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DISCUSSION
PAPER

Taxation of Nuclear Rents: Benefits, Drawbacks, and Alternatives[☆]

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Abstract

The taxation of nuclear energy is studied using a stylized model of the electricity sector, with one dominant nuclear producer and a competitive fringe of fossil-fuel plants. We show that an unanticipated tax on nuclear production can generate significant government revenue in the short run without disturbing the market, but will harm investment incentives in the long run, especially if the government cannot credibly commit to a future tax rate. Even if the government is capable of credibly committing to an optimal long-run tax, government revenues from the long-run tax will be very low due to the market power of the incumbent. Lifetime extension agreements negotiated with multiple potential players, and competitive auctioning of new nuclear licenses are shown to be the most attractive policies. The analytical results are illustrated with a numerical simulation for the case of Belgium.

Keywords: electricity market, nuclear rent, taxation
JEL: H25, L12, Q41, Q48

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1. Introduction

Towards the end of 2008, the Belgian government attempted to reduce its budget deficit by imposing a tax of 250 million euro on nuclear power producers. Despite appeals to the Constitutional Court, the tax was upheld and repeated as an annual tax in 2009 and 2010. The tax burden is allocated to nuclear producers in proportion to their capacities, and amounts to around 5 euros per MWh produced. Meanwhile in Germany, in the second half of 2010, the center-right government and the nuclear power producers agreed to extend the planned lifetime of Germany's nuclear power plants in return for a new fuel-rod tax and a compulsory contribution to a renewable energy fund, later to be replaced by a renewables levy per MWh produced. The total resulting charge to the nuclear producers in Germany amounts to slightly over 15 euros per MWh.[1]

This paper analyzes the short-run and long-run economic implications of the introduction of such taxes on nuclear production, and compares taxation with alternative policy measures.[2] The economic model is applicable to various countries. Table 1 provides an overview of European countries that have nuclear energy in their generation mix. The table also shows that nuclear firms often have large, concentrated market shares and may therefore be able to exercise market power on national or regional electricity markets. This is an important feature of the nuclear sector, which we will explicitly include in this paper using a 'dominant firm – competitive fringe' model. The model allows us to analyze the different types of nuclear rents, the potential for short-run taxation (as in the above example of Belgium), the possible long-run effects of such taxes, and alternative policy measures such as comprehensive lifetime extension deals (as in the German example), auctioning of licenses, and renewables investment quota.

The issue of nuclear rents has been studied from a policy perspective by e.g. CREG (2010a) and Matthes (2010). CREG (2010b) also study the German taxation solution. Such studies focus on detailed quantified analysis of specific cases. Our paper aims to complement this literature by developing a formal model that allows for graphical and analytical demonstration of the underlying economic principles.

The oligopolistic nature of our proposed model embodies a number of issues studied in the vast literature on electricity market deregulation, such as Newberry's (2002) analysis of the effectiveness of the deregulation process and the accompanying problems. Indeed, the ongoing policy challenges regarding taxation of nuclear rents are a consequence of the liberalization of formerly regulated electricity monopolies. A large number of papers analyze the electricity market

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[1] The information in this paragraph is obtained from articles in De Tijd (March 3 2010 and December 8 2010), Financial Times (Sep 7 2010) and The Economist (June 2 2011). Note that as a result of the Fukushima accident, however, the German government eventually annulled the lifetime extension and maintained the plans for a phase-out by 2022.

[2] Note that our paper is focused on taxation of economic rents. The Fukushima accident has illustrated the external cost of nuclear power, which could be addressed separately through a Pigouvian tax. The latter is not the subject of this paper.

Table 1: Overview of nuclear electricity generation capacity in Europe.

Country	**Nuclear capacity** (Dec 31, 2010) MW	**Share of nuclear in total gross electricity generation** (2008) %	**Share of nuclear capacity owned by largest 2 players** (Dec 31, 2010) %	**Policy outlook** (Dec 31, 2010)
France	62950	76%	99.7%	Expansion ongoing
Germany	19895	23%	50.1%	Decommissioning by 2022
Sweden	9248	43%	75.0%	Stable
United Kingdom	9218	13%	100.0%	Stable
Spain	7409	19%	61.2%	Stable
Belgium	5839	54%	97.3%	Decommissioning 2015-2030
Czech Republic	3775	32%	100.0%	Expansion proposals
Switzerland	3220	40%	66.3%	Expansion proposals
Finland	2721	30%	100.0%	Expansion ongoing
Hungary	1946	37%	100.0%	Expansion proposals
Slovakia	1940	58%	100.0%	Expansion proposals
Bulgaria	1906	35%	100.0%	Expansion proposals
Romania	1310	17%	100.0%	Expansion proposals
Slovenia	664	38%	100.0%	Expansion proposals
Netherlands	479	4%	100.0%	Expansion proposals

Source: Platts (2010), Eurostat (2011).

as an oligopoly and many studies like Borenstein et al. (1999), Bushnell et al. (2004) and Cardell et al. (1997) focus on the market power of incumbent firms, which may transform their previous regulated monopoly rights into substantial unregulated market power.

Our monopolistic 'dominant firm – competitive fringe' equilibrium concept and its oligopolistic extensions are more similar to the typical Cournot models than to the more sophisticated Supply Function Equilibria (SFE). The advantage of the former is clearly computational convenience, as acknowledged by e.g. Ventosa et al. (2005), Borenstein et al. (1999), Hobbs & Pang (2007) and Wei and Smeers (1999). Willems et al. (2009) confront Cournot models and SFE with data of the German electricity market. The authors conclude that SFE models do not significantly outperform the Cournot approach when studying the German electricity market but that they rely on fewer calibration parameters and may therefore be more robust. Willems et al. (2009) suggest that Cournot models are "*…aptly suited for the study of market rules…*", while SFE are suited to study e.g. long-term effects of mergers. In our setting, the Cournot-style approach seems therefore justified.

The paper is structured as follows. Section 2 develops our analytical model of an electricity market with a significant share of nuclear production, and identifies the different types of nuclear rents. Section 3 investigates the potential magnitude and impact of a nuclear tax in the short run. Next, section 4 demonstrates the long-run commitment disadvantages of a nuclear tax. Section 5 studies alternative policy measures. Section 6 illustrates the results numerically for the case of Belgium. Section 7 concludes the paper.

2. Model set-up

2.1. Demand and supply

We study a stationary electricity market with linear demand:

$$q(p) = q_0 - \beta p \tag{1}$$

with constant parameters q_0 and $\beta \geq 0$. To focus our thoughts, we assume that this is the electricity market of one single country. The demand $q(p)$ represents an 'average' demand in the course of a year, and we do not consider any demand variations within the year (or even within the days of the year).[3]

Two supply technologies are available: (i) nuclear generation with short-run marginal production cost c_n, and (ii) fossil-fuel-based generation with linearly increasing short-run marginal production costs $c_0 + \alpha q$. Because of the low short-run marginal production costs of nuclear power, we assume $c_n \ll c_0$. Nuclear generation q_n is limited by the installed nuclear capacity $q_{n,inst}$. Furthermore, we assume that there is a limit $q_{n,max}$ to the amount of nuclear capacity that can be installed: $q_{n,inst} \leq q_{n,max}$. The constraint may be due to various reasons: technical (e.g. access to cooling, or insufficient ability of nuclear power to cope with demand variability), political, ethical, etc. For the sake of simplicity, we assume $q_{n,inst} = q_{n,max}$, i.e. nuclear capacity has already been installed up to maximum allowable level. The cost curve $c_0 + \alpha q$ also includes any relevant foreign production capacity that can be imported. Additional transmission costs for foreign production are included in $c_0 + \alpha q$.

2.2. Equilibrium concept

We consider a 'dominant firm – competitive fringe' game, which is fairly standard in microeconomic analysis.[4] We assume that all nuclear production

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[3] As we will see below, supply and demand are assumed to always intersect in the same linear part of the supply curve, so the 'average' demand corresponds to the 'average' price. In this case, the fact that we analyze only the average demand is therefore not a restriction per se.

[4] See e.g. Carlton and Perloff (2000).

capacity is controlled by one 'dominant firm'. Considering the strong concentration in nuclear power as shown in Table 1, this assumption is not unrealistic, and serves as a 'worst case' baseline for the cases with more than one producer. The fossil-fuel and foreign capacity represented by $c_0 + \alpha q$ is assumed to be controlled by a 'competitive fringe'. In this model, the dominant firm behaves strategically, while the competitive fringe always behaves fully competitively (and hence always produces up to the point where price equals marginal cost).

Figure 1: Equilibrium in the 'dominant firm – competitive fringe' game described in this paper.

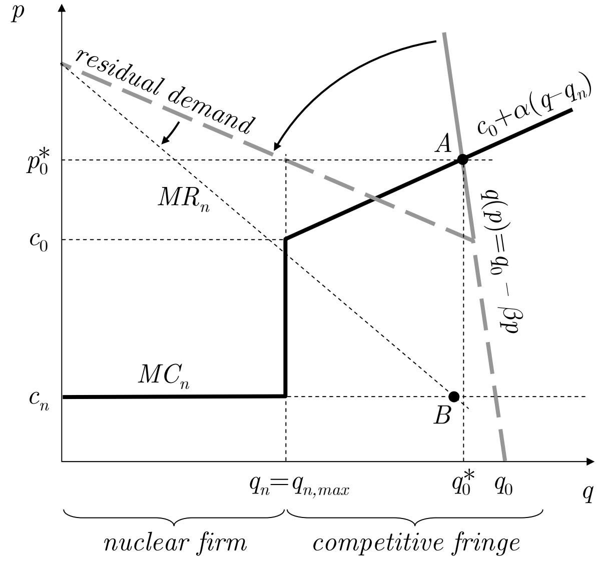

Figure 1 illustrates our equilibrium concept. The thick black line is the industry marginal cost curve. Under perfect competition, the market equlibrium would be at point A, the intersection of the industry marginal cost curve and the demand curve. Since it is in practice technically impossible to serve an entire electricity system with nuclear power, we assume that the intersection of supply and demand is always in the upward sloping part of the supply curve (i.e. the part provided by the competitive fringe). The equilibrium price and quantity under perfect competition are p_0^* and q_0^*:

$$p_0^* = \frac{c_0 + \alpha(q_0 - q_{n,max})}{1 + \alpha\beta} \tag{2}$$

$$q_0^* = \frac{q_0 - \beta(c_0 - \alpha q_{n,max})}{1 + \alpha\beta} \tag{3}$$

In our 'dominant firm – competitive fringe' model, however, the equilibrium can be determined by considering the residual demand curve (i.e. demand minus the quantities supplied by the competitive fringe) and analyzing the dominant firm as a monopolist on this residual demand curve.[5] As shown in Figure 1, the residual demand curve translates into a marginal revenue curve (MR_n) of the dominant firm. If nuclear capacity was not constrained by $q_{n,inst}$ then the 'dominant firm – competitive fringe' equilibrium would be at point B, i.e. the intersection of MR_n and the dominant firm's (constant) marginal cost curve. However, given the nuclear capacity constraint ($q_n \leq q_{n,inst}$), the dominant firm's quantity decision q_n becomes equal to $q_{n,inst} = q_{n,max}$. As a result, the equilibrium prices and quantities are the same as under perfect competition, at least in the case shown in Figure 1. Only with high operating costs and large capacity would the dominant nuclear have an interest in exploiting his market power by not fully using the available capacity. However, due to the relatively low short-run marginal cost of nuclear production, the constraint $q_n \leq q_{n,inst}$ is generally binding. As a result, in this model, even a single dominant nuclear firm typically does not have an incentive to withhold production. In order to keep our argument focused, we will assume that – in the absence of taxes on nuclear production – the constraint $q_n \leq q_{n,inst}$ is indeed binding.

This assumption can be expressed mathematically. From equation (1) and the cost curve of the competitive fringe, we can easily derive the inverse residual demand curve $p_R(q)$, and subsequently MR_n:

$$p_R(q) = \frac{c_0 + \alpha(q_0 - q)}{1 + \alpha\beta} \tag{4}$$

$$MR_n = \frac{c_0 + \alpha(q_0 - 2q)}{1 + \alpha\beta} \tag{5}$$

In the absence of the constraint $q_n \leq q_{n,inst}$, the nuclear firm's unconstrained production quantity $q_{n,uncon}$ can be computed by setting $MR_n = MC_n = c_n$:

$$q_{n,uncon} = \frac{1}{2}(q_0 - \beta c_n + \frac{c_0 - c_n}{\alpha}) \tag{6}$$

The constraint $q_n \leq q_{n,inst}$ will be binding iff $q_{n,inst} \leq q_{n,uncon}$. Since we assume $q_{n,inst} = q_{n,max}$, that condition can be expressed as:

$$2q_{n,max} \leq q_0 - \beta c_n + \frac{c_0 - c_n}{\alpha} \tag{7}$$

The first two terms of the right-hand side together ($q_0 - \beta c_n$) are slightly larger than total electricity demand, hence it is reasonable to assume $q_{n,max} \ll q_0 - \beta c_n$. The last term $(c_0 - c_n)/\alpha$ is also large, because the difference in short-run marginal production cost between nuclear power and the mostly fossil-fuel fired

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[5] Note that our model description implicitly provides the dominant firm with a Stackelberg leadership position vis-à-vis the competitive fringe. Ulph and Folie (1980) analyze an alternative configuration, in which a Nash equilibrium is reached between the dominant firm and the competitive fringe, and find that this leads to a number of undesirable properties, hence we do not consider this option here.

power plants of the competitive fringe is large, and because the slope of the fringe cost curve is not very steep. With the calibration parameters of Section 6, condition (7) is satisfied for all European countries in Table 1.

2.3. Rents

Figure 1 demonstrates that nuclear producers obtain a rent $(p_0^* - c_n)q_n$. Three types of rent can be distinguished.

First, a large part is the perfectly competitive *inframarginal rent* required to cover the fixed costs (mostly investment costs) incurred by the nuclear firm. Indeed, while short-run marginal production costs are relatively low, the upfront capital investment of nuclear power is comparatively high. The discounted sum of inframarginal rents needs to cover that investment cost in order to provide sufficient investment incentives. We assume that the sum of the annuity of investment costs plus any relevant fixed operating costs is given by $f_n q_{n,inst}$.

Secondly, there may be a *scarcity rent.* Indeed, without the constraint $q_{n,max}$, the long-run equilibrium installed capacity of nuclear power would evolve such that the electricity price equals $f_n + c_n$. As a result of the constraint, the nuclear firm in Figure 1 obtains a scarcity rent $(p_0^* - c_n - f_n)q_n$.

Thirdly, nuclear firms may obtain rents due to *market power.* In Figure 1, no withholding takes place, hence there is no market power rent. As mentioned before, the low level of short-run marginal costs makes short-run withholding of nuclear capacity unlikely in general. However, as we will see below, there may be circumstances (e.g. in the event of nuclear taxation) that can lead to the long-run variety of withholding, namely underinvestment.

2.4. Government

In this paper, we study the policy options of the national government of the country under consideration. We assume that the government maximizes national welfare W:

$$W = CS + \sigma_n \pi_n + \lambda G \tag{8}$$

with CS the consumer surplus, π_n the profits of the nuclear firm, σ_n ($0 \leq \sigma_n \leq 1$) the fraction of the nuclear firm's shares owned by nationals of the country, G the government revenues from the nuclear sector (taxes, licenses, etc.), and λ the marginal cost of public funds[6]. We ignore the potential contribution of the competitive fringe's profits to national welfare. The choice of λ depends on the view one takes regarding government revenues. An assumption $\lambda = 0$ implies that government revenues are wasted. On the other hand, assuming $\lambda > 1$ implies that nuclear revenues are used productively to reduce other taxes, thereby eliminating distortions elsewhere in the economy. For the sake of simplicity, we assume $\lambda = 1$ in the remainder of this paper. Note that if, for ideological or other reasons, the government does not attach any importance to the income of the nuclear firm's national shareholders, this is equivalent to setting $\sigma_n = 0$.

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[6] See e.g. Browning (1976).

Assuming a reservation price $\bar{p}$, we can conveniently write CS as:

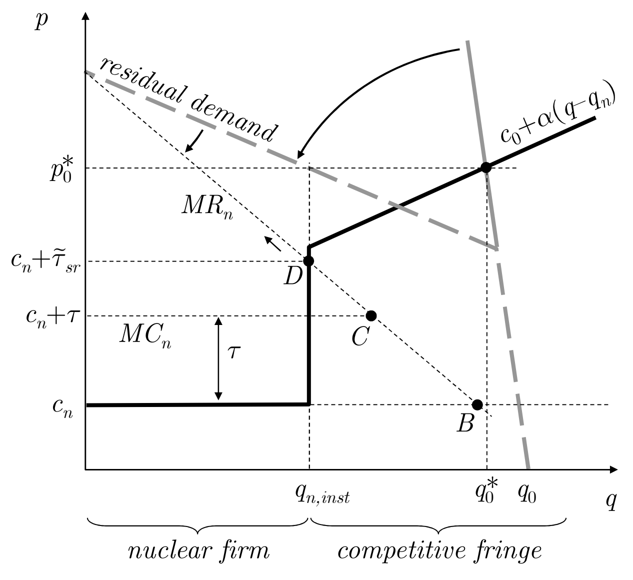
$$CS = \int_{p^*}^{\bar{p}} q(p)dp = (\bar{p} - p^*)q_0 - \frac{\beta}{2}(\bar{p}^2 - p^{*2}) \tag{9}$$

with p^* the market price of electricity in the equilibrium under consideration.

3. Short-run taxation potential

We now consider the introduction of an unexpected tax on nuclear production, as it happened in the case of Belgium. 'Unexpected' means that the tax was not anticipated at the time of investment in the nuclear capacity. We consider a tax of τ per unit of nuclear electricity produced. The effect is illustrated in Figure 2. For the nuclear firm, the tax increases the short-run marginal cost of production from c_n to $c_n + \tau$. As a result, the intersection point of MR_n and MC_n moves from point B to point C. If τ is high enough, the intersection point may shift to point D or beyond. When the intersection point is beyond point D (indicated with a little arrow in Figure 2) the constraint $q_n \leq q_{n,inst}$ is no longer binding and the nuclear firm withholds some of its capacity.

Figure 2: Short-run impact of an unexpected tax on nuclear production.



Proposition 1. *Under the assumptions of Section 2 and the additional condition that:*

$$2q_{n,max} \leq q_0 - \beta\frac{c_n + c_0}{2} + \frac{c_0 - c_n}{2\alpha} \tag{10}$$

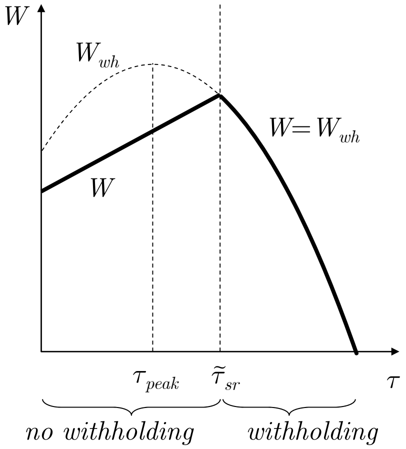
the government's optimal choice of the short-run nuclear tax rate is:

$$\tilde{\tau}_{sr} = \frac{c_0 + \alpha(q_0 - 2q_{n,max})}{1 + \alpha\beta} - c_n \tag{11}$$

Proof. First, observe that $\tilde{\tau}_{sr}$ is the maximum tax rate the government can impose without causing the nuclear firm to withhold. This can be easily seen by replacing c_n with $c_n + \tau$ in equation (7) and solving for τ.

Lowering the tax rate below $\tilde{\tau}_{sr}$ keeps the constraint $q_n \leq q_{n,inst}$ binding, hence it does not change the equilibrium. The only effect of lowering the tax rate below $\tilde{\tau}_{sr}$ is a linear transfer from government revenue to nuclear profits. Since $\sigma_n \leq 1$ this cannot increase the government's objective function W in equation (8). This is shown in Figure 3, for $\tau \leq \tilde{\tau}_{sr}$.

Figure 3: Shape of W as a function of τ.



Raising the tax rate τ above $\tilde{\tau}_{sr}$ leads to withholding. The constraint $q_n \leq q_{n,inst}$ is not binding anymore and nuclear production $q_{n,1}$ is given by equation (6) with c_n replaced by $c_n + \tau$. The equilibrium price can then be easily derived:

$$p_1^* = \frac{1}{2}\left[c_n + \tau + \frac{c_0 + \alpha q_0}{1 + \alpha\beta}\right] \tag{12}$$

which can be substituted into equation (9) for CS. Using also $G = \tau q_{n,1}$, one can derive an analytical expression for the government's objective function W_{wh} in case of withholding, which is a concave quadratic function of τ. As mentioned before, we assume $\lambda = 1$. For $\sigma_n = 0$, the maximum value of W_{wh} is reached for:

$$\tau_{peak} = \frac{c_0 - c_n}{2} \tag{13}$$

However, due to condition (10), this value τ_{peak} is lower than $\tilde{\tau}_{sr}$, hence it is outside the domain where withholding takes place. As a result, W declines with

τ when $\tau \geq \tilde{\tau}_{sr}$, as is illustrated in Figure 3. This result is also valid if $\sigma_n \geq 0$, because then τ_{peak} will be even smaller since in this case a larger τ contributes an additional negative term to W through π.

Since it is impossible to increase W – neither by lowering τ below $\tilde{\tau}_{sr}$ nor by raising it above $\tilde{\tau}_{sr}$ – the choice $\tau = \tilde{\tau}_{sr}$ must be an optimal value. ☐

Condition (10) is very similar to condition (7), but slightly more restrictive. With the calibration parameters of Section 6 the condition is satisfied when the maximum nuclear capacity represents less than 60% of total demand. Except for France, this is satisfied for all countries in Table 1.

Proposition 1 demonstrates that it is possible (and optimal in the short run) for governments to impose a substantial[7] unexpected tax on nuclear production, without even affecting the equilibrium on the electricity market. The next section will study the long-run effects of such a tax.

4. Long-run effects of taxation on reinvestment

The government's ability and incentives to introduce ex-post taxes on nuclear production in the short run, as in the previous section, may hamper investments in new nuclear capacity – or any other generating capacity with high capital costs – because firms may fear expropriation of profits. This is a well-known problem in the tax competition literature. Janeba (2000) uses a model in which one firm produces for the world market and its profits are taxed by the government. When the production has to be local, there is a standard time inconsistency problem. The government has an interest to raise the tax after the investment, the firm understands this ex ante and the firm would never invest. In Janeba's model this problem can be avoided by the firm at a high cost by building extra capacity in another country and to shift production to the country where the net profit is the highest. According to Janeba, when capacity costs are sufficiently low, this is the equilibrium. For higher capacity costs, there is an equilibrium without investment. In our case, even if there is enough international transmission capacity, high (nuclear) capacity costs would rule out an equilibrium with excess capacities. A second way to avoid the time inconsistency problem is to rely on other constraints on the behavior of governments. One legal option is to have constitutions that rule out governments changing the tax rules. This type of rule exists in order to limit government debt but is rather naive as governments have by definition the power to tax profits more and lower other taxes. A second constraint could be reputation. In order to assess this constraint we need a behavioral model of the government as an agent that desires to be reelected by its voters (Besley, 2006). A government raising taxes ex post can be seen as an unreliable government by investors but voters with a shorter-term memory and/or perceiving the nuclear tax as a justified tax on excess profits or compensating nuclear risks may consider such

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[7] An indication of the likely size of such a tax is provided in Section 6.

a government as defending its interests. The best evidence is that in countries such as Germany and Belgium, such an ex-post nuclear tax has been agreed upon in Parliament. In conclusion, credible commitments not to raise the tax ex post are difficult. The remainder of this section therefore considers multiple cases, with different levels of commitment.

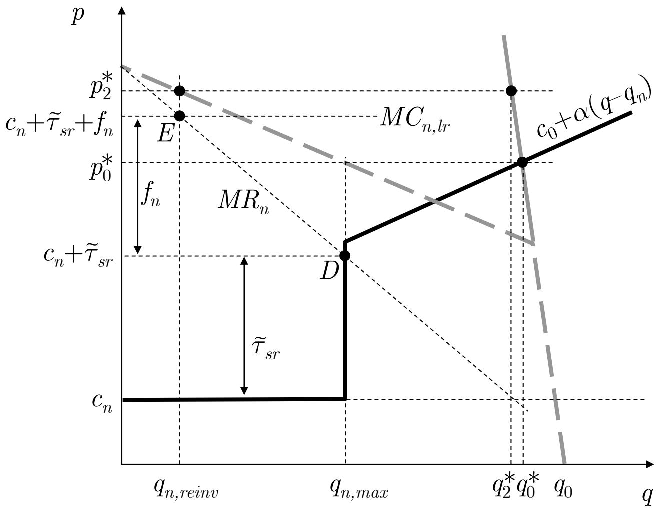
Subsection 4.1 first analyzes the effects of the tax $\tilde{\tau}_{sr}$ (from equation (11)) on investment incentives, when this tax is made permanent and the government is able to commit to it. Subsection 4.2 investigates a situation in which the government cannot make any credible commitment. Subsection 4.3 investigates the opposite situation, in which the government is capable of making credible commitments to an optimal long-run tax rate, which would be lower than $\tilde{\tau}_{sr}$.

4.1. Credible commitment to the short-run tax rate

Suppose the government imposes a tax $\tilde{\tau}_{sr}$ on current nuclear power production, according to Proposition 1. When the current nuclear capacity expires and needs to be replaced, nuclear firms will take the tax $\tilde{\tau}_{sr}$ into account when making the reinvestment decision. In this subsection we assume that the government can credibly commit to maintaining – i.e. not increasing – $\tilde{\tau}_{sr}$ after the replacement capacity has been built.

In their long-run reinvestment decision, firms will not only take into account the short-run marginal cost c_n and the tax $\tilde{\tau}_{sr}$ but also the fixed (investment) costs f_n per unit of capacity built. Figure 4 illustrates the decision of the nuclear firm. The relevant marginal cost curve is now $MC_{n,lr}$, which intersects with MR_n at E instead of D. The resulting reinvestment decision can be found by

Figure 4: Long-run impact of an unexpected tax on nuclear investments, assuming government can commit to $\tilde{\tau}_{sr}$.



replacing c_n with $c_n + \tilde{\tau}_{sr} + f_n$ in equation (6):

$$q_{n,reinv} = \frac{1}{2}\left(q_0 - \beta(c_n + \tilde{\tau}_{sr} + f_n) + \frac{c_0 - (c_n + \tilde{\tau}_{sr} + f_n)}{\alpha}\right) \tag{14}$$

Using equation (11) this can be simplified to:

$$q_{n,reinv} = q_{n,max} - \frac{f_n(1 + \alpha\beta)}{2\alpha} \tag{15}$$

which is obviously lower than the technical maximum $q_{n,max}$.[8]

With the existing fringe capacity marginal cost curve, the reduction of nuclear capacity from $q_{n,inst} = q_{n,max}$ to $q_{n,reinv}$ increases electricity prices from p_0^* to p_2^*. One can easily compute that:

$$p_2^* - p_0^* = \frac{f_n}{2} \tag{16}$$

i.e. the underinvestment in nuclear capacity due to the introduction of a tax according to Proposition 1, may lead to an increase in electricity prices equal to half the per-unit fixed (investment) cost.[9]

4.2. No credible commitment

The caveat with Figure 4 is that once the capacity $q_{n,reinv}$ is installed, the government would be incentivized to increase the tax rate above $\tilde{\tau}_{sr}$. In Figure 4, the government could increase the tax to $\tilde{\tau}_{sr} + f_n$ without causing any withholding of the capacity $q_{n,reinv}$. In fact, by analogy with Proposition 1, it is easy to see that for any level of $q_{n,reinv}$ the government's optimal ex-post short-run tax $\tilde{\tau}'_{sr}$ can be found by following the MR_n curve:

$$\tilde{\tau}'_{sr} = MR_n - c_n \tag{17}$$

A rational nuclear firm anticipates the government's ex-post tax increases. Hence, the $MC_{n,lr}$ curve changes to include the ex-post tax increase:

$$MC_{n,lr} = c_n + f_n + \tilde{\tau}'_{sr} = f_n + MR_n \tag{18}$$

For $f_n > 0$ there is no more intersection between $MC_{n,lr}$ and MR_n, hence no nuclear capacity is built if the government cannot make any credible commitment regarding the future tax rate.

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[8] In the case shown in the figure, we have $f_n \leq \tilde{\tau}_{sr}$, so that in the absence of taxes even a single dominant firm would reinvest up to the the full technical maximum $q_{n,max}$. If $f_n > \tilde{\tau}_{sr}$, this need not be the case but the resulting capacity in the case with taxes is always lower than in the case without taxes.

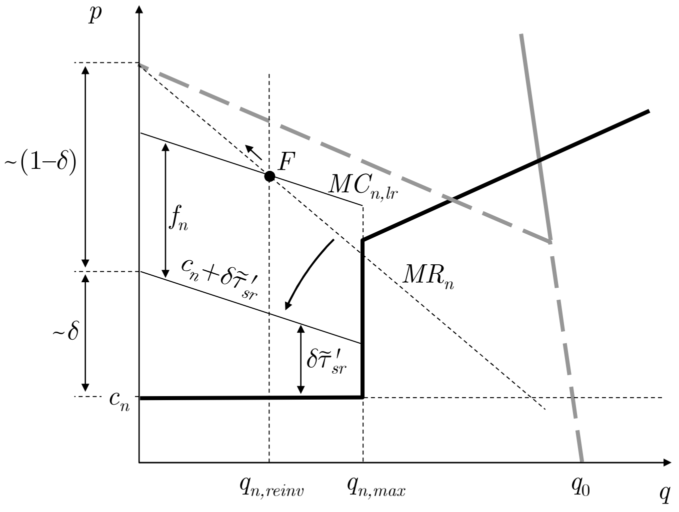
[9] For the sake of simplicity, we have implicitly assumed that long-run price elasticity of electricity demand is the same as in the short run. In reality, in the long run, households may adapt and industries may decide to relocate to other countries, so long-run demand would be less inelastic.

Full loss of commitment power of the government is not required to create the conditions for underinvestment. Indeed, the *possibility* of the government changing tax rates ex-post, may be sufficient to deter investment. Suppose that there is a probability δ that the government makes an ex-post decision to apply the tax $\tilde{\tau}'_{sr}$ according to equation (17). Conversely, with probability $(1-\delta)$, the government does not apply any tax. A risk-neutral firm will behave as if government imposed the expected value of the tax, i.e. the weighted average $\delta\tilde{\tau}'_{sr}$. This is illustrated in Figure 5. The nuclear firm's reinvestment decision is at point F, the intersection of MR_n and $MC_{n,lr}$, with the latter including the expected value of the tax. As δ increases, the point F moves further up the MR_n curve – as indicated with a little arrow – and reinvestment is further reduced. One can show that $q_{n,reinv}$ becomes 0 when:

$$\delta \geq 1 - \frac{f_n}{\frac{c_0+\alpha q_0}{1+\alpha\beta} - c_n} \tag{19}$$

Hence, reinvestment may be completely deterred even if it is not certain that the government cannot commit to a tax rate.

Figure 5: Long-run impact of an unexpected tax on nuclear investments, assuming a probability δ that the government cannot credibly commit to a tax rate.



4.3. Credible commitment to optimal tax rate

Let us assume that the government can choose a tax rate before the nuclear firm's reinvestment decision, and that the government can make a credible commitment to maintain this tax rate after the capacity has been built. By analogy with Proposition 1, essentially by replacing c_n with $c_n + f_n$, we can derive the government's optimal choice of the tax rate. However, since f_n may be large, the analog of condition (10) is not necessarily fulfilled, hence two cases need to be considered.

Proposition 2. *Under the conditions of Section 2, the optimal choice of the nuclear tax rate for a government capable of making credible commitments is:*

$$\tilde{\tau}_{lr} = \max\left\{ \tilde{\tau}_{sr} - f_n \, , \, \frac{(1-\sigma_n)(c_0 - c_n - f_n) - \alpha\sigma_n q_0}{2-\sigma_n} \right\} \tag{20}$$

Proof. The proof is analogous to Proposition 1. For $\tau \leq \tilde{\tau}_{sr} - f_n$, the constraint $q_{n,reinv} \leq q_{n,max}$ is binding, and lowering τ below $\tilde{\tau}_{sr} - f_n$ cannot increase W.

For $\tau > \tilde{\tau}_{sr} - f_n$ the constraint is not binding anymore. In the absence of the constraint, the government's objective function W has a peak at:

$$\tau_{peak} = \frac{(1-\sigma_n)(c_0 - c_n - f_n) - \alpha\sigma_n q_0}{2-\sigma_n} \tag{21}$$

Note that, unlike in equation (13), we have not set $\sigma_n = 0$. With $\sigma_n = 0$ and $f_n = 0$ the two equations obviously become identical again.

If $\tau_{peak} \leq \tilde{\tau}_{sr} - f_n$ then W declines when τ is raised above $\tilde{\tau}_{sr} - f_n$, similar to the situation in Figure 3. If $\tau_{peak} > \tilde{\tau}_{sr} - f_n$, then the maximum of W is reached for $\tau = \tau_{peak}$. Combining both cases, we find $\tilde{\tau}_{lr} = \max\{\tilde{\tau}_{sr} - f_n \, , \, \tau_{peak}\}$, hence equation (20). □

Note that $\tilde{\tau}_{lr}$ according to equation (20) is not necessarily positive, for example when $\sigma_n = 1$ and $f_n > \tilde{\tau}_{sr}$. In general, it is easy to see that large f_n will make $\tilde{\tau}_{lr}$ small or negative. The government therefore faces a trade-off: on the one hand, short-run welfare maximization would require taxing current nuclear capacity at a rate $\tilde{\tau}_{sr}$, but this would harm government credibility thereby hampering reinvestment. On the other hand, the optimal long-run tax rate $\tilde{\tau}_{lr}$ in this setting is rather low. If, in order to preserve its credibility, the government decides to apply $\tilde{\tau}_{lr}$ also to current capacity, this would leave a very large part of current nuclear rents untouched. Ideally, the government would be able to make a credible commitment to distinguish its tax rate on current capacity from its tax rate on new capacity, but this may be difficult to do.

5. Alternative policy instruments

The previous section has highlighted the challenges of imposing an unexpected short-run tax on a dominant nuclear firm. In this section we explore alternative policy measures.

5.1. Lifetime extension agreements

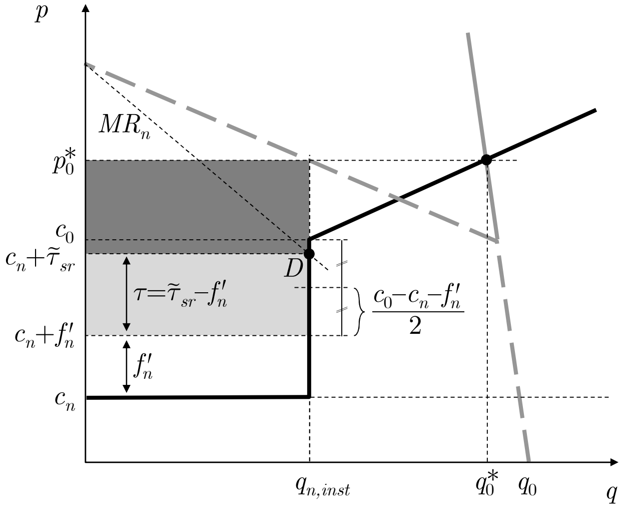
Belgium's government first decided to extend the lifetime of the country's nuclear power plants. Only later, it imposed a contested tax on nuclear producers. An alternative is the German approach, in which a tax was agreed between government and the nuclear firms in return for a lifetime extension.[10] The latter option is arguably preferable from the perspective of government credibility and investment incentives.

We can analyze such a lifetime extension agreement using the reasoning of Section 4.3. Indeed, lifetime extension is very similar to reinvestment, but the reinvestment cost f_n is replaced by a significantly lower refurbishment cost f'_n. We simplify the bargaining process between the government and the nuclear industry by assuming a Stackelberg structure in which the government credibly commits to a tax rate τ in the first stage, and the dominant nuclear firm responds in a second stage by deciding on how much of the nuclear capacity will have its lifetime extended. The optimal tax to be set in return for a lifetime extension can then be derived from Proposition 2. For the sake of simplicity, we assume $\sigma_n = 0$, so that the optimal tax rate is:

$$\tau = \max\left\{\tilde{\tau}_{sr} - f'_n \, , \, \frac{c_0 - c_n - f'_n}{2}\right\} \tag{22}$$

which can be conveniently analyzed graphically, as in Figure 6, where $(c_0 - c_n - f'_n)/2 < \tilde{\tau}_{sr} - f'_n$, hence $\tau = \tilde{\tau}_{sr} - f_n$. We shall maintain this assumption in this and the next section.

Figure 6: Taxation in return for lifetime extension.



Because $f'_n \ll f_n$, the agreed tax τ allows the government to capture at least a sizeable part of the nuclear lifetime extension rent $(p_0^* - c_n - f'_n)q_{n,inst}$.

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[10] The lifetime extension was later revoked in the aftermath of the Fukushima accident, which is, in fact, an illustration of ineffective government commitment.

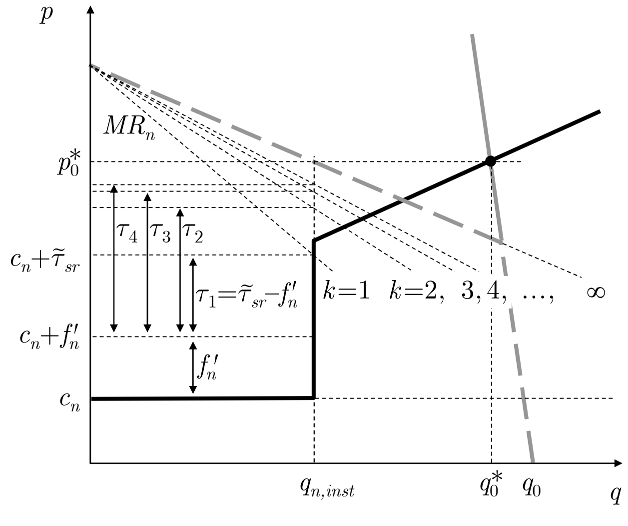
The part captured by the government is indicated in light shading in Figure 6. However, a large part of the rent – shown in dark shading in Figure 6 – cannot be captured through a lifetime extension and taxation agreement with a dominant nuclear firm, because a further increase of the tax rate would trigger a reduction of the amount of capacity of which the lifetime is extended, and therefore lead to lower tax revenues.

5.2. Auctioning

The main underlying reason why a large part of the nuclear rent cannot be captured in the setting of Figure 6, is the fact that the nuclear firm is assumed to be a monopolist on the residual demand curve. One way to increase the share of rent captured by taxes – and thus increase welfare – is to introduce competition. More specifically, the government could open up the lifetime extension licensing not only to the incumbent dominant firm but also to other players, in an auction.

Suppose there are k players, including the incumbent. For the sake of simplicity, we model the auctioning process as a Cournot game between nuclear firms. First the government sets a lifetime extension tax τ_k, as in Section 5.1. Then, in Cournot competition, the k players each decide on an amount of the capacity to be extended. In the previous sections, the response of the dominant firm as a function of costs plus taxes, was always given by MR_n, which, as is well-known, has twice the slope of the inverse residual demand curve. In a Cournot game the resulting total quantity of the k players, as a function of costs plus taxes, is a similar line, but with a slope of $(k+1)/k$ times the slope of the inverse residual demand curve. This is shown in Figure 7. The reasoning from

Figure 7: Auctioning of lifetime extension licenses.



Section 5.1 can now be applied almost identically. The optimal tax rate τ_1 in

the case of one dominant firm is the same as in Section 5.1. The optimal tax rates τ_k for $k > 1$ become larger and larger, thereby allowing the government to capture an ever larger share of the nuclear rent. In the limit case of perfect competition ($k \to \infty$) the tax becomes $\tau_\infty = p_0^* - c_n - f_n'$, and the government captures the entire nuclear rent. There may however be some drawbacks to this approach. In particular, the auctioning process may suffer from asymmetric information. Indeed, the nuclear firm currently operating the power plant may have private information that is unavailable to other potential contenders in the auction. Furthermore, if ownership changes as a result of the lifetime extension auction, the power plant may continue to be operated by the original owner, which could lead to principal-agent problems.

In this section, we have applied the auctioning mechanism to the lifetime extension decision. Clearly, the same auctioning mechanism can be applied to the reinvestment decision.

5.3. Other taxation instruments

In this paper, the optimal nuclear energy tax has been derived for the case of an *excise* tax on nuclear production. This is a fixed amount per MWh of nuclear energy produced. Alternatively, the government could opt for an ad valorem tax, a profit tax, or a lump sum tax. The former two taxes are in fact similar in structure to the excise tax we have considered so far. In theory, in the case of a pure monopoly, an *ad valorem* tax – proportional to the nuclear firm's revenues – yields a larger nuclear output for the same tax revenue than an excise tax.[11] In our case however, the difference will be small since c_n is small. A special *profit* tax – proportional to the nuclear firm's profits – circumvents the problem of withholding, since the nuclear firm's incentives remain unaltered. However, it leads to the same long-term investment problems as the excise tax discussed so far. Moreover, the special nuclear profit tax may be difficult to implement: firms may attempt to evade the nuclear profit tax by inflating costs, shifting costs between non-nuclear and nuclear plants, or overstating the allocation of overhead costs to nuclear subsidiaries. From a legal perspective, it may be challenging to tax the same profit twice, i.e. both through regular corporate taxation and through the special nuclear profit tax. In any case, the profit tax bears some resemblance to the excise tax, because also the optimal excise tax depends on the difference between the price of the fossil fuel alternative (via c_0) and the marginal cost of nuclear power (c_n). A pure *lump sum* tax, set independently of nuclear output, is a superior instrument compared to the excise tax. However, in many countries, lump sum taxes would not be constitutional as they are not linked to a defined tax base.

5.4. Mandatory investments in renewable energy

Instead of pure taxation, governments are also considering the possibility of obliging nuclear producers to invest a part of the nuclear rent in renewable en-

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[11] See e.g. Salanié (2003).

ergy. For instance, the annulled German lifetime extension agreement included a compulsory contribution to a renewable energy fund. In fact, such a scheme is conceptually equivalent to the combination of a tax plus a commitment to invest the tax revenues in renewable energy. Hence, it is only optimal if renewable energy investments are indeed the best use of tax money, among all other possible government investment options. This seems unlikely, unless one assumes that other government expenditures are generally wasted, i.e. λ in equation (8) very small.

6. Numerical simulations for the case of Belgium

6.1. Calibration and baseline

In this section we apply the results from previous sections to a numerical simulation for the case of Belgium. Table 2 lists the calibration parameters. More information on how these values are obtained, can be found in Appendix A. We assume $\lambda = 1$ as before. Unless specified otherwise, we assume $\sigma_n = 0$, i.e. there are no local shareholders of the nuclear firm, or the government does not include their interests in its objective function.

Table 2: Numerical values of parameters for the case of Belgium.

Parameter	**Value**	**Unit**
q_0	9422	MW
β	0	MW · MWh/EUR
$q_{n,max}$	5345	MW
c_n	20.1	EUR/MWh
f_n	34.7	EUR/MWh
f'_n	6.9	EUR/MWh
c_0	39.3	EUR/MWh
α	0.0053	EUR/MWh / MW

Since demand is assumed to be completely inelastic ($\beta = 0$), the equilibrium quantity in the absence of any intervention is obviously $q_0^* = 9422$ MW. The equilibrium price in the absence of any intervention is $p_0^* = 60.9$ EUR/MWh, a fairly realistic number.

The total rent obtained by the nuclear firm in this model is given by:

$$(p_0^* - c_n)q_n = 1910 \text{ million EUR} \tag{23}$$

which is in line with the estimate of 1.75 to 2.3 billion EUR made by the Belgian electricity regulator CREG (2011). It should be emphasized that the estimation of the nuclear rent is not the objective of our model. Rather, the similarity with CREG (2011) indicates that the calibration of the model is likely to be fairly realistic.

6.2. Taxation and the effect on new investments

The parameters of Table 2 fulfill condition (10). The optimal unanticipated short-run tax according to Proposition 1 is:

$$\tilde{\tau}_{sr} = 12.5 \text{ EUR/MWh} \tag{24}$$

and the corresponding government revenues G are 584 million EUR per year. This tax is quite a bit higher than the 5 EUR/MWh tax introduced by the Belgian government in 2008, but it still captures only 31% of the total rent.

In the longer run, if the 12.5 EUR/MWh tax is credibly maintained for new nuclear investment when current capacity has expired, then equation (15) indicates that only 39% of nuclear capacity will be replaced. This is obviously dependent on the assumption that there is only one nuclear firm that can decide to invest in Belgium. The resulting electricity price increase according to equation (16) would be 17.4 EUR/MWh. Note that in this dominant firm – competitive fringe model, with only one nuclear firm, the nuclear firm would not replace all nuclear capacity even if no tax is imposed (see footnote 8). Indeed, even in the absence of any taxes, the dominant nuclear firm would only reinvest in 61% of capacity. Still, the 12.5 EUR/MWh tax reduces reinvestment by more than a third.[12]

If no taxes are imposed on new nuclear capacity but there is a probability δ that the government will impose a short-run optimal tax ex-post, new nuclear investment may also be severely reduced, as explained in Section 4.2. Figure 8 shows how the amount of replacement capacity $q_{n,reinv}$ changes as a function of δ. According to equation (19), as soon as $\delta \geq 0.50$, there will be no more nuclear investment. In other words: in this dominant firm – competitive fringe model, a 1-in-2 chance of an ex-post nuclear tax, of which the level will be decided by the government after investment, is sufficient to deter all investment.

Let us now consider the case in which the government can set a long-term tax rate $\tilde{\tau}_{lr}$ for new investment according to Proposition 2 and commit to it. Figure 9 shows the optimal tax $\tilde{\tau}_{lr}$ as a function of σ_n, the share of local shareholders in the nuclear firm. The optimal tax is the maximum of two alternatives: $\tilde{\tau}_{lr} - f_n$ and τ_{peak}, as explained in Proposition 2. Interestingly, the optimal tax is negative, even when σ_n is very low. Since the dominant firm has an incentive to reinvest less than the technical maximum, it is optimal for the government to *subsidize* the construction of nuclear power, in order to prevent underinvestment and too low production. The subsidy is 7.8 EUR/MWh when $\sigma_n = 0$, and increases with σ_n up to a maximum of 22.2 EUR/MWh for $\sigma_n = 0.51$, after which it remains constant because the maximum possible reinvestment $q_{n,max}$ is reached.

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[12] An obvious question is then why the current capacity $q_{n,max}$ has been built in the first place, given that a monopolist would build less capacity according to our model. One likely explanation is that the capacity was built during the time of regulated monopoly, in which the incumbent electricity firm would operate in a cost-plus scheme, and not on a free market as in our model.

Figure 8: Reinvestment in nuclear capacity as a function of the probability δ that government will impose an ex-post tax.

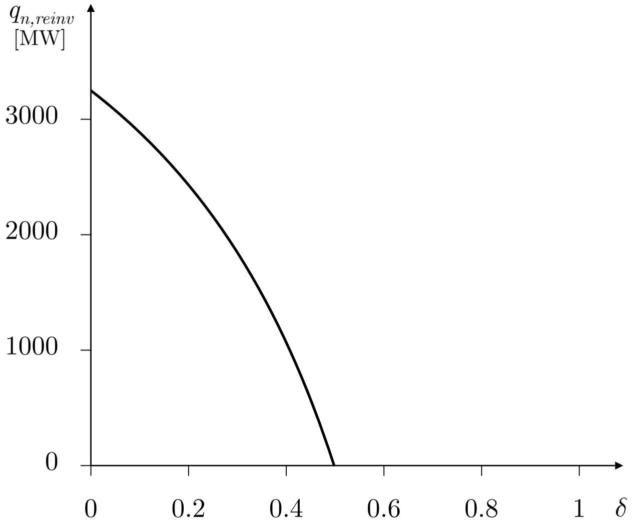
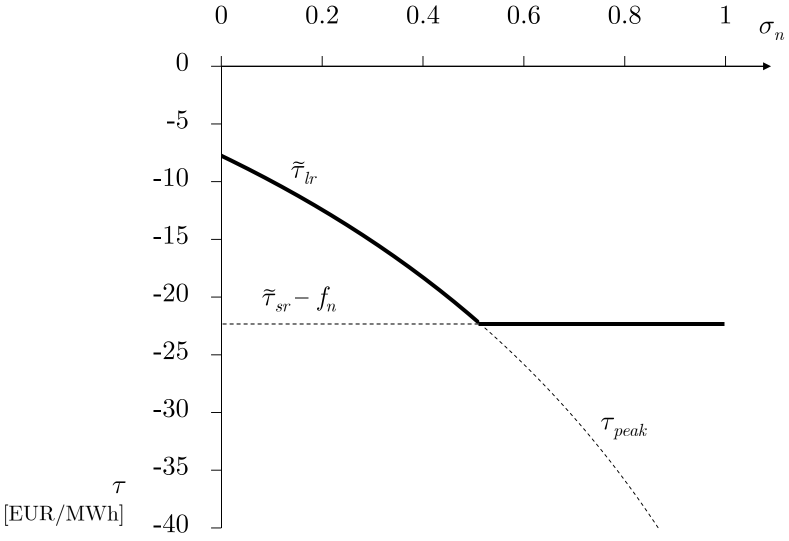


Figure 9: Optimal long-run tax when the government can credibly commit, as a function of σ_n.



6.3. Lifetime extension agreement and auctioning

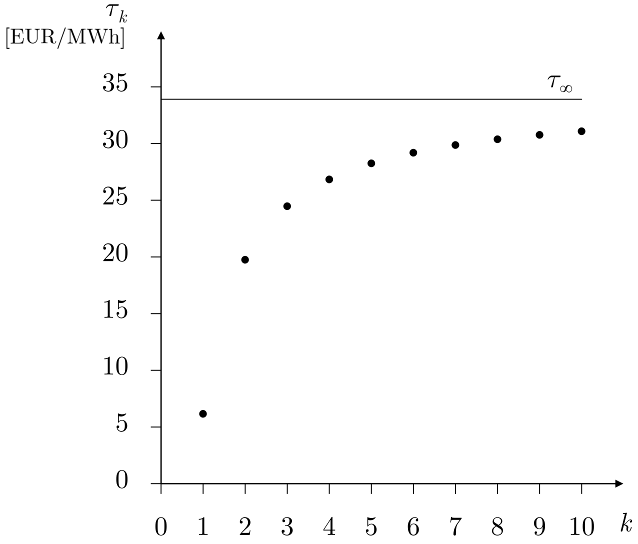
Let us now analyze the case of a lifetime extension agreement between the government and the nuclear firm. As mentioned in Section 5.1 the problem is similar to the question of reinvestment treated in the previous section, but with a lower cost f_n' instead of f_n. Applying equation (22) we find:

$$\tilde{\tau}_{sr} - f_n' = 5.6 \text{ EUR/MWh} \tag{25}$$

$$\frac{c_0 - c_n - f_n'}{2} = 6.2 \text{ EUR/MWh} \tag{26}$$

hence the optimal tax is 6.2 EUR/MWh. The situation is slightly different from what is depicted in Figure 6 in that the government will increase the tax rate slightly above the point where the nuclear firm starts to withhold capacity from the lifetime extension. This effect disappears when multiple nuclear firms are invited to an auction of lifetime extension licenses, as in Section 5.2. With more than one player, in this numerical setting, the government will set exactly the maximum tax rate that will make sure the lifetime of all capacity gets extended. Figure 10 shows the optimal lifetime extension tax as a function of the number of players k in the auction. The total potential rent in this case is 1588 million EUR, which is less than the nuclear rent of 1910 million EUR mentioned earlier because of the lifetime extension cost f_n'. With one player, the above-mentioned tax of 6.2 EUR/MWh captures only 18% of this rent. With more than one player, the taxation potential rapidly increases with k: in an auction with three players, the government would set a tax of 24.5 EUR/MWh, capturing 72% of

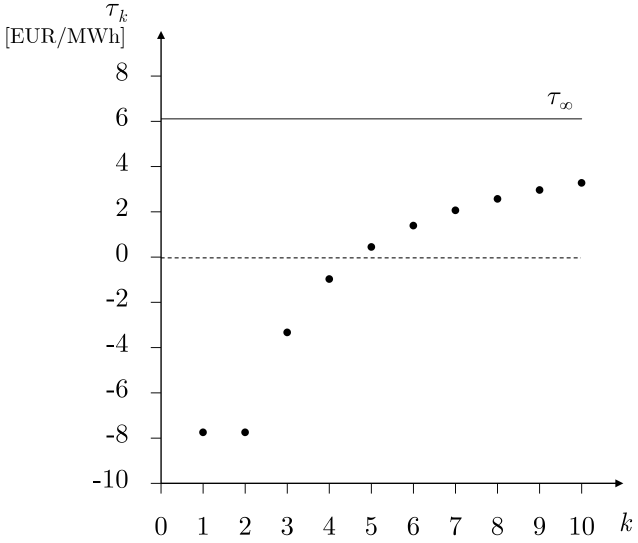
Figure 10: Lifetime extension tax as a function of the number of participants in the auction.



the maximum potential. In a perfectly competitive setting, i.e. when $k \to \infty$, the government can capture the full rent with a tax of 33.9 EUR/MWh.

As mentioned before, the same principle can be applied to the auctioning of new nuclear power plant licenses, if the government can credibly commit to an optimal long-run tax rate. The total potential rent is much smaller, because $f_n \gg f'_n$. In this numerical simulation, the total rent would be 286 million EUR per year. However, a large number of players would be required in order for the government to capture a significant share of this rent, as shown in Figure 11. For $k = 1$ and $k = 2$, we obviously find again the subsidy of 7.8 EUR/MWh shown earlier in Figure 9. For higher k the subsidy decreases, and becomes a tax when $k \geq 5$. In the fully competitive situation in which $k \to \infty$, the tax is 6.1 EUR/MWh and the entire rent is captured by the government.

Figure 11: Long-term tax on new nuclear investments as a function of the number of participants in the auction.



The main numerical results are summarized in Table 3.

7. Conclusions

In this paper we have studied nuclear taxation using a stylized model of the electricity sector with one dominant nuclear producer and a competitive fringe of fossil-fuel plants. The graphical and analytical results are illustrated using a numerical simulation for the case of Belgium.

We find that an unanticipated tax on nuclear production can generate significant government revenues in the short run without disturbing the equilibrium on the electricity market. In the simulation, the optimal short-run tax is 12.5

Table 3: Summary of numerical results.

Situation	**Scenario**	**Tax** EUR/MWh	**Comment**
Current nuclear power plants	Optimal unanticipated short-run tax	12.5	31% of rent captured, but risk of harming reinvestment
Reinvestment in new nuclear power plants	Commitment to same short-run tax	12.5	A third less investment than without tax
	No government commitment (or more than 50% chance of short-run tax ex-post)	/	No new nuclear investments
	Commitment to optimal long-run tax, with one nuclear firm	-7.8	Negative tax, i.e. subsidy, to mitigate monopoly power
	Commitment to optimal long-run tax, with perfect competition for nuclear licenses	6.1	Complete rent captured by government
Lifetime extension of old nuclear power plants	Negotiation with incumbent only	6.2	18% of total rent captured
	Auctioning with three players	24.5	72% of total rent captured
	Perfect competition for licenses	33.9	Complete rent captured by government

EUR/MWh and captures around 31% of the total nuclear rent. However, the tax may harm reinvestment incentives in new nuclear capacity in the long run. Assuming the government commits to maintaining the short-run tax rate in the long run, reinvestment is reduced by a third in the simulation, compared to a situation without the tax. If the probability that the government cannot commit to a tax rate is higher than 50%, reinvestment is completely deterred. If, on the other hand, the government can credibly commit to an optimal long-run tax rate, government revenues would be very low because the socially optimal tax would be very small or negative, due to the market power of the nuclear firm.

An agreement on lifetime extension between the government and a dominant nuclear producer generates less revenues than the unanticipated tax (18% of the lifetime extension rent in the simulation). However, by inviting multiple competing bidders for the lifetime extension licenses, government revenues increase rapidly: in the simulation, a lifetime extension negotiation with three bidders captures 72% of the rent for the government. Likewise, inviting multiple players to bid for reinvestment in new nuclear capacity can increase the potential revenues from reinvestment in new capacity because it can make the socially optimal tax positive.

Government credibility has proven to be crucial for enabling long-run optimal nuclear taxation policy. One way to achieve such credibility is to transfer some authority to a supranational body, so that appeals are possible when taxation agreements are not honored. The sensitive nature of taxation may make such a transfer difficult to realize in practice, however.

Our stylized representation of the electricity market of a country with nuclear power could be further refined. In particular, it would be useful to enhance the integration of international imports in our model, as these may be quite important in the event of large underinvestment. Furthermore, since our analysis shows that multi-party negotiation of lifetime extension agreements and auctioning of new nuclear licenses seem to be the most attractive policies, further research on the details of such auctioning processes would be beneficial.

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Appendix A. Industry marginal cost curve for the Belgian electricity sector

We estimate coefficients c_0 and α based on a cost curve of Belgian electricity supply for the year 2010. The Belgian Transmission System Operator *Elia* provides data on available total power per 15-minute time slice. Average available total power in 2010 was 11927 MW (Elia, 2011). Table A.4 provides a breakdown of available capacity by fuel.[13] Elia (2011) also provides the available amounts of international import transmission capacity from neighboring countries to Belgium, shown in Table A.5. The latter capacities are relevant, since the fringe cost curve $c_0 + \alpha q$ should also include potential imports, as mentioned in Section 2.1.

Data on efficiencies, emissions and maintenance costs per technology are taken from European Commission (2008) and summarized in Table A.6. Coal, gas and oil[14] prices are based on the average price over the period 2006-2010 according to BP (2011). Nuclear fuel price is taken from the European Commission (2008), and includes provisions for waste management. Table A.7 provides an overview.

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[13] Note that the available nuclear capacity is less than in Table 1, because not all capacity is available at any given time. Overall, average total available capacity is much lower than total installed capacity, which was 17084 MW in 2010 according to Elia (2011).

[14] For simplicity we do not distinguish crude oil from the various refined products used in power generation. Since oil-based generation is anyhow located at the far right-hand side of the cost curve, this does not significantly affect results.

Table A.4: Average available power generation capacity by fuel.

Fuel	**Average available capacity**
	MW, 2010
Nuclear	5345
Gas	3133
Hydro	1480
Coal	817
Oil (Fuel)	285
Wind	159
Other	753
Total	**11972**

Source: Elia (2011).

Table A.5: International import transmission capacity from neighboring countries to Belgium.

Country	**Net Transfer Capacity – NTC**
	MW, 2010
France	1700
Netherlands	830
Total	**2530**

Source: Elia (2011).

In order to construct the industry marginal cost curve, we make a number of additional assumptions:

- The large majority of hydropower in Belgium is pumped storage, which does not make a net contribution to the power supply. The 1480 MW of hydropower in Table A.4 is therefore excluded from the analysis.
- The available capacities for Wind and Other in Table A.4 are assumed to be non-dispatchable capacity, i.e. they do not run as a function of demand but as a result of another constraint (wind, cogeneration of heat and power, etc.). We therefore subtract them from demand (using a 50% load factor) and do not include them in the cost curve.

Table A.6: Techno-economic characteristics of power plant technologies.

Technology	**Typical characteristics**		
	Efficiency	**CO2 Emissions**	**Maintenance costs**
	Percent	kg/MWh	EUR/MWh
Nuclear – Fission	35%	0	12.1
Coal – PCC	47%	725	8.1
Coal – CFBC	40%	850	9.4
Gas – CCGT	58%	350	3.4
Gas – GT	38%	530	5.4
Oil – CC	53%	505	6.7

Source: European Commission (2008).

Table A.7: Fuel prices.

Fuel	**Reference**	**Price** EUR/MWh(thermal)
Coal	Northwest Europe marker 2006-2010	8.3
Gas	European Union cif 2006-2010	21.9
Oil	Brent (dated) 2006-2010	32.2
Nuclear	Price cited by European Commission (2008)	2.8

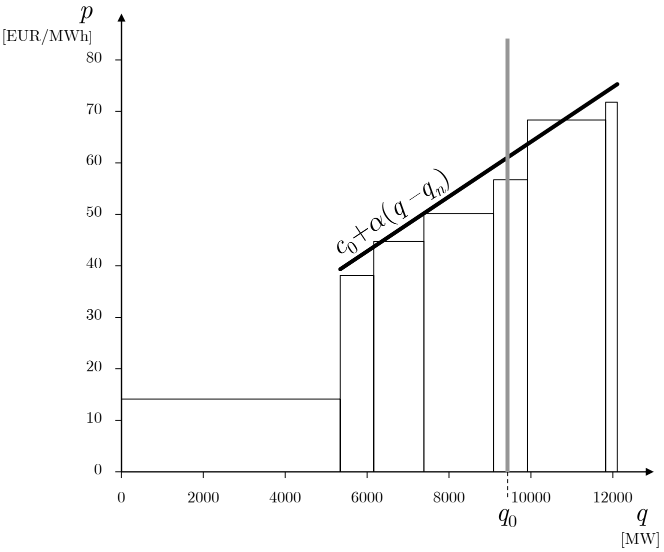
Source: BP (2011), European Commission (2008).

- Older coal plants typically have lower efficiencies than the Best Available Technology (BAT) efficiencies listed in Table A.6. For the purpose of the coal part of our cost curve, we therefore use the least favorable characteristics among the two coal technologies listed in Table A.6.
- Imported generation from the Netherlands is assumed to be gas-based.
- Imported generation from France is assumed to be coal-based. Although France has very large nuclear capacity, our model does predict that this capacity is already fully utilized, due to its low marginal costs (see Section 2.2). On average, it would therefore not be able to make an incremental contribution to serving Belgian load. A similar argument can be made for France's large hydropower capacity. The next largest technology in France's generation system is coal (Platts, 2010).
- To take into account the additional transmission costs incurred by importing power from neighboring countries, a flat fee of 12.0 EUR per MWh is added to the cost of imported power. This value corresponds to the average revenue of Elia (2011) per MWh of load in Belgium.
- The maintenance costs cited in Table A.6 comprise both fixed (FOM) and variable (VOM) costs. For the industry marginal cost curve, only the variable part should be included. We assume this variable part is 50% of the maintenance cost.
- The carbon emissions allowance price is assumed to be 15 EUR per tonne.

The resulting industry marginal cost curve is shown in Figure A.12. Based on this cost curve, one can estimate $c_0 = 39.3$ EUR/MWh and $\alpha = 0.0053$ EUR/MWh/MW. The figure also shows the net demand, which, after subtraction of the Wind and Other capacities, is $q_0 = 9422$ MW. Demand is assumed to be completely inelastic: $\beta = 0$.

The fixed capital charge f_n for nuclear power is estimated using the capex estimate provided by the European Commission (2008), but with a lower discount rate: 7%, which is in line with the pre-tax weighted average cost of capital of a large European utility (see e.g. E.ON, 2009), instead of the 10% discount rate suggested by the European Commission (2008). The result is $f_n = 34.7$ EUR/MWh. For the variable cost c_n of nuclear power, we include not only the

Figure A.12: Simplified industry marginal cost curve for the Belgian electricity sector.



marginal cost of 14.1 EUR/MWh, as shown in Figure A.12 but also the FOM of 6.0 EUR/MWh, bringing the total to $c_n = 20.1$ EUR/MWh. Indeed, although the industry marginal cost curve – as used for pricing – does not include the FOM, the FOM will be relevant for the nuclear firm in deciding whether or not to withhold some of its nuclear capacity over the timeframe of a year. Finally, we assume that the fixed capital charge for lifetime extension is 20% of f_n: $f'_n = 6.9$ EUR/MWh.