma-\gamma}{(3-\sigma)(3-\gamma)}\right].$$

Therefore, for $\sigma > \gamma$ an increase in the carbon tax will lead to an increase in innovation in the renewable sector if the elasticity of substitution between the two sectors is greater than the price elasticity of demand for energy. Only in the case of a very elastic market in which demand falls as prices rise we would have a decrease of innovation in this sector. For what regards the fossil-fuel sector instead, the function is non-monotone and we find that:

$$\operatorname{sgn}\left[\frac{\partial A^*_{FF}}{\partial \tau}\right] = \operatorname{sgn}\left[\frac{1-\sigma}{3-\sigma} - \frac{\gamma-1}{3-\gamma}(\omega-1)\right].$$

In this case, the effect depends on the elasticities as well as on the value of the carbon tax τ. For certain values of the elasticities the function will be monotone (increasing for $\sigma < 1$ and $\gamma < 1$, and decreasing for $\sigma > 1$ and $\gamma > 1$)[8]. Thus, if the market is very flexible in demand and in substitution of intermediates, innovation in fossil fuel energy will decline, as it will be more convenient to invest more in renewables. If instead the market is rigid, it will be necessary to invest more in fossil fuel technologies to keep production costs down. For $\sigma > 1$ and $\gamma < 1$, or $\sigma < 1$ and $\gamma > 1$, the function will be non-monotone and concave. It will achieve a maximum at:

$$\tau_{max}^{A^*_{FF}} = \eta\theta^{\frac{\sigma}{(\sigma-1)}}\left[\frac{(1-\sigma)(3-\gamma)}{(\gamma-1)(3-\sigma)}\right]^{\frac{3-\sigma}{2(1-\sigma)}}$$

Below this threshold increases in τ will cause innovation to increase in fossil fuel energy, whereas above it innovation in this sector will decline. Below $\tau_{max}^{A^*_{FF}}$ the additional costs of the tax are still low enough that the firm will invest more in R&D to increase profits. Above the threshold instead the costs are high enough that the research costs outweigh the profit loss so that innovation in fossil fuels declines. Given this, the regulator should aim at fixing the tax at the $\tau_{max}^{A^*_{FF}}$ level, as too high taxes could reduce the level of innovation below the pre-tax values.

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[8] These intervals are for $\sigma < 3$ and $\gamma < 3$ as these are more plausible values. However, the same reasoning applies for when considering also higher values of the elasticities.

4.3 Empirical Analysis

With the purpose to estimate the relationship between relative input prices and directed innovation, we set up an empirical model to estimate equation (4.9). However, this relationship does not tell us whether the decrease (increase) in relative innovation due to a change in prices, is due to innovation increasing in both sectors but increasing less (more) in the fossil-fuel sector, or whether there is an actual decrease of innovation in either sector. This is why, we will also estimate the necessary parameters in the model, so as to be able to numerically evaluate equations 4.10 and 4.11. The elasticity of substitution will be estimated from equation (4.9). The price elasticity of demand will be estimated from equation (4.4). The R&D productivity parameters will be estimated from the technology-specific equations (4.8). Finally, the production cost share parameters will be derived combining the results from the from estimation of equations (4.9) and (4.8). The different data and estimation methods will be explained in the next sections.

4.3.1 Empirical model

The starting point for this analysis is equation (4.9), which indicates how the relative innovation changes according to changes in relative prices. In particular we expect the relative use of fossil fuel energy to decrease with an increase in relative prices. In order to test this hypothesis we need to linearize equation (4.9) so as to make it possible to estimate it. By taking logs we have:

$$ln\ A = \frac{2}{3-\sigma} ln\ \eta + \frac{\sigma}{3-\sigma} ln\ \theta + \frac{1-\sigma}{3-\sigma} ln\ \tau \qquad (4.12)$$

This is a steady state equation establishing a long-run relationship between relative prices and relative innovation. As such it is natural to hypothesize a cointegrating relationship between the variables. A usual representation of cointegrating relationships is done through the Error Correction Model (ECM). According to the Granger representation theorem, time series that are cointegrated have an error correction representation, and time series that can be represented by an ECM are cointegrated (Engle and Granger [35]). The advantage of using an ECM is that it allows to consider both the short run and the long run effects. In our case this is particularly interesting as the short and long run effects of a carbon tax on the direction of innovation can be expected to be different, with a long run adjustment being more consistent.

We set up an ECM for the equation to be estimated to obtain, for country j and year t:

$$\Delta ln(A_{jt}) = \alpha_0 + \alpha_1 \Delta ln(\tau_{jt}) + \lambda[ln(A_{jt}) - \beta ln(\tau_{jt})]_{t-1} + \epsilon_i + u_{jt} \qquad (4.13)$$

Where all variables are in logarithmic form and correspond to the ratio of the levels of fossil fuels over renewables. In this representation the coefficient α_1 captures the immediate effect of relative prices on relative innovation. This is the short run effect. The long term effect occurs at a rate dictated by the error correction parameter λ. This is an adjustment coefficient illustrating the speed at which the system can go back to the equilibrium. We expect the error correction term to be negative to show that there is a correction towards the equilibrium. The empirical model in equation 4.13 can be linked to the structural model with the purpose to find values for the parameters of the model. In particular we have that the coefficient expressing the effect of τ on A^* corresponds to β in equation 4.13. This can be calculated as the ratio of the estimated parameter on the relative prices ($\beta\lambda$), and the error correction coefficient (λ). Comparing this to the original equation 4.12, this can be used to obtain the elasticity of substitution $\sigma = (1 - 3\beta)/(1 - \beta)$. Note also that the constant term corresponds to the first part of equation 4.12, so that $\alpha_0 = \frac{2}{3-\sigma} ln\, \eta + \frac{\sigma}{3-\sigma} ln\, \theta$.

Besides exploring the steady state relationship between relative prices and relative innovation, we also want to estimate the model's parameter values in order to be able to infer on the model's conclusions on the effect of relative prices on innovation in the single technologies. In order to obtain estimates of the R&D productivities we estimate the steady state relationship between R&D expenditures and knowledge stocks given by equations (4.8). As this is another steady state relationship, it is also modeled with an ECM:

$$\begin{cases} \Delta(A_{FFjt}) = \alpha_{FF}\Delta R\&D_{FFjt} + \lambda_{FF}[A_{FFjt} - \beta_{FF}R\&D_{FFjt}]_{t-1} + \epsilon_{FFi} + u_{FFjt} \\ \Delta(A_{RENjt}) = \alpha_{REN}\Delta R\&D_{RENjt} + \lambda_{REN}[A_{RENjt} - \beta_{REN}R\&D_{RENjt}]_{t-1} \\ \qquad\qquad + \epsilon_{RENi} + u_{RENjt} \end{cases} \tag{4.14}$$

The disturbances in the two equations are likely to be correlated. As they are two different types of energy, the correlation could come for common shocks in the energy market. In order to gain efficiency, the equations are estimated as a system following the Seemingly Unrelated Regressions (SUR) firstly introduced by Zellner [98]. The increase in efficiency also applies to the ECM estimation, as demonstrated by Thompson et al. [91]. From these equations we can derive $\eta_{FF} = (\beta_{FF}/\lambda_{FF})\delta$, and $\eta_{REN} = (\beta_{REN}/\lambda_{REN})\delta$.

Finally, we estimate the energy demand to energy prices relationship given by equation (4.4) in order to obtain estimates for the price elasticity of demand:

$$ln(E_{jt}) = ln(M) - \gamma ln(p_{Ejt}) + \epsilon_i + u_{jt} \tag{4.15}$$

Which can be used to derive the price elasticity of demand γ. As this is not an equilibrium relationship we do not estimate it as an Error Correction Model.

4.3.2 Data

The key part of the empirical analysis is to construct measures of technology-specific knowledge stocks for the augmentation parameters A_i. In order to do this we chose patent data as an indicator of innovative activity. Patents are an output measure of innovation, and as such reflect the innovative performance of firms and economies (Griliches, 1990). They are a useful indicator as they can be distinguished by the nature of the applicant, and of the invention. This allows dividing patents by country and by technological field. Although not all inventions are patented, as underlined in Dernis and Guellec [28] there are few examples of economically significant inventions that have not been patented. Patents are issued by national offices and answer the necessity to protect new technologies with property rights that exclude others from the production for a defined number of years, which varies upon the nature of innovation and the rules of the national offices. Patent data can be disaggregated by technology, which proves useful for the selection of the technological areas of interest. The International Patent Office (IPO) supplies patent classification codes developed by the World Intellectual Property Organization (WIPO), thanks to which patents are classified into different technological areas and at several hierarchical levels. The International Patent Classification (IPC) (WIPO [74]) is application-based, thus facilitating the identification of specific technology classes, and particularly for the scope of the present work, of classes including energy-efficiency patents.

Relevant patent classes have been selected in the area of energy-efficient fossil fuel technologies, considering gas turbines, compressed ignition engines, cogeneration, combined cycles, superheaters, steam engines, boilers, burners and fluidized beds. Technology classes for the renewable technologies have been taken from previous selections (Johnstone et al. [57]) which provide codes for the relevant renewable electricity generation technologies. These include energy-efficient technologies which are not based on the use of fossil fuels, namely wind, solar, geothermal, ocean, biomass and waste. Patents relative to these technologies have been obtained from the EPO/OECD Worldwide Patent Statistical Database (usually referred to as PATSTAT).

Although very useful, patents are an imperfect measure of innovation. It is difficult to identify the value of a patent. Some patents may have a higher impact on the market than others. For this reason patents are usually weighted to account for their difference in value. The most common procedure to weight patents is to use citations[9] (Popp [77]). As an alternative methodology, instead of taking all patent applications we only count the 'claimed priorities'[10]. Previous research has shown that the number of additional patent applications (other than the priority application) is a good indicator of patent value (see Guellec and van Pottelsberghe [43];

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[9] The number of times the patent has been cited in other patent applications. This is an indicator on the importance of the innovation in the technological field.

[10] Patents that have only been registered in one patent office are referred to as singulars. Patents that have been registered in multiple offices are instead referred to as claimed priorities. A patent that is registered in an office but that had already been registered before is referred to as a duplicate.

Harhoff et al. [45]). Claimed priority counts are generated separately for fossil-fuel based technologies and for renewable technologies. This allows us to construct two separate knowledge stocks for the two types of technologies, namely A_{FF} for the knowledge stock in fossil fuel energy and A_{REN} for the knowledge stock in renewable energy. Knowledge stocks are constructed using the perpetual inventory method and with a rate of decay $\delta = 0.1$ (Popp [77]).

Although the ideal variable to be used for the carbon tax τ would have been the carbon price or the actual value of carbon taxes, such data is not available yet. In the European Union, the Emissions Trading Scheme has detailed information on the price data, but only from its start date in 2005. However, as the other data are available only up to 2006, the panel size would be too small to obtain reliable estimates. Thus, we use the ratio of fossil fuel energy price p_{FF} over renewable energy price p_{REN}. The price data is derived from the price indices in the Energy Prices and Taxes database of the International Energy Agency (IEA [50]). The fossil fuel prices have been calculated as a production-weighted average of the price index of coal, gas, and oil. The price of non-carbon energy is used as a proxy for the price of renewable energy. Although this is not the perfect policy variable, it fits the initial set up of the theoretical model. Furthermore, energy prices, and in particular fossil fuel prices, have been at the center of the debates on climate change and use of exhaustible natural resources. The ratio of the prices should capture the pressure that is given on fossil fuels due to climate policies and debates, and resource scarcity. On the other hand, the non-fossil fuel energy price should reflect the regulatory support that has been given to carbon-free electricity generation. The price of the final energy good p_E is also taken from the Energy Prices and Taxes database of the International Energy Agency (IEA [50]).

Data on the demand for energy is taken from the Energy Balances database of the IEA [49]. R&D expenditures are taken from the technology-specific R&D database of the IEA [51]. Although this database is technology specific and thus makes it possible to create separate R&D variables for fossil fuels and renewables, it is limitative as it only includes data from public sources. However, as pointed out by Nemet and KammenčiteNemet who study R&D trends in the United States, the private R&D in the energy sector has been decreasing and public R&D has been the main source of funding. The detailed databases of the IEA allow us to construct a panel in which all variables are technology specific. Tables 4.1 and 4.2 respectively summarize the data sources and characteristics. The data form a panel of 23 OECD countries with a time span of 28 years (from 1978 to 2006)[11]. The number of observations is reduced when variables with a shorter time interval are included.

Table 4.1: Data sources (1978-2006)

Variable	Source	Measure	Countries
A_{FF}	PATSTAT, OECD	Patent stock	23
A_{REN}	PATSTAT, OECD	Patent stock	23
$R\&D_{FF}$	IEA	Billion US$	20
$R\&D_{REN}$	IEA	Billion US$	20
p_{FF}	Energy Prices and Taxes, IEA	real index	23
p_{REN}	Energy Prices and Taxes, IEA	real index	23
p_E	Energy Prices and Taxes, IEA	real index	23
$Prod_{FF}$	Energy Balances, IEA	ktoe	23
$Prod_{REN}$	Energy Balances, IEA	ktoe	23

Table 4.2: Descriptive Statistics

Variable	Obs	Mean	Std.Dev.	Min	Max
A_{FF}	644	15.45	28.48	0.00	133.40
A_{REN}	644	12.62	27.54	0.00	212.88
$R\&D_{FF}$	580	0.07	0.18	0.00	1.82
$R\&D_{REN}$	580	0.04	0.11	0.00	1.38
p_{FF}	644	102.77	22.74	51.15	199.77
p_{REN}	644	111.86	21.86	51.03	210.66
p_E	644	102.43	18.45	56.76	179.28
X_{FF}	644	61736.92	125422.50	1211.95	691480.80
prod$_{REN}$	644	11313.59	21148.35	3.70	116517.20

In order to verify whether the ECM specification is correct, we test for the presence of cointegration on equations (4.13), and (4.14). There are a number of panel cointegration tests, most of which are based on the null hypothesis of cointegration. These test whether there is a unit root in the panel, assuming that long-and short run effects are the same. Examples are the Im-Pesaran-Shin test (see Im et al. [53]), the Levin-Lin test (Levin and Lin [63]). A more flexible test has been introduced

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[11] Although patent data are available for more recent years, it is not advisable to take them into consideration as the processing of the patents takes 2-3 years and the data from 2007 to 2009 may be still incomplete.

by Westerlund [96]. This is based on the null hypothesis of no cointegration, and directly tests an ECM specification. By testing whether the Error Correction parameter is zero, it allows to conclude whether the ECM specification is correct. Table 4.3 illustrate results from the Westerlund test for the four equations to be estimated[12]

Table 4.3: Cointegration tests

Statistic	Value	Z-value	P-value
log(A)	-2.453	-6.806	0.000
A_{REN}	-1.464	-2.097	0.018
A_{FF}	-1.646	-2.879	0.002
E	-0.668	1.423	0.923

The results show that the ECM specification is correct for the long-run equilibrium equations, but not for the demand equation. Thus, the innovation equations will be estimated with an ECM.

The demand equation will be estimated following a more appropriate specification. Coherently with the literature on estimation of energy demand, we estimate equation (4.15) with a dynamic panel data methodology, drawing on previous works by as Balestra and Nerlove [9], and Liu [64]. In this model energy demand is estimated as a dynamic panel data, therefore including the lagged dependent variable between the regressors. The authors used use the Arellano and Bond [5] estimator, which uses a generalized method of moments estimation to correct for the autocorrelation deriving from the inclusion of the lagged dependent variable. However, the Arellano and Bond estimator assumes no autocorrelation in the idiosyncratic errors. As this is a very strict assumption, we use an alternative estimator developed by Arellano and Bover [6], and Blundell, and Bond [12], which allows for autocorrelation in the error terms.

4.3.3 Estimation results

Induced Innovation

As this is an equilibrium long-run relationship, we can model it through an Error Correction Model (ECM). We have already checked that this fits with the data.

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[12] Results are reported only for the Westerlund test having null hypothesis cointegration in the full panel.

Furthermore, this allows us to explore both the short- and the long-run effect of a change in relative prices. Table 4.4 illustrates the results from the ECM estimation.

Table 4.4: Induced Innovation Equation

	Coefficient	ΔlnA
Const	α_0	1.7619**
		(0.011)
$\Delta ln\tau$	α_1	-1.2844***
		(0.000)
$ln(A_{t-1})$	λ	-.5126***
		(0.000)
$ln(\tau_{t-1})$	$\lambda\beta$	.2454*
		(0.084)
Fixed Effect		Yes
Observations		667
Adjusted R^2		0.27

Significance levels: $*$ 10% $**$ 5% $***$ 1%

Results are consistent with the induced innovation hypothesis. The negative coefficient on the difference in own-price ratio indicate that an increase in the price ratio generates a short-run decrease in relative innovation. The error correction term is negative and significant, which means that when the system is not in equilibrium, there is an adjustment towards the long-run equilibrium. The error correction term is -.5126, indicating an adjustment towards the long-run equilibrium of around 51%. The long run effect of the price on innovation is given by the coefficient on the lag relative prices ($\lambda\beta$) over the error correction term (λ). This is negative showing that increasing relative prices of fossil fuel energy will lead to a fall in relative innovation in the long run. These results also allow us to calculate the elasticity of substitution, which can be derived from the coefficient on the relative prices and the error correction term[13]. We find that the elasticity of substitution is $\sigma = 1.64$. This shows that there is a relatively high level of substitutability between fossil-fuel and renewable energy. As there are no previous estimates of this elasticity it is not possible to compare the result with previous works. However, it is interesting to compare it with the values of the elasticities between fossil-fuel and non-carbon energy used in the modeling literature. The WITCH [14] model uses an

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[13] As explained in the previous section.

elasticity of substitution of 2, whereas the GTAP-E model [18][14] uses an elasticity of 1. Other models only give a range of values. The DEMETER model, developed by van der Zwaan and Gerlagh [94] uses a range of elasticities between 1 and 8, and the GREEN [61] model developed by the OECD uses values between 0.25 and 2. Therefore, the value obtained is in the range of the existing literature and can give empirical foundation for the chosen elasticities.

R&D productivities

The productivities are also estimated on an ECM as from equation (4.14). The two equations are estimated simultaneously with a seemingly unrelated regression (SUR). Table 4.5 illustrates the results.

Table 4.5: Estimation Results - R&D Productivities (SUR)

Variable	Coefficient	ΔA_{FF}	Coefficient	ΔA_{REN}
$\Delta R\&D$	$\alpha_F F$	6.5822	$\alpha_R EN$	22.1285**
		(0.254)		(0.036)
A_{t-1}	λ_{FF}	-.2996***	λ_{REN}	-.1895***
		(0.000)		(0.000)
$R\&D_{t-1}$	$\lambda_{FF}\beta_{FF}$	-1.8487***	$\lambda_{REN}\beta_{REN}$	-4.1128*
		(0.000)		(0.058)
Fixed Effect		Yes		Yes
Observations		560		560
Adjusted R-sq		0.2273		0.2187

Significance levels: $*$ 10% $**$ 5% $***$ 1%

We find that higher R&D expenditure leads to higher innovation, as expected. We also find that in the renewable sector there is a significant positive short-run effect of R&D. The short run effect is non significant for fossil fuel energy instead. This may be due to the fact that this is a more stable sector with lower levels of short-run changes in R&D investments. The error correction terms are negative and significant in both equations. The adjustment rate is higher in the fossil fuel sector, so that adjustments take longer in the renewable sector. From the results we can calculate the technology specific productivity parameters, which we find are $\eta_{FF} = \beta_{FF}/\delta = 61.4$ and $\eta_{REN} = \beta_{REN}/\delta = 217.0$, so that their ratio is $\eta = .29$.

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[14] This is the energy version of the GTAP (Global Trade Analysis Project) model developed by the University of Purdue.

Note that the productivity parameters indicate the amount of knowledge stock per unit of R&D. Therefore the average output in terms of knowledge created for an additional billion US$ spent in fossil fuel energy will give 61.4 additional patent stock (discounted sum of patents), whereas it will give 217.0 if invested in renewables. The fossil fuel R&D is less productive. This may be due to the fact that the R&D data we are using is only relative to public expenditure, whereas in the fossil fuel sector the share of private expenditure is more consistent.

Energy demand

The demand equation, as it is not cointegrated, is estimated as a dynamic panel. The chosen estimator is the Arellano-Bover [6]/Blundell-Bond [12], as it allows for autocorrelation between the idiosyncratic errors. Table 4.6 illustrates results for both estimators, as well as for simple fixed effect estimation for comparison.

Table 4.6: Estimation Results - Energy Demand

Variable	$ln(E)$
Constant	1.0017***
	(0.000)
$ln(E)_{t-1}$	.9422***
	(0.000)
$ln(p_E)$	-.0849***
	(0.000)
Fixed Effect	Yes
Observations	560
Wald chi2	5914.38

Significance levels: $*$ 10% $**$ 5% $***$ 1%

The results illustrate that the effect of an increase in price has a negative effect on demand. This negative short run effect is very small and it shows that the energy market does not respond strongly to price changes in the short run. Energy demand is also significantly dependent on the values of demand in the previous years. The positive and significant coefficient shows that the previous period demand positively influences current period demand. From the results it is also possible to calculate the long-run price elasticity of demand. This can be obtained by equating demand in the two time periods, as demand in the long run will be constant. The price elasticity of demand is then $\gamma = .0901$. This is a low value, but coherent with the expectations on the rigidity of the electricity market. It is reasonable that the price elasticity of demand for energy is so low, as the energy market is rigid and only very substantial increases in prices can lead to a change in the demand for energy. The result is also coherent with the previous literature. Liu [64] finds values in the range of 0.030 and 0.191, Nordhaus [73] finds values between 0.03 and 0.68, and De Cian et al. [26] between 0.031 and 0.23. Such a low value of the price elasticity of demand mean that in the model the main adjustments will take place in substitution between inputs, rather than in changes in demand in response to price increases.

Numerical analysis

From the calculations we have obtained values for the relative productivity parameter $\eta = .29$, for the elasticity of substitution $\sigma = 1.64$, and for the price elasticity of demand $\gamma = .09$. However, it is still necessary to obtain the values of the relative production cost share parameter θ. From the estimation of the induced innovation equation the constant term and the error correction term give us $\alpha_0 = \frac{2}{3-\sigma} ln\, \eta + \frac{\sigma}{3-\sigma} ln\, \theta = 1.76$. Using the estimated parameter values we find $\theta = 5.75$. From this, knowing that the production cost shares sum to 1, we have $\theta_{FF} = .85$ and $\theta_{REN} = .15$. These are reasonable values given that most energy is produced from fossil fuels.

In order to verify the effect of an increase in relative prices on innovation in the single technology types, we apply a numerical analysis based on the estimated parameter values. The results are as follows:

$$\left[\frac{\sigma-\gamma}{(3-\sigma)(3-\gamma)}\right] > 0 \Rightarrow \left[\frac{\partial A^*_{REN}}{\partial \tau}\right] > 0$$

As the elasticity of substitution between the two energy types is greater than the price elasticity of demand, a marginal increase in the carbon tax leads to an increase in innovation in renewable technologies. For what regards the fossil-fuel technologies instead, the results depend on the value of the tax. We can compute the tax level for which the highest amount of innovation is achieved in the fossil fuel sector. Given the estimated parameter values, $\tau_{max}^{A^*_{FF}} = 18.22$, that is to say that innovation will continue to increase in the fossil fuel sector despite the imposition of a carbon tax until the carbon price has reached its maximum value of 18.22US$. Innovation will increase until the threshold level and then it will decrease:

$$\left[\frac{1-\sigma}{3-\sigma} - \frac{\gamma-1}{3-\gamma}(\omega-1)\right] < 0 \Rightarrow \left[\frac{\partial A^*_{FF}}{\partial \tau}\right] < 0 \text{ if } \tau > 18.22$$

$$\left[\frac{1-\sigma}{3-\sigma} - \frac{\gamma-1}{3-\gamma}(\omega-1)\right] > 0 \Rightarrow \left[\frac{\partial A^*_{FF}}{\partial \tau}\right] > 0 \text{ otherwise}$$

Figure 4.1[15] illustrates this relationship. For the given elasticities and parameter values, innovation in fossil fuel energy is a concave function of the carbon tax. The function is steeper for lower values of the tax demonstrating that innovation is responsive to changes in relative prices. After the threshold level instead innovation declines slowly. The maximum is achieved for a value of the carbon tax $\tau = 18.22\$$. Note that although the estimations have been done using relative prices as a proxy for τ, in the theoretical model it has been assumed that the prices of the two energy types are both normalized to 1, so that τ is the value of the carbon tax.

Allowances in the EU Emissions Trading Scheme have been prices at around 13*e* in 2009, equivalent to around 18US$. Thus, we should expect innovation in fossil-fuel energy to start declining as prices increase further. Although innovation in fossil fuel is initially increasing, as shown before, the relative amount of innovation is always decreasing. Therefore, we have that below the threshold level all types of innovation are increasing, but that innovation increases relatively more in the renewable sector. Above the threshold instead innovation will still increase in the renewable sector, but it will decline in fossil fuel electricity generation. This is interesting, as it shows that firms will carry on innovating in both sector till the relative price of fossil fuel is high enough for them start decreasing innovation in fossil fuel energy.

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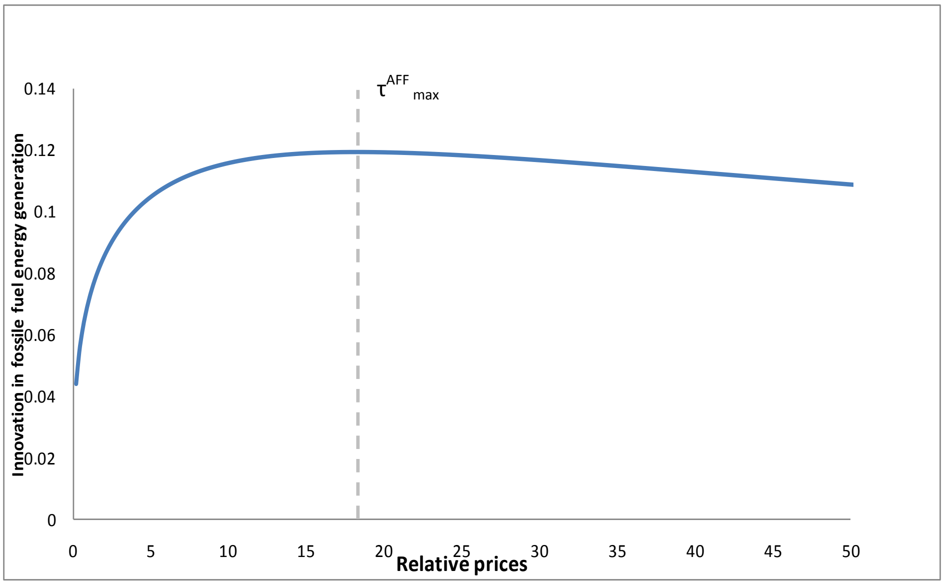
[15] Note that in the figure the initial level of innovation has been normalized to $k_1 = 1$, so that the figure should be interpreted only for what regards its time path rather than magnitude.

Figure 4.1: Innovation in fossil fuel energy in response to a carbon tax



4.4 Conclusions

This paper presents an analysis of the changes in the direction of technical change induced by increases in fossil fuel prices. By using a dynamic two-sector model of directed technical change, we establish and estimate a relationship between relative energy prices and relative innovation between the fossil-fuel and the renewable energy sectors. We propose an Error Correction Model (ECM) estimation methodology for this type of model. The ECM specification allows us to estimate the steady state relationship while correcting for short run deviations from the equilibrium. We find that increasing fossil fuel prices lead to a change in the direction of technical change from fossil-fuel towards renewables. From the model solution we also obtain expressions that illustrate the effects of increasing relative prices of fossil fuels on innovation in the single type of technology. These expressions are evaluated with estimated model parameters. It is found that the decrease in relative innovation due to an increase in relative prices corresponds to an actual decrease in innovation in the fossil fuel sector only above a certain level. Below this threshold innovation increases in both sectors, although it increases more in the renewable sector. This shows that the increasing prices of fossil fuel energy lead to an increase in innovation in both energy sectors, unless they are too high, which causes innovation in the renewable sector to decline. The aim should thus be to achieve relative prices level close to the threshold so that innovation is high in both sectors.

Appendix

Model solution

After deriving an expression for p using equation (4.4), we can use it in the maximization problem to derive the current-value Hamiltonian:

$$H = M^{\frac{1}{\gamma}} E^{\frac{\gamma-1}{\gamma}} - p_{REN}X_{REN} - p_{FF}X_{FF} - \frac{1}{2}[(1+\psi_{REN})R_{REN}^2 + (1+\psi_{FF})R_{FF}^2]$$

$$+\lambda_{REN}(\eta_{REN}R_{REN} - \delta A_{REN}) + \lambda_{REN}(\eta_{FF}R_{FF} - \delta A_{FF})$$

where E is given by (4.1), and λ_i are the adjoint variables dual to the knowledge stocks A_i. After substituting for the production function, the first-order conditions can be derived as:

$$\frac{\partial H}{\partial X_i} : -p_i + \frac{\gamma+1}{\gamma} M^{\frac{1}{\gamma}} E^{\frac{1}{\sigma}-\frac{1}{\gamma}} \theta_i A_i^{\frac{\sigma-1}{\sigma}} X_i^{-\frac{1}{\sigma}} = 0$$

$$\Rightarrow X_i = M^{\frac{1}{\gamma}} \left(\frac{\gamma+1}{\gamma}\right)^{\sigma} E^{\frac{\gamma-\sigma}{\gamma}} \theta_i^{\sigma} A_i^{\sigma-1} p_i^{-\sigma} \tag{4.16}$$

$$\frac{\partial H}{\partial R_i} : -R_i + \eta_i \lambda_i = 0$$

$$\Rightarrow \lambda_i = R_i/\eta_i \tag{4.17}$$

$$\frac{\partial H}{\partial A_i} : r\lambda_i - \dot{\lambda}_i = \left(\frac{\gamma+1}{\gamma}\right) M^{\frac{1}{\gamma}} E^{\frac{1}{\sigma}} \theta_i A_i^{\frac{-1}{\sigma}} X_i^{\sigma-\frac{1}{\sigma}} - \delta\lambda_i \tag{4.18}$$

By normalizing the units of outputs to 1 ($M\gamma^{-\gamma}(\gamma-1)^{\gamma} = 1$), we find output as a function of its unit cost of production χ:

$$E = \chi^{-\gamma} \tag{4.19}$$

where $\chi = (\theta_{REN}^{\sigma} A_{REN}^{\sigma-1} p_{REN}^{1-\sigma} + \theta_{FF}^{\sigma} A_{FF}^{\sigma-1} p_{FF}^{1-\sigma})^{\frac{1}{1-\sigma}}$ is the CES unit cost function. Substituting (4.19) into (4.16) yields to the unconditional input demands:

$$X_i = \theta_i^{\sigma} A_i^{\sigma-1} p_i^{-\sigma} \chi^{\sigma-\gamma} \tag{4.20}$$

Finally substituting (4.4) into (4.18), and using (4.16) and (4.19) we find the equation of motion for the R&D variables in equation (4.6) which is now only parameter dependent.

Conclusion

The message of this dissertation is that it is important to consider intra sectoral dynamics, as they can influence the costs and efficiency of climate policies. I present four papers that share the common basic structure of considering "clean" and "dirty" sectors.

In the first chapter a theoretical model is used to analyze the issue of capital malleability and its linkages to climate policies. An applied computable general equilibrium (CGE) model is also used to show an application to the case of the EU Emissions Trading Scheme (ETS). The results confirm that when capital is not malleable costs of climate policy are higher. In the second chapter, the issue of the coverage of the dirty sector in an emission trading system is addressed both theoretically and with an application to the case of the enlargement of the EU ETS to aviation. It is found that although several factors can lead to higher costs of inclusion of additional sectors in the ETS, costs can be lowered by allocating extra allowances. The third chapter focuses on innovation within the energy sector, in which various intermediate technologies are considered. Using a panel of OECD countries, and data relative to patents to proxy for innovation, it is found that fossil fuel prices lead to higher innovation in energy-generation technologies but that the effect varies for different technologies. Finally, the last chapter uses a model of directed technical changes applied to the energy sector to establish and estimate a long-run relationship between relative prices and relative innovation. It is found that increasing fossil-fuel prices lead to a change in the direction of innovation from fossil fuels towards renewables.

Throughout the chapters different techniques are used, and theoretical arguments are combined to both applied CGE models and empirical analysis. This allows to achieve theory-compatible results that are however applicable to interesting policy-relevant issues. In particular the results of the dissertation would encourage the use of climate policy for achieving higher levels of innovation, particularly in the "cleaner" and more energy-efficient sectors. Given that once a long-term investment in physical capital is made it is hard to reallocate capital between sectors, it would be more efficient to have early investments in cleaner sectors.

Various extensions and applications of this work would be interesting. First of all, the results of the empirical analysis could be applied to climate-economy models to obtain better empirically-based results. Secondly, the theoretical analysis of directed technical change could be adapted to other market structures, in particular taking into consideration the fixed capacity of the renewable sector. Finally, it would be interesting to study the role of capital malleability in a dynamic framework in order to study the effect of timing in climate policy and innovation.

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