Nuclear market power: taxation or liberalization?

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Abstract

This paper analyzes the case of a country where a dominant producer has efficient nuclear production capacity and faces a competitive fringe of non nuclear producers. Three types of public policies are considered. The first are proportional taxes on nuclear energy. The second policy is liberalizing the market by a divestiture of the existing capacity. The third policy is to increase the interconnection capacity at the border. Effects of policies are compared in the short run (before investment) and in the long run with and without government commitment.

1. Introduction

In recent years electricity markets have become a major topic of research both in the U.S. and in Europe. Several concerns about the effectiveness of the deregulation process and the accompanying problems have been expressed by Newberry (2002). A large number of papers therefore analyze the electricity market as an oligopolistic market 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. Incumbent firms may transform their previous regulated monopoly rights into substantial unregulated market power. This paper concerns one aspect of the (de)regulation and liberalization of the wholesale electricity market.

We consider three types of government interventions. The first are taxes on nuclear energy. The second policy is liberalizing the market by a divestiture of the existing capacity. The third policy is to increase the interconnection capacity at the border. The latter two policies try to minimize windfall profits on nuclear power by increasing the level of competition in the market, while the former policy tries to extract and expropriate these rents from the nuclear firm.

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The generation segment[1] of concern is the nuclear power segment. The reason for this is that the possibility of market power of the dominant firm is most pronounced in the nuclear segment where the dominant firm owns almost all capacity and where barriers to entry are high. Over the last decade many firms entered the non-nuclear generation market; so we can expect that the market power of the incumbent is less pronounced in fossil-fuel electricity generation. In most European countries, there is one nuclear generator that controls almost all nuclear generation capacity. The political stance towards this nuclear electricity generation, however, differs a lot across countries. This is illustrated in table 1. There is no common European policy towards nuclear electricity generation. In our model, we start from a dominant firm in the nuclear segment of the market. Table 1 supports this assumption. Historically, the single nuclear operator had a regulated monopoly. This papers investigates the behavior of this incumbent monopolist in a deregulated environment.

Table 1: Electricity generation capacity in Europe

Country	generation capacity	Share nuclear in production	future plans	# operators
Belgium	16258 MW	54%	Decommissioning by in 2015 - 2030	1
Finland	16557 MW	27%	Building new plants	+2:consortium
France	115496 MW	78%	Building new plants	2
Germany	125001 MW	26%	Decommissioning by 2022	6
Spain	81074 MW	20%	Stable	4

To investigate the behavior of these large dominant firms in a deregulated environment, suitable market behavioral models are needed. Several attempts have been made to model electricity markets. Ventosa et al. (2005) focus on the generation market. In this paper we use the traditional Cournot equilibrium model. One of the major drawbacks of this type of models is that generators' strategies are expressed in term of quantities and not in terms of supply curves. This implies that prices are determined only by demand functions and therefore these are extremely sensitive to the demand representation. One of the consequence of this sensitivity is that calculated prices tend to be higher than observed. As we also focus on analytical results, this is not such a drawback.

Another advantage of Cournot-Nash models acknowledged by Ventosa et al. (2005), Borenstein et al. (1999), Hobbs & Pang (2007) and Wei & Smeers (1999) is computational convenience. Cournot equilibria are easier to calculate than Bertrand equilibria and Supply Function Equilibria (SFE). Willems et al. (2009) confront Cournot models, SFE with data of the German electricity market. The authors conclude that SFE do not significantly outperform the Cournot approach to study the German electricity market but SFE 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 long-term effects of mergers etc. Therefore we will use the Cournot model.

This paper analyses the case of a country where a dominant producer has efficient nuclear production capacity and faces a competitive fringe of non nuclear producers. First an analytical model

[1] In this study we refer to the generation stage also by calling it the electricity market, for the sake of conciseness

of the market is built in section 2. Then, this model is used to consider three types of public policies. The first are taxes on nuclear energy, both in the short run and in the long run; these are discussed in section 3. In the long run both the behavior of the government and the ability of the government to commit to a specific tax rate influence the investments in nuclear power capacity. Section 4 analyzes the second policy: liberalizing the market by a divestiture of the existing nuclear capacity.Section 5 analyzes the third policy that is to increase the interconnection capacity at the borderThe results of the different policies are compared for the Belgian case in section 6. Section 7 concludes.

2. Model set-up

2.1. Local demand

We study the case of one country and assume a linear demand curve for local (i.e. domestic) demand:

$$D(p) : q = ap + b \tag{1}$$

In this expression q is the amount of electrical power (MW) for a unit period and p is the price for the energy (€/MWh). a is the slope of the demand curve By definition $a \leq 0$ and $b > 0$. We neglect the period variations of demand.

2.2. Generation costs

In an imperfect competitive electricity market, a supply curve does not really exist. Since generators can have market power, they can withhold capacity This curve consists of the accumulation of all generation units ranked at increasing marginal costs. To simplify the cost curve, we assume that there are only two types of technologies available: nuclear power units and gas-fired power plants. Since it is generally much cheaper to run a nuclear power plant than a gas-fired power plant, i.e. the marginal costs of a nuclear power plant are below those of a gas fired power plant as can be seen on figure 1, the nuclear operator will provide the first units of power. This means that the gas operator will only start to produce when the demand is not met by the production of the nuclear operator.

We also assume that the capacity of nuclear power is limited, $q_n \leq \bar{Q}_N$. The next assumption is that each operator is free to determine its activated generation capacity, which can be smaller than the total capacity. The nuclear and gas-fired companies can thus freely decide what capacity q_n and q_g they respectively activate.[2] The marginal cost function can be described by:

$$\begin{aligned} MC(q) &= c_n \text{ for } 0 < q < q_n && (2) \\ &= c_g \text{ for } q_n \leq q \leq q_e && (3) \end{aligned}$$

We always assume that demand for electricity is large enough so that the demand curve always cuts the cost curve in the second (gas) part as can be seen on figure 1 (i.e. $q_e \geq q_n$). This is

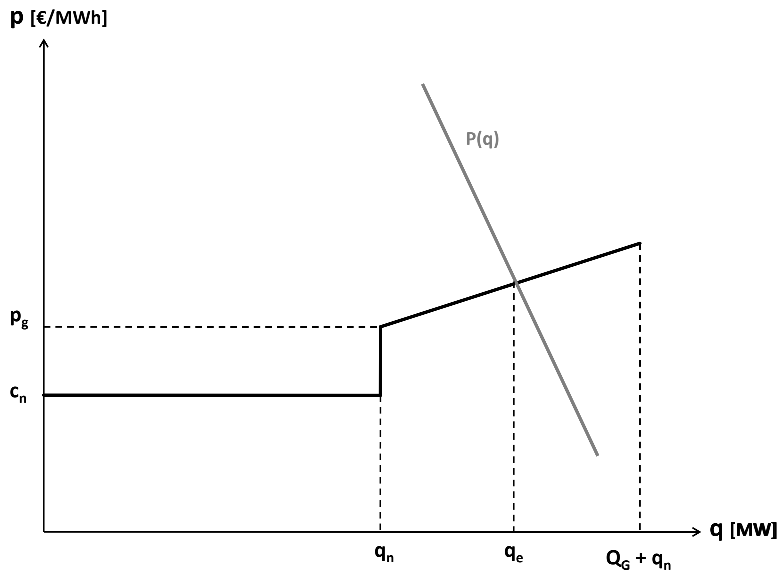


Figure 1: Simplified model of the market

a realistic assumption as gas-fired power plants are more flexible to meet varying demand conditions.

It is also realistic to assume that the marginal cost of nuclear power remains constant at every output level, i.e. $c_n = \bar{c_n}$. The marginal cost of gas-fired power plants, however, is not constant: the marginal cost of operation highly depends on the fuel cost. Therefore high-efficiency units, like CCGT[3], have lower operation costs than units with lower efficiencies, like OCGT.[4] we assume that operators will use first their units with a lower marginal cost. This leads to a rising marginal cost of production for gas technology:

$$
\begin{aligned}
c_n &= \bar{c}_n && (4)\\
c_g &= c\,(q - q_n) + \bar{p_g} && (5)
\end{aligned}
$$

A graphical representation of this simplified model of costs and demand in the electricity market is shown in figure 1.

2.3. Equilibrium concept

The model proposed above is a standard dominant firm/competitive fringe model,[5] built with two groups of firms, i.e. a dominant firm and a competitive fringe. The competitive fringe firms are

[2] In reality, this is of course not the case for nuclear power plants. These power plants are large baseload plants that are difficult to run a partial load. One can, however, stop one unit for maintenance or other reasons.

[3] Combined Cycle Gas Turbine, see also paragraph B.1

[4] Open Cycle Gas Turbine, see also paragraph B.1

[5] i.e. a Stackelberg model

the electricity producers that use gas-fired power plants. We assume that there is enough competition in this market, so that they produce up to the point that marginal costs equal the market price. In this paper the nuclear player is the large dominant firm with monopolistic powers. This firm has a great strategic power over the market price because it is much larger than the competitive fringe firms.[6] The competitive fringe limits the market power of the dominant firm. According to Ulph & Folie (1980) this Stackelberg model always increases the profits of the dominant firm compared to a perfect competition situation.

The model can be interpreted by the concept of residual demand. We assume that the producers using gas plants have no market power and produce until their marginal cost equals the market price.

$$p = \frac{q_e - b}{a} = c\left(q_e - q_n\right) + p_g \tag{6}$$

The residual demand curve is graphically illustrated in figure 2. The residual demand $D_n(p)$ for the nuclear operator is given by (for $p \geq p_g$:

$$D_n(p) : q - q_g = \frac{ac-1}{c}p + \frac{bc + p_g}{c} \tag{7}$$

$$P_n(q) : p = \frac{cq - cb - p_g}{ac - 1} \tag{8}$$

Maximizing the profits of the dominant producers, $\pi_n = \left(p_{e1} - c_n\right) q_{n1}$, with respect to the nuclear production q_{n1} gives the quantity of nuclear output, the electricity price and the consumer surplus.

$$q_{n1} = \frac{p_q + cb - \left(1 - ac\right) c_n}{2c} \tag{9}$$

$$p_{e1} = \frac{1}{2}\frac{-bc + acc_n - p_g - c_n}{-1 + ca} \tag{10}$$

where p_{e1} is the equilibrium price for electricity [€/MWh] in the absence of government interventions.

$$CS_1 = \frac{q_{e1}^2}{2a} - \frac{b}{a}q_{e1} - p_{e1}q_{e1} \tag{11}$$

where q_{e1} is the equilibrium quantity of nuclear power [MW] when there are no government interventions, i.e. $q_e = q_n + q_g$. For more information about the calculus, we refer to appendix A.2.

[6]There are two possible ways to define the market mechanism. The dominant firm can maximize its profits without taking into account the fringe's reaction on the price. The assumption made here is that the output of the competitive fringe is fixed. This is a pure Cournot model according to Ulph & Folie (1980). The second way is the Stackelberg model: even though the dominant player has control over its output, the output of the competitive fringe is not fixed and reacts to the output changes of the dominant firm. Of course this has a direct effect on the revenues of the dominant firm by introducing extra demand elasticity to the residual demand.

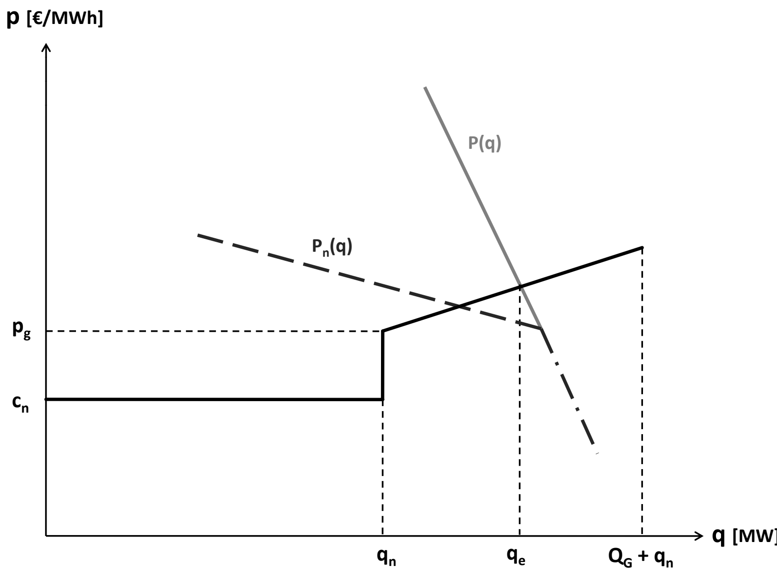


Figure 2: Residual demand curve nuclear operator

2.4. Government objective function

The government can intervene in the market in order to maximize social welfare. We define the change in social welfare as the sum of change in local consumer surplus, ΔCS, the change in government tax revenues, ΔG, and change in local share of profits, $\Delta \pi_L$[7], minus the external costs. These external costs are assumed to be constant and are incorporated in the marginal costs of the different technologies.

3. Policy option 1: proportional taxation of nuclear production

3.1. Taxation effects in the short run

The government can impose a proportional tax, $\bar{t}$, on nuclear production. Suppose that $q_e = q_n + q_g$ is the total amount of capacity activated and q_g is the amount of gas-fired capacity activated, then the price for electricity when the gas market is fully competitive can be computed by substituting in equation 10 c_n by $c_n + \bar{t}$:

$$p_{e2} = \frac{1}{2} \frac{c_n (1 - ac) + \bar{t} (1 - ac) + p_g + bc}{1 - ac} \tag{12}$$

And also the activated nuclear capacity changes when a tax $\bar{t}$ is imposed by the government. Using equation 9 where c_n is replaced by $c_n + \bar{t}$ gives:

[7] We assume that the local public owns $s_l 100\%$ of this company, while the other $(1 - s_l)\,100\%$ is owned by foreign shareholders. This means that $s_l 100\%$ of the profits flows back to its local shareholders if capital markets are liberalized

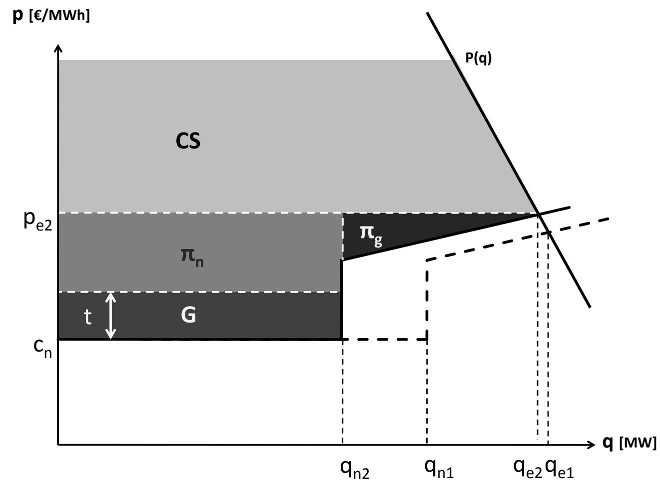


Figure 3: Simplified model of the market

$$q_{n2} = \frac{p_g - cb - (1 - ac)(c_n + \bar{t})}{2c} \leq q_{n1} \tag{13}$$

We see a lower production by the dominant firm because the marginal revenue of any extra quantity sold now has to match an increased marginal cost. The decrease results in a higher electricity price.
The government can impose a tax that maximizes the social welfare taking into account the effect the behavior of the dominant firm. The optimal tax maximizes the sum of $\Delta CS + \Delta G + \Delta \pi_L$ and is given by (for a very small):

$$\bar{t}_{opt2} = \frac{(1 - s_l)(p_g - c_n) - s_l bc}{2 - s_l} \tag{14}$$

From this experience we learn that $\frac{\partial \bar{t}_{opt}}{\partial s_l} < 0$ so higher taxes on the nuclear profits are less interesting if a larger share of the nuclear firm is owned by locals. If $s_l = 0$ than the optimal tax level is half of the difference between the marginal cost of the nuclear operator and the marginal cost of the cheapest gas turbine. Half of the proportional tax will be taken up by the dominant firm himself. A graphical representation of the welfare effects can be found in figure 3.

3.2. Taxation effects in the long run.

In the long run, taxation may affect investments by the firm. The effect will depend on whether the government can make commitments or not. If the government can commit to a fixed long term proportional tax rate the firm will invest more in generation capacity. The investment behavior of a firm is very sensitive to the incentives given by the government to stimulate investments, according to de Vries & Heijnen (2008). The no-commitment assumption, however, is more realistic than a credible commitment of the government to a constant tax rate.[8] Examples of attempts of commitments of a government are the different 'pax electrica' in Belgium in which there was an agreement between the federal government and the large dominant incumbent generator.

There are two possible scenarios to model the commitment of the government.

1. The government can guarantee a long term commitment to a fixed rate, which does not change after the firm's investment.
2. The government cannot guarantee a long term commitment. Taxes can be changed once the firm has invested. This inhibits the dominant firm to make their optimal investment.

A second difference with the short-run scenarios is that fixed costs, F, do matter in determining the nuclear capacity that a dominant firm wants to build. The fixed cost, F is given per unit installed capacity, i.e. €$/MW_{installed}$. Since the dominant firm will make strategic capacity decisions based on average costs[9], AC, these costs need be transformed into €$/MWh_{produced}$, by using the expected lifetime of a nuclear power plant, L in years, and the number of operating hours per year, H. The average costs are then given by:

$$AC = c_n + \frac{F}{LH}$$

We assume that both the long run competitive fringe and the demand curve are identical to the short run counterparts. This is a simplification in order to obtain results that can be compared with the short run results from section 3.1.

We analyze the case in which the dominant firm believes that the government can make a **credible commitment** to a single tax-rate over the lifetime of a power plant with backward induction. The process consists of several stages that need to be solved in a backward way to determine the right outcome. This process is illustrated in figure 4. The three consecutive stages are solved in a backward order since the strategic decisions in each stage take the decisions of the previous stages into account. *First, (i.e. the third stage) the dominant firm decides what quantity of its capacity to operate.* This decision is made based on the marginal costs of production, the imposed tax $\bar{t}$ and is limited by the installed capacity, Q_N^{comm}. After all, in the short run, fixed costs are sunk. This decision is the process discussed in section 3.1.

$$\pi_n^{LT} = p\, q_n - (c_n + \bar{t})\, q_n$$

It is easy to see that the dominant firm wants to activate all capacity. This is because $c_n + \bar{t} \leq c_n + \frac{F}{HL} + \bar{t}$. Therefore $q_n^{comm} = Q_N^{comm}$, i.e. the dominant firm uses all its nuclear power plants and in the short run (section 3.1), the firm is always in a constrained optimum.

Second, the dominant firm makes a decision on the capacity that would maximize its long term profits given the fixed costs and the proportional tax. Decisions made here are based on the average costs of the dominant firm and on the expected profits as determined in third stage. The dominant

[8] Since changes in the composition of political majorities are not unfamiliar, a political commitment over several legislatures is very exceptional.

[9] We neglect the time value of the costs

firm does not take the fixed costs of the competitive fringe into account (see figure 6). These are sunk so they do not affect the price of electricity. The competitive fringe's companies will make short term production decisions based on their marginal costs which equal the market price. For capacity decisions, the long term profit needs to be maximized anticipating this future market price. The optimal capacity decision, based on the average long term costs, is:

$$Q_N^{commit} = \frac{p_q - cb - (1-ac)\left(c_n + \bar{t} + \frac{F}{H\,L}\right)}{2c} \tag{15}$$

The electricity price is given by equation 10 where c_n is replaced by $c_n + \bar{t} + \frac{F}{HL}$.

In the next step, i.e. the first stage, the government sets the appropriate tax rates and commits to this tax, $\bar{t}$, during the whole lifetime of the power plant. The optimal proportional tax can be derived based on the results obtained in paragraph 3.1. This is depicted in figure 6. The government can, as a rational player, anticipate the decision of the nuclear firm in order to maximize local Welfare $\Delta W_b = \Delta G + \Delta CS + \Delta\pi_L$. Using equation 14 and a is very small:

$$\bar{t}_{opt}^{comm} = \frac{(1-s_l)\left(p_g - c_n - \frac{F}{LH}\right) - s_l bc}{2 - s_l} \tag{16}$$

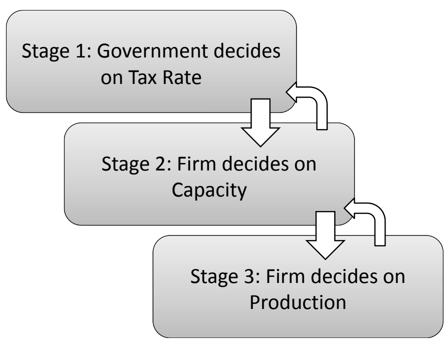


Figure 4: Flow chart of the decision process when the government is committed to single tax rates.

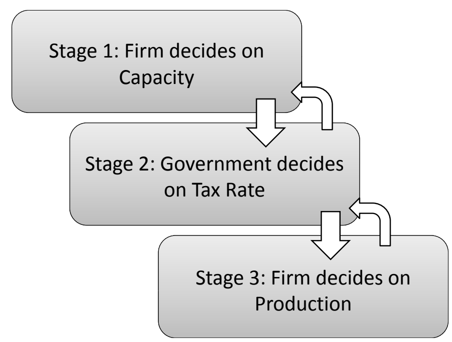


Figure 5: Flow chart of the decision process when the government is not committed to single tax rates.

The method of backward induction is also used in the case in which there is **no credible commitment** of the government in the long term. The government after all has an incentive to raise the taxes after the investments have been made. The strategic decisions are made in a somewhat different sequence as illustrated in figure 5.

Again we use backward induction. We started solving this process in the last stage. *In this stage of the decision flow, the firm makes a short term decision in order to maximize their short term profits* based only on this proportional tax as the fixed costs are sunk. This is a situation similar to the benchmark scenario, with the difference that the capacity restriction is analytically known (Q_N^{n-comm}) where Q_N^{n-comm} represents the capacity chosen in the no-commitment case.

In the second stage the government sets its tax, based upon the activated capacity of the firm, maximizing welfare of the public. The government is not committed to a fixed tax rate and so it does not take into account the fixed costs of the firm: the government optimizes in the short run. Notice

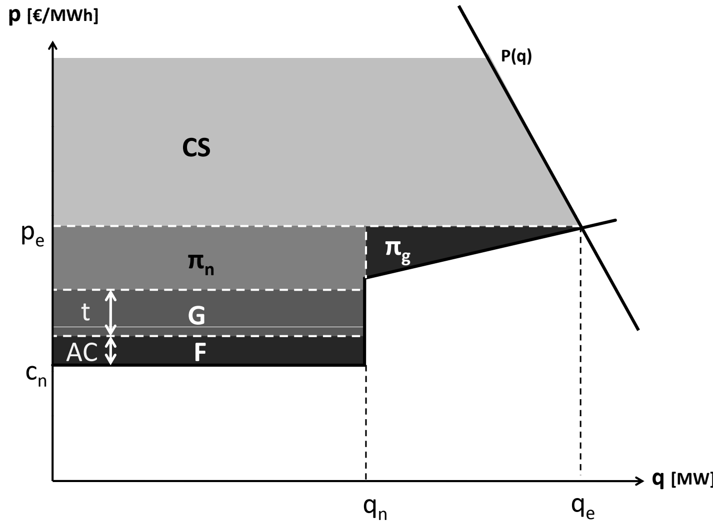


Figure 6: Long term decisions.

that up to now, the decisions were the same as described in section 3.1.
The first stage of the decision flow is the dominant firm decides what capacity it will build. Therefore the nuclear operator looks forward to what to expect in the other stages. In fact the firm sees the short term scenario as described in paragraph 3.1. The nuclear operator has to estimate the most probable future tax. As a rational player it knows that the government that cannot commit to any tax, will act rationally and levy a tax in order to maximize the short run local welfare given by equation 14. This tax is much higher than $\bar{t}_{opt}^{comm}$.Based on this estimation of the proportional tax, $\bar{t}_{est}^{n-comm}$, the nuclear power plant's capacity is determined in a similar way as in equation 15.

The conclusion of this reasoning is that the firm will under-invest in nuclear capacity because $\bar{t}_{est}^{n-comm} \geq \bar{t}_{opt}^{comm}$ as there is no commitment of the government. Therefore $Q_N^{n-comm} \leq Q_N^{comm}$. This leads to inefficiencies: there is not enough capacity resulting in higher electricity prices and lower consumer surplus. There are fewer investments than socially desirable. The dominant firm's profits also decrease significantly. At the same time government revenues increase. The net-effect however is that local welfare $\Delta W_b = \Delta G + \Delta CS + \Delta \pi_L$ will be smaller as Q_N^{comm} and $\bar{t}_{opt}^{comm}$ are determined so that the government maximizes local welfare on the long run.

4. Policy option 2: liberalization and forced divestiture

In this section, we look into the gradual opening of the nuclear market to competition in the long term. Therefore the number of electricity producers with nuclear capacity on the local market needs to increase. We incorporate the long term because this gives a more realistic interpretation of the investment behavior of the firms. It also implies that all capacity installed, will be used to

serve the local market[10]
In this section we consider first a divestiture of the incumbent firm active in the nuclear segment. This will result in a straightforward Cournot-Nash equilibrium on the nuclear power market as explained in this section. A second policy instrument to increase the level of competition (i.e. by increasing the transmission capacity) is discussed in the next section. The assumptions made in the basic scenario (paragraph 3.1) still apply.

Many of the results obtained in paragraph 3.1 can be used in this scenario. The electricity price is still determined by the cost curves of the competitive fringe and the oligopolistic nuclear market. Therefore the result for the equilibrium price obtained in paragraph 3.1, i.e. $p_e = \frac{p_g - c(q_n - b)}{1-ac}$ still applies. The difference with the benchmark scenario, however, is that the dominant firms do not maximize their profits anymore only based on $q_n = q - q_g$. Instead, we have an equilibrium with more oligopolistic players that take the actions of the other players in the nuclear power market into account.

The dominant firms will act as oligopolists in a Nash-Cournot equilibrium on their individual residual demand curve. In a similar way as described in paragraph 3.1 the residual demands and the marginal revenues can be calculated. X_n is the amount produced by the other nuclear operators. As all firms have the same cost structure, they will, in a symmetrical equilibrium, all produce equal amounts of electricity and they will activate equal amounts of capacity. Therefore $X_n = (z-1)q_i$, where z is the number of nuclear generators. Each firm will maximize its profits on its residual demand curve by setting the marginal revenues equal to their long run marginal costs, AC.

$$MR = \frac{bc + p_g - (z+1)\,cq_{ind}}{1-ac} = c_n + \frac{F}{HL} = AC \tag{17}$$

This results in a closed expression for the capacity each dominant firm will use and for the total amount of nuclear capacity activated.

$$\begin{aligned} q_{ind} &= \frac{bc + p_g - (1-ac)\,AC}{c\,(1+z)} && (18)\\ q_n^{split} &= \sum_{i=1}^{z} q_i = z\frac{bc + p_g - (1-ac)\,AC}{c\,(1+z)} && (19)\\ p_e^{split} &= \frac{zAC}{1+z} + \frac{p_g + bc}{(1+z)\,(1-ac)} && (20) \end{aligned}$$

q_{ind} stands for the nuclear production per nuclear generator, while q_n^{split} stands for the total nuclear production under the divestiture case. p_e^{split} is the electricity price under these assumptions. These expressions are similar to the results obtained in paragraph 3.2: equation 19 is equal to equation 10 multiplied with $\frac{2z}{1+z}$. If $z=1$ equation 19 equals equation 10. This expression 19 gives also insights in the evolution of electricity prices and quantities. As the number of competitors increases, q_n^{split} increases and p_e^{split} decreases.

[10]Only the capacity that will be used to serve the Belgian market, is installed in the long run. Capacity to serve other markets are build in those respective markets.

5. Policy option 3: improve the interconnectivity between countries

The second possibility to model the European liberalization is to model foreign producers that export electricity to the local market. There are however transmission costs, T, related to this export of electricity. This transmission cost finds it origin in the costs related to the use of a transmission grid.It are the transmission costs that protect the market power in the domestic market and price differences can appear with neighboring countries because of these costs. We assume that with increasing liberalization, more countries get connected to the domestic market. The implicit assumption is that each additional generator connected to the domestic local market, faces a higher transmission cost. Evidently those producers with low production marginal costs, nuclear electricity producers, will have a cost advantage when the interconnection capacity can be used.[11] The number of Cournot generators is limited by p_g: once the costs of foreign producers equal those of the competitive fringe, we assume that it does not make sense to export to the local market. The maximum number, $\bar{z}$, of generators on the domestic market is therefore $\bar{z} = \frac{p_g - AC - \bar{t}}{T}$, i.e. the number of players that face increasing transmission costs $(i-1)T$. The highest transmission cost $(\bar{z}-1)T$ cannot exceed the difference between the marginal operation costs of the competitive fringe and the costs facing nuclear operators.

The mathematics of this case are rather similar as described in the previous model with the difference that with increasing number of generators, z, the marginal costs increase with an additional T. For the i^{th} firm, the transmission costs are given by (firm($i = 1$) is the domestic firm):

$$c_i = AC + (i-1)T \tag{21}$$

The nuclear outputs of firm i is given by:

$$q_i = \frac{bc + p_g - (1-ac)\,AC + (1-ac)\left[\frac{z(z-1)}{2} - (i-1)(z+1)\right]T}{c\,(1+z)} \tag{22}$$

This means that the production depends on the total number of generators. The more generators, the less each generator will produce. The activated production capacity also depends on the costs. The more borders have to be crossed, the higher the costs, the less capacity is activated, as can be seen in equation 22. After all, q_i decreases with increasing i as with each border a quantity $\frac{T(1-ac)}{c}$ is subtracted. This is illustrated in figure 7. The total quantity of nuclear production will be lower than in the case of the split-up of local nuclear capacity:

$$q_n^{trans} = \sum_{i=1}^{z} q_i = z\,\frac{bc + p_g - (1-ac)\,AC}{c\,(1+z)} - \frac{(1-ac)\left[\frac{z(z-1)}{2}\right]T}{c\,(1+z)} \tag{23}$$

[11] By assuming that nuclear operators have an advantage and will use the capacity, we neglect cyclical demand variations. In reality however gas-fired power plants have an advantage in responding to cyclical effects and will make more frequently use of the medium and short term allocation of the interconnection capacity. For this study however this is unimportant because we do not put limits on the interconnection capacity. In the end, when there is one big integrated European market, the interconnection capacity will also be used by nuclear operators. The only requirement for this scenario is that the interconnection capacity between countries is large enough.

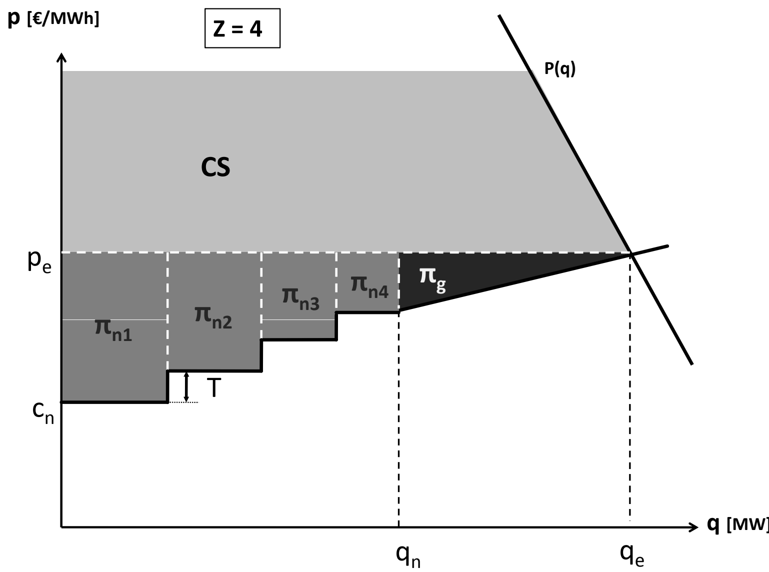


Figure 7: Model with transmission costs

If $T = 0$ equation 23 equals equation 19. The price of electricity is given by:

$$p_e^{trans} = \frac{zAC}{1+z} + \frac{z\,(z-1)\,T}{2\,(z+1)} + \frac{p_g + bc}{(1+z)\,(1-ac)} \tag{24}$$

The fact that $q_n^{trans} < q_n^{split}$ implies that $p_e^{trans} > p_e^{split}$.

6. Numerical results

We calibrate the model on the situation in Belgium. Full details can be found in appendix B.2.

6.1. Numerical results

The different scenarios are evaluated on the basis of the change in Belgian welfare ΔW_b, the change in the activated nuclear capacity Δq_n and the change in electricity prices Δp. To prevent numerical instabilities, we calculated the difference in Belgian welfare as (with $s_l = 0$):

$$\begin{aligned} \Delta W_b &= \left(p_e^{situation} - p_e^{reference}\right)\left(q_e^{situation} + \frac{q_e^{situation} - q_e^{reference}}{2}\right) + q_n^{situation} t_{opt}^{situation} & (25) \\ &= \Delta CS + \Delta G & (26) \end{aligned}$$

I evaluate the different scenarios based on 3 results: their improvement in Belgian welfare (table 2), their effect on the nuclear output (table 3) and their effect on the electricity price (table 4). The differences in welfare are calculated compared to the reference scenario which is the case in which there is no tax and only one dominant firm. We do not take into account political decisions. They will not affect prices nor produced quantities.

Table 2: Comparison of Belgian welfare in different scenarios. ΔW_b in $[\frac{million\ EUR}{year}]$ is measured compared to the respective scenarios with one dominant firm without a tax. $[s_l = 0]$

Scenario	Instrument	Short term	LT: commitm	LT: no commitm
		ΔW_b	ΔW_b	ΔW_b
Dominant firm Competitive fringe	proportional tax	169	47	10
Liberalization	Divestiture capacity $[z = 3]$ Transmission $[z = 3]$		1 349 984	

Table 3: Comparison of activated nuclear capacity $[MW]$ in different scenarios. $[s_l = 0]$

Scenario	Instrument	Short term	LT: commitm	LT: no commitm
		q_n	q_n	q_n
Dominant firm Competitive fringe	no tax proportional tax	8736 7149	7243 6402	7243 5656
Liberalization	Splitting up capacity $[z = 3]$ Transmission $[z = 3]$		10865 9884	

Table 4: Comparison of the electricity prices $[\frac{EUR}{MWh}]$ in different scenarios. $[s_l = 0]$

Scenario	Instrument	Short term	LT: commitm	LT: no commitm
		p	p	p
Dominant firm Competitive fringe	no tax proportional tax	49.63 55.70	55.33 58.55	55.33 61.40
Liberalization	Splitting up capacity $[z = 3]$ Transmission $[z = 3]$		41.49 45.24	

By imposing an optimal tax which is 12.13 €/MWh for the given parameters ($s_l = 0$),[12] the government can change the welfare distribution. The proportional tax increases the perceived marginal cost of the nuclear power plants, leading to more withholding, higher prices and lower consumer surplus. The gain in Belgian welfare is 168.7 million €/year while the nuclear operator loses 844.3 million €/year of profits. The electricity prices increase with a value of approximately half of the imposed proportional tax, i.e. they increase from 49.63 €/MWh to 55.70 €. This implies that

[12]We assume in the following results that $s_l = 0$, except when explicitly mentioned. The influence of s_l will be discussed further on.

the consumers will have to carry half of the tax-burden as can be seen in figure 8. As one can see taxes destroy total welfare[13] since the gain in Belgian welfare is smaller than the loss in producer profits. It is remarkable that both the nuclear outputs with and without tax, $q_{n1} = 8736$ MW and $q_{n2} = 7149$ MW respectively, are larger than and thus bounded by the installed nuclear quantity in Belgium, 5825 MW. This can be explained by the fact that short term strategies do not take into account the investment costs.

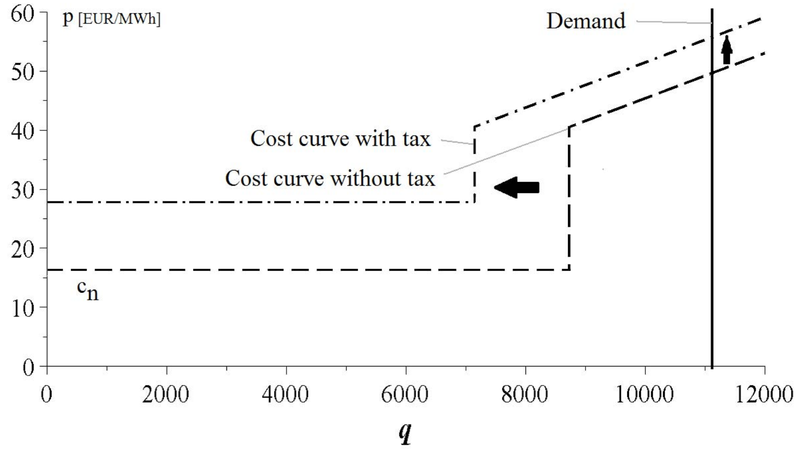


Figure 8: Basic short run scenario: effect of taxes. Taxes drive up the costs of production leading to higher prices and lower produced quantities. [$s_l = 0$]

As s_l increases, the optimal tax decreases. This can be seen in figure 9: as the Belgian shareholdership increases there is a point where it becomes profitable for the Belgian government to subsidize nuclear power production. The same trend can be seen in other scenarios. The optimal tax when $s_l = 0$ (this is the easiest case to consider) is an equilibrium between two forces: the higher the tax, the higher the government tax revenues, but the lower the consumer surplus as is illustrated in figure 10. As s_l increases there acts a third (downward) force on the tax, i.e. the share of the generator's profits that goes to local owners.

If the numerical results are considered in the long run (i.e. including investment decisions) we obtain comparable conclusions. The welfare effects and the activated nuclear capacity are given in table 2 and 3 respectively. These welfare effects are rather limited in the long run due to the smaller difference between p_g and AC (see eq. 16). This results in fewer opportunities for the government to intervene.

[13]Total welfare is the sum of the producer profits and the Belgian welfare that incorporates government tax revenues, share profits and consumer surplus.

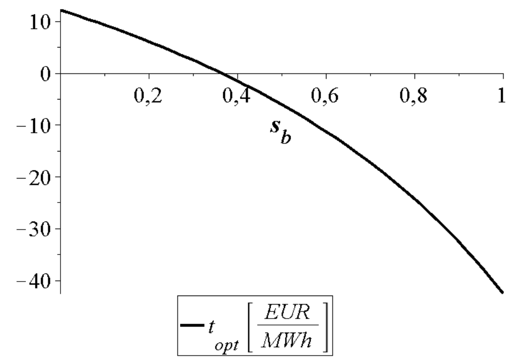


Figure 9: Basic short run scenario: evolution of the optimal tax with varying ownership shares. As s_l increased, the optimal tax decreases and becomes negative.

The activated nuclear capacity in this case will always be equal to the installed capacity. In the case of a credible commitment of the government to a tax rate up front, the investments in nuclear capacity are approximately 6402 MW, while in the case of no commitment the investments in nuclear capacity decrease to 5656 MW as can be seen in figure 11. This means a decrease in investments of 746 MW if the corresponding tax rate increases from 6.4 to 12.1 €/MWh. It is remarkable that the predicted investments are close to the actual installed nuclear capacity in Belgium.

In this figure, one can also see that an optimal short term tax (12.13 €/MWh), i.e. when there is no commitment of the government, increases the perceived costs of the nuclear generator above the long term optimal tax (6.43 €/MWh) to 39.8 €/MWh. These cost level come very close to the marginal costs of the cheapest gas turbine , i.e. ±41 €/MWh. Since we assume that nuclear operators will not invest in capacity if their costs exceed the costs of the competitive fringe, this is a case in which the absence of commitment by the government may lead to no investments in nuclear capacity at all. The investment decision depends thus also on the marginal costs of the cheapest gas turbine (p_g) and the tax level which is illustrated in figure 12. One can see that there are situations in which the government cannot levy the optimal tax from equation 16 without inhibiting investments. Only when $t_{opt}^{no-comm}$ enters the shaded zone, it is possible for the government to impose this tax. If the government can commit, it takes the reaction of the investor into account and it is thus always possible to levy t_{opt}^{comm}. After all, the right hand side of the line, t_{opt}^{comm}, falls in the shaded zone.

A divestiture of the nuclear power generation capacity has a favorable effect on prices and welfare (consumer surplus).An important remark here is that allowing four competitors or more on the nuclear segment would satisfy Belgium's electricity demand with a price set at $p = p_g$.[14] If we take

[14]There is a possibility of multiple equilibria because of the bend in the residual demand curve for the nuclear sector. Prices can go down to the average cost on the long run. In that scenario there is no competitive fringe. This causes problems with cyclical demand variations. Therefore we should distinguish the solutions between peak (with fringe) and off-peak situations (without fringe). These scenarios fall outside the scope of this paper.

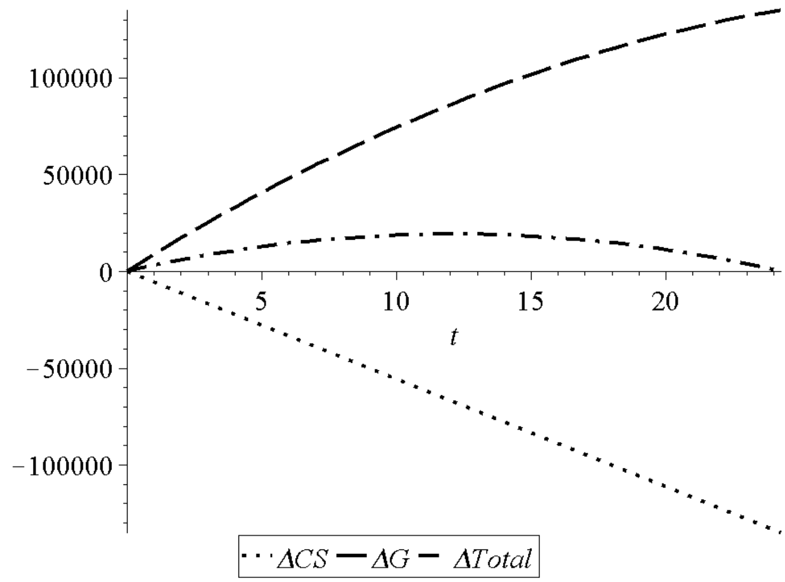


Figure 10: Basic scenario: Trade off in tax calculation.[$s_l = 0$]

a larger market, a larger number of competitors is possible on the market because the maximum number of competitors increases with b.[15] The evolution of the price would be the same. As one can see in figure 13 the effects on the consumer surplus are significant. A price decrease of 10 €/MWh would lead to a gain in consumer surplus of approximately 975 million €/year or 92 € per Belgian Citizen per year.

The effect of an increase in interconnection capacity is also significant. The effects of the transmission costs are obvious as can be seen in figure 13. Because of the higher costs, the increase in consumer surplus is slowed down, while the decrease in prices is smaller and tends to level off. It is thus obvious that a split-up outperforms an increase in interconnection capacity with respect to electricity prices and consumer surplus. For more numerical results we refer to table 2.

7. Conclusions

In this paper, we use a simple analytical model of a national electricity market to analyze the effect of different government interventions on a dominant supplier with nuclear capacity.The government can intervene either by imposing proportional taxes or by liberalizing the country's nuclear

[15]Solving the equation $b = q_n^{split}$ results in $z_{max} = \frac{bcHL}{-c_n LH + ac_n LHc + LHp_g - F + Fca}$. z_{max} increases with increasing market size.

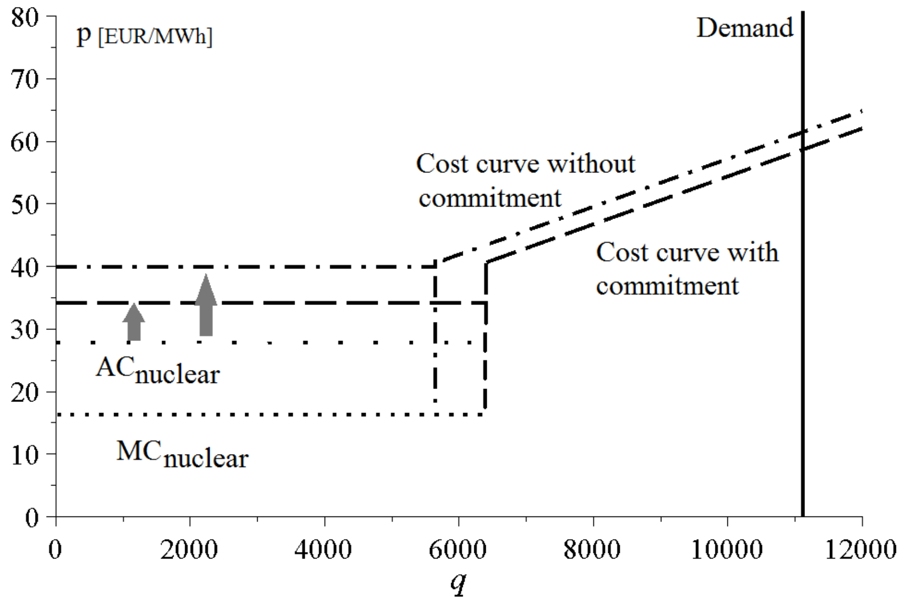


Figure 11: Long term scenario: effect on long term of government commitment and taxes. The taxes and the average costs are summed. This causes the costs to increase. The tax without government commitment causes the largest increase. $[s_l = 0]$

segment. Liberalization means splitting up the country's nuclear capacity or ensuring larger transmission capacity with neighboring countries.

The analytical solutions and the numerical illustration for the specific case of Belgium point to the following conclusions. First, liberalizing the nuclear segment by *splitting up the country's nuclear capacity is the most efficient instrument to maximize local welfare*, defined as the sum of consumer surplus, government tax revenues and profits earned by local shareholders of the nuclear firm. For the specific case of Belgium, the net increase in local welfare is 1,349 million € per year in our numerical simulations. If – instead of splitting up the country's nuclear capacity – the country increases its cross-border interconnection capacity and allows foreign nuclear generators to import electricity into the country, the net increase of local welfare is 984 million € per year. The difference is explained by the increasing costs of cross-border transmission. Second, *the welfare gains obtained by imposing proportional taxes are much smaller than those obtained by liberalization.* In the short run, the net increase in local welfare gained by imposing the optimal tax when no profits of the nuclear firm are flowing back to the home country, is 169 million €/year. If the percentage of local shareholders in the nuclear firm increases, the optimal tax decreases and can become negative: a subsidy. Third, the *welfare effects of taxes are found to be less favorable when one considers the negative long-run effects on investments.* In the long run, capacity decisions are endogenous, hence the nuclear firm has greater possibilities to use its market power to shift part of the tax burden onto consumers. The solution in the long run depends on whether the government can make a credible

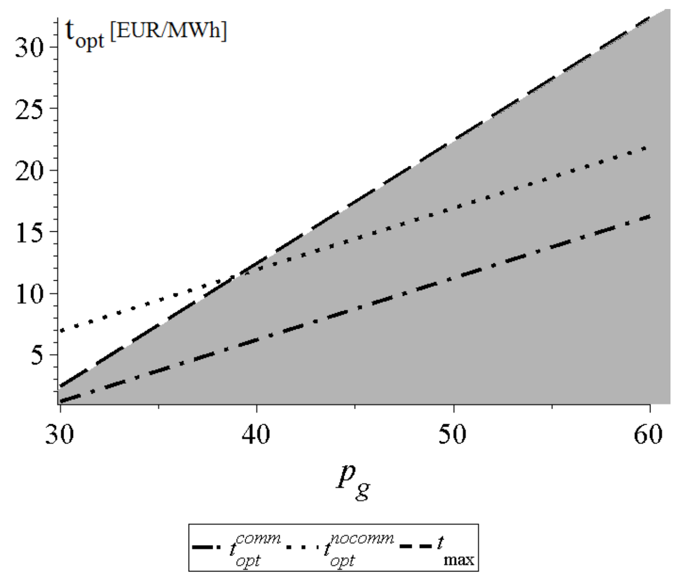


Figure 12: Long term scenario: influence of p_g on the optimal tax. The gray zone indicates the taxes the government can levy without blocking investments. The dashed line indicates the maximum tax a government can levy in function of p_g without inhibiting investments. $[s_l = 0]$

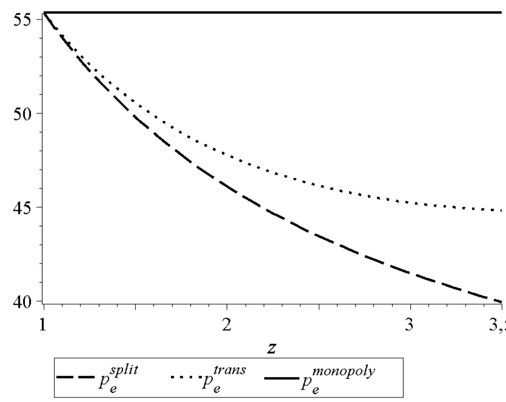
commitment to a long-run stable tax or not. In the case of a credible commitment, taxes are lower, resulting in larger nuclear capacity investments and a net increase in local welfare of 47 million € per year, compared to an increase of 10 million € per year when no commitment can be made. All welfare gains are measured compared to the long-run scenario without taxes. Finally, since liberalization is often difficult to accomplish and proportional taxes are relatively inefficient, some governments consider *lump sum taxes on nuclear energy as an alternative* instrument, although anti-discrimination laws makes it generally difficult to impose such taxes. In principle, a lump sum tax does not affect electricity prices, however, the tax may foster an investment climate that deflects capacity investments away to neigboring countries.

The proposed model has a number of limitations, which are discussed throughout the paper. We mention the most important caveats, which suggest ideas for further research:

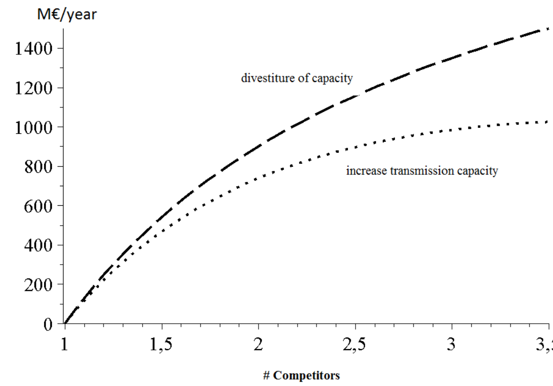
Time values. This model did not take the time value of profits and costs into account for the sake of conciseness. Future research may incorporate the time value of these flows.

Investments and government policies. If policies towards nuclear energy are too restrictive, investments in nuclear capacity will be deflect away from the local market. Future research could include this option explicitly into the model.

Capacity strategy. Having capacity in a certain country is a way to be able to produce in that country, because it offers greater production flexibility to respond to variations on the demand side, stabilizes the market and it can be used as an entry deterrent. Future research may include these strategic considerations into the model.



A: price in function of the number of competitors



B: ΔCS in function of the number of competitors

Figure 13: Effects of a liberalization of the Belgian nuclear generation capacity on the electricity price and the consumer surplus. (^{split} is the case of a divestiture (split-up) of the nuclear capacity while ^{trans} is the case with the increased interconnection capacity)

Withholding. On the one hand, there are political and legal arguments to say it is very unlikely that generators withhold capacity. On the other hand, in the long term there are arguments to say that generators can withhold capacity. It is possible to direct the long term investments in order to manipulate the short term production. In the short term the generator will use its full capacity so they cannot be accused of abusing market power. Nevertheless, there are also some strategic arguments against the abuse of market power. According to Wolfram (1999) firms with market power will not fully use their power in a liberalized electricity market. This phenomenon is explained by regulatory constraints and a threat of entry. Financial contracts between suppliers and their customers may also explain the observed difference between the prices predicted by market power models and the real electricity prices. Prices can be strategically set just below the long term costs of new entrants. Wolfram (1999) estimates that the actual use of market power is only 20% of the potential monopoly margin. The effects of this strategic withholing and the autoregulation could be investigated in future research.

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A. Mathematics

A.1. Welfare distribution and profits

The profits the nuclear operator(s) make are given by:

$$\pi_n = \int_0^{q_n} \frac{(q_e - b)}{a} - c_n \, dq \tag{27}$$

Where $q_e = q_n + q_g$. The profits of the gas-fired power plants are given by:

$$\pi_g = \int_{q_n}^{q_e} \frac{(q_e - b)}{a} - c\,(q - q_n) - p_g \, dq \tag{28}$$

The consumer surplus is given by the difference between the marginal utility of and the price for electricity:

$$CS = \int_0^{q_e} \frac{(q - b)}{a} - \frac{(q_e - b)}{a} dq = \int_0^{q_e} \frac{(q - q_e)}{a} \, dq = -\frac{q_e^2}{2a} \tag{29}$$

The share profits are given by:

$$\pi_n = p\, q - c_n \, q \tag{30}$$

The changes in welfare are given by:

$$\Delta G = \frac{p_q + cb - (1 - ac)\,(c_n + \bar{t})}{2c} \; \bar{t} \tag{31}$$

$$\begin{aligned} \Delta CS &= \frac{\bar{t}}{8\,(1 - ac)} \left[a\,(ac - 1)\,\bar{t} + 2\left(a^2 c c_n + bca - a\,(c_n + p_g) - 2b\right)\right] && (32) \\ &= -\frac{\bar{t}b}{2} \quad \text{when } a = 0 && (33) \end{aligned}$$

The consumer surplus is given by a simplified expression for $a = 0$. If the government imposes a proportional tax and the producer has monopoly powers, half of it is paid by the consumers when demand is inelastic. The consumer surplus decreases by imposing such a tax.

$$\Delta \pi_L = s_l \left(\frac{1 - ac}{4c} \, \bar{t}^2 - \frac{c_n\,(2ca - 2) + 2p_g + 2bc}{4c} \, \bar{t} \right) \tag{34}$$

A.2. Model mathematics of the basic model

In this model the nuclear operator is a monopolist and, therefore, he has complete control over the activated nuclear capacity, q_n, subject to $q_n \leq \bar{Q_N}$. If in a numerical case appears that $q_n > \bar{Q_N}$ then the outcome is $q_n = \bar{Q_N}$. In a perfect competitive gas market the price p is set by the intersection of the demand curve and the cost curve, assuming that $q_n \leq b$. The equilibrium total quantity of active capacity, q_e, in function of q_n, and using equation 6 is:

$$q_e = \frac{b + ap_q - acq_n}{1 - ac} \tag{35}$$

The equilibrium electricity price is:

$$P(q_e) = p_e = \frac{p_g - c\,(q_n - b)}{1 - ac} \tag{36}$$

If this price is used in equation 27, the profits of the dominant firm can be calculated. These profits can be maximized by setting $\frac{\partial \pi_n}{\partial q_n} = 0$. This is what a monopolist will do if he controls all nuclear capacity. He can withhold capacity in order to drive the electricity price up.

$$\frac{\partial \pi_n}{\partial q_n} = \left(\frac{p_g + cb}{1 - ac} - c_n \right) - \frac{2cq_n}{1 - ac} = 0 \tag{37}$$

The interpretation of these equations is straightforward when one assumes that $a = 0$. A monopolist sets its output by setting the marginal revenues (MR) equal to the marginal costs ($MR = MC = c_n$). The marginal revenues are known as $MR = [p_g - c\,(q_n - b)] - cq_n$, which has twice the slope of the residual demand curve (equation 36) as is well-known for linear demand curves. The extremum of the profits can be found when the nuclear operator activates a capacity q_n:

$$q_{n1} = \frac{p_q + cb - (1 - ac)\,c_n}{2c} \tag{38}$$

In this equation, q_{n1} is q_n when there is no government intervention. Furthermore $\frac{\partial^2 \pi_n}{\partial q_n^2} = -\frac{2c}{1-ac} < 0$, since $c > 0$ and $a < 0$. The second-order derivative is thus negative, guaranteeing that the found extremum is indeed a maximum.[16] The only boundary condition to this result is that $q_n \leq Q_N$. The price is given by:

$$p_{e1} = \frac{1}{2} \frac{-bc + acc_n - p_g - c_n}{-1 + ca} \tag{39}$$

The consumer surplus is given by equation 29. In this basic scenario, the consumer surplus is:

$$CS_1 = \frac{q_{e1}^2}{2a} - \frac{b}{a} q_{e1} - p_{e1} q_{e1} \tag{40}$$

where q_{e1} is the equilibrium activated capacity without government interventions, i.e. when $q_n = q_{n1}$.

B. Numerical data

B.1. Calibration

To make a model that simulates the Belgian electricity market, I make estimates about demand, marginal cost curves and nuclear investment costs.

First, I assume a nearly vertical demand curve[17]: $a = 10^{-7}$. The value of b is estimated based on the demand data provided by London Economics (2004). London Economics (2004) writes that 50% of the time, Belgian demand is lower than 9744 MW, while Belgian electricity demand is in

[16] This check is also performed in the remainder of the paper, but it will not be mentioned anymore.

[17] I do not take $a = 0$ since this can cause numerical problems.

1% of the time higher than 12503 MW with a peak around 13000 MW. Since I do not take into account these cyclical differences, I work with the average Belgian demand which is 11124 MW.[18]

Second, I make an estimation of the cost curve of Belgian generator capacities. Appendix B.2 gives a detailed description of this procedure. To construct this cost curve, I take the Belgian generation capacity park from the Elia website (Elia, 2009). Then, I estimate the costs of production for each technology mentioned in this generation park, based on the average efficiencies of these different generation technologies and on average fuel prices. The resulting cost curve is given in figure 14. The slope of the competitive fringe cost curve is calculated as the slope of the line between the cheapest and most expensive non-peak unit. The values of $c,\ p_g,\ c_n$ are given in table 5.

Third, I estimate the fixed costs of a nuclear power plant. (Millborrows, 2008) suggests to take $2720\frac{GBP}{kW}$, which equals[19] 3 424 000 €/MW. With 7500 hours a year (i.e. at 86% utilization) and a lifetime of 40 years, this equals 11.4 €/MWh.[20]

Table 5: Numerical values of parameters

Parameter	Value	Parameter	Value
a	10^{-7}	F	3 242 000
b	11124	H	7500
c	0.003823	L	40
c_n	16.23	T	5
p_g	40.5		

B.2. Cost curves

The costs curve is built based on:

- Belgian generation capacity composition provided by Elia (2009)
- Average efficiencies of generation technologies.
- Fuel prices averaged over the 2003-2007 period.

The excel-file provided by Elia gives all Belgian generation plants with their respective fuels. These data are however too elaborated for a simple "estimation". Therefore I make some simplification:

- I will take one efficiency for a certain technology even though different plants will have different efficiencies. For a summary of efficiencies, please consult table 6
- I will not make a distinction between compositions of fuels

[18]Since I work with linearized functions, the conversion to peak and off-peak demand is easily done: linear functions do not change after a transformation. This means that the actions of transforming the demand curve (i.e. taking the average) and performing linear calculations can be switched.
[19]at average exchange rate for the period 2003-2007
[20]Millborrows (2008) suggests a discount rate of 10% and a lifetime of 40 years.

- I will not make a distinction between different specific types of generation technologies, eg. CCST or CCGT.
- Generation technologies like cogeneration, water power generation and wind energy will not be considered in this estimation of the cost curve since these technologies are baseload generation technologies and therefore they will not affect the slope of the competitive fringe.

Table 6: Average efficiencies of Generation technologies

Generation technology	Average efficiency
Combined Cycle	55%
Classical	37%
Diesel	45%
Gas Engine	40%
Gas Turbine	37%
Turbojets	30%

To calculate the fuel costs, I took an average of the fuel prices over the 2003-2007 period.[21] For the fuel prices (Natural gas (BP, 2008), Coal (BP, 2008), Gas Oil, Fuel A (eia, 2008), Jet Fuel (eia, 2008)) , please consult table 7. The fuel cost is calculated as the fuel price divided by the average efficiency of the generation technology. These costs are the main share of the generation costs.

Table 7: Fuel costs over period 2003-2007

Fuel type	Fuel price [€/MWh]
Natural Gas	20.91
Coal	8.9
Gas Oil	32.4
Fuel A	193.2
Jet Fuel	199.2

Besides the fuel costs, other costs like operation costs are important. For simplicity we assumed that the O&M cost of gas technologies and coal technologies are equal, i.e. $1,92$ €/MWh (Rokke, 2006). The O&M cost of nuclear power plants are estimated on $10,8$ €. CO_2-costs are also calculated based on the average CO_2 emissions and a certificate price of 15 €/$ton\ CO_2$ (Rokke, 2006). The total operational costs of the different technologies are given in figure 14.

A reasonable transmission cost is 5 €/MWh.[22]

[21] taking into account the average exchange rate between 2003-2007

[22] The average transmission costs of Belgium, France, Germany and the Netherlands. Calculated from www.elia.be.

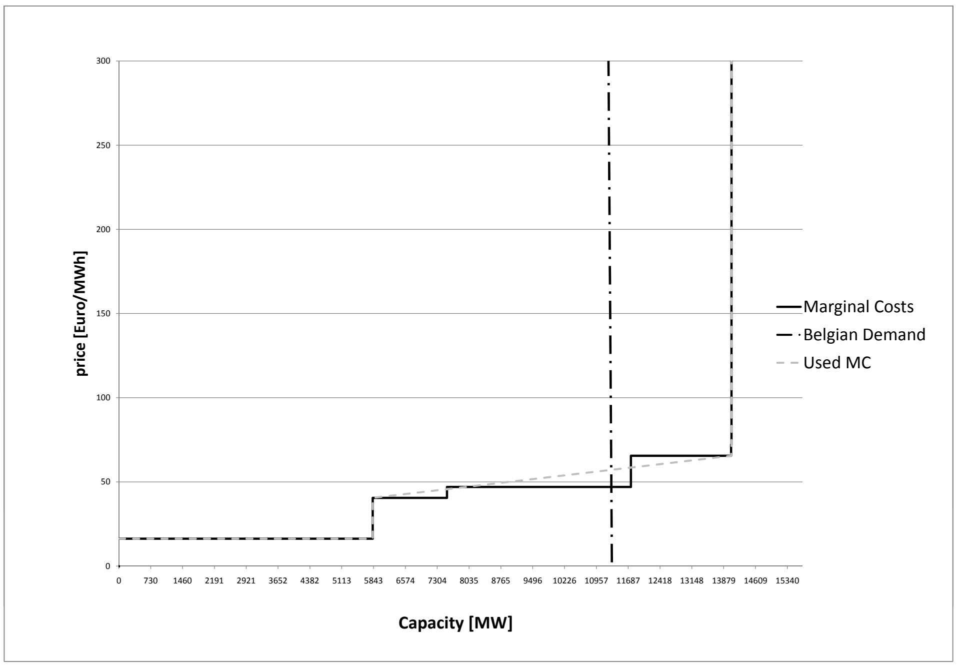


Figure 14: Estimation of the Belgian generation production curve

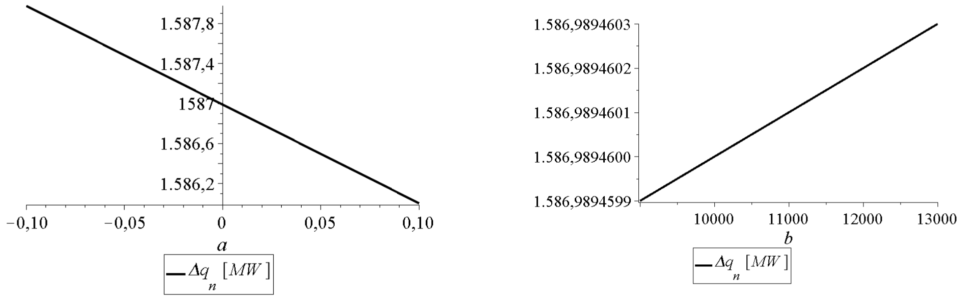
C. Sensitivity of the results

We looked at the sensitivity of Δq_n (the difference in nuclear capacity), Δp (the difference in electricity price) and ΔW_b (the difference in Belgian welfare) between the basic scenario (paragraph 3.1) and the case with an optimal tax imposed by the government on the short run. we am interested in the differences because the relative effects of governmental instruments are more important to this study than their absolute change. First we looked at the influence of a within the range of $-0.1 \ldots + 0.1\ MW^2h/€$. The reason for this is that demand for electricity is rather independent of the price within the discussed range of prices. Apparently the results are not very sensitive to variations in a within the discussed range: the variations of the results are smaller than 0.5%.

Second the sensitivity of the outcomes is discussed in terms of b. The appropriate range is the range between $9000MW$ and $13000MW$, which surely includes the difference between peak and off-peak demand. As can be seen in figures 15.B, 17.B, 19.B, the results are highly independent from b.

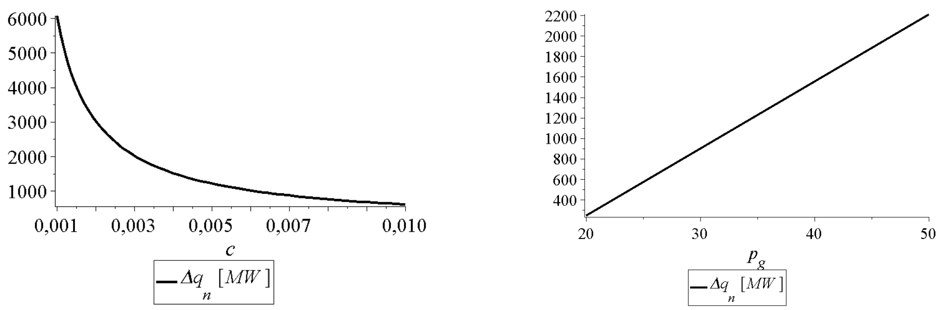
Third, we plotted the results under consideration in function of varying c in figures 16.A, 18.A, 20.A. Except for the price difference, the results are sensitive to variations in c. This can be explained by the fact that the higher the slope of the competitive fringe, the more incentive the dominant firm has to withhold nuclear capacity. An extreme case is when the slope of the competitive fringe's costs curve is horizontal. Then the dominant firm has no incentive to withhold much of its capacity as discussed in chapter 3. The appropriate range was less evident and chosen on the range between $0.001 \ldots 0.01\ €/MW^2h$ since this range includes possible realistic slopes of the cost curve of the competitive fringe.

Fourth, the dependence of Δq_n, Δp and ΔW_b on p_g is investigated. In figures 16.B, 18.B, 20.B. one can see that the results are very depending on p_g within the interval chosen on $20 \ldots 50\ €/MWh$ based on literature (D'Haeseleer et al. (2007) and CREG (2006)). Δq_n varies with 5.6% per unit increase in p_g while Δp changes with approximately 7 $€/MWh$ over the considered interval. The implicitions on Belgian Welfare are significant. When p_g changes from 20 $€/MWh$ to 50 $€/MWh$, the difference in Belgian welfare increases with $\pm$30000 € per hour, i.e. $\pm$26 million€ per year . This is a significant effect. In the calculated difference in welfare i.e. at $p_g = 40,5$ the curve has an elasticity of $\frac{\frac{\Delta W_b}{19270.85}}{\frac{\Delta p_g}{40.5}} = 1.82$. Apparently the tax instrument is more effective when the difference between c_n and p_g is larger.



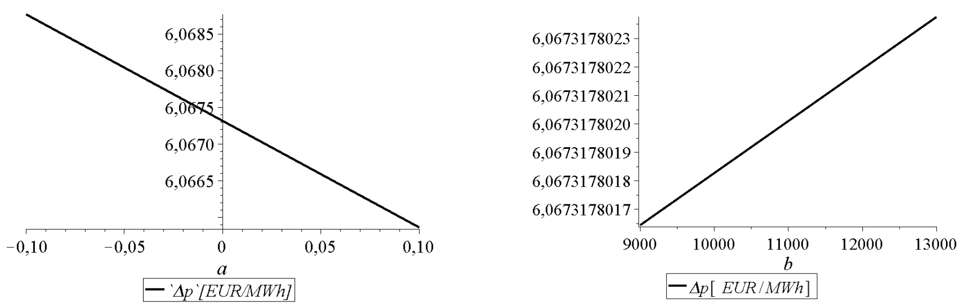
A: Δq_n in function of a B: Δq_n in function of b

Figure 15: Sensitivity of Δq_n in function of a and b. $[s_b = 0]$



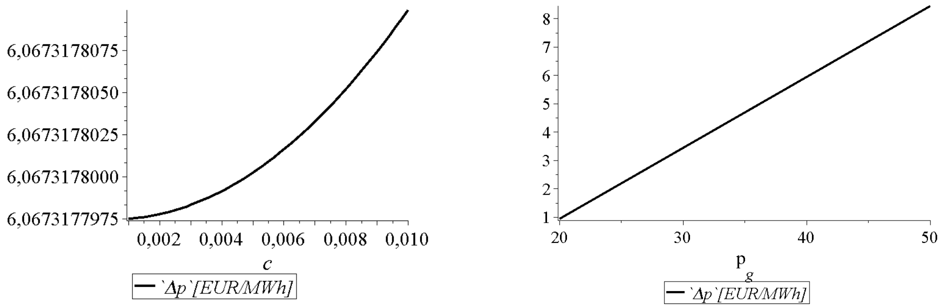
A: Δq_n in function of c B: Δq_n in function of a

Figure 16: Sensitivity of Δq_n in function of c and p_g. $[s_b = 0]$



A: Δp in function of a B: Δp in function of b

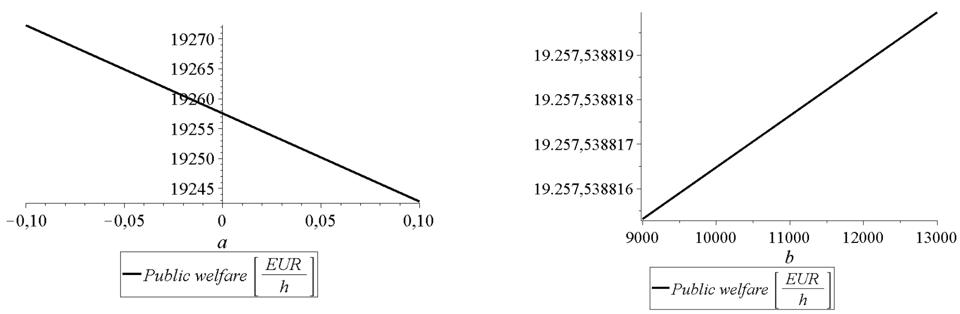
Figure 17: Sensitivity of Δp in function of a and b. $[s_b = 0]$



A: Δp in function of c

B: Δp in function of a

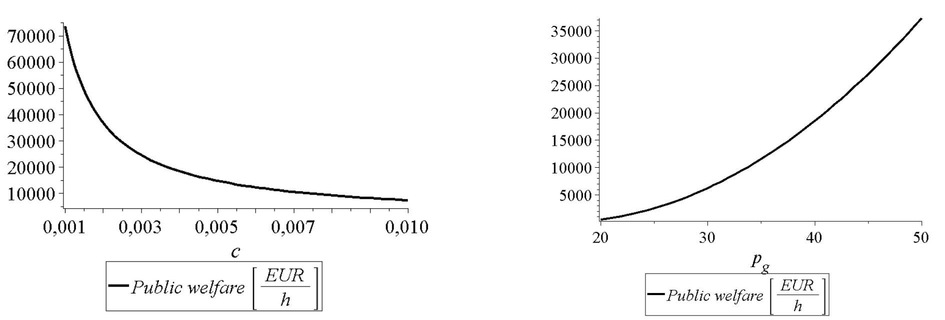
Figure 18: Sensitivity of Δp in function of c and p_g. $[s_b = 0]$



A: ΔW_b in function of a

B: ΔW_b in function of b

Figure 19: Sensitivity of ΔW_b in function of a and b. $[s_b = 0]$



A: ΔW_b in function of c

B: ΔW_b in function of a

Figure 20: Sensitivity of ΔW_b in function of c and p_g. $[s_b = 0]$