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Energy policy and the power sector in the long run

Baran Doda* and Sam Fankhauser

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Abstract

This paper simulates the distributional consequences of alternative carbon emission reduction policies on power producers. To that end we propose a simple partial equilibrium model in which power generation takes place at technology-specific sites which can differ in productivity. We calibrate the model with six technologies. Hydro, wind and solar generation feature site-specific productivity, and combine capital and sites to produce power. The productivity of coal, gas and nuclear generation is constant across sites. We use the calibrated model to analyse effects of alternative tax and subsidy schemes which imply the same reduction in carbon emissions. A carbon tax outperforms all other instruments and does not reduce the profits of carbon-free generators. Technology-specific subsidies are more costly socially, and those directed at output, rather than inputs, imply a larger transfer from the government to the subsidy recipient. Power consumption taxes typically have very high social costs and should not be the instrument of choice to reduce emissions or to finance subsidies aiming to reduce emissions.

Keywords: market-based regulation of power sector; renewable energy subsidy; carbon pricing; fiscal implications

JEL Classification codes: Q41, Q48, H23.

*Corresponding author: L.B.Doda@lse.ac.uk

"... the electricity system is being re-regulated as investment goes chiefly to areas that benefit from public support."

The Economist, 25 February 2017

1 Introduction

Fossil fuel use by the power sector is the largest source of carbon emissions in most countries. According to the International Energy Agency, power and heat production currently accounts for about 40% of carbon emissions from fuel combustion globally and among the OECD and EU member countries (IEA, 2017). In addition the demand for power is expected to grow when transport, heating and perhaps parts of industry are electrified as part of their decarbonisation strategies (Fankhauser, 2013). As such, the decarbonisation of the power sector is crucial for countries to meet their climate change targets under the Paris Agreement, motivating many governments to introduce policies tailored to this end.

The opening quote suggests that to a large extent these policies have come to determine the allocation of resources in the power sector. The policies also vary in the way their costs and benefits are distributed among power producers using different generation technologies, and between producers, consumers and the government. The existing academic literature has focused predominantly on the demand side. See for example reviews by Dechezleprêtre and Sato (2017) for industrial power consumers and Farrell and Lyons (2016) for households. In this paper we study the supply-side distributional impacts of government policies aiming to reduce carbon emissions from the power sector.

To do so, we propose a simple deterministic partial equilibrium model of the power sector with multiple generation technologies. The policy instruments we examine include a comprehensive carbon tax,[1] technology-specific taxes and subsidies to inputs or outputs of various generators, and power consumption taxes. Throughout we keep track of the policies' fiscal implications. The model is stylised and has a macroeconomic flavour. Given exogenous government policies, input prices and a demand function, we characterise the long run equilibrium in the power market. In our context, long run means the time horizon that is long enough to be able to abstract from hourly, daily, seasonal and

[1] We use carbon tax to refer to a price on carbon, noting that in our deterministic framework implementing a carbon price using a tax or emissions trading (with auctions) are observationally equivalent.

annual fluctuations in supply and demand. At the same time we assume this horizon is short enough so that we can take the production technology to be approximately constant. For simplicity we ignore all other market imperfections and externalities that arise in the climate change context. There are several such imperfections, e.g. innovation and network externalities, and barriers to the adoption of energy efficiency, which potentially warrant policy intervention (Bowen and Fankhauser, 2017), but the markets in our model are well-behaved.

A novel feature of our model is that production takes place at technology-specific sites, which can differ in productivity. A representative firm decides whether or not to develop these sites and, if developed, the quantity of inputs to use at each site to maximise the net present value of its profits, which are positive in our model even in the long run due to decreasing returns to scale at each site. The constraints imposed by site-specific production are central to our model and we study three main types of constraints that may affect the productivity of technology-specific power generation: physical geography constraints, system-level technological constraints and political-economy constraints.

To provide intuition for how these constraints work, we consider first hydroelectric generation. The hydroelectric potential of a country is primarily constrained by its topography and precipitation patterns. For example, according to Eurelectric (2011) Norway is unlikely to run out of hydroelectric sites to meet its domestic demand but Germany has already utilised most of its technically feasible potential, which itself is rather limited. In between these two extremes are countries like Spain and France. They have developed their most productive sites, yet there remains ample potential to exploit in the future.

The physical geography constraints are also relevant for variable renewable energy sources such as wind and solar, but the system-level technological constraints are most prominent for these technologies. In the absence of large-scale energy storage capacity and taking a country's grid infrastructure as given, Papaefthymiou and Dragoon (2016) and Heptonstall et al (2017) show that these constraints become increasingly binding with the level of penetration of the variable renewable resources, and can become prohibitive when intermittent sources come to dominate the generation mix.

Finally, the political-economy constraints are most clearly illustrated in the case of nuclear generation. France's nuclear dominated power system demonstrates that physical geography and system-level technological constraints are virtually absent for this technology. However, political decisions in Austria, Germany, Italy and most recently

Switzerland have limited the scope for new nuclear power stations in these countries. In the UK, a political decision was taken to limit the use of onshore wind.

Each type of constraint plays a role in our model. In principle, they simultaneously apply to a given generation technology. In practice, we use the most stringent constraint among them to calibrate the technologies we analyse quantitatively. Our model distinguishes between broadly defined technology groups that account for most of power generation in the real world. These groups include technologies whose productivity is site-specific but do not require fossil fuel inputs; technologies whose productivity is site-independent but require a fossil fuel input; and technologies whose productivity is site-independent and which require only capital to generate power.

In the quantitative model wind, hydro and solar constitute the first set of technologies. For these technologies, the productivity of sites declines as more are developed because the most stringent of the constraints discussed above becomes increasingly binding. In particular, we calibrate the productivity function for hydro by assuming that the physical geography constraint binds before all other constraints. To calibrate the wind and solar productivity parameters, we assume the system-level technological constraints bind first.

The second set of technologies include coal and gas, which emit carbon as a by-product of generation, while nuclear is the only technology in the final group. Nuclear is carbon-free and requires only capital to generate power. For each of these three technologies, the level of productivity is constant across sites by construction, and to calibrate their productivity we assume that the political-economy constraint is binding after a fixed mass of sites is developed.[2]

We calibrate the model to Spain because its generation mix features a balanced mix of different generation technologies with just over a quarter of power generated from gas, 14%-22% from each of hydro, coal, wind and nuclear, and about 4% from solar. We then solve the calibrated model under alternative instruments, which all target the same relative reduction in emissions, for comparability. Our welfare measure is the sum of changes, relative to the benchmark, in the present value of (*i*) consumer surplus; (*ii*) firms' profit streams taking into account the site development costs, which may be forfeited when sites are abandoned; and (*iii*) government's net revenues.

[2]When neither constraint binds for a given technology, we can expect *almost-corner solutions* such as hydro in Norway, nuclear in France and coal in Poland.

Despite its simplicity, the model offers a consistent equilibrium framework to evaluate the effects of alternative policies on the distribution of output and firm values across generation technologies and yields a number of policy-relevant results.

First, among the instruments we consider, a carbon tax is unambiguously the most cost-effective. Importantly, it treats the carbon-free firms neutrally and does not reduce their value in equilibrium.

Second and conversely, the welfare costs of a power consumption tax are very high because this instrument shrinks the market and reduces the value of all firms. It also reduces consumer surplus substantially.[3] From a welfare perspective it should not be the instrument of choice to reduce emissions or to finance subsidies aiming to reduce emissions.

Third, input and output subsidies to a given technology can be designed to achieve the targeted emissions reduction at the same overall welfare cost. However, firms will prefer output subsidies, because it increases their value by more, while the government would rather offer input subsidies, because it requires less revenue. These subsidies make the recipient more competitive relative to others, including carbon-free firms who lose market share and see their values decline.

Finally, technology-specific subsidies financed by a carbon tax lead to a more equitable distribution of the costs of emissions reduction among the different generators. While they are more cost-effective than subsidies financed by lumpsum taxation, they are not as effective as a carbon tax alone. A sensitivity analysis confirms that country context matters quantitatively. That said, our results continue to hold qualitatively when we calibrate the model to other countries and when we alter our calibration assumptions.

The rest of the paper is organised as follows. The next section provides a brief overview of the related literature. Section 3 describes the theoretical model and defines the long-run equilibrium. Section 4 and 5 explain the paper's quantitative strategy and discuss the results of the numerical analysis. Section 6 undertakes a sensitivity analysis by re-calibrating the model to other country targets, and by altering some of the important parameters in a systematic way. Section 7 concludes. All numbered tables and figures are provided at the end.

[3]Allowing consumers to make costly investments in energy efficiency would limit the decline in consumer surplus but not alter our conclusions qualitatively.

2 Related Literature

Power is an essential input to virtually every modern economic activity so the literature on various issues related to the power sector is voluminous. Much of this literature addresses two challenges that are specific to the power market: the requirement that demand and supply must balance in real time and the requirement that there must pre-exist a grid infrastructure to allow supply to serve demand. Ventosa et al (2005) and Hobbs (1995) review the implications of these challenges for generators, grid operators and regulators over various time horizons. The models they consider typically have a detailed, often plant-level, description of power supply, and are essential for an orderly operation of the power market.

More recently, the high carbon intensity of power generation has made the sector prominent in the discussions around climate change policy. In a special issue of Climate Change Economics focusing on the impacts of the EU's energy and climate change polices beyond 2020, Knopf et al (2013) provide an overview of the results of a model comparison exercise, namely EMF28. Based on the results from six global computable general equilibrium (CGE) models and seven global or regional partial equilibrium models of the energy sector, they find that ambitious decarbonisation is feasible but requires a major transformation of the energy sector, with costs rising significantly after 2040. The models used in this and similar exercises analyse the transition to a low-carbon economy over many decades, and embed the power sector in a detailed energy sector, which in a CGE model itself is but one of the several moving parts.

The model of the current paper is significantly simpler. This is deliberate. We seek to study the most parsimonious model that fits our purpose, which is to study the supply-side distributional impacts as well as fiscal and welfare consequences of alternative policy instruments. In this respect our strategy is similar to a number of recent papers that analyse the problem of integrating intermittent renewables into the power system. The model of Ambec and Crampes (2017) features two technologies, one polluting and the other intermittent. The authors explicitly model the uncertainty in the availability of the latter. Like us, they find that a carbon tax is the best instrument to reduce emissions by integrating intermittent renewables. Using a similar model, Helm and Mier (2016) study the efficient diffusion of variable renewable energy and find that intermittency induces an S-shaped deployment profile. In their model, competitive markets and dynamic pricing of power lead to an efficient mix of intermittent and polluting technologies, provided thata carbon tax internalises the climate change externality.

Liski and Vehvilainen (2016) is similar in spirit to our paper but analyses the specific circumstances of the Nordic power market. These authors argue that the welfare cost of subsidies to the entry of new wind capacity is biased upwards if it fails to take into account the decline in the rents extracted by incumbent generators. In a carefully constructed quantitative analysis of the Nordic case, the authors find that taking this channel into account, there are in fact welfare gains to consumers at the expense of incumbent generators' pure rents. Our paper differs from Liski and Vehvilainen (2016) in that our model does not distinguish between incumbents, who earn pure rents, and entrants. Moreover, we do not assume that generation by the subsidy recipient replaces thermal generation one-for-one. Finally, in our model we study the response of each firm to a broader set of technology-specific taxes and subsidies while explicitly keeping track of fiscal implications of these interventions.

The rich model of the power market in Green and Leautier (2015) yields somewhat more pessimistic conclusions, both theoretically and in an application to the UK, regarding the expansion of renewable capacity for the government's fiscal position and welfare. Their model of capacity investment in multiple conventional and renewable technologies features uncertainty on the level of demand and renewable generation, as well as learning-by-doing for renewable technologies. The authors then analytically study the implications of price support to renewables financed by power consumption taxes. They find that subsidies, and as a consequence taxes, may have to be sustained in the long run and indeed may even increase when renewable penetration is high.

Kalkuhl et al (2012 and 2013) evaluate the welfare costs of alternative climate change polices using the same underlying global multi-sector dynamic general equilibrium model. In this setup energy can be produced using a generic carbon-emitting technology and two carbon-free technologies: renewable energy and nuclear. Kalkuhl et al (2012) study how to best address the learning-by-doing externality which only affects the renewable technology. The authors compare the welfare costs of canonical technology support polices. They find that a carbon tax is a poor instrument to address the learning-by-doing externality and that subsidies financed by lumpsum taxes, feed-in-tariffs and well-designed renewable portfolio standards typically perform better.

Kalkuhl et al (2013) abstracts from the learning-by-doing externality but introduces the policy constraint that optimal carbon prices can only be imperfectly implemented, if at all. The authors find that replacing optimal carbon prices with permanent renewable subsidies implies "disastrous welfare losses" and provide a welfare ranking of alternative policies, echoing some of our conclusions. The innovation of the current paper derives from our explicit focus on a more detailed power sector and our analysis of the distribution of profits across technologies under alternative policies.

3 Theoretical model

This section presents the general theoretical model, describes government policies and characterises equilibrium allocations. The model is a static deterministic partial equilibrium model of the power sector, where N power generation technologies compete to meet a price-sensitive demand in a perfectly competitive market. Firms determine the production sites they want to develop for each technology as well as the amount of capital to deploy at each site to maximise their profits. The government aims to implement carbon emission reductions by introducing taxes and/or subsidies that alter the prices facing the generators. The price of power adjusts endogenously to clear the market. In equilibrium the generators' factor input decisions, the resulting generation mix, the value of firms and the government's fiscal position can be readily computed.

Production technologies

There are N power generation technologies indexed by $i = 1, 2, ..., N$. Production takes place at technology-specific sites indexed by $s_i \geq 0$. Sites are ordered so that $s_i = 0$ is the most productive site and productivity declines as s_i increases. In $t = 0$, the initial period, a site can be developed and capital installed. Developing a site incurs an immediate one-time fixed cost of $\psi_i \geq 0$. Capital depreciates at the constant rate δ_i after production and its stock evolves according to $k_{it+1} = (1 - \delta_i)k_{it} + x_{it}$ where x_{it} denotes investment in period $t = 0, 1, 2, \ldots$.

A developed site s_i combines k_{it} and possibly fossil fuel input e_{it} to generate power using

$$q_i(k_{it}, e_{it}; s_i) = A_i(s_i)F_i(k_{it}, e_{it})$$

where site- and technology-specific productivity is given by $A_i(s_i)$ and $F_i(k_{it}, e_{it})$ is a production function satisfying the Inada conditions. Since sites are ordered by productivity as s_i increases, site productivity declines, i.e. $dA_i(s_i)/ds_i \leq 0$.

Profit maximisation

Generation technology i is operated by a representative firm, also indexed by i. Firm i maximises the net present value of its profits. When solving firm i's problem, we suppress the technology and firm indexes in this section to avoid clutter. The focus is on the solution to the profit maximisation problem of the firm in a stationary environment where all variables the firm takes as given are constant over time. These variables include the output and input prices the firm faces $\{p, p_k, p_e\}$ as well as the site development cost ψ. To maximise profits, the firm chooses whether or not to develop a site and, if developed, the quantity of inputs to use at that site. That is, the firms choose the optimal values of s, k and e.

It is helpful to study the firm's problem in two steps, starting from the profit-maximising input choices in a developed site s. In other words, we first look at the capital and fuel choices of firms for a given (developed) site s. The per-period profit from this site is

$$\pi(k, e; s) = pA(s)F(k, e) - p_k\delta k - p_e e$$

where we have already imposed the restriction that in the stationary environment analysed capital will be constant over time and so $x_t = \delta k$ in all periods other than the initial period. In the initial period, the firm pays the site development cost ψ and installs capital at cost $p_k k$. The net present value of profits from the site is given by

$$\begin{aligned} v(k, e; s) &= \sum_{t=0}^{\infty} \beta^t \pi(s, k, e) - p_k k - \psi \\ &= \frac{1}{1-\beta}\pi(s, k, e) - p_k k - \psi \qquad (1) \end{aligned}$$

where β is the firm's discount factor. Then the profit maximizing choices $k^*(s)$ and $e^*(s)$ must satisfy

$$F_1\Big(k^*(s), e^*(s)\Big) = \frac{1}{A(s)}\frac{p_k}{p}(1 - \beta + \delta) \qquad (2)$$

$$F_2\Big(k^*(s), e^*(s)\Big) = \frac{1}{A(s)}\frac{p_e}{p} \qquad (3)$$

It is straightforward to show that equations (2), (3) and the Inada conditions imply $k^*(s) > 0$ and $e^*(s) > 0$. Moreover, if $dA_i(s_i)/ds_i < 0$, both $k^*(s)$ and $e^*(s)$

are decreasing in s. Finally, under the same premise the envelope theorem implies $\frac{d}{ds}v\left(k^{*},e^{*};s\right)<0$. In words, less productive sites generate smaller profits for the firm.

Having determined the capital and fuel choice for each site s, the next step of the profit maximisation problem is to determine which sites a firm should develop and operate. Ignoring the trivial case when $v(k^{*},e^{*};0)\leq 0$ and the technology is idle, the firm decides whether or not to develop a given site based on the site's potential contribution to profits.

Formally, when $v(k^{*},e^{*};0)>0$ and $dA_i(s_i)/ds_i<0$, it is possible to find $\bar{s}>0$ such that

$$v\Bigg(k^{*}(\bar{s}),e^{*}(\bar{s});\bar{s}\Bigg)=0. \tag{4}$$

Below we refer to the site with index $\bar{s}$ that satisfies (4) as *the marginal site.* All sites with $s\leq\bar{s}$ are profitable to develop and the firm's input choices in these sites satisfy (2) and (3). Conversely, the net present value of profits from the sites with $s>\bar{s}$ is negative so the firm leaves them undeveloped with $k^{*}(s)=0$ and $e^{*}(s)=0$.

With the marginally profitable site $\bar{s}$ so determined, we can express the implications of profit maximisation for key endogeous variables in full. Using capital letters to distinguish firm-level variables from site-level variables and re-introducing technology/firm index i, we have

$$Y_i=\int_0^{\bar{s}_i}y_i(s_i)ds_i \tag{5}$$

where the variable y_i can stand in for any element of $\{k_i^{*}(s_i),e_i^{*}(s_i),q_i^{*}(s_i),v_i^{*}(s_i)\}$. For example, $Q_i^{*}=\int_0^{\bar{s}_i}q_i(s_i)ds_i$ is the total power generation by all the sites firm i has developed and is operating. This implies that the net present value of the firm is given by $V_i^{*}=\int_0^{\bar{s}_i}v_i(s_i)ds_i$.

Government

Government policy is exogenous and has two components. First, the government can restrict site space available to firms using a licensing parameter (σ_i) so that only sites $s_i\leq\sigma_i$ can be operated. Second, the government can introduce a collection of technology-specific ad valorem taxes/subsidies on output (τ_i), capital (τ_i^k), fossil fuels(τ_i^e) and site development costs (τ_i^ψ) of firm i. The government policies are collected in the matrix

$$\Gamma = \begin{bmatrix} \sigma_1 & \sigma_2 & \dots & \sigma_N \\ \tau_1 & \tau_2 & \dots & \tau_N \\ \tau_1^k & \tau_2^k & \dots & \tau_N^k \\ \tau_1^e & \tau_2^e & \dots & \tau_N^e \\ \tau_1^\psi & \tau_2^\psi & \dots & \tau_N^\psi \end{bmatrix} \tag{6}$$

One can think of the sites $s_i \in [0, \sigma_i]$ as those for which the government issues a license, a precondition for site development by assumption.[4] For example, if the government sets $\sigma_i = 0$, it precludes generation by technology i by fiat. At the other extreme, if σ_i is large, in particular greater than $\bar{s}_i$ that would obtain under laissez-faire, the licensing parameter will have no effect on equilibrium allocations.[5] Regarding the taxes and subsidies in the remaining rows, note that each entry can be positive representing a tax, negative representing a subsidy, or zero representing no intervention. Using this notation an ad valorem carbon tax is simply $\tau_c^e = 2\tau_g^e$ because per unit of energy coal contains twice the carbon content of gas.

It is possible to express the absence of intervention by the government using Γ. Specifically, when all σ_i are large enough *and* when all $\{\tau_i, \tau_i^k, \tau_i^e, \tau_i^\psi\}$ are zero, government does not impose any additional constraints on the firms or affect their incentives. We denote the government's actions in this laissez-faire world Γ_{LF}.

Using this notation, we provide a more precise description of the firm-specific capital, fossil fuel and power prices as well as site development costs

$$p_{ki} = (1+\tau_i^k)\tilde{p}_k, \quad p_{ei} = (1+\tau_i^e)\tilde{p}_e, \quad p_i = \tilde{p}/(1+\tau_i) \tag{7}$$

$$\psi_i = (1+\tau_i^\psi)\tilde{\psi}_i \tag{8}$$

where $\tilde{p}_k$ and $\tilde{p}_e$ are the *exogenous* capital and fossil fuel prices, $\tilde{p}$ is the *equilibrium* power price paid by the consumer per unit of energy. Note that without government intervention all firms face the same prices indicated by the absence of subscript i from $\{\tilde{p}_k, \tilde{p}_e, \tilde{p}\}$. In contrast, site-development costs $\tilde{\psi}_i$ may in principle vary across firms, even in the absence of government intervention.

[4]We assume sites are identical except in their technology-specific productivity. If they were not, say because some sites feature outstanding natural beauty, government restrictions to protect them may result in a discontinuous permissible site space.

[5]We will later use σ_i to incorporate in the model the political-economy constraints highlighted in the Introduction.

Demand and equilibrium

In the model demand is extremely simple and only depends on the power price and an exogenous shift factor:

$$D(\tilde{p}) = A_d G(\tilde{p})$$

This demand function implicitly assumes that the energy efficiency of consumers, that is the rate at which they transform energy to energy services, does not respond to changes in the price of power. Put differently, we assume that the change in consumer surplus evaluated using the demand for power, rather than the more appropriate demand for power services, is a good approximation.

It is now possible to provide a definition of the market equilibrium that is at the core of the quantitative analysis below. It is important to be explicit about two of its properties at the outset. First, this equilibrium is one that obtains only in the long run because it must be preceded by a sufficiently long period of stationary policies and prices. Second, it is a partial equilibrium in the sense that input prices are determined outside the model and there is no explicit restriction on the government budget balance.

Definition. *Equilibrium*
Given technologies $i = 1, 2, ..., N$, exogenous government policy Γ defined in (6), and constant input prices $(\tilde{p}_k, \tilde{p}_{ei})$, a market equilibrium consists of

- *a marginal site $\bar{s}_i$ for each i which*
  - *solves equation (4) with $\bar{s}_i \leq \sigma_i$ or*
  - *$\bar{s}_i = \sigma_i$*
- *capital input $k_i(s)$ satisfying (2) for $s_i \leq \bar{s}_i$ and $k_i(s) = 0$ for $s_i > \bar{s}_i$ for all i*
- *energy input $e_i(s)$ satisfying (3) for $s_i \leq \bar{s}_i$ and $e_i(s) = 0$ for $s_i > \bar{s}_i$ for all i*
- *a power price $\tilde{p}$ which clears the market i.e. $D(\tilde{p}) = \sum_i Q_i(p_i)$*

For a given government policy the generation mix across technologies and the distribution of profits across firms is well defined in this equilibrium and we can readily perform a comparative static analysis of how these objects respond to alternative government policies. Below we approach these issues quantitatively by selecting functional forms, imposing parameter restrictions and calibrating the model.

4 Quantitative strategy and calibration

In this section, we specialise the general model to three technology groups to study the model's quantitative properties. These groups include technologies with site-specific productivity, i.e. wind (w), hydro (h) and solar (pv); those with fossil fuel inputs, i.e. coal (c), gas (g); and nuclear (n). These technologies account for almost all power generation in practice.

4.1 Functional forms and parameter restrictions

We assume productivity is linear in the site index. That is,

$$A_i(s_i) = A_i - \omega_i s_i \tag{9}$$

with $A_i > 0$ and $\omega_i \geq 0$. Modelled in this way the most productive site's productivity level is A_i. When $\omega_i > 0$, site productivity declines as s_i increases. Otherwise it is constant at A_i. For simplicity, we further assume that $F_i(k_i, e_i)$ is Cobb-Douglas

$$F_i(k_i, e_i) = k_i^{\alpha_i} e_i^{\theta_i} \tag{10}$$

with cost shares of capital and fossil fuels given by α_i and θ_i respectively.[6] These simple functional forms impose sufficient structure to distinguish between the high-level features of the generation technologies we focus on. To that end we impose three joint restrictions on the parameters $(\omega_i, \alpha_i, \theta_i)$ in (9) and (10).

The first group of technologies includes hydro, wind and solar where site-specific productivity and the absence of fossil fuel inputs from the production process are key defining features. As a consequence, we impose the following restrictions

$$\begin{aligned}
\text{Wind} &: \quad \omega_w > 0 \quad \alpha_w > 0 \quad \theta_w = 0 \\
\text{Hydro} &: \quad \omega_h > 0 \quad \alpha_h > 0 \quad \theta_h = 0 \\
\text{Solar} &: \quad \omega_{pv} > 0 \quad \alpha_{pv} > 0 \quad \theta_{pv} = 0
\end{aligned}$$

[6]Labour is typically omitted from power sector production functions because its cost share is minute.

With $\theta_i = 0$ for these technologies, (3) is not an equilibrium condition for wind, hydro and solar.

Coal and gas technologies are in the second group and loosely speaking have the opposite features. Their productivity is site-independent and they require fossil fuels to generate power. These properties imply the following restrictions on the technology-specific characteristics.

$$\begin{aligned} \text{Coal} &: \quad \omega_c = 0 \quad \alpha_c > 0 \quad \theta_c > 0 \\ \text{Gas} &: \quad \omega_g = 0 \quad \alpha_g > 0 \quad \theta_g > 0 \end{aligned}$$

For the technologies with $\omega_i = 0$, the solution strategy for the marginal site $\bar{s}_i$ is no longer valid. To see why, observe that if $v_i(k_i, e_i; 0)$ defined in (1) is positive, then it is positive for all $s_i > 0$ and the more profitable technology among coal and gas captures the entire market.

This type of corner solution is not observed in reality and we implement it in the model by exogenously imposing a political-economy constraint. In other words, we assume the existence of social (e.g. NIMBYism) and/or political (e.g. lobbying by would-be competitors) pressures that induce the government to limit the number of coal and gas plants that can be built, even when additional sites would have been profitable for the firms. Specifically, we assume that the government restricts the site space to $[0, 1]$ for coal and gas firms by setting $\sigma_c = 1$ and $\sigma_g = 1$.[7]

In our quantitative analysis nuclear is the only technology in the final group. It only requires capital as a factor of production and its productivity is site-independent.[8] In other words, we have

$$\text{Nuclear} \quad : \quad \omega_n = 0 \quad \alpha_n > 0 \quad \theta_n = 0$$

Like wind and hydro, (3) is not an an equilibrium condition for nuclear, and like coal and gas, the nuclear technology's site space is restricted by setting $\sigma_n = 1$.

In passing we note that capital-only technologies can be expanded to include inter-

[7]This is equivalent to shutting down site-specificity at the outset by imposing $A_i(s_i) = A_i$ so that s is not a choice when $\omega_i = 0$. Setting the upper bound of the permissible sites at 1 is without loss of generality when $\omega_i = 0$ because (5) implies that in any specific calibration $\sigma_i A_i$ is what matters for firm-level variables.

[8]We include nuclear fuel costs in the capital costs because trade in nuclear fuel is extremely regulated and likely price inelastic. In addition, its share in overall costs is typically small.

connection with neighbouring countries. After all, the power supply from abroad in the long run is an increasing function of the power price, which makes interconnection equivalent to building and maintaining the transmission infrastructure to tap into (augment) the international supply, provided the domestic price is sufficiently high (low) in the absence of international power trade. However, doing so without modelling the joint determination of long-run generation mixes at home and abroad as well as the appropriate investment in interconnection capacity does not yield new insights. From a more practical perspective, the net power imports in Spain, our main calibration target, has typically been a small share of domestic generation. We therefore abstract from interconnection in the rest of this paper.

4.2 Calibration

In this section we calibrate the benchmark model by targeting the Spanish power sector. We illustrate the rationale behind our country target choice using Table 2. Based on Eurostat data the table provides the generation mix in eight EU countries as well as in the EU28, averaged over the the 2010-15 period. First, Spain has a well-balanced generation mix in the sense that no single technology is dominant (unlike in France and Poland) and all six generation technologies are operated (unlike in Italy, Portugal and Denmark). Second, Spain has ample potential to expand its hydroelectric generation. On the contrary, Germany and the UK have used up a large share of their hydro potential, which is quite small to start with. Third, the final row of the table shows that the six technologies we focus on comprise about 93% of the actual generation in Spain, meaning those technologies that are excluded from the model, such as biomass, geothermal and tidal, account for a small share of power supply. Accordingly, when the generation mix changes in response to the policy interventions we consider, the bias introduced by the substitution towards the excluded technologies will be second order. Finally, its substantially larger wind- and smaller coal share notwithstanding, Spain has the generation mix that is the most similar to the EU28 average out of the countries in the table.

Next, we impose the values of the (*i*) cost share parameters, (*ii*) depreciation rates, (*iii*) discount factors, and (*iv*) some of the productivity and site development cost parameters based on IEA (2015) and restrictions discussed in Section 4.1. The imposed parameters are reported in Table 3. For all technologies, we adopt the central discount rate in IEA (2015), which is 7% and which implies $\beta_i = 0.930$. We then calculate the capital and fossil fuel cost shares based on the components of the levelised cost of electricity for each of the European projects reported. For our purposes, capital costs include investment costs as well as refurbishment and decommissioning costs. Fuel costs for coal and gas technologies consist of the cost of the fossil fuel and the carbon cost.[9] This point is important for the interpretation of our starting point and we come back to it below.

To minimise the effect of project- and country-specific factors on α_i and θ_i, we average over all projects by technology. More specifically, α_i and θ_i reported in Table 3 are based on a sample of 19 wind, 12 hydro, nine solar, eight coal, six gas and six nuclear projects. The depreciation rates are calculated by combining the technology-specific plant lifetimes in IEA (2015) and the assumption that 1% of a unit of capital remains at the end of a plant's life under constant exponential depreciation.

The theoretical parameter restrictions in Section 4.1 imply that $\omega_i = 0$ for coal, gas and nuclear technologies. We also set $\psi_i = 0$ for these technologies since it only affects the level of profits but not decisions at the margin.[10] Regarding power demand, we normalise $A_d = 1$ and set its long run price elasticity to -0.35, which is consistent with Bernstein and Madlener (2015), Deryugina et al (2017) and references therein.

The remaining parameters of the model are jointly selected so that the model's equilibrium matches relevant features of the Spanish power sector. These features include the generation mix, the maximum amount of wind, hydro and solar generation that can be integrated in the system and the ratio of CO_2 emissions from coal to gas generation. We discuss each in turn.

In Section 3 we emphasised that the model's equilibrium is static and should be interpreted as one that obtains in the long run. As a corollary, the empirical counterparts of the endogenous variables of the model must be approximately stationary at the starting point for the model. We refer to this starting point as the benchmark equilibrium hereafter. Table 4 illustrates the evolution of the Spanish power generation mix over the 1990–2015 period based on the same underlying Eurostat data as in Table 2. We observe that prior to 2010 there are important and persistent trends in the share of

[9] Nuclear fuel costs are relatively small as a share of the levelised cost of nuclear power. Therefore, we include them in the capital costs of the plant. See also footnote 8.

[10] This is innocuous because we study the deviations from the benchmark in response to policy intervention. For the same reason, profit taxes and subsidies in these sectors do not have an effect on allocations.

individual technologies. The trends are much less prominent or entirely absent post-2010. In addition, the share of excluded technologies is also stationary in the post-2010 period. As a consequence, in the benchmark equilibrium we target the generation mix averaged over the 2010–2015 period.

With $\omega_i = 0$ for coal, gas and nuclear, (9) implies A_i is the only productivity parameter we must calibrate. It is clear from (2) and (3) that the optimal input choices and therefore the share of these technologies in total generation are determined by A_i in the benchmark equilibrium. As a consequence and holding all else constant, the generation shares of these technologies will in large part determine the calibrated values of A_i. This is also true for wind, hydro and solar. However, $\omega_i > 0$ are also instrumental for determining these technologies' generation shares since they affect which sites are profitable. Put differently, in addition to their shares in the generation mix, we need three additional equations to calibrate both (A_i, ω_i) for wind, hydro and solar.

To that end we use the level of maximum feasible generation these technologies can achieve under current technology. The factors that restrict the maximum generation are different for hydro on the one hand and wind and solar on the other. In our calibration, hydro generation potential is constrained by a country's physical geography, e.g. its precipitation patterns, topography and river/fluvial systems, and are assumed to be beyond the control of its government. We use the average generation of 36 TWh per year over 2010–2015 from Eurostat, and the technically feasible potential estimate of 62 TWh per year from Eurelectric (2011), which gives us a generation-to-potential ratio of 58.1%. All else constant, this is sufficient to calibrate to A_h and ω_h.

Specifically, we select (A_h, ω_h) that satisfy

$$\frac{Q_h}{\sum_i Q_i} = 0.136 \tag{11}$$

$$\frac{Q_h}{Q_h^{max}} = \frac{\int_0^{\bar{s}_h} q_h(s_h) ds_h}{\int_0^{A_h/\omega_h} q_h(s_h) ds_h} = 0.581 \tag{12}$$

The right-hand side of (11) is the average share of hydro generation in Spain over 2010–2015 from Table 4. The denominator of (12) is computed assuming that all sites with $A_w(s_h) \geq 0$, i.e. those with an index less than A_h/ω_h, are operated even though sites with $s_h > \bar{s}_h$ are not profitable with current technology and market environment.

In the case of wind and solar generation, physical geography continues to play an important role in determining the productivity of sites. Eurek et al (2017) provide evidence on country-level onshore and offshore wind energy potential, controlling for a host of factors related to physical geography, available technology and spatial distribution of demand. Suri et al (2007) and Castello et al (2016) provide a similar analysis for solar generation potential in Europe.

Abstracting from challenges related to intermittency of wind and solar generation for the moment, both technologies' potential is vast relative to current and future power demand. Eurek et al (2017) estimate the technical potential for wind generation in Spain to be 3600 TWh per year, almost two orders of magnitude greater than current annual demand. Šúri et al (2007) estimate that covering 0.32% of Spain's surface area with PV modules would satisfy the country's annual power demand. The authors argue that this estimate is conservative because at the time they conducted their research technology was already more efficient than that underpinning their calculations. The impact of technological progress is all the more positive a decade after the publication of their results. The vast technical potential notwithstanding, the wind and annual irradiation maps of Spain[11] illustrate that the geographical distribution of the country's wind and solar resources is heterogeneous over space.

Taken together this presents a challenge for calibrating (A_w, ω_w) and (A_{pv}, ω_{pv}) based on generation-to-potential ratio alone. The fact that we observe such large potential and at the same time relatively small shares of wind and solar in total generation would be reflected in A_i, which are small and ω_i, which are effectively zero. This is inconsistent with the evidence above and suggests that a key constraint on the potential of these technologies is missing from our calibration strategy.

Indeed, constraints imposed by the intermittency of wind and solar are absent from the model but interact with physical geography constraints in the real world. In particular, energy storage capacity is extremely limited, and the existing grid infrastructure and power market arrangements are not optimised for intermittency or the spatial dispersion of wind and solar sites. All of these factors evolve very slowly.[12] Heptonstall et al (2017) survey the large literature that estimates the external costs due to the intermittent nature of wind and solar power. The authors find that the level of costs differ based on the level of flexibility of a country's power system and its market arrangements but are typically low for low levels of penetration. However, the system-level costs of

[11]See, for example, IDAE (2017) for wind and EC (2017) for solar maps.

[12]Martinot (2016) reviews the issues around integrating high wind and solar generation.

intermittency typically increase with share of wind and solar. Most existing studies reviewed estimate these costs for penetration levels up to 50%, and find they can be substantial, even prohibitive, near and beyond this level.[13]

To calibrate (A_w, ω_w) and (A_{pv}, ω_{pv}) while taking these external costs into account, we make the assumption that the maximum share wind or solar can achieve individually is no more than 50% of total generation. In other words, externality costs reduce the effective productivity of each site so that when wind/solar generation reaches half of total generation, the marginal site has zero productivity.[14] By doing so, we are effectively imposing that the unmodelled system-level technological constraints become binding before physical geography constraints do. This is a crude way to capture the costs of intermittency but is broadly in line with Heptonstall et al (2017).

Next we introduce four normalisations. We use capital as numeraire, i.e. set the price of a unit of capital $p_k = 1$. We also set the fixed site development cost $\psi_i = 1$ for wind, hydro and solar. Loosely speaking, it is equivalent to letting site size vary across the technologies and is innocuous so long as we are careful in interpreting the levels of $\bar{s}_i$.

Finally, we calibrate the prices (p_{ec}, p_{eg}) of coal and gas respectively, by setting the total power sector emissions in Spain to 1. We then assume that (i) coal generates twice the carbon emissions that gas does per unit of useful energy, i.e. $2E_c + E_g = 1$; and (ii) the mix of carbon emissions from coal and gas plants matches the ratio observed in Spain, i.e. $2E_c/E_g = 1.74$. Table 5 shows the evolution of this ratio between 1990 and 2014, which declines rapidly at the beginning of the sample period as gas capacity is built up, but is approximately stable more recently. Note that despite the change in its mix, total coal and gas emissions from power plants in Spain are a stable and substantial portion of Spain's total emissions.

To summarise, Tables 3 and 6 provide the values of all parameters required for solving the equilibrium of the benchmark model quantitatively. In our quantitative analysis below we will will keep these parameters constant but introduce *new* policies. We emphasise the adjective 'new' because all existing policies and distortions that have a bearing on the power market equilibrium are subsumed into the benchmark parameters. We also underline the fact that given our normalisations, the levels of variables in

[13] See also Hirth et al (2015). The challenges associated with 100% renewable energy systems are also highlighted by Papaefthymiou and Dragoon (2016).

[14] Effectively, we replace the generation-to-potential ratio 0.581 in (12) with 0.500 for wind and solar. In Section 6 we check the robustness of our results with respect to variations in the latter threshold.

equilibrium are difficult to interpret. As a consequence, in the next section the focus is on the changes relative to the benchmark equilibrium.

5 Results and discussion

5.1 Government policies

Before reporting our results, we illustrate the types of policies we examine with a few examples to clarify how they affect the incentives of the decision makers in non-neutral ways. In Table 1 we list seven distinct policies targeting coal and wind generation.

The table shows how a given policy is represented as the matrix of policies Γ introduced in (6). In particular, the middle column of the table indicates the entries in Γ that are different from Γ_{LF}. The final column computes the per-period fiscal implications where net revenues (NR) is defined as the difference between the total revenues (TR) and total outlays (TO).

Policy (I) imposes the political-economy constraint on the sites that the coal firm can develop and operate, namely those with $s_c \in [0, 1]$. The constraint must be satisfied even if additional sites would have been profitable. Under the licensed site interpretation of this policy, the government can sell or give away these licences. For simplicity, we assume the licences are given away so there are no fiscal implications for the government.

Policy (II) introduces a technology-neutral wedge between the price paid by the consumers and that received by the firms. It is a tax on power consumption because it affects all firms neutrally. Each period the tax generates net revenues for the government. Policy (III) also introduces a price wedge but it is not technology-neutral. Specifically, since $\tau_w < 0$ the policy raises the price received by the wind firm above the price paid by the consumer and that received by the coal firm. The difference is paid for by the government, leaving its net revenues negative.

The coal tax in policy (IV) raises the energy input price for the coal firm and discourages coal use. We emphasise that τ_c^e is a coal tax rather than a carbon tax τ^c. Effectively, the latter consists of two taxes imposed simultaneously, one on coal and another on gas input. In addition, these taxes are related in a particular way, i.e. $\tau_c^e = 2\tau_g^e > 0$. The carbon tax and its revenue implications are illustrated in policy (V).

Policy (VI) combines policies (III) and (V) so the revenue generated by the carbon tax just covers the outlays required for the output subsidy to wind, resulting in zero net revenue. Finally, policy (VII) reduces the site development costs of the wind firm proportionally. The one-time total outlay associated with this policy depends on the number of sites developed by the wind firm and the fixed cost of developing those sites.

In order to ensure that the comparison of impacts across policies is valid, we set the same stringency for each policy instrument in our analysis. For example, the power consumption tax in policy (II) is set to achieve a fixed relative reduction in carbon emissions. Similarly, the level of the output subsidy to wind in policy (III) is such that it also achieves the same relative reduction in emissions. Fixing the policy stringency this way implies that any benefits from emissions reductions are identical across policies. In what follows we analyse the impact of a 25%reduction in carbon emissions from the power sector in Spain relative to the country's average emissions over the 2010–2014 period using a broad set of instruments.[15]

5.2 Evaluating the impact of policies

We present our results in a series of tables (Tables 7–10), which have a standardised structure as follows. The final column in these tables is titled BM for benchmark and will serve as a reference throughout. It reports *the levels* of the variables in the BM equilibrium. The remaining columns provide information on how the new equilibrium under a given policy intervention differs from the BM equilibrium.

The first three rows report *the percentage deviation* of aggregate variables, namely equilibrium price, quantity and emissions.[16] The block of six rows that follow are the generation shares of each technology, reported as *percentage shares* in all policy intervention and BM columns. By construction the BM column replicates the final column of Table 4, i.e. Spain's generation mix.

The next block of six rows shows *the percentage deviation* of the present discounted value of each firm relative to the BM column. This value is obtained by integrating (1) over the interval $[0, \bar{s}_i]$. It can be interpreted as the stock market value of the firm.

[15]The EU's current target for the sectors covered under the EU Emissions trading System is about 90% reduction in 2050 compared with 2005. If we make the strong assumption that this target applies to the Spanish power sector exactly, the 25% reduction we analyse below delivers about 28% of the targeted reductions.

[16]With our normalisations, the level of price, quantity and emissions are 1 in the BM equilibrium.

Any change in the firms' value in the new equilibrium takes into account the forfeited fixed cost associated with the sites operational in the BM equilibrium but which may be abandoned subsequently in response to policy intervention.

The final four rows of the table are crucial for comparing the welfare impact of alternative policy interventions. They report *the level difference* in the key components of welfare relative to the BM equilibrium. Specifically, these components are changes in the present discounted value of (*i*) the power sector Δ^V; (*ii*) the net revenues of the government Δ^{NR}; (*iii*) the consumer surplus Δ^{CS} and (*iv*) our overall measure of welfare $\Delta = \Delta^V + \Delta^{NR} + \Delta^{CS}$, which includes Δ^{NR}, assuming the government can use lumpsum taxes and transfers. Welfare is measured in real terms although its units are unspecified. However, the magnitudes are comparable across components for a given policy intervention, and across policies for a given component.

5.3 Carbon, coal and power consumption taxes

Consider Table 7 first. The carbon tax in column τ^c, the coal tax in column τ^e_c and the power consumption tax in column $\tau_i = \tau$ are set so that the policy intervention reduces emissions by 25%. A carbon tax increases the equilibrium power price paid by the consumer by 2.0% and reduces demand by 0.7%, whereas a coal tax only results in a more modest increase of 0.7% in the price and a 0.3% decline in demand.[17] In contrast, under the power consumption tax the price paid by the consumer almost doubles and equilibrium quantity declines by almost 21%.

Another important difference between input taxes on fossil fuels and the consumption tax is that the former increase the generation share and value of all firms that are not subject to the tax. In contrast, the consumption tax reduces the overall size of the market as well as the generation and the value of each firm. The values of wind, hydro, and solar firms are strongly impacted by the consumption tax. This is because the less productive sites, which were nonetheless profitable in the BM and hence were developed, are abandoned under the consumption tax.

From our partial equilibrium welfare perspective and among the policies considered in Table 7, the carbon tax achieves the 25% reduction in carbon emissions at the lowest cost. The cost is split between the coal and gas firms whose values decline, and

[17] We do not consider a gas-only tax because due to fuel switching, the maximum feasible emission reduction with this instrument is 7.8%.

consumers who experience a decline in consumer surplus. However, we note that the policy increases the values of wind, hydro, solar and nuclear firms. These increases more than compensate for the decline in the value coal and gas firms, i.e. $\Delta^V > 0$. Moreover, the carbon tax generates revenues for the government. To put it in perspective, this value is approximately equal to the value of the wind firm in the BM equilibrium but not large enough to compensate the consumers for the loss in consumer surplus.

All things considered, welfare declines in response to the introduction of the carbon tax because there are no externalities in the BM equilibrium and because we do not take account of the local and global welfare benefits of emission reductions. As noted above, the carbon tax achieves these reductions at the minimum welfare cost. Specifically, coal and consumption taxes imply welfare costs about 24% and 5,000% greater respectively, relative to that of the carbon tax. The large welfare cost of the power consumption tax is due to the decline in consumer surplus relative to the BM equilibrium. This is likely an overestimate of the actual drop in consumer surplus because we are assuming a one-to-one relationship between power and power services. If instead power consumers can invest in improving their energy efficiency, the loss in consumer surplus is likely to be limited. However, in this case the aggregate costs of energy efficiency investments would have to be accounted for in the welfare measure.

Both of these policy interventions also reduce the value of the power sector as a whole, albeit only marginally in the case of the coal-only tax. The most important takeaway message from Table 7 is that from a social perspective the carbon tax has a very low welfare cost.[18] This is in contrast to the power consumption tax, which is an extremely costly instrument for reducing emissions despite the sizeable revenues it generates for the government. As we will demonstrate, the welfare cost of other policies analysed below all lie in between these two extremes.

5.4 Technology-specific output and input subsidies

Next we turn to the implications of technology-specific subsidies targeting a 25% reduction in emissions. The first three columns of Table 8 analyse three distinct subsidy schemes directly impacting the wind firm to achieve this target: (*i*) an output price subsidy τ_w; (*ii*) a capital input subsidy τ_w^k; and (*iii*) simultaneous input subsidies to

[18] Using a different framework Millstein and Tisler (2012) also conclude that while generation/profit mix can change significantly in response to a tax, overall welfare implications are small.

capital and site development (τ_w^k, τ_w^ψ). We note that the equilibrium prices, quantities and generation shares are identical: each scheme reduces the equilibrium price by 2.3%, increases power consumption by 0.8% and shifts the generation mix towards wind at the expense of all other firms. This is intuitive because without directly altering the incentives of the coal and gas firms, the government can only induce emissions reductions by engineering a lower equilibrium price. That is, it sets the subsidy level to achieve the price level that is consistent with the scaling back of coal and gas generation to reduce emissions by 25%. Moreover, observe that the change in the value of all firms other than wind is the same under the three schemes with the value of the solar (coal) firm declining the most (least).[19]

The difference between the three schemes is in the change in the value of the wind firm and the resources the government must expend. An output price subsidy raises the returns to all inputs used in production, creating a windfall for the existing sites and capital stock. A capital input subsidy can discriminate between existing and new capital, but also introduces a distortion in the margin between capital and sites in inducing greater wind generation. As a consequence, it increases the value of existing sites because the wind firm installs more capital at each site. The joint use of input subsidies to capital and site development removes this distortion and reduces government outlays and value of the wind firm, albeit at the cost of a more complex policy intervention that requires an additional instrument. That is, the three subsidy schemes differ in the way the required expansion in wind output is generated. The first and third schemes are identical in terms of their welfare cost. The wind firm clearly prefers the first scheme, whereas the government clearly prefers the latter because it is costly to raise the revenues required to pay for the subsidies.

This is true more generally for subsidies to carbon-free generation technologies: output subsidies are costlier to the government than input subsidies, consumers and the firms that are not directly impacted by the subsidy scheme are indifferent between the two options, and with output (input) subsidies the profits of the subsidy recipient and government outlays are higher (lower) by approximately the same amount.[20] In other words, firms would prefer measures that raise the output price because these increase their profits by more. Conversely, the government prefers to reduce the cost of capital

[19] The change in firm values are qualitatively consistent with the results in Liski and Vehvilainen (2016), who study the Nordic market.

[20] The qualifier "approximately" is required for technologies with site-specific productivity due to the distortion just explained. For nuclear, the statement is exactly true.

input because this increases the revenues it must raise by less. Both types of subsidies are observed in practice (CEER 2015). This suggests that the magnitude of the government's cost savings under input subsidies is likely to be comparable in size to the political costs of resisting the sector's lobbying efforts as well as other potential benefits of output subsidies, which, due to the direct link between government outlays and the carbon-free energy it purchases, may be politically more palatable.

In the remaining columns of Table 8 we report only the results for capital input subsidies to hydro, solar and nuclear firms one at a time or simultaneously. We do so in order to avoid clutter and because the difference between capital input subsidies on the one hand and more complex schemes with joint capital and site development subsidies on the other is small. Comparing Δ and Δ^{NR} across these policy instruments, we observe that if the government is restricted to support only one technology, it faces a dilemma. Subsidising wind has a smaller overall welfare cost but implies a greater fiscal burden than subsidising hydro. The welfare cost is smaller primarily because in the BM equilibrium the wind firm is more valuable than the hydro firm and the rise in its value more than compensates for the greater government subsidy outlays.

Capital input subsidies to solar and nuclear are not particularly attractive for the government or for society as a whole. In fact, in order to reduce emissions using subsidies to solar only, the amount that the government must spend is comparable in size to the total value of the power sector firms in the BM equilibrium. This is largely because the share of solar in generation is very small to start with so its output must increase more than five-fold to bring the equilibrium price down by 2.3% to the level consistent with achieving the targeted emissions reduction. Even though subsidising capital input in wind or hydro implies much lower welfare costs, it is worth noting that these costs are about an order of magnitude larger than the welfare cost of using a carbon tax to achieve the same target.

Against this backdrop the last column of the table highlights that a technology-neutral subsidy scheme, i.e. one in which all carbon-free technologies receive the same capital input subsidy τ^k, can limit both the total cost of the scheme to the government and the welfare cost it imposes on society. Specifically, the fiscal cost of the technology-neutral scheme is almost 40% lower than a capital input subsidy only to the hydro firm, the government's cheapest alternative to the technology-neutral subsidy. Moreover, the welfare cost of this scheme is about 80% lower than a capital input subsidy to the wind firm, the alternative with the least welfare impact. While this suggests technology-neutral input subsidies should be preferred to technology-specific ones, we note that the welfare cost of a carbon tax is lower still, and in addition, it generates revenues for the government.

Table 9 concentrates on subsidies to site development costs. In the first three columns a single technology receives the subsidy. Observe that when these subsidies target a single firm they cannot deliver the targeted 25% reduction. As a consequence, we lower the bar to a 5% reduction, an amount somewhat smaller than the maximum feasible using the least flexible technology, which is solar in the BM calibration. The intuition for the patterns in the first three columns carry over from our previous discussion in a straightforward way. What is novel here is the relative ineffectiveness of site development subsidies, which in the best case deliver a 5% reduction at the approximately the same welfare cost as that of a 25% reduction using the carbon tax.

The welfare cost of achieving a given reduction in emissions is likely to be lower if the government offers a uniform subsidy to wind, hydro and solar at the same time. This is the policy experiment in the column entitled $\tau^{\psi} = \tau^{\psi}_{low}$. The 5% emissions reduction is achieved at a much lower cost to society and the government as the technologies that receive the subsidy increase their generation as well as their generation share, while the others shrink. However, the value of the power sector declines as A whole due to two counteracting forces. On the one hand the subsidy works to increase the profits of the subsidy recipients. On the other hand, the equilibrium price is lower and this depresses the profits. For this policy target, the latter Effect dominates the former for each firm and as a consequence for the sector as a whole.

The final column of the table shows that this need not always be the case. For example, when targeting a 25% emissions reduction using uniform site development subsidies, the former Effect dominates the latter for wind and solar, which exhibit increases in their value despite the fact that the power sector as a whole loses value relative to BM equilibrium. Noting that the policy targets are comparable, we highlight that the welfare cost and fiscal implications of using uniform site development subsidies is similar to that of capital input subsidies to wind and hydro in Table 8.

5.5 Fiscally-neutral policies

An important feature of the various policy interventions involving subsidies has been the fact that government could finance these policies using lumpsum taxation. We relax this assumption by considering fiscally-neutral polices in Table 10. In the first four columns, we review technology-specific capital input and uniform site development subsidies financed by a carbon tax.

It is not a surprise that the coal and gas firms' output and value decline because each firm is adversely affected by both the carbon tax and the subsidies to its competitors. For a carbon-free firm that is not receiving a subsidy, the outcome is less clear a priori. On the one hand, the carbon tax gives them a comparative advantage relative to coal and gas. On the other hand, a subsidy to its competitor can reverse some or all of this advantage. Quantitatively, each of these interventions increases the value of the firms other than coal and gas because their generation shares are higher. This fact, combined with the relatively inelastic demand in the benchmark calibration, delivers an increase in the value of all carbon-free firms.

For technology-specific capital input subsidies observe that the change in firm value is the greatest for the firm receiving the subsidy. However, the change is much more modest compared with the cases in Table 8 where the subsidies are not financed by a carbon tax. Moreover, combining technology-specific capital input subsidies with a carbon tax reverses the decline in the value of those carbon-free technologies which do not benefit from the subsidy and results in a more equitable burden-sharing among firms. A similar result is also present for uniform site development subsidies financed by a carbon tax. This is demonstrated in the column titled $(\{\tau_i^{\psi}\}, \tau^c)$. When site development subsidies are financed by a carbon tax, the equilibrium price does not decline as in the case without carbon tax in Table 9. This reverses the decline in the value of the hydro and nuclear firms.

The final column of Table 10 reports the results when a technology-specific capital input subsidy to wind is financed using a power consumption tax. The contrast with the first column of the table is stark. The loss in consumer surplus more than doubles, the increase in the aggregate value of the sector turns into a decline of similar magnitude, and the distribution of value across firms is much more skewed. Taken together, the welfare cost of using consumption taxes is more than five times larger than using carbon taxes to finance the subsidies to the wind firm.[21]

[21] Bohringer et al (2017) use a CGE model and microsimulation analysis to conclude that German technology-specific subsidies paid for by a power consumption tax have a high welfare cost and are regressive.

6 Sensitivity

In this section we conduct a sensitivity analysis to gauge how different our results would look under different assumptions regarding calibration. First, we recalibrate the model to France and Poland, two countries whose generation mix is significantly different from Spain, and compare the effects of two policy experiments, a carbon tax and a capital input subsidy which, as in Spain, induce a 25% reduction in emissions. Below we will consistently refer to these as *tax* and *subsidy* interventions. Second, we consider the implications of alternative values for key parameters for the results under tax and subsidy interventions.

6.1 Sensitivity with respect to the targeted country

The results under tax or subsidy interventions for each country are reported in the three panels of Table 11, where the first panel reproduces the results for Spain for reference.[22] The generation mix in France's BM equilibrium is dominated by nuclear and the share of all other technologies are much smaller relative to Spain. As a consequence, the tax intervention has a much smaller impact on equilibrium price, quantity and welfare.[23] The subsidy intervention, in contrast, implies a similar change in equilibrium price and quantity but at roughly double the cost to the government compared to Spain. This is because the wind firm is relatively small in the BM equilibrium and needs to increase its share of total generation more than fivefold.

We highlight two observations in the model calibrated to Poland. First, there is no nuclear generation in Poland. We implement this in the quantitative model by exogenously imposing a political-economy constraint, i.e. by setting $\sigma_n = 0$. In light of the discussion in section 3, this restriction can be seen as the government not permitting the nuclear firm to operate in Poland. Note that this is more than just a parametric restriction because nuclear is the only technology that does not emit carbon, and that does not feature declining site-productivity. Second, the Polish power generation relies heavily on coal in the BM equilibrium. With one less margin of adjustment and a small

[22]For brevity, we do not report the (re-)calibrated parameter values for France and Poland. These are available from the authors upon request.

[23]Note that our calibration implies that the present value of total revenue is $(1-\beta)^{-1}\tilde{p}\sum_i Q_i = 14.286$ in all countries. Therefore, our overall welfare measure and its constituents *relative to this quantity* are comparable across countries.

base for all non-coal generation technologies, the impacts on market price and quantity are much greater, particularly under the tax intervention.

Against this backdrop we discuss the tax intervention in detail because unlike in Spain and France, generation, market share and profits for the gas firm increase in the carbon tax equilibrium relative to the benchmark. To see why this happens, recall that in the quantitative model τ^c is simply the simultaneous use of coal and gas taxes such that $\tau_c^e = 2\tau_g^e$. In the case of Poland the tax intervention requires $\tau_c^e = 23.9\%$ and $\tau_g^e = 11.9\%$. This raises the *relative* price of coal because the equilibrium power price rises by 12.2% and delivers the intended reduction in coal use, given equation (3) and holding all else constant. At the same time, it reduces the *relative* price of gas, increasing the gas firm's output, profits and value in the new equilibrium.

The main message of the analysis with alternative target countries is that context matters enormously from a quantitative perspective. The fiscal, supply-side distributional and aggregate welfare implications of interventions, which are standardised in some loose sense, can vary significantly across countries. In special cases, such as Poland's power sector, a carbon tax can even improve the profits of the less carbon-intensive gas firm due to the interplay between changes in input and output prices. Note also that the welfare effects are proportional to the share of carbon-emitting firms in the generation mix in the BM equilibrium. This may be one reason why the magnitude of the political-economy challenge Poland faces in reducing emissions is considerable. However, broadly speaking the results in Table 11 confirm our conclusions in Section 5 regarding the relative cost effectiveness of alternative instruments and their effects on the distribution of value among firms and across producers, consumers and the government.

6.2 Sensitivity with respect to key parameters

Next, we return to the Spanish calibration but assume there is an exogenous 5% increase in the productivity parameter A_i for wind, nuclear, coal and gas.[24] We analyse how this change affects welfare under tax and subsidy interventions.

To see how this thought experiment works, consider wind as an example. Suppose that just before the tax intervention τ_0^c is announced, there is a one-time and permanent

[24] The results for hydro and solar firms, as well as those for a smaller ω_i, are similar to those for wind and are omitted for brevity.

increase in the productivity level of all wind sites from A_{w0} to $A_{w1} = 1.05A_{w0}$, all else being constant. This may be due to a new grid connection technology for sites that feature lower transmission losses, or the emergence of energy storage technologies that on average reduce losses due to the intermittency of wind. Given this change, a lower carbon tax $\tau^c(A_{w1}) < \tau^c(A_{w0})$ can achieve the 25% reduction in emissions. As a consequence, $\{\Delta^V, \Delta^{NR}, \Delta^{CS}\}$ evaluated at the two tax rates will differ, although the sign and relative magnitude of each component are not obvious.

The top and bottom panels of Figure 1 corresponding to tax and subsidy interventions illustrate the results of these thought experiments for a 5% increase in A_w, A_n, A_c and A_g. Note that changes in the former two parameters make it easier to achieve the targeted emissions reduction while the latter two make it more difficult. The blue bars in each case are the results obtained using the parameters underpinning the BM equilibrium. We also emphasise that the horizontal axis scales in the two panels are different.

Starting with the tax intervention, we note the overall welfare loss associated with $\tau^c(A_0)$ becomes a welfare gain under $\tau^c(A_{i1})$, regardless of technology. That is,

$$\Delta\big(\tau^c(A_0)\big) < 0 < \Delta\big(\tau^c(A_{i1})\big)$$

for all i.[25] For wind and nuclear, this is primarily due to a smaller decline in consumer surplus engendered by higher productivity in a carbon-free technology. In contrast, when A_c is higher the decline in consumer surplus associated with $\tau^c(A_{i1})$ is even greater. However, it is more than compensated for by the rise in the revenues generated from the tax. In the case of the productivity improvement impacting the gas firm, the decline in consumer surplus is small because relatively clean gas generation displaces coal even without a carbon tax. Indeed, with the tax intervention the decline in the coal firm's value is so large it more than offsets the rise in the value of all other firms, resulting in $\Delta^V\big(\tau^c(A_{i1})\big) < 0$.

For the subsidy intervention, the response of aggregate welfare is more heterogeneous. We observe that with the BM parameters capital input subsidies to wind imply welfare losses largely because the increase in consumer surplus does not cancel out the negative impact on the government's budget. The 5% productivity improvement in carbon-free technologies is sufficient to reverse this result because total spending required is lower

[25] With slight abuse of notation A_0 denotes $\{A_w, A_h, \ldots, A_n\}$ are as in Table 6.

to obtain the same increase in consumer surplus with negligible impact on aggregate firm value.

When the productivity improvements affect the coal or gas firms, the model still implies aggregate welfare losses for subsidy intervention. However, now we have

$$\Delta\big(\tau_w^k(A_{c1})\big) < \Delta\big(\tau_w^k(A_0)\big) < \Delta\big(\tau_w^k(A_{g1})\big) < 0$$

In words, from a social perspective the subsidy intervention becomes more costly when A_c increases but less costly when A_g increases. This is because reducing coal generation despite the improvement in its productivity calls for much larger subsidies to wind, approximately doubling Δ^{CS} and Δ^{NR} and consequently their difference. On the contrary, with A_{g1} gas generation in part displaces the more carbon-intensive coal, which in turn requires a smaller increase in subsidies to wind than under A_{c1}. One consequence of smaller subsidies is that the increase in the value of the wind firm is more limited and not sufficient to cancel out the decline in the value of all other firms. That is $\Delta^V\big(\tau_w^k(A_{g1})\big) < 0$.

Figure 1 sheds some light on how potential future improvements in technology interact with energy policies in mediating the distribution of gains associated with higher productivity. For example, it suggests that with a tax intervention consumers are better off, albeit still impacted negatively, if productivity increases are in carbon-free or low-carbon sectors, whereas the government raises more revenue if the productivity of carbon-emitting sectors improves. Under a subsidy intervention, consumers are indifferent to productivity improvements in the carbon-free sectors, whose benefits accrue to the government in the form of a lower subsidy bill. Consumers strictly prefer productivity improvements in the carbon-emitting sectors, which forces the government to increase the subsidies to achieve the emissions target. This reduces the power price in equilibrium below the level that would be implied by productivity improvements in the emitting sectors alone, benefiting the consumers.

Finally, we note in passing that we also recalibrated the model under the following assumptions: (i) the maximum amount of wind and solar generation that can be accommodated is 40% and 60% as opposed to 50% in the BM; (ii) the level of fixed costs ψ_i in one or more sectors with $\omega_i > 0$ is 0.9 or 1.1, as opposed to being 1.0 for all in the BM; (iii) the elasticity of demand is -0.20, -0.50 or -1.00 as opposed to -0.35 in the BM; and (iv) the share of capital for the nuclear firm excluding the nuclear fuel costs is 0.728, as opposed to 0.84 in the BM. When we introduce the tax and subsidy interventions in these alternatively calibrated models, there are minor quantitative changes to our numerical results. However, our conclusions regarding the cost-effectiveness of these interventions and their impacts on the distribution of output and profits are qualitatively the same as in the benchmark model. The results are available upon request.

7 Conclusions

This paper is concerned with the distributional impact of carbon emissions reduction policies on power suppliers. We construct, calibrate and solve a partial equilibrium model of the power sector in the long run. A novel feature of the model is site-specific generation in key renewable technologies where productivity differs across sites. We use the model to analyse quantitatively the differential effects of popular policy instruments deployed by governments to reduce carbon emissions. We pay particular attention to how they affect the value of different firms and the fiscal position of the government.

Our analysis yields four stylised policy messages. First, a carbon tax is unambiguously the most cost-effective instrument to reduce the power sector's carbon emissions. This is a well-established result. What is novel here is that a carbon tax treats all the carbon-free generators equally and does not reduce their market value.

Second, a power consumption tax implies a very high welfare cost because it reduces the size of the power market, decreases the value of all generators (both carbon-emitting and carbon-free) and reduces consumer surplus. From a welfare perspective, power consumption taxes should not be the instrument of choice, neither to reduce emissions, nor to finance subsidies aiming to reduce emissions.

Third, technology-specific input and output subsidies can be designed to achieve emissions reduction at the same welfare cost. From a welfare perspective, therefore, they are substitutes. However, firms will prefer output subsidies, because they increase their market value by more, while the government would rather offer input subsidies, because they are less costly to finance. Importantly, these subsidies can damage carbon-free generators that do not receive subsidies by making them lose market share and profits.

Fourth, technology-specific subsidies financed by a carbon tax result in a more equitable distribution of the burden of emissions reduction policies. However, while they are more cost-effective than subsidies financed by lumpsum taxation, they are not as effective as carbon pricing alone.

The model is deliberately simple. We abstract from several relevant aspects of reality to isolate the key distributional channels we are interested in. However, one can envision a number of extensions that would bring more realism and allow us to study issues crucial for both research and policy. Importantly, there are no externalities in the model which are often the main justification for subsidies in reality. For example, the innovation externalities in renewables generation are well documented but we take technology to be constant, deterministic and exogenous. Similarly, energy consumption taxes are sometimes justified as a means of encouraging energy efficiency improvements. To the extent that they overcome energy efficiency barriers, their negative welfare effect will be diminished. Energy storage capacity, be it in the form of greater hydro capacity or large-scale deployment of batteries, is absent from the model. Adding it would improve the productivity of firms with intermittent generation. Our model takes as given the existence of a grid infrastructure, the vintage and sophistication of which affects generators differentially and may result in under- or delayed investment in modernising it. Methodologically, an important element that is missing from the model is time. By adding an explicit time dimension, the model can go beyond simply characterising the broad features of a future low-carbon economy and study the many challenging issues that arise in the dynamic transition to it.

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Tables

Table 1: Examples of policies to reduce carbon emissions

Policy Description	**Restrictions on Γ**	**Per Period fiscal implications** (NR = TR - TO)
(I) Restriction on coal sites	$\sigma_c = 1$	0
(II) Power consumption tax	$\tau_w = \tau_h = \tau_{pv} = \tau_c = \tau_g = \tau_n > 0$	$\frac{\tau_c}{1+\tau_c}\tilde{p}(Q_c + Q_w) > 0$
(III) Output subsidy to wind	$\tau_w < 0$	$\frac{\tau_w}{1+\tau_w}\tilde{p}Q_w < 0$
(IV) Energy input tax to coal	$\tau_c^e > 0$	$\tau_c^e \tilde{p}_{ec} E_c > 0$
(V) Carbon tax	$\tau_c^e = 2\tau_g^e > 0$	$\tau_c^e \tilde{p}_{ec} E_c + \tau_g^e \tilde{p}_{eg} E_g > 0$
(VI) III financed by V	$\tau_w < 0,\ \tau_c^e = 2\tau_g^e > 0$ $(\tau_c^e \tilde{p}_{ec} E_c + \tau_g^e \tilde{p}_{eg} E_g) + \frac{\tau_w}{1+\tau_w}\tilde{p}Q_w = 0$	0
(VII) Wind site development subsidy*	$\tau_w^\psi < 0$	$\tau_w^\psi \bar{s}_w \tilde{\psi}_w < 0$

* One time outlay in the period the subsidy is introduced.

Table 2: Generation mix in eight selected EU countries (2010-2015 average)

	DEU	DNK	**ESP**	FRA	GBR	ITA	POL	PRT	EU28
Wind	0.09	0.41	**0.18**	0.03	0.08	0.05	0.04	0.23	0.07
Hydro	0.05	0.00	**0.14**	0.12	0.02	0.20	0.02	0.27	0.13
Solar	0.05	0.01	**0.04**	0.01	0.01	0.07	0.00	0.01	0.02
Coal	0.48	0.43	**0.16**	0.03	0.33	0.18	0.89	0.25	0.28
Gas	0.15	0.15	**0.26**	0.04	0.36	0.50	0.05	0.24	0.20
Nuclear	0.18	0.00	**0.22**	0.78	0.20	0.00	0.00	0.00	0.29
$\frac{Model}{Actual}$	0.91	0.83	**0.93**	0.98	0.93	0.86	0.93	0.89	0.92

Table 3: Imposed parameters in the benchmark model

	α_i	θ_i	δ_i	β_i	ω_i	ψ_i	A_d	ϵ
Wind	0.728	0	0.168	0.930	Table 6			
Hydro	0.819	0	0.056	0.930	Table 6			
Solar	0.776	0	0.168	0.930	Table 6			
Coal	0.307	0.584	0.109	0.930	0	0		
Gas	0.121	0.823	0.142	0.930	0	0		
Nuclear	0.840	0	0.074	0.930	0	0		
Demand							1	-0.350

Table 4: Generation mix in Spain

	1990	1995	2000	2005	2010	2011	2012	2013	2014	2015	**2010-15**
Wind	0.00	0.00	0.02	0.08	0.16	0.16	0.18	0.21	0.20	0.19	**0.18**
Hydro	0.18	0.16	0.16	0.09	0.16	0.12	0.08	0.15	0.17	0.12	**0.14**
Solar	0.00	0.00	0.00	0.00	0.03	0.03	0.04	0.05	0.05	0.05	**0.04**
Coal	0.42	0.44	0.40	0.30	0.09	0.16	0.20	0.15	0.17	0.20	**0.16**
Gas	0.02	0.03	0.11	0.31	0.34	0.32	0.27	0.22	0.19	0.21	**0.26**
Nuclear	0.38	0.37	0.31	0.22	0.22	0.21	0.22	0.21	0.22	0.22	**0.22**
$\frac{Model}{Actual}$	0.94	0.90	0.89	0.88	0.93	0.93	0.93	0.93	0.93	0.91	0.93

Table 5: Power sector emissions in Spain

	1990	1995	2000	2005	2010	2011	2012	2013	2014	**2010-14**
$\frac{Coal}{Gas}$	90.73	35.30	12.04	2.89	0.74	1.43	2.02	1.91	2.60	**1.74**
$\frac{Coal+Gas}{Total}$	0.29	0.28	0.29	0.30	0.23	0.28	0.30	0.25	0.26	0.26

Table 6: Calibrated parameters and normalizations in benchmark model

Parameter	**Value**	**Note**
A_w	0.355	
A_h	0.208	
A_{pv}	0.350	
A_c	0.467	Target $\sum_i Q_i = 1$ and i's share in generation mix Q_i
A_g	0.746	
A_n	0.178	
ω_w	0.092	
ω_h	0.110	Target $Q_i/Q_i^{max} = 0.500$ for $i = w, pv$ and $Q_h/Q_h^{max} = 0.581$
ω_{pv}	0.410	
$\tilde{p}_k$	1	
$\tilde{\psi}_w$	1	Normalization
$\tilde{\psi}_h$	1	
$\tilde{\psi}_{pv}$	1	
$\tilde{p}_{ec}$	0.296	Target $2E_c + E_g = 1$ and $2E_c/E_g = 1.740$
$\tilde{p}_{eg}$	0.582	

Table 7: Carbon, coal and power consumption taxes

			τ^c	τ^e_c	$\tau_i = \tau$	BM
Agg	% diff rel BM	Price	2.0	0.7	94.5	1
		Quantity	-0.7	-0.3	-20.8	1
		Emissions	-25.0	-25.0	-25.0	1
Gen Mix	Levels in %	Wind	21.1	19.3	19.1	18.3
		Hydro	16.3	14.6	13.6	13.6
		Solar	5.1	4.6	4.3	4.3
		Coal	12.7	9.4	16.7	16.1
		Gas	20.4	29.3	21.8	25.8
		Nuclear	24.4	22.8	24.4	21.9
Value	% diff rel BM	Wind	30.8	11.0	-75.5	0.180
		Hydro	36.3	12.7	-69.5	0.116
		Solar	36.8	13.0	-86.1	0.036
		Coal	-20.4	-41.2	-19.5	0.251
		Gas	-19.8	13.9	-34.5	0.206
		Nuclear	13.0	4.7	-13.8	0.501
Welfare	Level diff rel BM	Δ^V	0.084	-0.012	-0.436	0
		Δ^{NR}	0.111	0.083	10.962	0
		Δ^{CS}	-0.282	-0.105	-11.891	0
		Δ	-0.027	-0.033	-1.365	0

Table 8: Subsidies to carbon-free inputs and outputs

			τ_w	τ^k_w	(τ^k_w, τ^ψ_w)	τ^k_h	τ^k_{pv}	τ^k_n	$\tau^k_i = \tau^k$	BM
Agg	% diff rel BM	Price	-2.3	-2.3	-2.3	-2.3	-2.3	-2.3	-2.3	1
		Quantity	0.8	0.8	0.8	0.8	0.8	0.8	0.8	1
		Emissions	-25.0	-25.0	-25.0	-25.0	-25.0	-25.0	-25.0	1
Gen Mix	Levels in %	Wind	36.5	36.5	36.5	15.0	15.0	15.0	21.4	18.3
		Hydro	10.7	10.7	10.7	32.1	10.7	10.7	17.2	13.6
		Solar	3.4	3.4	3.4	3.4	24.8	3.4	5.3	4.3
		Coal	13.2	13.2	13.2	13.2	13.2	13.2	13.2	16.1
		Gas	17.2	17.2	17.2	17.2	17.2	17.2	17.2	25.8
		Nuclear	19.2	19.2	19.2	19.2	19.2	40.6	25.8	21.9
Value	% diff rel BM	Wind	288.2	159.7	150.8	-75.5	-75.5	-75.5	10.2	0.180
		Hydro	-69.5	-69.5	-69.5	160.8	-69.5	-69.5	0.6	0.116
		Solar	-86.1	-86.1	-86.1	-86.1	1190.6	-86.1	16.7	0.036
		Coal	-19.5	-19.5	-19.5	-19.5	-19.5	-19.5	-19.5	0.251
		Gas	-34.5	-34.5	-34.5	-34.5	-34.5	-34.5	-34.5	0.206
		Nuclear	-13.8	-13.8	-13.8	-13.8	-13.8	110.6	2.0	0.501
Welfare	Level diff rel BM	Δ^V	0.218	-0.013	-0.029	-0.170	0.022	-0.124	-0.085	0
		Δ^{NR}	-0.818	-0.594	-0.571	-0.475	-1.164	-0.567	-0.297	0
		Δ^{CS}	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0
		Δ	-0.264	-0.271	-0.264	-0.309	-0.806	-0.355	-0.046	0

Table 9: Subsidies to site development costs

			τ_w^ψ	τ_h^ψ	τ_{pv}^ψ	$\tau_i^\psi = \tau_{low}^\psi$	$\tau_i^\psi = \tau_{high}^\psi$	BM
Agg	% diff rel BM	Price	-0.4	-0.4	-0.4	-0.4	-2.3	1
		Quantity	0.1	0.1	0.1	0.1	0.8	1
		Emissions	-5.0	-5.0	-5.0	-5.0	-25.0	1
Gen Mix	Levels in %	Wind	21.9	17.7	17.7	20.1	27.3	18.3
		Hydro	13.1	17.2	13.1	14.3	17.0	13.6
		Solar	4.1	4.1	8.3	4.7	6.2	4.3
		Coal	15.5	15.5	15.5	15.5	13.2	16.1
		Gas	24.0	24.0	24.0	24.0	17.2	25.8
		Nuclear	21.4	21.4	21.4	21.4	19.2	21.9
Value	% diff rel BM	Wind	1.4	-13.7	-13.7	-4.0	39.0	0.180
		Hydro	-12.8	10.8	-12.8	-6.0	-4.4	0.116
		Solar	-15.7	-15.7	282.2	-5.3	25.6	0.036
		Coal	-3.8	-3.8	-3.8	-3.8	-19.5	0.251
		Gas	-7.2	-7.2	-7.2	-7.2	-34.5	0.206
		Nuclear	-2.6	-2.6	-2.6	-2.6	-13.8	0.501
Welfare	Level rel from BM	Δ^V	-0.055	-0.055	0.025	-0.053	-0.115	0
		Δ^{NR}	-0.030	-0.046	-0.301	-0.013	-0.503	0
		Δ^{CS}	0.059	0.059	0.059	0.059	0.336	0
		Δ	-0.025	-0.042	-0.217	-0.007	-0.282	0

Table 10: Fiscally neutral subsidies

			(τ_w^k, τ^c)	(τ_h^k, τ^c)	(τ_{pv}^k, τ^c)	$(\{\tau_i^\psi\}, \tau^c)$	$(\tau_w^k, \{\tau_i\})$	BM
Agg	% diff rel BM	Price	0.7	0.4	1.0	0.1	1.4	1
		Quantity	-0.3	-0.2	-0.3	-0.0	-0.5	1
		Emissions	-25.0	-25.0	-25.0	-25.0	-25.0	1
Gen Mix	Levels in %	Wind	25.8	18.9	19.7	24.0	35.6	18.3
		Hydro	14.5	22.2	14.9	16.5	10.8	13.6
		Solar	4.6	4.5	9.9	5.6	3.4	4.3
		Coal	12.8	12.8	12.8	12.9	13.3	16.1
		Gas	19.5	19.3	19.7	19.0	17.4	25.8
		Nuclear	22.8	22.4	23.1	22.0	19.4	21.9
Value	% diff rel BM	Wind	64.5	6.5	14.6	18.2	144.4	0.180
		Hydro	12.5	71.8	17.0	10.5	-69.5	0.116
		Solar	12.7	7.7	246.1	17.5	-86.1	0.036
		Coal	-20.1	-20.1	-20.2	-20.0	-19.5	0.251
		Gas	-24.1	-25.1	-23.2	-26.2	-34.5	0.206
		Nuclear	4.6	2.8	6.2	0.6	-13.8	0.501
Welfare	Level rel from BM	Δ^V	0.058	0.009	0.067	-0.050	-0.041	0
		Δ^{NR}	0.000	0.000	0.000	0.000	0.000	0
		Δ^{CS}	-0.103	-0.063	-0.138	-0.014	-0.205	0
		Δ	-0.045	-0.053	-0.071	-0.064	-0.245	0

Table 11: Carbon taxes and capital input subsidies in other countries

			Spain			**France**			**Poland**		
			τ^c	τ^k_w	BM	τ^c	τ^k_w	BM	τ^c	τ^k_w	BM
Agg	% diff rel BM	Price	2.0	-2.3	1	0.3	-2.4	1	12.2	-3.0	1
		Quantity	-0.7	0.8	1	-0.1	0.8	1	-4.0	1.1	1
		Emissions	-25.0	-25.0	1	-25.0	-25.0	1	-25.0	-25.0	1
Gen Mix	Levels in %	Wind	21.1	36.5	18.3	2.8	16.7	2.7	7.6	27.9	3.8
		Hydro	16.3	10.7	13.6	11.9	9.4	11.6	8.6	0.5	1.9
		Solar	5.1	3.4	4.3	0.7	0.6	0.7	1.6	0.5	0.7
		Coal	12.7	13.2	16.1	2.4	2.4	3.0	75.1	68.0	88.5
		Gas	20.4	17.2	25.8	3.0	2.7	4.1	7.1	3.0	5.1
		Nuclear	24.4	19.2	21.9	79.2	68.2	77.9			
Value	% diff rel BM	Wind	30.8	159.7	0.180	4.3	1369.2	0.027	259.3	1743.2	0.037
		Hydro	36.3	-69.5	0.116	4.2	-51.8	0.117	1495.5	-612.6	0.006
		Solar	36.8	-86.1	0.036	5.1	-86.6	0.006	329.8	-110.6	0.006
		Coal	-20.4	-19.5	0.251	-20.1	-19.6	0.047	-8.6	-24.6	1.378
		Gas	-19.8	-34.5	0.206	-25.6	-34.7	0.033	49.4	-42.4	0.041
		Nuclear	13.0	-13.8	0.501	1.9	-13.8	1.781			
Welfare	Level rel from BM	Δ^V	0.084	-0.013	0	0.022	0.031	0	0.105	0.252	0
		Δ^{NR}	0.171	-0.594	0	0.018	-1.051	0	1.397	-2.062	0
		Δ^{CS}	-0.282	0.336	0	-0.042	0.338	0	-1.711	0.436	0
		Δ	-0.027	-0.271	0	-0.003	-0.683	0	-0.209	-1.374	0

Figure 1: Sensitivity of welfare impacts with higher productivity