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Market Power and Instrument Choice in Climate Policy

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Abstract

This paper compares a clean energy standard (CES) and a carbon tax (CT), using theory and quantitative experiments. A two-stage duopolistic competition in the electricity sector between a polluting plant and its non-polluting rival anchors the model underlying these experiments. The CT induces both plants to contribute to clean electricity, whereas the CES only incentivizes the non-polluting plant. Ultimately, what matters for the ranking of these instruments is the size of the pre-existing competitive gap between the two rival plants. When this gap is sufficiently small, the CES becomes the more cost-effective instrument, irrespective of the pre-specified emissions reduction target.

Keywords: Electricity, Cost-effectiveness, Duopoly, Innovation, Quantitative analysis.

JEL Classification: H20; H32; L13; L51

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1. Introduction

The centerpiece of public policy aimed at reducing emissions of greenhouse gases (GHGs) is the instrument chosen to implement it. There are two main types of policy instruments: fiscal instruments—e.g., carbon tax and cap-and-trade— and regulatory mandates—e.g., the clean energy standard. The debate over which of these two classes of instruments of climate policy is the more cost-effective took a new twist recently. Prior to 2016, the existing literature unanimously favored fiscal instruments over regulatory mandates. However, focusing on the electricity sector, Goulder *et al.* (2016) show that for modest emissions reduction targets, regulatory mandates such as the clean energy standard can out-perform fiscal instruments on cost-effectiveness grounds. This finding is interesting because, like import quotas in trade policy, regulatory mandates are a more direct and precise form of intervention than fiscal instruments whose optimal level is not easily determined in the real world.

However, it is interesting to note that all existing assessments of the relative performances of these two types of instruments of climate policy have been carried out exclusively in model environments where competition between energy suppliers is perfect, and includes only one stage, namely the output stage. Yet, competition, whether perfect or imperfect, gives firms or plants an incentive to be innovative (Holland et al. 2009). This naturally opens up two different stages in which these agents compete with one another: an innovation stage, and the subsequent output stage.[4] Further, with particular reference to the electricity generation sector, even though several political jurisdictions have enacted laws lowering barriers to entry into the generation side of the electricity market, there is evidence that market power persists (Joskow and Tirole 2007).[5] These facts suggest that imperfect competition and innovation are fundamental features of the electricity generation sector.

[4]Goulder and Mathai (2000) introduce innovation in their assessment of the cost-effectiveness of a carbon tax. However, they are not explicitly concerned with the effect of competition in the electricity generation market, nor are they explicitly concerned with instrument choice.

[5]The *Energy Policy Act* enacted in 2005 by the US federal government is a good example. Among other things, this Act provides loan guarantees for entities involved in the use innovative technologies that enhance emission-free energy production.

Studies that ignore this fact inadvertently shut down realistic microeconomic mechanisms by which the burdens of climate policy are channeled on to households. This paper shows that opening the microeconomic black box of the effects of climate policy can shed new light into sources of heterogeneity in the ranking of potential instruments for implementing such policy.

We use a calibrated two sector-general equilibrium model to explore the implications of technological innovation and imperfect competition for the ranking of the carbon tax (hereafter, CT) and the clean energy standard (hereafter, CES), based on their relative cost-effectiveness at achieving a pre-specified emissions reduction target in the electricity sector.[6] Our model combines strategic and non-strategic elements as characteristics of the interactions between the different agents comprising the economy. Non-strategic elements essentially characterize the interactions between a stand-in household, and firms that use labor services and supply the final good consumed. Strategic elements, in contrast, are a feature of the industrial organization of the electricity generation sector. In this sector, two power plants engage in a two-stage competition to supply electricity. They differ from one another with respect to two important characteristics: the technology used to generate electricity and the relative efficiency with which they each supply the market. One power plant operates a technology that emits GHGs as a by-product of electricity generation (e.g., a coal-fired power plant), while the other generates electricity with an emission-free technology (e.g., a windmill farm). The latter faces a pre-existing competitive disadvantage for generating electricity with emission-free sources, and may look to overturn this disadvantage through technological innovation.

From a microeconomic perspective, the issue confronting climate policy is how to expand the output of clean electricity relative to that of "dirty" electricity at the lowest

[6] By restricting our quantitative assessment of the relative cost-effectiveness of the CT vis-à-vis the CES to the electricity sector, we do not by any mean claim that this sector is the only source of GHGs emissions. Instead, the focus on this sector is motivated by the facts that it is one of the largest sources of GHGs emissions. For example, in 2013, the US *Environmental Protection Authority* (EPA) estimated that the power generation sector accounted for 31 % of all GHGs emissions in the US. Furthermore, this sector is also one where intensity standards are still widely used to mitigate GHGs emissions, particularly in the United States— 29 States—, and Canada— at the federal level (OECD 2015).

possible cost to the economy. A key insight conveyed by our model is that the CT has a diversification effect on the production of clean electricity, whereas the CES has a specialization effect instead. The CT induces both the non-polluting plant and its polluting rival to contribute to expanding the output of clean electricity, at the expense of that of "dirty" electricity. Underlying this diversification effect of the CT is the fact that it makes the polluting plant pay for the uncontrolled by-production of GHGs, thus bumping up its operational costs, and exerting a downward pressure on its market share relative to the non-polluting plant. To protect its market share, therefore, the polluting plant may invest in a technological innovation aimed at out-fitting its production unit with an efficient device for controlling emissions. An example of such emissions abatement technology is the so-called carbon capture and sequestration technology (also known as CCS technology), which allows the plant to produce clean electricity with polluting sources, proportionately to the quantity of GHG emissions successfully captured and sequestrated.[7]

In contrast, the CES ties the polluting plant's level of output to the mandated minimum ratio of clean, over total, electricity generated. In compliance with this minimum ratio, the polluting plant can only raise its output in proportion to the increase in the non-polluting plant's output. In that sense, our model shows that the CES, unlike the CT, provides the polluting plant with virtually no incentive to invest in a CCS technology that would have enhanced its contribution to the production of clean electricity through carbon capture and sequestration. The CES mandate, as a result, essentially leaves the non-polluting plant as the only source of clean electricity. This CES-induced specialization effect provides the non-polluting plant with the incentive to overturn its pre-existing competitive disadvantage through investment in a productivity-enhancing innovation.

[7] In November 2014, *The Wall Street Journal* reported that an emissions restriction on coal-fired power plants was a major driver for the emergence, in the Canadian Province of Saskatchewan, of the world's first commercial-scale coal power plant equipped with CCS. It is reported that this technology allowed for the capture of about 90% of the CO_2 generated by SaskPower's Boundary Power Dam—a coal-fired power plant. Further, the same article reports that CCS technology is not the only innovative path to "clean coal" as, "state-of-the-art coal-fired power plants are being built with much higher efficiencies that result in a 20% reduction in CO_2 emissions per kilowatt-hour of electricity produced." See: *Does 'Clean Coal' Technology Have a Future?* Published online at http://www.wsj.com/articles/does-clean-coal-technology-have-a-future-1416779351.

In a nutshell, from a microeconomic perspective, what matters for the ranking of these two instruments of climate policy is the size of the pre-existing competitive gap between the two rival power plants. When this competitive gap is large, it is like a "boulder" trapping the cost-effective expansion of the clean electricity output. On one hand, the technological effort the disadvantaged non-polluting plant must exert to pull this "boulder" out of the path to expansion of clean electricity production may only yield very little in terms of improving its competitive position. On the other hand, a large pre-existing competitive advantage for the polluting plant gives it enough leeway to invest in a CCS technology to boost its production of clean electricity, without losing its competitive edge over the non-polluting plant. In this context, these two related facts seem to hand the advantage to the CT, which, unlike the CES, induces both plants to inadvertently join forces in pulling this "boulder" out of the path to a cost-effective expansion of clean electricity production. However, when the pre-existing competitive gap between the two power plants is small, for the disadvantaged non-pollutant plant, it reduces to a "pebble" size obstacle to the expansion of its clean electricity output. In this context, the CES' specialization effect provides this non-polluting plant with the stimulus enabling it to kick that "pebble" out of the path to a cost-effective production of clean electricity. In contrast, the CT-induced diversification effect loses its edge, because with only a small pre-existing competitive advantage, the polluting plant no longer has the leeway that would allow it to invest in a CCS technology without losing its competitive edge. The insights conveyed through these intuitive microeconomic effects of climate policy therefore suggest that the CES may be more cost-effective than the CT, when the pre-existing cost-disadvantage of the non-polluting plant is sufficiently small, with the reverse being true when this disadvantage is sufficiently large.

Our quantitative analysis formally establishes this prediction. There are three steps to this quantitative cost-effectiveness analysis. In the first step, we calibrate the model to match selected macroeconomic data of the US economy for the period 2012 - 2013. In the calibrated model, there is neither a CT nor a CES. The equilibrium values of the variables computed in this context thus represent *Laissez-faire* values. The goal of climate policy is to reduce the *Laissez-faire* level of GHG emissions to an exogenously given recommended level, under revenue-neutrality. Climate policy is revenue-neutral whenever it keeps the level of the *Laissez-faire* tax revenue unchanged.

In the second step of our cost-effectiveness analysis, we introduce climate policy whose aim is to reduce the *Laissez-faire* level of GHG emissions by 10%, and compute the level of a given policy instrument used to implement this reduction, as well as all other policy-sensitive macroeconomic variables. Technically, this consists of numerically solving a system of equations. When the CT is the chosen policy instrument, this system involves five equations in five unknowns, whereas the corresponding system under the CES consists of seven equations in seven unknowns. We then compare the values of the macroeconomic variables generated by this experiment to their *Laissez-faire* counterparts. We make this comparison in a context where the relative cost-disadvantage of the non-polluting plant is set at 1.92, as estimated from the US data. In other words, the pre-existing marginal cost of the non-polluting plant is 92% higher than that of its polluting rival. For these specific parameter values, our computations show that the CT dominates the CES on cost-effectiveness grounds.

In the third and final step, we explore potential sources of heterogeneity in the ranking of these two instruments of climate policy. We first vary the pre-specified emissions reduction target, moving from modest, to more ambitious, targets, while holding the level of the pre-existing cost-disadvantage of the non-polluting plant constant at 1.92. We then repeat this experiment for different levels of this cost-disadvantage that are consistent with a duopolistic market structure.[8] Our quantitative results show that when the pre-existing cost-disadvantage of the non-polluting plant drops from 1.92 to 1.50, the CES emerges as the more cost-effective instrument of climate policy, irrespective of the pre-specified emissions reduction target. Our analysis thus establishes the size of the pre-existing competitive disadvantage of the non-polluting plant as a very important source of heterogeneity in the

[8] Indeed, above a level of cost-disadvantage equal to 2.1, the electricity generation market becomes a monopoly with the polluting plant as the only supplier.

ranking of the CT and the CES.

This work contributes to the climate policy literature focusing on emissions reduction, aside from the global or collective benefits of mitigating climate change. This include Goulder (1995), Parry, Williams, and Goulder (1999), Bento and Jacobsen (2007), Goulder and Parry (2008), Holland *et al.* (2009), Fullerton and Heutel (2010), Krupnick and Parry (2012), Jorgenson *et al.* (2013), Goulder (2013), Parry *et al.* (2014), Ambec and Ehlers (2014), Marron *et al.* (2015), Goulder *et al.* (2016), and Bushnell *et al.* (forthcoming). Our cost-effectiveness analysis is most closely related to Goulder et al. (2016) who contrast the performances of a carbon tax and a CES mandate, subject to the constraint that (i) both instruments yield the same level of emissions reduction, and (ii) both are revenue-neutral. In this context, they highlight factors that cause the CES to dominate the CT, as the most cost-effective instrument of emissions reductions. Our quantitative analysis revisits Goulder *et al.* (2016)'s experiment in a context where the industrial organization of the electricity generation sector is characterized by a duopolistic two-stage competition between a plant generating electricity from polluting sources, and a rival generating it with non-polluting sources. In fact, we show that for a level of cost-disadvantage of the polluting plant equal to 1.75,[9] there exists a threshold level for the emission reduction target below which the CES emerges as more cost-effective than the CT, and above which the reverse is true instead. For this level of the pre-existing cost-disadvantage of generating electricity with non-polluting sources, our cost-effectiveness analysis indeed replicates the main result of Goulder *et al.* (2016). It is important to note that the addition of market power and innovation as features of the electricity generation sector is not just factual; it also opens up the black box from which to uncover the microeconomic mechanisms channeling the overall burden of climate policy on the economy. This allows us to bring these mechanisms to bear on the ranking of alternative instruments for implementing such policy. As a result, not only does our quantitative cost-effectiveness analysis replicate the main result of Goulder *et al.* (2016), it goes further to show that the cost-effectiveness of the CES is not limited

[9] This implies that the marginal cost of the non-polluting plant is 75% higher than that of its polluting rival.

to modest emissions reduction targets only. Instead, it extends to more ambitious targets as well, provided the pre-existing competitive gap between non-polluting, and polluting, sources of electricity is not too large.

The rest of the paper is organized as follows. Section 2 presents the analytical model. The main features of equilibrium are discussed in section 3. Section 4 presents the quantitative analysis and the results of the associated quantitative experiments. Section 5 offers conclusions. Finally, mathematical details of our results are included in the Appendix section.

2. The Environment

Consider a Regulator who wants to achieve a pre-specified emissions reduction target κ in the electricity generation sector. One can think of κ as the percentage reduction in the status quo's emissions level, resulting from the implementation of this climate policy. Suppose that to achieve this target, the Regulator has a choice between the carbon tax (CT), specifying the price, τ_d, a polluting power plant must pay for each unit of GHG released in the atmosphere, and the clean energy standard (CES), mandating the minimum ratio of clean electricity over total electricity generated $\bar{x}_c \in (0,1)$ that the sector must comply with. For all $\kappa > 0$, denote the Regulator's choice of climate policy instrument as $g \in \{\tau_d, \bar{x}_c\}$. For any given instrument g selected, the Regulator's problem is to set the level of this instrument such that the resulting level of emissions represents a proportion $1-\kappa$ of its *Laissez-faire* level. The higher κ, the more ambitious the emissions reduction target. The aim of this paper to compare τ_d and $\bar{x}_c$, based on their relative cost-effectiveness at meeting the target κ. In what follows, we describe the model environment providing the framework for our comparative cost-effectiveness analysis.

There is a stand-in household endowed with one unit of labor and who is the absentee owner of all firms and plants operating in the economy.[10] There are two production sectors.

[10]That there is a stand-in household reflects the fact that our study is not explicitly concerned with the distributive effects of climate policy.

In the final good sector, there is a representative firm that produces a composite consumption good using electricity and labor. In the electricity sector, there are two power plants each endowed with an exclusive right over the use of a different, non-transferable, technology for generating electricity. One such technology generates electricity with polluting sources—e.g., coal—, while the other technology generates electricity with non-polluting sources— e.g., wind, solar, or geothermal technologies, hydro-power, or nuclear reactors, all of which are negligible sources of GHGs. For ease of exposition, we abstract away from household consumption of electricity, and instead assume that all the electricity generated is consumed by the non-household sector.[11]

The final good market is perfectly competitive, while the electricity market is duopolistic and characterized by a two stage competition. At the start of the economy, the non-polluting power plant has a pre-existing cost-disadvantage for electricity generation relative to its polluting rival, and must invest in technological innovation to reduce, and eventually overturn, this disadvantage. For the plant generating electricity with polluting sources, depending on which climate policy instrument is used, it may or may not invest in technological innovation. For this plant, innovation essentially aimed at out-fitting its production unit with an emissions abatement technology, such as the well known CCS technology. When such innovation occurs, the polluting plant becomes a contributor to the production of "clean" electricity, proportionately to the quantity of GHGs successfully captured and sequestrated.

2.1. Preferences and Budget Constraint

Since we are not concerned with the distributional effects of climate policy, we rely on the concept of a stand-in household to craft a measure of the burden such policy puts on households. In particular, we take the stand-in household's equilibrium utility level as a proxy for social welfare. As welfare thus defined is responsive to climate policy, we

[11]This assumption is consistent with data from the US *Energy Information Agency* (EIA) showing that total primary residential electricity consumption in the US amounted to only 6.57% of total energy consumption in 2015. See EIA (2017). *Montly Energy Review*, available online at http://www.eia.gov/totalenergy/data/monthly/#consumption

interpret a climate policy-induced decrease in its level as a measure of the burden a given policy instrument puts on the economy. In what follows, we detail the steps underlying our characterization of social welfare.

The stand-in household has preferences over consumption of the numeraire, c, leisure, l, and a public good G. These preferences are described as follows:

$$u(c, l, G) := \lambda \ln(c - \underline{c}) + (1 - \lambda) \ln l + \nu \ln G, \tag{2.1}$$

where $\lambda \in (0, 1)$, $\underline{c} \geq 0$ denotes the subsistence level of consumption, and $\nu > 0$. Provision of the public good is financed by tax revenue.

The stand-in household budget constraint is given by:

$$c \leq (1 - \tau_R)[\omega(1 - l) + \Pi] \tag{2.2}$$

where τ_R denotes the income tax rate, ω, the labor wage, and Π, the level of profits earned and formally defined further below. Utility maximization by the representative household yields the following labor supply function:

$$L^S = \lambda - \frac{(1 - \lambda)[(1 - \tau_R)\Pi - \underline{c}]}{(1 - \tau_R)\omega}. \tag{2.3}$$

In other words, having more income from non-labor sources tends to reduce the stand-in household's labor supply (i.e., $\partial L^S / \partial \Pi < 0$); whereas a higher income tax tends to raise this labor supply (i.e., $\partial L^S / \partial \tau_R > 0$), due to the subsistence constraint for consumption. Moreover, if the subsistence requirement for consumption is not too large, then the stand-in household labor supply tends to rise with an increase in the wage (i.e., $\partial L^S / \partial \omega > 0$). Thus factors that deflate the wage tend to discourage labor supply.

Combining (2.1), (2.2), and (2.3), we obtain the stand-in household optimal welfare level as follows:

$$U(\tau_R, \omega, \Pi, G) := \bar{\lambda} + \ln[(1 - \tau_R)(\omega + \Pi) - \underline{c}] - (1 - \lambda) \ln(1 - \tau_R) + \nu \ln G \tag{2.4}$$

where $\bar{\lambda} := \lambda \ln \lambda + (1-\lambda) \ln (1-\lambda)$.

Expression (2.4) provides a basis for assessing the economic costs of climate policy. In particular, we interpret a climate policy-induced decrease in the level of (2.4) as a measure of the burden this policy puts on households. Given a pre-specified emissions reduction target to be achieved by climate policy, the more cost-effective policy instrument is therefore one that yields the smallest decrease in the level of $U(\tau_R, \omega, \Pi, G)$. We will return to this issue in our quantitative analysis further below.

2.2. Production of the Final Good

The final good is a composite numeraire whose production process combines electricity, X, and labor, L, to obtain a level of output described by the following Cobb-Douglas technology:

$$Y = AX^{\alpha}L^{\eta}, \tag{2.5}$$

where α, η are the output elasticities of electricity and labor, respectively, and satisfy

$$\alpha + \eta < 1. \tag{2.6}$$

The inequality in (2.6) implies that the term A captures the impact of other production factors such as land and physical capital, for example, whose level is assumed to be exogenously given. The representative firm in the final good sector purchases a quantity of electricity, X, at a market price, P_x, and hire L units of labor at a market wage, ω. Profit-maximization thus yields the following demand functions:

$$X = \left[\frac{\alpha A^{\frac{1}{1-\eta}}}{P_x}\right]^{\frac{1-\eta}{\varepsilon}} \left(\frac{\eta}{\omega}\right)^{\frac{\eta}{\varepsilon}}, \tag{2.7}$$

$$L^D = \left[\frac{A\eta^{1-\alpha}\alpha^{\alpha}}{\omega^{1-\alpha}(P_x)^{\alpha}}\right]^{\frac{1}{\varepsilon}}, \tag{2.8}$$

where $\varepsilon := 1 - \alpha - \eta > 0$.

To keep the model more tractable, the labor supply function in (2.3) and the inputs' demand functions in (2.7) and (2.8) can all be linearized respectively as follows using first order *Taylor Series Expansions* that preserve all their original properties:

$$L^S \approx \psi_0 (\tau_R, \Pi) + \psi_1 (\tau_R, \Pi) \omega, \tag{2.9}$$

$$X \approx \gamma_0 - \gamma_\omega \omega - \gamma_p P_x \tag{2.10}$$

$$L^D \approx \delta_0 - \delta_\omega \omega - \delta_p P_x \tag{2.11}$$

where

$$\gamma_0 = \frac{(1+\varepsilon)}{\varepsilon} \left[\alpha \left(\eta^\eta A\right)^{\frac{1}{1-\eta}}\right]^{\frac{1-\eta}{\varepsilon}}; \qquad \delta_0 = \frac{(1+\varepsilon)}{\varepsilon} \left[A \eta^{1-\alpha} \alpha^\alpha\right]^{\frac{1}{\varepsilon}};$$

$$\gamma_\omega = \frac{\eta}{\varepsilon} \left[\alpha \left(\eta^\eta A\right)^{\frac{1}{1-\eta}}\right]^{\frac{1-\eta}{\varepsilon}}; \qquad \delta_\omega = \frac{(1-\alpha)}{\varepsilon} \left[A \eta^{1-\alpha} \alpha^\alpha\right]^{\frac{1}{\varepsilon}};$$

$$\gamma_p = \frac{(1-\eta)}{\varepsilon} \left[\alpha \left(\eta^\eta A\right)^{\frac{1}{1-\eta}}\right]^{\frac{1-\eta}{\varepsilon}}; \qquad \delta_p = \frac{\alpha}{\varepsilon} \left[A \eta^{1-\alpha} \alpha^\alpha\right]^{\frac{1}{\varepsilon}};$$

$$\psi_0 (\tau_R, \Pi) = \frac{\lambda(1-\tau_R) - 2(1-\lambda)\left[(1-\tau_R)\Pi - \underline{c}\right]}{(1-\tau_R)}; \quad \psi_1 (\tau_R, \Pi) = \frac{(1-\lambda)\left[(1-\tau_R)\Pi - \underline{c}\right]}{(1-\tau_R)}.$$

The linearization in (2.9) preserves all the properties of the labor supply function in (2.3) for all ω satisfying

$$0 < \omega < 2. \tag{2.12}$$

Combining (2.9) and (2.11) yields the following market-clearing wage:

$$\omega = \frac{\delta_0 - \psi_0 (\tau_R, \Pi) - \delta_p P_x}{\delta_\omega + \psi_1 (\tau_R, \Pi)}. \tag{2.13}$$

In other words, a higher electricity price tends to reduce the labor wage because it decreases the demand for electricity, which, in turn, reduces labor productivity in the final good sector, thus inducing the representative firm to cut its demand for labor.

To characterize the market demand for electricity, we combine (2.10) and (2.13) by way of substitution, re-arranging terms to get:

$$P_x = \xi_0 \left(\tau_R, \Pi\right) - \xi_p \left(\tau_R, \Pi\right) X, \tag{2.14}$$

where

$$\begin{aligned} \xi_0 \left(\tau_R, \Pi\right) &:= \frac{\left[\delta_\omega + \psi_1 \left(\tau_R, \Pi\right)\right] \gamma_0 - \left[\delta_0 - \psi_0 \left(\tau_R, \Pi\right)\right] \gamma_\omega}{\delta_\omega \gamma_p - \delta_p \gamma_\omega + \gamma_p \psi_1 \left(\tau_R, \Pi\right)} \\ \xi_p \left(\tau_R, \Pi\right) &:= \frac{\delta_\omega + \psi_1 \left(\tau_R, \Pi\right)}{\delta_\omega \gamma_p - \delta_p \gamma_\omega + \gamma_p \psi_1 \left(\tau_R, \Pi\right)}. \end{aligned}$$

Since $\mu_\omega \gamma_p - \mu_p \gamma_\omega > 0$ by construction, the term $\xi_p \left(\tau_R, \Pi\right)$ is strictly positive so that the inverse demand function in (2.14) is well-behaved.

2.3. Electricity Generation Sector

The two plants generating electricity are indexed by $j \in \{c, d\}$, and produce electricity from two different sources, a clean source ($j = c$) and a dirty source ($j = d$). Each plant j generates a quantity of electricity X_j at a constant marginal cost described further below. Thus, total supply of electricity is

$$X = X_c + X_d, \tag{2.15}$$

which, under market-clearing, implies that

$$P_x = \xi_0 \left(\tau_R, \Pi\right) - \xi_p \left(\tau_R, \Pi\right) \left(X_c + X_d\right). \tag{2.16}$$

The pre-existing marginal cost of generating electricity with non-polluting sources is ϕ_c. In the case of renewable sources of electricity, one can think of ϕ_c as capturing the severity of the intermittency and/or grid problems facing Plant c prior to any technological innovation. Therefore, if Plant c invests in a technological innovation aimed at mitigating its pre-existing technical problems, its production technology will be up-graded at a level of efficiency, $\theta_c \in [0,1]$, corresponding to the fraction of the initial marginal cost, ϕ_c, knocked down. Thus, Plant c will face a post-innovation investment marginal cost given by:

$$\bar{\phi}_c(\theta_c) = (1-\theta_c)\,\phi_c. \tag{2.17}$$

However, innovation is costly and Plant c must incur a cost $\rho_c(\theta_c)^2$ for achieving a level of technological up-grade θ_c, where $\rho_c > 0$ is an exogenously efficiency parameter. Therefore, given (g, X_d), the net profit generated by Plant c's operations is:

$$\Pi_c(g) = [P_x - (1-\theta_c)\,\phi_c]\,X_c - \rho_c(\theta_c)^2 \tag{2.18}$$

where P_x denotes the market price as defined in (2.16). Plant c's problem is to choose (θ_c, X_c) so as to solve

$$\max_{\langle\theta_c, X_c\rangle} \Pi_c(g).$$

Consider next Plant d's problem. Its pre-existing marginal cost of electricity generation is exogenously given at $\phi_d < \phi_c$. Since the production process of this plant generates GHG emissions as a by-product, the total cost this plant will face depends on the Regulator's choice of instrument of emissions reduction policy. If the Regulator decides to mitigate emissions with the carbon tax ($g = \tau_d$), Plant d must pay a carbon tax τ_d per unit of GHGs released in the atmosphere. To lower its carbon tax outlay, Plant d may consider investing in a technological innovation aimed at capturing and sequestrating GHGs emitted as a by-product of electricity generation with fossil fuels. For convenience, we referred to this innovation as CCS technology. It is assumed that a level of innovation that brings about a level of effectiveness θ_d in the CCS technology costs $\rho_d(\theta_d)^2$ to the plant, where $\rho_d > 0$ is an exogenously given efficiency parameter.

Let βX_d denote the total level of GHGs emitted as a by-product of generating X_d unit of electricity with fossil fuel, where β is a strictly positive parameter. In the absence of CCS use, all of βX_d is released in the atmosphere. However, when the power plant is outfitted with a CCS technology with level of efficiency $\theta_d \in (0, 1)$, a fraction θ_d of the GHGs emitted is successfully captured and sequestrated. This implies that if Plant d invests in a CCS technology, clean electricity in this economy will turn out to have two different sources, including X_c generated by Plant c, and X_d^c generated by Plant d. To characterize the quantity of clean electricity generated by the polluting plant (i.e., Plant d), observe that X_d units of output cause an emission of

$$E = (1 - \theta_d) \beta X_d \tag{2.19}$$

units of GHGs. One can therefore think of $(1 - \theta_d) X_d$ as the share of "dirty" electricity generated by Plant d, which implies that the share of clean electricity generated Plant d is

$$X_d^c = \theta_d X_d. \tag{2.20}$$

Plant d's carbon tax outlay thus reduces to

$$T^d = \tau_d (1 - \theta_d) \beta X_d. \tag{2.21}$$

Factoring in the additional cost induced by the carbon tax outlay, the actual marginal cost of generating electricity with fossil fuel thus has two components, including ϕ_d and the contribution of the carbon tax outlay to the marginal cost, $\tau_d (1 - \theta_d) \beta$. Therefore, when the CT is the instrument of climate policy selected by the Regulator, plant d's post innovation marginal cost is

$$\Phi_d (\tau_d, \theta_d) = \phi_d + \tau_d (1 - \theta_d) \beta. \tag{2.22}$$

Note here how the carbon tax as determined by τ_d mediates the impact the innovation in CCS technology has on the marginal cost of generating electricity with fossil fuels. In other words, when $\tau_d = 0$, Plant d has no incentive to innovative, because $\Phi_d (0, \theta_d) = \phi_d$.

Now suppose that the Regulator decides to mitigate GHG emissions using a regulatory mandate such as the CES (i.e., $g = \bar{x}_c$). Under the CES, the mandated minimum ratio of clean electricity in total electricity generated is $\bar{x}_c \in [0, 1]$. If Plant d invests in CCS technology, total clean electricity output is $X_c + X_d^c$, where X_d^c is as defined in (2.20), and X_c is the output of Plant c. Therefore if the Regulator chooses the CES, and thus imposes the mandate $\bar{x}_c$, Plant d will be restricted to choosing a level of output, X_d, that satisfies:

$$\frac{X_c + X_d^c}{X_c + X_d} \geq \bar{x}_c. \tag{2.23}$$

To the extent that the CES is binding, from (2.23), it follows that Plant d's best output response function to Plant c's output strategy X_c becomes exogenously given by

$$X_d = \frac{1 - \bar{x}_c}{\bar{x}_c - \theta_d} X_c \equiv \chi^d \left(\theta_d, \bar{x}_c, X_c\right). \tag{2.24}$$

In other words, when a CES $\bar{x}_c$ is mandated, Plant d reacts to its rival's choice of output strategy X_c, by choosing to play the strategy $\chi^d \left(\theta_d, \bar{x}_c, X_c\right)$. Observe that compliance with the CES mandate implies that to reach the production stage (i.e., $X_d > 0$), the polluting plant must choose the level of innovation effort θ_d such that:

$$\bar{x}_c - \theta_d > 0. \tag{2.25}$$

Condition (2.25) implies that, for modest emissions reduction targets (i.e., $\bar{x}_c$ is sufficiently small), the CES does not provide the polluting plant with an incentive to contribute to the production of clean electricity through investment in a CCS technology. Emissions reduction targets will have to be sufficiently high for the CES to provide this plant with the incentive to invest in a CCS technology. This fact implies that the CES essentially promotes specialization as a feature of clean electricity production, as it tends to prevent the polluting plant from contributing to clean electricity production.

Let us turn next to the characterization of Plant d's profit function. Given (g, X_c), Plant d's profit is given by:

$$\Pi_d(g_d) = \begin{cases} (P_x - [\phi_d + (1-\theta_d)\tau_d\beta]) X_d - \rho_d(\theta_d)^2 & \text{if } g = \tau_d \\ \\ \Pi_d(\bar{x}_c) & \text{if } g = \bar{x}_c \end{cases} \tag{2.26}$$

where

$$\Pi_d(\bar{x}_c) = \begin{cases} (P_x - \phi_d)\chi^d(\theta_d, \bar{x}_c, X_c) - \rho_d(\theta_d)^2 & \text{if the CES is binding} \\ \\ (P_x - \phi_d) X_d - \rho_d(\theta_d)^2 & \text{if not} \end{cases}$$

When $g = \tau_d$, Plant d's problem is to choose the strategy vector (θ_d, X_d) so as to solve

$$\max_{(\theta_d, X_d)} \Pi_d(\tau_d),$$

while under a binding CES mandate, this problem reduces to

$$\max_{\theta_d} \Pi_d(\bar{x}_c)$$

because Plant d's output best response function is exogenously given under the CES.

2.4. Timing of Events

The timing of events in this economy is thus as follows. In the beginning of the period, the Regulator announces his emissions reduction target κ, along with his choice of instrument of revenue-neutral climate policy $g \in \{\tau_d, \bar{x}_c\}$, which determines the levels of the triplet $(\tau_R, \tau_d, \bar{x}_c)$. After κ and g are announced, Plant c and Plant d then play a two-stage game, where in the first-stage, they compete by choosing their respective levels of innovations that determine the levels of efficiency of their respective electricity generation technologies. Next, in the second stage, given the outcome of the first-stage game $\left(\hat{\theta}_c, \hat{\theta}_d\right)$, the two plants then play a Cournot-Nash game to determine their respective supplies of electricity,

$\hat{X}_c$ and $\hat{X}_d$. Inputs markets opens; production in the final good sector then takes place; immediately after, the market for the final good opens, and finally consumption of the final good takes place, and the economy ends.

3. Analytics

Our analytical results are disciplined by the equilibrium of this two-sector economy. In defining the equilibrium, care must be taken to distinguish between strategic and non-strategic elements. The key strategic element is the two-stage non-cooperative game between the non-polluting (c), and the polluting (d), plant. The final good sector is perfectly competitive, and thus provides the non-strategic elements of the equilibrium, along with the stand-in household optimal decisions. Interactions between strategic and non-strategic elements underlie equilibrium conditions, which we characterize for each policy regime $g \in \{\tau_d, \bar{x}_c\}$. In this convex environment, and for each policy regime, g, an equilibrium necessarily exists. Due to structural differences between the two policy regimes, we characterize this equilibrium one such regime at a time.

3.1. Equilibrium Under the CT Regime

Equilibrium variables under the CT include the Nash-equilibrium of the non-cooperative game between the two rival plants in the electricity sector, $\left(\hat{\theta}_c, \hat{\theta}_d, \hat{X}_c, \hat{X}_d\right)$, the pair of profit levels, $(\hat{\pi}_c, \hat{\pi}_d)$, one per electricity generation plant, the labor wage, $\hat{\omega}$, the aggregate demand for electricity, $\hat{X}$, the level of GHG emissions, $\hat{E}$, the electricity price, $\hat{P}_x$, and the residual claim in the final good sector, $\hat{\pi}_y$.

To characterize this equilibrium, we start by solving for the Nash equilibrium of the two-stage noncooperative game between the two plants, c and d.

3.1.1. Nash Equilibrium under the CT Regime

Just to recall this game includes an innovation stage where both plants compete by investing in innovation aimed at improving the efficiency of their electricity generation technologies, and a Cournot stage where they compete in the market for electricity, by simultaneously choosing their respective electricity output levels. The two-stage game is solved by backward induction. The details of the solution to this two-stage noncooperative game are contained in the Appendix section. In particular, we show that the unique Nash equilibrium of the second-stage Cournot subgame is:

$$\hat{X}_c = \frac{1}{3\bar{\xi}_p}\left[\bar{\xi}_0 - 2(1-\hat{\theta}_c)\phi_c + \phi_d + \tau_d\left(1-\hat{\theta}_d\right)\beta\right]; \tag{3.1}$$

$$\hat{X}_d = \frac{1}{3\bar{\xi}_p}\left[\bar{\xi}_0 - 2\left[\phi_d + \tau_d\left(1-\hat{\theta}_d\right)\beta\right] + (1-\hat{\theta}_c)\phi_c\right]; \tag{3.2}$$

where

$$\bar{\xi}_0 \equiv \frac{\left[\delta_\omega + \psi_1\left(\tau_R, \hat{\Pi}\right)\right]\gamma_0 - \left[\delta_0 - \psi_0\left(\tau_R, \hat{\Pi}\right)\right]\gamma_\omega}{\delta_\omega\gamma_p - \delta_p\gamma_\omega + \gamma_p\psi_1\left(\tau_R, \hat{\Pi}\right)} \tag{3.3}$$

$$\bar{\xi}_p \equiv \frac{\delta_\omega + \psi_1\left(\tau_R, \hat{\Pi}\right)}{\delta_\omega\gamma_p - \delta_p\gamma_\omega + \gamma_p\psi_1\left(\tau_R, \hat{\Pi}\right)}. \tag{3.4}$$

and

$$\hat{\Pi} = \hat{\pi}_c + \hat{\pi}_d + \hat{\pi}_y \tag{3.5}$$

denotes total profits accrued to the stand-in household as the absentee owner of all firms and plants.

Partial derivation of (3.1) and (3.2) respectively, yields the following results.

Claim 1. (i) A plant's investment in innovation causes it output to rise ($\partial X_j/\partial\theta_j > 0$) at the expense of its rival's output ($\partial X_{-j}/\partial\theta_j < 0$), where $j, -j = c, d$;

(ii) Increasing the level of the carbon tax tends to increase the electricity output of the non-polluting plant ($\partial X_c/\partial\tau_d > 0$) at the expense of the output of the polluting plant ($\partial X_d/\partial\tau_d < 0$).

Claim 1-(i) simply formalizes investment in innovation as a tool of market expansion under the CT regime. It allows each plant to increase or defend its share of the electricity market. Claim 1-(ii) establishes the output substitution effect of a carbon tax. Since the polluting plant is more cost-competitive than the non-polluting plant, the bigger this substitution effect, the higher the price of electricity. However, since the carbon tax also influences both plants' innovation decisions, as we show below, it has an indirect effect on their respective shares of the electricity market.

Let us now turn to the first-stage subgame between the two plants. In this innovation stage, the actions of the players are the levels of efficiency of their respective technologies, θ_c and θ_d. These actions entail costs for each plant amounting to $\rho_c (\theta_c)^2$ and $\rho_d (\theta_d)^2$ respectively.

To derive the best-response functions for the two players at the innovation stage of the game, we need the following assumption:

Assumption 1. The following inequalities simultaneously hold:

$$9\bar{\xi}_p \rho_c - 4 (\phi_c)^2 > 0 \tag{3.6}$$

$$9\bar{\xi}_p \rho_d - 4 (\tau_d \beta)^2 > 0. \tag{3.7}$$

Assumption 1 ensures that each player's payoff function is strictly concave in its choice variable, so that its best response function exists and is well-defined. Therefore, under Assumption 1, the unique Nash equilibrium of the innovation subgame is characterized by:

$$\hat{\theta}_c = \frac{2\phi_c \left(\bar{\xi}_0 - 2\phi_c + \phi_d + \tau_d \beta\right) \left[9\bar{\xi}_p \rho_d - 4 (\tau_d \beta)^2\right] - (2\tau_d \beta)^2 \phi_c \left[\bar{\xi}_0 - 2 (\phi_d + \tau_d \beta) + \phi_c\right]}{\left[9\bar{\xi}_p \rho_d - 4 (\tau_d \beta)^2\right] \left[9\bar{\xi}_p \rho_c - 4 (\phi_c)^2\right] - (2\tau_d \beta \phi_c)^2} \tag{3.8}$$

$$\hat{\theta}_d = \frac{2\tau_d \beta \left(\bar{\xi}_0 - 2 (\phi_d + \tau_d \beta) + \phi_c\right) \left[9\bar{\xi}_p \rho_c - 4 (\phi_c)^2\right] - (2\phi_c)^2 (\tau_d \beta) \left[\bar{\xi}_0 - 2\phi_c + \phi_d + \tau_d \beta\right]}{\left[9\bar{\xi}_p \rho_d - 4 (\tau_d \beta)^2\right] \left[9\bar{\xi}_p \rho_c - 4 (\phi_c)^2\right] - (2\tau_d \beta \phi_c)^2}, \tag{3.9}$$

Given the outcome of this two-stage noncooperative game, we can now compute the equilibrium profits levels for both Plant c and Plant d. Indeed from (2.18) and (2.26), we can just rewrite these profits as follows:

$$\hat{\pi}_c = \frac{1}{9\bar{\xi}_p}\left[\bar{\xi}_0 - 2(1-\hat{\theta}_c)\phi_c + \phi_d + \tau_d\left(1-\hat{\theta}_d\right)\beta\right]^2 - \rho_c\left(\hat{\theta}_c\right)^2 \tag{3.10}$$

$$\hat{\pi}_d = \frac{1}{9\bar{\xi}_p}\left[\bar{\xi}_0 - 2\left[\phi_d + \tau_d\left(1-\hat{\theta}_d\right)\beta\right] + (1-\hat{\theta}_c)\phi_c\right]^2 - \rho_d\left(\hat{\theta}_d\right)^2, \tag{3.11}$$

where $\hat{\theta}_c$ and $\hat{\theta}_d$ are as defined in (3.8) and (3.9). Recall that these profits accrued to the stand-in household—the absentee owner of all plants.

3.1.2. Aggregate and Household Variables under the CT Regime

We next characterize the remaining equilibrium variables under a CT regime. From (3.1) and (3.2), we obtain equilibrium total electricity output as follows:

$$\hat{X} = \frac{1}{3\bar{\xi}_p}\left[2\bar{\xi}_0 - (1-\hat{\theta}_c)\phi_c - \phi_d - \tau_d\left(1-\hat{\theta}_d\right)\beta\right]. \tag{3.12}$$

Straightforward differentiation of (3.12) yields the following claims:

Claim 2. (i) The carbon tax tends to have a negative effect on total electricity output $\hat{X}$;

(ii) Plants' respective innovation efforts, in contrast, tend to have a positive effect on this output;

(iii) Further, the higher the non-polluting plant's pre-existing cost-disadvantage (i.e., the higher ϕ_c), the lower this output.

Claim 2 suggests that the carbon tax tends to induce an increase in the electricity price. The chain of reactions triggered by this price increase is most likely to result in a decrease in the stand-in household's welfare, as we show in our quantitative experiment. However, Claim 2-(ii) states that both plants' respective innovation efforts may (partially) mitigate this negative output effect of the carbon tax, which in turn, may mitigate its negative welfare effect. Hence the importance of expanding competition in the electricity sector to include the innovation stage.

From (2.19) substituting in (3.2), yields the total level of GHGs released in the atmosphere as follows:

$$\hat{E} = \frac{1}{3\bar{\xi}_p}\left(1-\hat{\theta}_d\right)\beta\left[\bar{\xi}_0 - 2\left[\phi_d + \tau_d\left(1-\hat{\theta}_d\right)\beta\right] + (1-\hat{\theta}_c)\phi_c\right] \tag{3.13}$$

Unfortunately partial differentiation of (3.13) yields blurred pictures of the effect of the emissions reduction policy on the equilibrium level of GHG emissions.

Next, from (2.13) substituting in (2.16) and (3.12), we obtain the equilibrium wage level as follows:

$$\hat{\omega} = \frac{3\left[\delta_0 - \psi_0\left(\tau_R, \hat{\Pi}\right)\right] - \delta_p\xi_0 - \delta_p\left[(1-\hat{\theta}_c)\phi_c + \phi_d + \tau_d\left(1-\hat{\theta}_d\right)\beta\right]}{3\left[\delta_\omega + \psi_1\left(\tau_R, \hat{\Pi}\right)\right]}. \tag{3.14}$$

Expression (3.14) shows how Plants' respective innovation efforts affect the labor wage:

Claim 3. (i) The carbon tax tends to have a negative effect on the wage rate $\hat{\omega}$;

(ii) Plants' respective innovation efforts, in contrast, tend to have a positive effect on this wage;

(iii) Further, the higher the non-polluting plant's pre-existing cost-disadvantage (i.e., the higher ϕ_c), the lower this wage.

Claim 3 continues the chain of reactions triggered by the effect of the carbon tax on total electricity output (see Claim 2 above). The decrease in the wage is a result of the decrease in the demand for labor, itself induced by a decrease in the supply of electricity. Again, since the carbon induces abatement by the polluting plant through technological innovation, its negative effect on the wage is (partially) mitigated by the polluting plant's innovation effort, $\hat{\theta}_d$.

From (2.3), we thus obtain the aggregate labor supply under the CT regime as follows:

$$\hat{L} = \lambda - \frac{(1-\lambda)\left[(1-\tau_R)\hat{\Pi} - \underline{c}\right]}{(1-\tau_R)\hat{\omega}}. \tag{3.15}$$

Using (3.12) and (3.15), along with profit-maximizing conditions, it can be shown that the equilibrium residual claim in the final good sector thus is

$$\hat{\pi}_y = \varepsilon A \left[\frac{\left[2\bar{\xi}_0 - (1-\hat{\theta}_c)\phi_c - \phi_d - \tau_d\left(1-\hat{\theta}_d\right)\beta\right]}{3\bar{\xi}_p}\right]^\alpha \left[\lambda - \frac{(1-\lambda)\left[(1-\tau_R)\hat{\Pi} - \underline{c}\right]}{(1-\tau_R)\hat{\omega}}\right]^\eta, \tag{3.16}$$

where $\hat{\Pi} = \hat{\pi}_c + \hat{\pi}_d + \hat{\pi}_y$.

For the stand-in household, total pre-tax income is

$$\hat{R} = \hat{\omega}\hat{L} + \hat{\Pi}. \tag{3.17}$$

Finally, tax revenue under the CT regime has two sources, including an income tax and the carbon tax:

$$\hat{T} = \tau_R\hat{R} + \tau_d\hat{E}. \tag{3.18}$$

An equilibrium under the CT regime thus reduces to a system of 3 equations, (3.10), (3.11) and (3.16) respectively, in 3 unknowns, $\hat{\pi}_c$, $\hat{\pi}_d$, and $\hat{\pi}_y$ respectively. All remaining variables can be computed given the solution to this system of equations.

3.2. Equilibrium under the CES Regime

Under the CES regime, a general equilibrium has a similar definition to that given under the CT regime above. However, the strategic elements of this equilibrium are quite different under the CES regime compared to the CT regime described above.

3.2.1. Nash Equilibrium Under the CES Regime

Under this regime, the Regulator determines the relative share of clean electricity $\bar{x}_c \in (0,1)$, in total electricity generated, $X = X_c + X_d$. A necessary and sufficient condition for the CES mandate to be binding is that

$$\frac{1-\bar{x}_c}{\bar{x}_c - \theta_d} X_c < \frac{1}{2\bar{\xi}_p}\left[\bar{\xi}_0 - \bar{\phi}_d - \bar{\xi}_p X_c\right]; \tag{3.19}$$

If this condition doesn't hold, then the CES has no effect on Plant d's output. Under this condition, we show in Appendix B that the Nash equilibrium of the Cournot subgame is as follows:

$$X_c^* = \frac{\left(\bar{x}_c - \theta_d^*\right)\left[\bar{\xi}_0 - \left(1-\theta_c^*\right)\phi_c\right]}{\left(\bar{x}_c - 2\theta_d^* + 1\right)\bar{\xi}_p} \tag{3.20}$$

$$X_d^* = \frac{\left(1-\bar{x}_c\right)\left(\left[\bar{\xi}_0 - \left(1-\theta_c^*\right)\phi_c\right]\right)}{\left(\bar{x}_c - 2\theta_d^* + 1\right)\bar{\xi}_p}, \tag{3.21}$$

The following claim can therefore be made from straightforward partial derivation of (3.20) and (3.21) respectively:

Claim 4. Increasing the level of the CES mandate tends to increase the electricity output of the non-polluting plant ($\partial X_c / \partial \bar{x}_c > 0$) at the expense of that of the polluting plant ($\partial X_d / \partial \bar{x}_c < 0$).

This claim establishes the output substitution effect of the CES mandate.

From (3.20) and (3.21), it holds that total electricity output under the CES mandate is:

$$X^* = \frac{\left(1-\theta_d^*\right)\left[\bar{\xi}_0^* - \left(1-\theta_c^*\right)\phi_c\right]}{\left(\bar{x}_c - 2\theta_d^* + 1\right)\bar{\xi}_p^*}. \tag{3.22}$$

The following claims derive from straightforward differentiation of expression (3.22).

Claim 5. (i) The CES mandate tends to reduce total electricity output X^*;

(ii) Total electricity output is increasing in either plant's innovation effort;

(iii) The higher the non-polluting plant's pre-existing cost-disadvantage (i.e., the higher ϕ_c), the lower total electricity output under the CES.

Completing the backward induction process, we show in Appendix B that the Nash-equilibrium of the first-stage innovation subgame must solve the following system of two equations in two unknowns:

$$\frac{\phi_c \left(\bar{x}_c - \theta_d^*\right)^2 \left[\bar{\xi}_0^* - \Phi_c\left(\theta_c^*\right)\right]}{\left(\bar{x}_c - 2\theta_d^* + 1\right)^2 \bar{\xi}_p^*} - 2\rho_c\theta_c^* = 0 \tag{3.23}$$

$$\left(\beta\tau_d - \bar{\xi}_p^* \frac{\partial X^*}{\partial\theta_d}\right) X_d^* + \left[\bar{\xi}_0^* - \Phi_d\left(\theta_d^*\right) - \frac{\left(1-\theta_d^*\right)\left[\bar{\xi}_0 - \Phi_c\left(\theta_c^*\right)\right]}{\left(\bar{x}_c - 2\theta_d^* + 1\right)}\right] \frac{\partial X_d^*}{\partial\theta_d} - 2\rho_d\theta_d^* = 0. \tag{3.24}$$

Given the solution to this system, (θ_c^*, θ_d^*), we obtain the distribution of profits between the two plants as follows:

$$\pi_c^* = \frac{\left(\bar{x}_c - \theta_d^*\right)^2 \left[\bar{\xi}_0^* - \Phi_c\left(\theta_c^*\right)\right]^2}{\left(\bar{x}_c - 2\theta_d^* + 1\right)^2 \bar{\xi}_p^*} - \rho_c\left(\theta_c^*\right)^2, \tag{3.25}$$

$$\pi_d^* = \left(\frac{\left[\bar{\xi}_0^* - \Phi_d\left(\theta_d^*\right)\right]\left[\bar{\xi}_0^* - \Phi_c\left(\theta_c^*\right)\right]}{\left(\bar{x}_c - 2\theta_d^* + 1\right)\bar{\xi}_p} - \frac{\left(1-\theta_d^*\right)\left[\bar{\xi}_0^* - \Phi_c\left(\theta_c^*\right)\right]^2}{\left(\bar{x}_c - 2\theta_d^* + 1\right)^2 \bar{\xi}_p^*}\right)\left(1 - \bar{x}_c\right) - \rho_d\left(\theta_d^*\right)^2 \tag{3.26}$$

where

$$\bar{\xi}_0^* := \frac{\left[\delta_\omega + \psi_1\left(\tau_R, \Pi^*\right)\right]\gamma_0 - \left[\delta_0 - \psi_0\left(\tau_R, \Pi^*\right)\right]\gamma_\omega}{\delta_\omega\gamma_p - \delta_p\gamma_\omega + \gamma_p\psi_1\left(\tau_R, \Pi^*\right)} \tag{3.27}$$

$$\bar{\xi}_p^* := \frac{\delta_\omega + \psi_1\left(\tau_R, \Pi^*\right)}{\delta_\omega\gamma_p - \delta_p\gamma_\omega + \gamma_p\psi_1\left(\tau_R, \Pi^*\right)}. \tag{3.28}$$

$$\Phi_c\left(\theta_c^*\right) := \left(1 - \theta_c^*\right)\phi_c \tag{3.29}$$

and

$$\Pi^* = \pi_c^* + \pi_d^* + \pi_y^* \tag{3.30}$$

3.2.2. Aggregate and Household Variables under the CES Regime

Assuming that (3.19) holds, we next characterize the remaining equilibrium variables. We start with the level of emissions, E^*, from (2.19):

$$E^* = \frac{\beta\left(1 - \theta_d^*\right)\left(1 - \bar{x}_c\right)\left(\left[\bar{\xi}_0^* - \Phi_c\left(\theta_c^*\right)\right]\right)}{\left(\bar{x}_c - 2\theta_d^* + 1\right)\bar{\xi}_p^*}, \tag{3.31}$$

Next, from (2.13) substituting in (2.16) and (3.22), we obtain the equilibrium wage level as follows:

$$\omega^* = \frac{\left(\bar{x}_c - 2\theta_d^* + 1\right)\left[\delta_0 - \psi_0\left(\tau_R, \Pi^*\right)\right] - \delta_p\left[\left(\bar{x}_c - \theta_d^*\right)\xi_0^* + \left(1 - \theta_d^*\right)\Phi_c\left(\theta_c^*\right)\right]}{\left[\delta_\omega + \psi_1\left(\tau_R, \Pi^*\right)\right]\left(\bar{x}_c - 2\theta_d^* + 1\right)}. \tag{3.32}$$

Straightforward differentiation of (3.32) yields the following claims:

Claim 6. (i) The CES mandate tends to have a negative effect the wage ω^*;

(ii)This negative effect is mitigated by an increase by either plant's innovation effort;

(iii) In contrast, an increase in the non-polluting plant's pre-existing marginal cost ϕ_c tends to compound this negative effect.

The equilibrium labor supply, and the residual claim under the CES are given respectively by

$$L^* = \lambda - \frac{(1-\lambda)\left[(1-\tau_R)\Pi^* - \underline{c}\right]}{(1-\tau_R)\omega^*}$$

$$\pi_y^* = \varepsilon A \left(\frac{(1-\theta_d^*)\left[\bar{\xi}_0^* - \Phi_c\left(\theta_c^*\right)\right]}{\left(\bar{x}_c - 2\theta_d^* + 1\right)\bar{\xi}_p^*} \right)^{\alpha} \left(\lambda - \frac{(1-\lambda)\left[(1-\tau_R)\Pi^* - \underline{c}\right]}{(1-\tau_R)\omega^*} \right)^{\eta}. \tag{3.33}$$

The stand-in household pre-tax income R^*, thus is given by

$$R^* = \omega^* L^* + \Pi^*. \tag{3.34}$$

Finally, tax revenue under the CES regime only has one source, namely household income:

$$T^* = \tau_R \left[\omega^* L^* + \Pi^*\right]. \tag{3.35}$$

Under the CES policy regime, an equilibrium is a system of 5 equations, (3.23), (3.24), (3.25), (3.26) and (3.33) respectively, in 5 unknowns, θ_c^*, θ_d^*, π_c^*, π_d^* and π_y^*.

4. Quantitative analysis

In this section, we conduct a series of quantitative experiments aimed at eliciting the ranking of the CT and CES, based on their relative cost-effectiveness at reducing GHGs emissions in the electricity sector. We also explore sources of heterogeneity in this ranking. We start by calibrating our model to macroeconomic data from the USA in the years 2012-2013.

4.1. Calibration

We calibrate parameter values of our model to represent as close as possible relevant features of the US economy for the years 2012-2013. We need numerical values for the following parameters: α, η, A (production technology), $\rho_c, \rho_d, \phi_c, \phi_d$ (plants' costs parameters), β (emissions' parameter), $\tau_d, \tau_R, \bar{x}_c$ (regulatory policy parameters). Since we are only comparing the two policy instruments on the basis of their cost-effectiveness, the only preference parameters we need to worry about are λ and $\underline{c}$, respectively. The calibration is done in the case where $\bar{x}_c = \tau_d = 0$, as there is no Federal Government's carbon tax in USA, nor a Federal government's imposed intensity standard for clean electricity production.

We start by normalizing basic parameters. We normalize the subsistence consumption of the numeraire to unity $\underline{c} = 1$, so as to ensure that labor supply is sensitive to the income tax, τ_R. We set the cost parameter for the innovation effort at $\rho = \rho_c = \rho_d = 0.01$. Sensitivity analysis on these values do not bring any new qualitative insight into our cost effectiveness analysis, and so will not be included in this paper.

According to the *Internal Revenue Bulletin: 2013-5* of the US *Internal Revenue Service* (IRS), the average income tax for the seven brackets of rates in 2013 was 26.51%, we set $\tau_R = 0.2651$.According to the *US bureau of Labor Statistics* in 2012, the unemployment rate in USA was 6.67%. We take this figure as a proxy the share of household time allocated to leisure, this means that $\lambda = 0.9333$.

Since what matters to our analysis is mainly the level of relative cost-disadvantage of generating electricity with renewable sources, ϕ_c/ϕ_d, we normalize Plant d's pre-existing marginal cost to unity (i.e., $\phi_d = 1$), and define the relative cost-disadvantage of renewable sources as $\phi = \phi_c/\phi_d \equiv \phi_c$. The relative cost disadvantage of clean electricity varies depending on the renewable source used (e.g., hydropower, solar photovoltaic, windmill, etc.). In its *2013 Edition of Annual Energy Outlook*, the US *Energy Information Administration* (EIA) estimates the levelized cost of electricity (LCOE) by source for the period (2013-2018). The average LCOE for fossil fuels (conventional coal and gas) was 83.6\$/MHh and the corresponding figure for clean sources (solar, wind and hydroelectricity) was 160.84\$/MHh. Taking these data, we claim that $\phi = 1.92$. We later perform a sensitivity analysis to capture the effect of varying this level of this relative cost-disadvantage.

The four remaining parameters (α, β, η and A) are simultaneously calibrated to match the following observational targets for the US economy with the corresponding statistics computed in the model.

1. The share of electricity in the USA generated from renewable sources (*World Bank,* 2012):

$$x_c = \frac{X_c}{X_c + X_d} = 0.1201. \tag{4.1}$$

2. The share of total taxes revenue over GDP in the USA (*OECD,* 2013*)*:

$$\frac{\tau_R R}{Y} = 0.2566. \tag{4.2}$$

3. The emissions of GHGs in the USA in trillion of metric tons of GHGs (EIA, 2013):

$$E = \beta X_d = 0.0054. \tag{4.3}$$

4. The unemployment rate in the USA (*US bureau of Labor Statistics,* 2012):

$$l = 1 - L^D = 0.0667 \tag{4.4}$$

   where L^D is defined in (2.8). Here, we assume that the proportion of total time endowment allocated to leisure, l, by the stand-in household matches the figure for the unemployment rate in 2012, which equals 6.67%.

Since the equilibrium in the CT regime consists of a system of three equations with three unknowns, in total, the calibration procedure involves solving a nonlinear system of seven statistics ((3.10),(3.11),(3.16), (4.1),(4.2),(4.3) and (4.4)) with seven unknowns ($\hat{\pi}_c$, $\hat{\pi}_d$, $\hat{\pi}_y, \alpha, \eta, \beta$ and A). Table 1 below reports the results of the model calibration:

TABLE 1— CALIBRATION

	Target	Data	Model	Parameter	Value
(i)	x_c	0.1201	0.1201	α	0.014202128818416
(ii)	$\tau R/Y$	0.2566	0.2566	η	0.451403049518407
(iii)	E	0.0054	0.0054	β	0.311976540589170
(iv)	l	0.0667	0.0667	A	2.763777020257308

As Table 1 shows, our model reproduces our four calibration targets perfectly. The baseline policy corresponds to $\tau_d = \bar{x}_c = 0$, or *Laissez-faire*. Table 2 reports the baseline level of Plant c and d's innovation efforts, θ_c and θ_d, Plant c's production, X_c Plant d's production, X_d, total tax revenue, $\bar{T}$, the wage, ω, and a measure of social welfare built from (2.4):

$$\bar{W}_n := \ln\left[(1-\tau_R)(\omega+\Pi) - \underline{c}\right] - (1-\lambda)\ln(1-\tau_R) \tag{4.5}$$

where the terms $\bar{\lambda}$ and $\nu \ln G$ have been dropped since their respective levels are policy-invariant.

TABLE 2 — BASELINE KEY VALUES

Variables	Baseline Level
θ_c	0.302404128325400
θ_d	0
X_c	0.002362532252542
X_d	0.017308993778193
$\bar{T}$	0.650158782090652
ω	1.169783410392304
$\bar{W}_n$	-0.130640373601617

Since Plant d's innovation effort is designed to enhance its carbon capture and sequestration technology, when there is no carbon tax (i.e., $\tau_d = 0$), it has no incentive to invest in costly innovation. Hence $\theta_d = 0$.

Further, notice that the equilibrium wage in our baseline satisfies condition (2.12), implying that our Taylor Series approximation of the labor supply function preserves all the properties of the original labor supply function in (2.3).

4.2. Baseline Quantitative Experiment

In our baseline quantitative experiment, for each policy regime, we compute the income tax, τ_R, and the level of the chosen policy instrument for which the pre-specified emission reduction target, κ, is achieved subject to a revenue neutrality constraint, as in Goulder *et al.* (2016). We set the pre-specified emissions reduction target at $\kappa = 0.1$. In other words, the Regulator wants to reduce the level of GHG emissions by 10% compared to the *Laissez-faire* scenario.

In the CT regime, the environmental and fiscal policy vector, (τ_d, τ_R) and equilibrium profits $(\pi_c^*,\ \pi_d^*,\ \pi_y^*)$ are jointly determined as the solution to following system of five equations in five unknowns:

$$\begin{cases} \frac{E}{E_0} = 1 - \kappa \\ T\left(\tau_d, \tau_R\right) = T_0 \\ \text{(3.10),(3.11) and (3.16)} \end{cases}, \tag{4.6}$$

where E_0 and T_0 are the levels of emissions, and tax revenue, respectively, in the *Laissez-faire*.

In contrast, in the CES regime, the climate and fiscal policy vector, $(\bar{x}_c, \tau_R)$, the equilibrium profits $(\pi_c^*,\ \pi_d^*,\ \pi_y^*)$ are jointly determined with the vector of plants' innovation efforts, (θ_c^*, θ_c^*) as solution to the following system of seven equations in seven unknowns:

$$\begin{cases} \frac{E}{E_0} = 1 - \kappa \\ T\left(\tau_R, \bar{x}_c\right) = T_0 \\ \text{(3.23), (3.24), (3.25), (3.26) and (3.33)} \end{cases}, \tag{4.7}$$

Table 3 below presents for each regime, the computed levels of policy variables, $(\tau_R, \tau_d, \bar{x}_c)$, and of relevant economic variables $(\theta_j, X_j, \bar{W}_n)$ for a pre-specified emission reduction target of 10%. Starting from a baseline scenario where there is no action against pollution $(\tau_d = \bar{x}_c = 0)$, by how much the stand-in household's welfare decreases as a result of the Regulator's use of policy instrument $g \in \{\tau_d, \bar{x}_c\}$ to achieve an emissions reduction target κ? The answer to this question is the measure the overall burden placed on the economy by this climate action. We define this burden as the difference $W_n(g, \kappa) - W_n(0, 0)$, for $g \in \{\tau_d, \bar{x}_c\}$, where $W_n(0, 0)$ denotes the baseline (or *Laissez-faire*) welfare which is a constant function of κ, and $W_n(g, \kappa)$, the corresponding level under the policy regime $g \in \{\tau_d, \bar{x}_c\}$. The overall burden of climate policy, $W_n(g, \kappa) - W_n(0, 0)$, is measured in percentage in Table 3 below: Line 10, Column 4, for the CT, and Line 10, Column 6 for the CES.[12]

[12] Our computations show that the necessary and sufficient condition for the CES to be binding, as defined is (3.19), is satisfied. This condition can be rewritten as follows:

$$f(\bar{x}_c^*) > 0,$$

where

$$f(\bar{x}_c^*) = \frac{1}{2\bar{\xi}_p}\left[\bar{\xi}_0 - \bar{\phi}_d - \bar{\xi}_p X_c\right] - \frac{1 - \bar{x}_c}{\bar{x}_c - \theta_d} X_c$$

Under the CES regime, the optimal $\bar{x}_c^*$ yields

$$f(\bar{x}_c^*) = 0.0016$$

which means that condition (3.19) indeed holds.

TABLE 3— BASELINE EXPERIMENT ($\kappa = 0.1$)

	Baseline	CT	Change	CES	Change
τ_R	0.2651	0.265015	-0.0085%p	0.265309	0.0209%p
τ_d	0	0.147118	0.1471	0	0
$\frac{X_c+\theta_d X_d}{X}; \bar{x}_c$	0.1201	0.165192	4.5092%p	0.1440838	2.3984%p
θ_c	0.302404	0.289217	-4.3609%	0.2880618	-4.7428%
θ_d	0	0.050184	0.050184	0	0
X_c	0.002362	0.002259	-4.3609%	0.0026224	10.9993%
X_d	0.017309	0.016401	-5.2448%	0.0155781	-10.00%
$\bar{W}_n$	-0.130640	-0.132145	-1.1517%	-0.133039	-1.8360%

Notes:*% denotes percent change,%p denotes percentage point.

The results of this experiment show that the CT is more cost-effective than the CES, because the use of the yield a drop in welfare of 1.1517% relative to the *Laissez-faire*; whereas the corresponding figure the CES instead is 1.8360%, which is bigger.

4.3. Sensitivity Analysis

Note that the ranking of the CT and CES derived from the baseline experiment summarized in Table 3 corresponds to a level of pre-specified emissions reduction target set at $\kappa = 0.1$, and to a level of cost-disadvantage of the non-polluting plant (Plant c) set at $\phi = 1.92$. In what follows, we conduct a sensitivity analysis in order to assess the robustness of this ranking. First, we vary the level of the pre-specified emissions reduction target, κ, to see if this ranking is sensitive to the size of this target. We restrict the values of κ to be members of the set $\{0.01, ..., 0.4\}$. Thus, $\kappa = 0.01$ corresponds to a modest emission reduction target of 1% relative to the *Laissez-faire*; whereas $\kappa = 0.4$ corresponds to a relatively ambitious reduction target of 40%.

Second, for each κ, we vary the level of Plant c's cost-disadvantage, ϕ. Recall that this factor measures the competitive gap between Plant c and Plant d. We choose a range of values for the level of cost-disadvantage ϕ that are consistent with a duopolistic structure of the electricity generation sector: $\phi \in \{1.5; 1.75; 1.92\}$. We note that for $\phi > 1.92$, the structure of the industry changes into a monopoly of the polluting plant, with the non-polluting plant exiting the industry. Since changing ϕ changes the *Laissez-faire* equilibrium variables, including the equilibrium welfare, we recompute these *Laissez-faire* equilibrium variables, for each level of $\phi \in \{1.5; 1.75; 1.92\}$. The following table presents the values for *Laissez-faire* equilibrium variables, and for level of ϕ:

TABLE 4 — NEW BASELINE VALUES

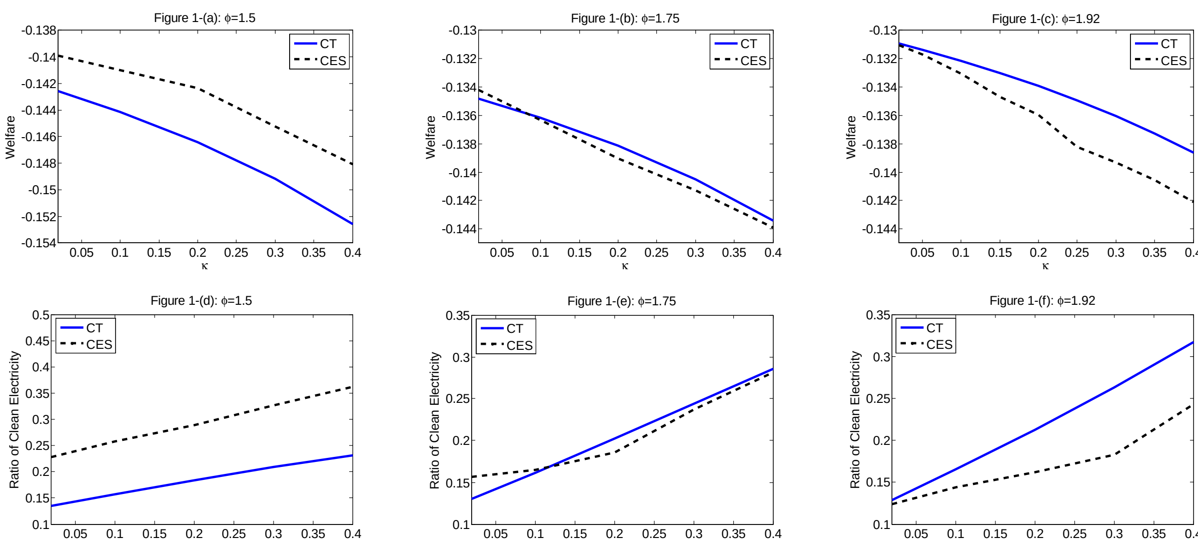
	$\phi = 1.5$	$\phi = 1.75$	$\phi = 1.92$
T^0	0.646832	0.649043	0.650159
E^0	0.003581	0.004769	0.005400
x_c^0	0.129045	0.122448	0.120100
$\bar{W}_n^0$	-0.142202	-0.134506	-0.130640

Table 4 shows that an exogenous decrease in the level of the pre-existing cost-disadvantage of Plant c increases the ratio of clean, to total, electricity generated. The *Laissez-faire* values reported in Table 4 form the benchmark against which the performance of each of the two alternative instruments of climate policy will be measured.

Technically, the experiment underlying our sensitivity analysis consists solving (4.6) for the CT regime and (4.7) for the CES regime, for each level of $\phi \in \{1.5; 1.75; 1.92\}$, and for all $\kappa \in \{0.01, ..., 0.4\}$. The intuition justifying this sensitivity analysis reads as follows. When ϕ is high, relying solely on Plant c as a source of clean electricity may be too costly to society because it takes too high a level of innovation effort for this plant to become a competitive producer of clean electricity. On the other hand, a high pre-existing competitive gap gives the polluting plant (Plant d) enough leeway to invest in an abatement technology, allowing it to contribute to the production of clean electricity, proportionately to the quantity of GHG emissions successfully captured and sequestrated. This fact tends to give the advantage to the instrument of climate policy that promotes diversification of sources of clean electricity to include both Plant c (the non-polluting plant) and Plant d (the polluting plant). Of the CT and the CES, only the former has a diversification effect, because it provides Plant d with the incentive to invest in a CCS technology that enables it to produce clean electricity. In contrast, when ϕ is relatively small, diversification of sources of clean electricity becomes too costly because the polluting plant no longer has the leeway that allows it to adequately invest in a CCS technology without losing its competitive edge. This fact tends to hand the advantage to the CES that tends to induce specialization as feature of clean electricity production.

Figure 1 below plots social welfare (Panels a, b, and c) and the ratio of clean, to total, electricity generated (Panels d, e, and f), respectively under the CT and the CES:

Figure 1: CT vs. CES for various levels of κ and ϕ



Panels a, b, and c indeed confirm our intuition that the ranking of these two instruments of climate policy is quite sensitive to the pre-existing competitive gap between the two rival plants. Panel (c) of Figure 1 corresponds to a level of cost-disadvantage for the non-polluting plant equal to 1.92. This panel shows that the CT (the blue-colored curve) is the more cost-effective of the two instruments, because social welfare is higher under this instrument than under the CES (dark-colored curve). The superiority of the CT at

$\phi = 1.92$ is also reflected in Panel (f) of Figure 1 showing that the ratio of clean, to total, electricity generated is higher for the CT (blue-colored curve) than the CES (dark-colored curve). For $\phi = 1.92$, therefore, the social costs of a CT-induced diversification are lower that the corresponding costs under CES-induced specialization.

Panel (b) replicates the main result obtained by Goulder *et al.* (2016), for $\phi = 1.75$. It shows that the CES is more cost-effective than the CT for less ambitious emissions reduction targets, with the reverse being true for more ambitious targets. This result is also reflected in Panel (e) where a threshold emissions reduction target exists, below which the ratio of clean, to total, electricity generated is higher under the CES than under the CT, and above which the reverse is true.

In Panel (a), the level of the cost-disadvantage of Plant c is sufficiently low at $\phi = 1.5$. In other words, the pre-existing marginal cost of Plant c is 50% higher than that of its rival (i.e., Plant d). In this context, the CES (the dark-colored curve) dominates the CT (the blue-colored curve) over the entire range of admissible emissions reduction targets. Panel (d) echoes this superiority of the CES by showing that the ratio of clean, to total, electricity is higher under the CES than under the CT, in the entire range of emissions reduction target. The main difference between Goulder *et al.* (2016) and our analysis, therefore, comes from Panels (a) and (c). These results suggest that there exists a threshold pre-existing cost-disadvantage of the non-polluting plant below which the CES is more cost-effective than CT for all admissible levels of emissions reduction targets $\kappa \in \{0.01, ..., 0.4\}$, with the reverse true, above this threshold. Compared to Goulder *et al.* (2016), our analysis uncovers a new source of heterogeneity in the ranking of the CT and the CES, based on their relative cost-effectiveness at reducing GHG emissions.

The intuition behind the heterogeneity of the ranking of the CT and the CES can also be perceived through the respective effects of these two instruments on the electricity price. Figure 2 below built from the results of the experiment reported in Figure 1 above, plots the equilibrium price of electricity for various levels of the cost-disadvantage ϕ, and various levels of the emissions reduction target κ.

Figure 2: CT vs. CES for various levels of κ and ϕ

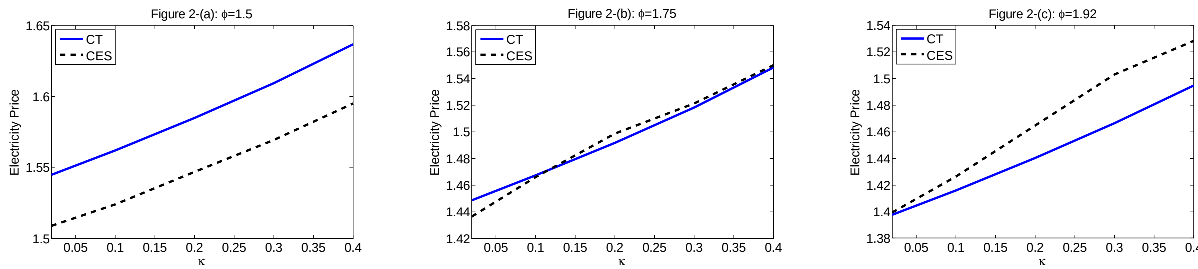


Figure 2 shows that as the cost-disadvantage ϕ decreases, the electricity price becomes higher under the CT than under CES. Since a high electictrics price is associtated with a lower level of production (as we can see in (2.16)), Figure 2 thus contributes to explain why the CES regime is more cost-efficient than the CT regime for lower levels of ϕ.

5. Conclusion

Choosing the best instrument of climate policy is important for political jurisdictions aiming to make the most of their emissions control efforts. Despite the fact that fiscal instruments such as the carbon tax have been gaining increased prominence around the world, the issue of which policy instrument is the best at mitigating GHG emissions remains contentious. In this paper, we develop a general-equilibrium model that provides the foundations of a quantitative experiment underlying the comparison between the CT and the CES, based on their relative effectiveness at reducing GHG emissions in the electricity sector.

The main contribution of this paper is to compare these two policy instruments in an environment where the industrial organization of the generation side of the electricity sector is characterized by a two-stage, duopolistic, competition between a polluting plant and its non-polluting rival. The addition of market power and innovation as features of electricity generation opens the black box of the microeconomic effects of climate policy on the economy, with implications for the ranking of alternative instruments for implementing this policy. A key insight of our analysis is that the CT has a diversification effect whereby it induces both the non-polluting plant and its polluting rival to contribute to expanding the clean electricity output; whereas, the CES has a specialization effect whereby it tends to undermine the polluting plant's incentive to contribute to clean electricity production, essentially leaving the non-polluting plant as the only source of clean electricity.

We show that, what matters for the ranking of these two instruments of climate policy is the size of the pre-existing competitive gap between the two rival power plants. When this pre-existing competitive gap is large, only the CT-induced diversification effect can pave the way to a cost-effective expansion of the clean electricity output. In contrast, when this gap is sufficiently small, the CES-induced specialization effect becomes more effective at driving a cost-effective expansion of the clean electricity output.

Our quantitative cost-effectiveness analysis not only replicates the main result of Goulder et al. (2016), whereby the CES dominates the CT only for less ambitious emissions reduction target, it goes further. It shows that the superiority of the CES over the CT on cost-effectiveness grounds is not limited to less ambitious emissions reduction targets; but also extends to more ambitious targets as well, provided the pre-existing competitive gap between the two plants is sufficiently small. In that sense, our analysis uncovers a new source of heterogeneity in the ranking of these two instruments of climate policy.

Of course, there are a number of limitations to our study. First, we only focus on electricity-related GHG emissions, which are mostly localized emissions. Extending the study to include emissions that are not localized would probably increase the administrative costs of mitigating them with an intensity standard such as a CES, which then will tend to tip the balance in favor of fiscal instruments. Second, in our model, we implicitly assumed that the polluting plant has reached the technological frontier in terms of the efficiency with which it generates electricity with polluting sources. The non-polluting plant is the one that plays catch-up to the polluting plant through investment in a productivity-enhancing innovation. For the polluting plant, innovation is essentially restricted to improvements in its efficiency at transforming "dirty", into "clean", electricity through a technological device such as the well-known carbon capture and sequestration (CCS) technology.

6. Appendix A

In this section we provide details on the computation of the Nash equilibrium of the two-stage duopoly game. This game is solved given the specific instrument of climate policy used by the Regulator. Since the structure of the game is specific to each such instrument, we solve it for each instrument, starting with the CT and applying a backward induction process.

6.1. Second-Stage Subgame under the CT

We start with the second-stage subgame which is has Cournot structure. The Plants' respective payoffs are:

$$\Pi_c(\theta_c, X_c, \theta_d, X_d) = P_x X_c - \bar{\phi}_c X_c - \rho_c(\theta_c)^2, \tag{6.1}$$

$$\Pi_d(\theta_d, X_d, \theta_c, X_c) = P_x X_d - \bar{\phi}_d X_d - \rho_d(\theta_d)^2. \tag{6.2}$$

where

$$P_x = \xi_0(\tau_R, \Pi) - \xi_p(\tau_R, \Pi)(X_c + X_d) \tag{6.3}$$

$$\bar{\phi}_d = \phi_d + \tau_d(1 - \theta_d)\beta \tag{6.4}$$

$$\bar{\phi}_c = (1 - \theta_c)\phi_c \tag{6.5}$$

Taking the action X_d of his rival as given, Plant-c determines its best response as a solution to the following first-order necessary and sufficient conditions:

$$\xi_0(\tau_R, \Pi) - 2\xi_p(\tau_R, \Pi) X_c - \xi_p(\tau_R, \Pi) X_d = \bar{\phi}_c \tag{6.6}$$

Likewise, taking the action X_c of his rival as given, Plant-d determines its best response as a solution to the following first-order necessary and sufficient condition:

$$\bar{\xi}_0 - \bar{\xi}_p X_c - 2\bar{\xi}_p X_d = \bar{\phi}_d. \tag{6.7}$$

The best response functions that solve these respective first order conditions are

$$X_c = \frac{1}{2\bar{\xi}_p}\left[\bar{\xi}_0 - \bar{\phi}_c - \bar{\xi}_p X_d\right], \tag{6.8}$$

and

$$X_d = \frac{1}{2\bar{\xi}_p}\left(\bar{\xi}_0 - \bar{\phi}_d - \bar{\xi}_p X_c\right), \tag{6.9}$$

where $\bar{\xi}_0 \equiv \xi_0(\tau_R, \Pi)$; $\bar{\xi}_p \equiv \xi_p(\tau_R, \Pi)$.

One can see from (6.8) and (6.9) that the Plants' actions are strategic substitutes: when a Plant increases the level of its action, this induces its rival to reduce the level of its own. A unique Nash equilibrium of this Cournot game is the solution to the system of two equations in two unknown described by (6.8) and (6.9). This solution is:

$$X_c = \frac{1}{3\bar{\xi}_p}\left(\bar{\xi}_0 - 2\bar{\phi}_c + \bar{\phi}_d\right); \tag{6.10}$$

$$X_d = \frac{1}{3\bar{\xi}_p}\left(\bar{\xi}_0 - 2\bar{\phi}_d + \bar{\phi}_c\right). \tag{6.11}$$

6.2. First-Stage Subgame under the CT

Given the solution to the second-stage game, we now turn to the solution of the first-stage innovation subgame. The plants' respective payoffs are constructed by combining (6.1) and (6.2) with the first-order condition in (6.6) and (6.7), and the outcomes of the second-stage Cournot game in (6.10), and (6.11). These payoffs are then obtained as:

$$\Pi_c^*(\theta_c, \theta_d) = \frac{1}{9\bar{\xi}_p}\left(\bar{\xi}_0 - 2\bar{\phi}_c + \bar{\phi}_d\right)^2 - \rho_c(\theta_c)^2, \tag{6.12}$$

$$\Pi_d^*(\theta_c, \theta_d) = \frac{1}{9\bar{\xi}_p}\left(\bar{\xi}_0 - 2\bar{\phi}_d + \bar{\phi}_c\right)^2 - \rho_d(\theta_d)^2. \tag{6.13}$$

Plant-c's best response to its rival's innovation effort is:

$$\theta_c = \frac{2\phi_c\left[\bar{\xi}_0 - 2\phi_c + \phi_d + (1-\theta_d)\,\tau_d\beta\right]}{\left[9\bar{\xi}_p\rho_c - 4\left(\phi_c\right)^2\right]}, \tag{6.14}$$

while Plant-d's best response is:

$$\theta_d = \frac{(2\tau_d\beta)\left[\bar{\xi}_0 - 2\left(\phi_d + \tau_d\beta\right) + (1-\theta_c)\,\phi_c\right]}{\left[9\bar{\xi}_p\rho_d - 4\left(\tau_d\beta\right)^2\right]} \tag{6.15}$$

By inspection of (6.8) and (6.9), one can see that in this innovation subgame, Plant c and Plant d respective actions are strategic substitutes: any public intervention that increases the level of action of a Plant, will induce a decrease in the level of action of his rival.

The unique Nash equilibrium of this innovation subgame between Plant c and Plant d is the solution to the system of two equations in two unknown represented by (6.8) and (6.9):

$$\hat{\theta}_c = \frac{2\phi_c\left(\bar{\xi}_0 - 2\phi_c + \phi_d + \tau_d\beta\right)\left[9\bar{\xi}_p\rho_d - 4\left(\tau_d\beta\right)^2\right] - \left(2\tau_d\beta\right)^2\phi_c\left[\bar{\xi}_0 - 2\left(\phi_d + \tau_d\beta\right) + \phi_c\right]}{\left[9\bar{\xi}_p\rho_d - 4\left(\tau_d\beta\right)^2\right]\left[9\bar{\xi}_p\rho_c - 4\left(\phi_c\right)^2\right] - \left(2\tau_d\beta\phi_c\right)^2} \tag{6.16}$$

$$\hat{\theta}_d = \frac{(2\tau_d\beta)\left(\bar{\xi}_0 - 2\left(\phi_d + \tau_d\beta\right) + \phi_c\right)\left[9\bar{\xi}_p\rho_c - 4\left(\phi_c\right)^2\right] - \left(2\phi_c\right)^2(\tau_d\beta)\left[\bar{\xi}_0 - 2\phi_c + \phi_d + \tau_d\beta\right]}{\left[9\bar{\xi}_p\rho_d - 4\left(\tau_d\beta\right)^2\right]\left[9\bar{\xi}_p\rho_c - 4\left(\phi_c\right)^2\right] - \left(2\tau_d\beta\phi_c\right)^2} \tag{6.17}$$

7. Appendix B

In this section we characterize the conditions that the Nash- equilibrium of the non-cooperative electricity generation game between Plant c and Plant d must satisfy under the CES. We start with the second-stage output determination subgame.

7.1. Nash-Equilibrium of the Second-Stage Subgame under the CES

Under the CES, the Regulator determines the relative share of clean electricity, $\bar{x}_c \in (0, 1)$, in total electricity generated, $X = X_c + X_d$. In the second-stage Cournot game, Plant d's best response function is given by

$$X_d = \min \left\{ \frac{1 - \bar{x}_c}{\bar{x}_c - \theta_d} X_c ; \frac{1}{2\bar{\xi}_p} \left[\bar{\xi}_0 - \bar{\phi}_d - \bar{\xi}_p X_c \right] \right\}, \tag{7.1}$$

while Plant c's best response to Plant d's action is

$$X_c = \frac{1}{2\bar{\xi}_p} \left[\bar{\xi}_0 - \bar{\phi}_c - \bar{\xi}_p X_d \right]. \tag{7.2}$$

From (7.1), we deduce the following condition for the CES to be binding, for all X_c:

$$\frac{1 - \bar{x}_c}{\bar{x}_c - \theta_d} X_c < \frac{1}{2\bar{\xi}_p} \left[\bar{\xi}_0 - \bar{\phi}_d - \bar{\xi}_p X_c \right]; \tag{7.3}$$

Assuming that this condition holds, from (7.1), (7.2) and (6.4), we obtain the Nash equilibrium of this Cournot subgame as follows:

$$\hat{X}_c = \frac{(\bar{x}_c - \theta_d) \left[\bar{\xi}_0 - (1 - \theta_c) \phi_c \right]}{(\bar{x}_c - 2\theta_d + 1) \bar{\xi}_p} \tag{7.4}$$

$$\hat{X}_d = \frac{(1 - \bar{x}_c) \left[\bar{\xi}_0 - (1 - \theta_c) \phi_c \right]}{(\bar{x}_c - 2\theta_d + 1) \bar{\xi}_p} \tag{7.5}$$

7.2. First-Stage Subgame under the CES

Therefore, from (2.18) and (2.26), substituting in (7.4) and (7.5) where appropriate yields a reformulation of profit functions for Plants c and d, respectively as follows:

$$\Pi_c = \frac{(\bar{x}_c - \theta_d)^2 \left[\bar{\xi}_0 - (1-\theta_c)\,\phi_c\right]^2}{(\bar{x}_c - 2\theta_d + 1)^2\,\bar{\xi}_p} - \rho_c\,(\theta_c)^2\,, \tag{7.6}$$

$$\Pi_d = \left(\frac{\left[\bar{\xi}_0 - \Phi_d(\theta_d)\right]\left[\bar{\xi}_0 - \Phi_c(\theta_c)\right]}{(\bar{x}_c - 2\theta_d + 1)\,\bar{\xi}_p} - \frac{(1-\theta_d)\left[\bar{\xi}_0 - \Phi_c(\theta_c)\right]^2}{(\bar{x}_c - 2\theta_d + 1)^2\,\bar{\xi}_p}\right)(1-\bar{x}_c) - \rho_d\,(\theta_d)^2 \tag{7.7}$$

where

$$\Phi_c(\theta_c) = (1-\theta_c)\,\phi_c$$

$$\Phi_d(\theta_d) = \phi_d + \beta\tau_d\,(1-\theta_d)$$

Therefore, in the first stage, Plant c and Plant d best responses satisfy the following respective first order conditions:

$$\theta_c: \quad \frac{\phi_c\,(\bar{x}_c - \theta_d)^2\left[\bar{\xi}_0 - (1-\theta_c)\,\phi_c\right]}{(\bar{x}_c - 2\theta_d + 1)^2\,\bar{\xi}_p} - 2\rho_c\theta_c = 0 \tag{7.8}$$

$$\theta_d: \quad \left(\beta\tau_d - \bar{\xi}_p\frac{\partial X}{\partial\theta_d}\right)X_d + \left[\bar{\xi}_0 - \phi_d - \beta\tau_d\,(1-\theta_d) - \bar{\xi}_p X\right]\frac{\partial X_d}{\partial\theta_d} - 2\rho_d\theta_d = 0 \tag{7.9}$$

where

$$\frac{\partial X_d}{\partial\theta_d} = \frac{2\,(1-\bar{x}_c)\left(\left[\bar{\xi}_0 - (1-\theta_c)\,\phi_c\right]\right)}{\bar{\xi}_p\,(\bar{x}_c - 2\theta_d + 1)^2} \tag{7.10}$$

$$\frac{\partial X}{\partial\theta_d} = \frac{(1-\bar{x}_c)\left[\bar{\xi}_0 - (1-\theta_c)\,\phi_c\right]}{(\bar{x}_c - 2\theta_d + 1)^2\,\bar{\xi}_p} \tag{7.11}$$

Unfortunately, the above of system of two equations, (7.8 and 7.9), in two unknowns cannot be solved analytically. Its solution, however, can be implicitly defined as follows:

$$\hat{\theta}_c = \Theta^c(\bar{x}_c)$$

$$\hat{\theta}_d = \Theta^d(\bar{x}_c)\,.$$

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