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May a greener technology mix mitigate market power? Mixed vs private competition in the EU electric power market

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ABSTRACT

We investigate the extent to which a greener-oriented technology mix may affect collusion incentives among private electric power generators (PEGs). In our model, the government decides whether to privatize the state-owned electric power generator (SOG) or keep it under public hands. Overall, even though collusion is easier to sustain when the state maintains the SOG, the extra benefits from collusion and the negative effects on consumer surplus are lower. This effect is reinforced when greener inputs attain a higher share in the technology mix. Moreover, when the number of PEGs is low, keeping the SOG under public hands mitigates the negative effects of collusion. We run simulations with data from the electric power market of several EU country members to study the effect that rocketing prices of fossil inputs and the composition of the technology mix have in the ability to collude, and how consumer surplus is affected. Our findings suggest that the SOG and the presence of green energy inputs may protect consumers in two ways: (*i*) the SOG acts as an output expanding agent enhancing consumer surplus, which decreases less when PEGs collude, and (*ii*) these effects are larger as the share of greener energy inputs increase in the technology mix.

1. Introduction

Sustainable economic growth requires greener technologies to manufacture environmentally-friendly products. Oligopoly models are useful tools to analyze how green production affects social welfare in different markets (see, for instance, [1]). One of the markets with the greatest impact on sustainable growth is the electric power sector. This sector has been largely liberalized in most developed countries since the last decade of the 20th century. Since then, in these countries, the wholesale electric power market is organized as a bidding market, where electric power generators compete by submitting price-quantity bids in daily interactions.[1] Although over this period technological improvements have enhanced the deployment of renewable generation technologies and the efficiency of nuclear plants, in the majority of cases electric power generation companies exert a high market power by bidding with power plants based in fossil inputs. Moreover, the deployment of off-shore solar and wind installations is far to be generalized, which makes the household and industry sector highly dependent on the on-shore market conditions. In this setting, collusion might be easily reached and thus, the decision to privatize the state-owned generator (SOG, hereinafter) strongly determines the extent to which the government may partially control the market. Hence, when the market experiences waves of high pollutant (fossil) input prices, the existence of a SOG may reduce the negative effects of the market power exerted by private electric power generators (PEGs, hereinafter). Moreover, the number of competitors and the share in the technology mix of pollutant inputs, nuclear power and renewable sources may impact the generators' behavior (see, for instance, [2]).

1.1. Privatization, technology mix and market power

In this paper, we study whether the decision to privatize the SOG may alter the strategic behavior of PEGs when they attempt to collude, its sustainability over time, and how consumer surplus is affected. We also focus in how the composition of the technology mix between greener and pollutant sources affect the level of production costs and thus the ability to exert market power. In our approach, the SOG maximizes its profits (avoiding public debt) plus consumer surplus, which contrasts with the traditional assumption of a social welfare-maximizing public firm. We argue that this objective is in

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[1] Generators submit day-ahead offers on an hourly basis according to the future demand forecast.

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accordance with the special characteristics of the electric power sector, where generators may exert high market power. This assumption may also be justified by the recent positions taken by antitrust authorities in different developed countries and, in particular, within the European Union (see, for instance, [3]).[2] Under this approach, in the event that private generators exert market power abuse reducing consumer surplus, the government may maintain a SOG in order to discipline the market because the SOG does not take part in a collusive agreement. In other words, the profits of the private companies are not included as part of the SOG's strategic behavior, expanding its electric power production, which in turn damages the profitability of the collusive companies.

The level of input prices and the composition of the technology mix also plays a key role in our research. Indeed, when there are multiple generation technologies, aggregate marginal costs are affected by the evolution of input prices. In the present context of rocketing fossil input prices as a result of the Ukraine invasion, and the environmental agreements in order to avoid the effect of climate change, national electric power markets have been strongly affected. The portfolio proposed by the EU in the model for 2030 reveals differences with the limits proposed for the 2010 horizon. It includes a share of nuclear technology between 23% and 30% (in 2010, it was 27.75%) as [4] pointed out. In addition, the electricity market is being increasingly challenged by the high penetration of intermittent renewable power and the transformation of the consumers' energy space. In accordance, several modifications to current electric power market designs have been proposed in the context of EU country members [5]. Renewable electricity subsidies and carbon pricing seems to be useful tools to mitigate carbon emission. In this respect, Yin et al. [6] have studied how the Regional Generation Cost Evaluation Model (RGCEM) can be applied to analyze the emission reduction potential in a region of China, where the power sector contributes 40% of the carbon emission.

To the best of our knowledge, the literature has neglected the study of how a SOG may affect the ability to collude by PEGs in electric power markets. Since the seminal paper by Klemperer and Meyer [7] the supply function competition approach has been largely used to model wholesale electric power markets. A pioneering paper by Green and Newbery [8] analyzed the British wholesale electricity markets showing that the Nash equilibrium in supply schedules implies a high mark-up over the marginal cost as well as substantial deadweight losses. Green [9] also uses the supply function competition approach to discuss the effect of government policies on the electricity spot market in England and Wales. He found that partial divestiture should lead to a substantial reduction in deadweight losses. More recently, in [10,11], several features of recent developments concerning spot electricity markets, and technical features of supply function competition have been studied. Several papers have considered the relationship between competition and the optimal privatization policy using different competition models. De Fraja and Delbono [12] and subsequent literature (see, for instance, [13]) found that, in some cases, a public company should be privatized maximizing profits rather than welfare. The intuition is that the public (private) firm's output level may be excessive (insufficient) from the welfare viewpoint, and privatization may induce welfare-improving production substitution from public to private firms. Considering a price-setting game with product differentiation, Anderson et al. [14] show that full nationalization is the best policy in the short-run with an exogenous number of firms while, in the long run, privatization may lead to further entry and become optimal. Other non-cooperative approaches to model the functioning of electric power markets include bilevel games. In [15], the authors present a detailed overview of one-level games within the Nash equilibrium approach in order to introduce a more sophisticated tool based on bilevel games, where players take decisions sequentially. More precisely, they consider Cournot, Bertrand, and Supply function equilibrium models when the participants make decisions simultaneously, while Stackelberg, Multiple-leader-multiple-follower, and generalized hierarchical equilibrium models are analyzed when the participants make decisions at different stages. They emphasize that the number of players (either leaders or followers) have different impact on the final results and the relationship between one-level and bilevel games.

1.2. Overview of the research issue

In Europe, the issue of the privatization of SOGs remains open. In the United Kingdom, the Central Electricity Generating Board (CEGB) was the state-owned responsible for generation and transmission whereas National Power and PowerGen, the two major electric power generators, were sold in 1991 although the government retained some of the Nuclear Electric power. Other generators such as Scottish Power and Scottish Hydro were also sold. In recent years, to meet challenging emission target set by Government, power system in the UK has a rapid increase of encourage renewable energy integration, adopt new technologies, stimulate consumers' participation, and ensure the power system resilience[3] In France, Électricité de France remains in public hands in a small mixed oligopoly where generation by nuclear power, which accounted for 68.8% of total production in 2021, is entirely owned by the French government. Conversely, in Spain, the former SOG Endesa was fully privatized at the end of the first decade of the 21st century. This difference contributes to the fact that these two countries are being affected in a different way by the soaring of European wholesale gas and coal prices: whereas in Spain the wholesale electric power price has strongly increased, in France, the increase has been relatively moderated. This comes from two different features. On the one hand, in France the presence of a SOG mitigates the ability to exert market power abuse by PEGs. On the other hand, the huge weight that nuclear power has in the French technology mix diminishes the impact that an increase in fossil input prices has in the cost structure. In other countries such as Germany and Sweden, the electric power sector is also a mixed oligopoly whereas in Italy, the former SOG monopolist ENEL was fully privatized.

Outside Europe, the results of privatization are mixed. In United States, there is not a nationally integrated market, and several different systems are adopted across regions and states. Moreover, some local governments may have its own electric power companies. In Canada, several provinces have their own large firm competing with other small generators. In those countries where electric power generation is provided at national level, some of them have favored public ownership of electric power supply (some examples are Brazil, Mexico, Morocco, and Algeria) whereas others such as Chile switched from a pure public to a pure private system in 1989. A complete survey for Latin American countries can be found in [17]. A good example of a mixed oligopoly is Japan, whose electric power market is characterized by a government-led approach but with partnerships with the private sector and local governments. For example, TEPCO, the largest electric power company in Japan, is partially owned by the central government and the Tokyo local government (see [18]). Another interesting example is Australia

[2] This paper focuses on the choice and implementation of what seems to be the dominant self-declared paradigm for many competition authorities that their job is to protect consumer welfare. It follows the discussion among economists about the merits of consumer welfare as opposed to total welfare. Modern EU competition policy, Commission Regulations, guidelines and other policy documents are about protecting consumer welfare in a large extent since the last two decades. For instance, in 2010 commissioner in charge of competition policy Joaquín Almunia stated, "Competition policy is a tool at the service of consumers. Consumer welfare is at the heart of our policy and its achievement drives our priorities and guides our decisions".

[3] For a recent overview of the British market see [16]

where historically the generation had been built under public ownership. Despite the industry restructuring from the early 1990s, several networks are still serviced by state-owned power corporations. In fact, between 1999 and 2016, 26% of new capacity occurred with public investment (see [19]).

1.3. The supply function competition approach

Although research considering supply function competition in mixed oligopolies is increasing, that literature is still scarce. Regarding the issue of collusion in mixed oligopolies, Wen and Sasaki [20] is among the first approach discussing this problem, whereas in [21] it discusses the extent to which government-leading may implement a welfare-improving collusion in a mixed duopoly. Other papers have already considered the possibility that private firms achieve a collusive agreement in a mixed oligopoly with either price or quantity competition (see, for instance, Delbono and Lambertini [22], Colombo [23] and Escrihuela-Villar and Gutiérrez-Hita [24]). It is generally found that the presence of a public firm makes collusion among private firms harder to sustain. In this paper, we contribute to fill this gap. Yasui and Haraguchi [25] study a duopoly with a partially privatized public firm and a profit-maximizing firm. They found that the public firm's aggressive behavior makes the private firm to be more aggressive and consequently full nationalization is advised. In [26] the case of heterogeneous goods in a mixed oligopoly is analyzed. It is found that social welfare and consumer surplus are affected by the heterogeneity of goods (substitutes or complements). In [27] a SOG that maximizes welfare is assumed to be (partially) privatized. They obtain that if the degree of privatization decreases, consumer surplus increases. Only when the number of generators increases, full privatization may provide similar levels of consumer surplus. Moreover, it is also obtained that price-cost margins increase as marginal cost increases. Another interesting contribution is [28] where, in a private oligopoly, the optimal environmental policies in a dynamic setting with R&D can be found. In their model, two private firms producing differentiated products compete in a differential game setting supply schedules. They show that the impact on the welfare of increased competition depends on the nature of preferences and technology.[4]

There are other approaches in the literature that model the organization of restructured wholesale electric power markets. For instance, in [30] a conjectural variations model to analyze market power in liberalized electricity markets is presented. They compute a parameter that represents the degree of competition to monitor the competitive behavior of generating operators. They also conducted an application to study the day-ahead Iberian electricity market (MIBEL). Mendes and Soares [31] develop a two-stage model for the MIBEL in order to highlight the impact of wind generation versus combined cycle gas turbines in electric power generation. They found that generators can be expected to increase their renewable generation capacity (wind power).[5] In a context of vertical integration, Guo et al. [33] investigate the extent to which it can be considered a right structure approach as a remedy of the market power abuse problem in a context of electricity market deregulation reforms. They use real generation mix data in Guangdong province, China, providing the market equilibrium with and without vertical integration.

[4] There are also studies focused in the importance of asset divestitures in market competition and the potential need of regulation (see for instance [29]).

[5] An application to identify the optimum electric power under boundary conditions can be found in [32]. They present a methodology based on artificial intelligence and apply the method to the specific case of the Spanish electricity market long-term decarbonization. Results show the significant barriers to achieve a 100% renewable electric power mix without excessive curtailments or installed power.

1.4. Research objectives

Our contribution to the literature that studies electric power generation under the assumption of supply function competition is twofold. Firstly, we characterize the effect that both the number of PEGs and how the level of greener and pollutant resources affect production costs in electric power markets weather may exist or not a SOG. Secondly, we introduce the study of collusion in the market assuming that the SOG does not take part in the agreement. We obtain that the privatization decision may alter the opportunity to collude and its sustainability over time depending on the composition of the technology mix. In addition, even though collusion is easier to sustain when the state maintains the SOG, the extra benefits from collusion and the negative effects on consumer surplus are lower than the case where the SOG is privatized. Finally, when the number of PEGs is low, privatization of the SOG is not advised because the public generator mitigates the negative effects of collusion on consumer surplus. Besides, this effect is reinforced when the technology mix is more pollutant. Conversely, the state may privatize the SOG when the number of PEGs is high enough, which in turn depends on the level of generation costs.

To illustrate our results, we run a simulation of our model by using real data from the EU electric power market. We highlight the extent to which the current situation of rocketing fossil input prices and the composition of the technology mix may affect electric power prices and the ability to exert abuse of dominant position by PEGs. This discussion is also relevant in the context of climate change. Climate neutrality by 2050 means renewable sources growth will further accelerate. Indeed, renewable sources in EU country members overtook pollutant sources to become the main source of electric power generation in 2020 [34]. Then, as renewable sources become the main energy input, fossil input prices may reduce their impact on final electric power prices. Additionally, the persistent volatility of fossil input prices and their impact on society has changed the traditional view about the position of regulatory authorities, which may influence the governmental decision on whether to privatize the SOG company or not.

The rest of the paper is structured as follows. In Section 2, we present the setup of the model, where a SOG competes with n PEGs. The former can be either privatized or remain in public hands. We characterize and solve the one-shot game for both scenarios, reporting the results as a function of a cost parameter, which stand for the level of production costs, and the number of generator companies. In Section 3, collusion is characterized by assuming that the SOG does not participate in the collusive agreement. Section 4 investigates the extent to which collusion can be sustained over time when colluding generators follow the well-known trigger strategies. Section 5 provides an empirical simulation for our model. Finally, Section 6 concludes. Selected proofs are relegated to the Appendix A.

2. Benchmark: a competitive oligopoly

In this section, we present the competitive oligopoly scenario where a SOG firm S (indexed 0), and n PEGs simultaneously compete by offering price-quantity auctions in a supply function fashion as in [35].[6] As in electric power markets organized as bidding systems price-quantity auctions are submitted day-ahead, the final realization of demand is unknown ex-ante. Hence, some level of uncertainty is needed because the level of electric power that consumers are going to demand is not known in advance.[7] Once the final realization of the demand is

[6] In the seminal paper by Klemperer and Meyer it can be found a complete characterization of the supply function equilibrium under uncertainty. In our model, the strategic variable of the generators is the slope of the supply function instead of the market price. It is equivalent in terms of results once the uncertainty is solved, and the model arrives at the same equilibrium.

[7] In our study, we focus on simultaneous competition, although other interesting approaches include sequential games as in [36].

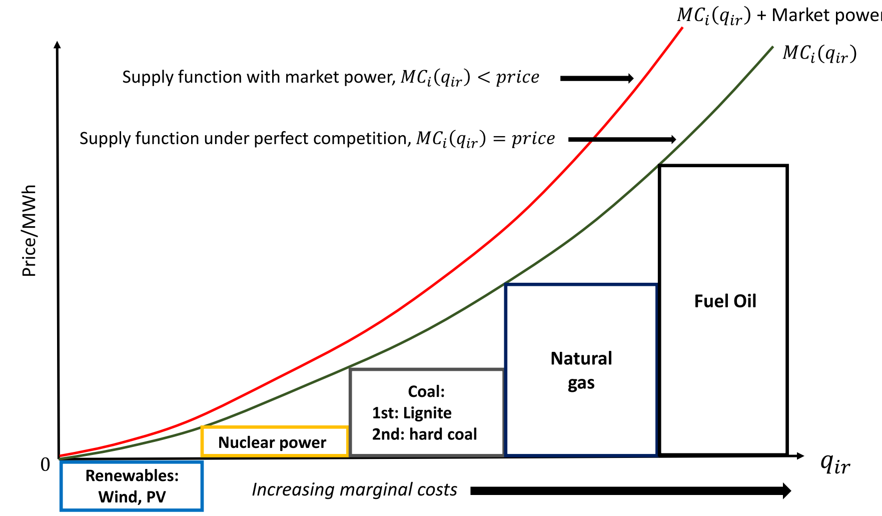

Fig. 1. Merit order of the technology mix (q_{ir} is the quantity of generator i using the resource r).

known the uncertainty is solved, and a unique market equilibrium is reached where the aggregate supply function meets consumer demand. We denote by q_i, $i = 0,\ldots,n$, $n \in \mathbb{N}$ the quantity of electric power each generator produces, where the quantity indexed by zero is the electric power generated by firm S. Let us denote by p the market price, define the vector $q := (q_0, q_1, \ldots, q_n) \in \mathbb{R}_+^{n+1}$ and $Q := \sum_{i=0}^n q_i$ the total amount of electric power. Market demand $D(p) = \alpha - p + \varepsilon$ comes from the surplus maximization of the representative consumer,[8] $CS(Q) = U(Q) - pQ$, where $U(Q) = (\alpha+\varepsilon)Q - Q^2/2$ is the utility function and ε is an additive shock with strictly positive density $f(\varepsilon)$ everywhere on the support $\Omega \subset \mathbb{R}_+$ such that $E(\varepsilon) = 0$ and $V(\varepsilon) = \sigma^2$. Electric power generators have quadratic costs $C_i(q_i) = (c/2)q_i^2$, where $c > 0$ stands for the slope of marginal cost ($MC_i(q_i) = cq_i$): the higher the greener composition of the technology mix, the lower the level of c. The quadratic costs assumption captures to some extent the existence of capacity constraints, which yield to an increasing marginal costs function (see for instance, among others, [7,35,37] or [27]). Capacity constraints are very relevant in modern electricity markets organized as bidding systems. This importance is increasing with the growing integration of renewables in energy markets. Capacity mechanisms play two fundamental roles in modern electricity markets. First, with the rising penetration of renewables, they provide important economic incentives for generators, especially due to the solar effect, create a "missing money" concern in the markets. Additionally, capacity mechanism offer an incentive to address security concerns arising from the variability and intermittency of these resources. Hence, the absence of an explicitly modeled capacity constraint is a limitation of the present work, leaving space for future research.

To better understand the model and the implications that differences in the technology mix have in the generation market, we introduce the concept of merit order. The merit order dispatch in electric power generation describes the sequence in which power plants deliver power, according to the principle of the lowest marginal costs. Thus, the final composition of the electric power production and the market price depends, on the one hand, of the composition of the technology mix and, on the other hand, the level of market power exerted. Fig. 1 illustrates the concept of merit order and its impact on the generation market.

Following the literature, we assume that electric power generators submit continuous price-quantity bids according to the linear supply function[9] $q_i = \beta_i p$. Each generator chooses its supply function slope $\beta_i \geq 0$ which determines the amount of electric power generated at any market price p. We denote by $\beta := (\beta_0, \beta_1, \ldots, \beta_n) \in \mathbb{R}_+^{n+1}$ the vector containing generators' strategies, whereas $\beta_{-i} \in \mathbb{R}_+^n$ stands for the vector containing all the strategies except β_i. We recall that β_0 stands for the strategy of the electric power generator S. Ex-ante market clearing conditions yield prices

$$p(\beta) = (\alpha+\varepsilon)\cdot\frac{1}{1+\sum_{i=0}^n \beta_i}. \tag{1}$$

By using (1), a supply function of generator $i \in \{0, 1, \ldots, n\}$ is

$$q_i(\beta) = \beta_i p(\beta). \tag{2}$$

The corresponding profit function is then $\pi_i(\beta) = p(\beta)q_i(\beta) - C_i(q_i(\beta))$, and the total electric power is given by $Q(\beta) = \sum_{i=0}^n q_i(\beta)$.

The electric power generator S maximizes its expected objective function under two possible scenarios. Firstly, under the state-owned scenario ($\lambda = 1$), the generator S maximizes the consumer surplus plus its profits. Secondly, when generator S is fully privatized ($\lambda = 0$), the generator S maximizes its expected profits solely. The following maximization problem covers both scenarios,

$$\max_{\beta_0 \geq 0} \int_\Omega \left[(1-\lambda)\pi_0(\beta) + \lambda\big(CS(\beta) + \pi_0(\beta)\big)\right] f(\varepsilon)\,d\varepsilon. \tag{3}$$

Each electric private generator $j \in \{1, 2, \ldots, n\}$ maximizes its expected profits,

$$\max_{\beta_j \geq 0} \int_\Omega \pi_j(\beta) f(\varepsilon)\,d\varepsilon. \tag{4}$$

The social welfare function is $SW(\beta) = CS(\beta) + \pi_0(\beta) + \sum_{j=1}^n \pi_j(\beta)$, which is different from the objective function of generator S under the state-owned scenario, as we pointed out previously. By substitution of (1) and (2), generators' profits can be expressed as functions of β,

$$\pi_i(\beta) = (\alpha+\varepsilon)^2\cdot\frac{\beta_i(2-c\beta_i)}{2\left(1+\sum_{i=0}^n \beta_i\right)^2},$$

[8] This specification of the demand function provides the same qualitative results that the usual form $D(p) = \alpha - \beta p$, where β stands for the inverse of the elasticity of demand. We do not include this parameter to enhance the clarity of exposition.

[9] Although a more general setting where $q_i = \upsilon_i + \beta_i p_i$ can be assumed, when the marginal cost has a zero intercept the supply function $q_i = \beta_i p_i$ exists (see [7]). Thus, without loss of generality, and following [37–39], we take $\upsilon_i = 0$.

whereas consumer surplus is

$$CS(\beta) = (\alpha+\varepsilon)^2 \cdot \frac{\left(\sum_{i=0}^n \beta_i\right)^2}{2\left(1+\sum_{i=0}^n \beta_i\right)^2}.$$

The generators' strategic behavior, derived from the first order conditions in (3) and (4), provides the best response functions:

$$\begin{aligned}\beta_0(\beta_{-0}) &= \frac{1+(1+\lambda)\sum_{i=1}^n \beta_i}{1-\lambda+c\left(1+\sum_{i=1}^n \beta_i\right)},\\ \beta_j(\beta_{-j}) &= \frac{1+\sum_{i\neq j}^n \beta_i}{1+c\left(1+\sum_{i\neq j}^n \beta_i\right)},\end{aligned}$$

that satisfy the appropriate second order sufficient conditions. Assuming that PEGs are symmetric,[10] it yields $\beta_j = \beta_r$ for all $j, r \in \{1,\dots,n\}$, and the above best responses come down to

$$\begin{aligned}\beta_0(\beta_j) &= \frac{1+(1+\lambda)n\beta_j}{1-\lambda+c(1+n\beta_j)},\\ \beta_j(\beta_0,\beta_j) &= \frac{1+\beta_0+(n-1)\beta_j}{1+c(1+\beta_0+(n-1)\beta_j)}.\end{aligned} \tag{5}$$

These functions characterize generators' optimal strategies provided in the theorem below.

Theorem 1. *Optimal supply functions for the generator S and the n (symmetric) private generators*[11] *are*

$$\begin{aligned}\beta_0^*(n,c,\lambda) &= \frac{(n-1)c\xi^2+(2+c-n)\xi-1}{1-c\xi},\\ \beta_j^*(n,c,\lambda) &= \xi,\end{aligned} \tag{6}$$

where $\xi \equiv \xi(n,c,\lambda)$ is the unique positive value satisfying $a_3\xi^3+a_2\xi^2+a_1\xi+a_0=0$ with

$$\begin{aligned}a_3 &= n(n-1)c^2,\\ a_2 &= (2n-1)c^2+(\lambda-1+4n-n^2)c,\\ a_1 &= c^2+(4-2n-\lambda)c+2(1-\lambda-n),\\ a_0 &= \lambda-2-c.\end{aligned}$$

We observe that, according to (5), one can equivalently write

$$\beta_0^*(n,c,\lambda) = \frac{1+(1+\lambda)n\xi}{1-\lambda+c(1+n\xi)}, \tag{7}$$

although the expression in (6) is useful to derive properties and simplify further expressions. Moreover, by using Theorem 1, optimal market price, total electric power traded, and consumer surplus, can be presented as functions of $\xi = \beta_j^*(n,c,\lambda)$, say

$$\begin{aligned}p^*(n,c,\lambda) &= (\alpha+\varepsilon)\cdot\frac{1-c\xi}{\xi(2-c\xi)},\\ Q^*(n,c,\lambda) &= (\alpha+\varepsilon)\cdot\frac{-c\xi^2+(2+c)\xi-1}{\xi(2-c\xi)},\\ CS^*(n,c,\lambda) &= (\alpha+\varepsilon)^2\cdot\frac{(-c\xi^2+(2+c)\xi-1)^2}{2\xi^2(2-c\xi)^2}.\end{aligned} \tag{8}$$

In what follows, we present the competitive oligopoly solutions under the two outstanding scenarios.

[10] We assume symmetry in order to keep tractability of the model. Indeed, this is a limitation of the model, because by allowing different levels of the parameter c the quantitative results change.

[11] The expressions of the optimal strategies given in *Theorem 1* are different from those in [27] where the state-owned generator maximizes the social welfare function. Moreover, if we denote by $\widetilde{a}_i$, $i=0,1,2,3$, the coefficients given in [27, Theorem 1], then we have that $\widetilde{a}_3 = a_3+\lambda nc^2$, $\widetilde{a}_2 = a_2-3\lambda nc$, $\widetilde{a}_1 = a_1+2\lambda n$ and $\widetilde{a}_0 = a_0$.

2.1. Privatization of the electric power generator s

In this subsection, we report the case for $\lambda = 0$, when the electric power generator S is fully privatized. In this setting, we have a private oligopoly with $n+1$ generators.

Proposition 1. *The symmetric optimal strategy in a private oligopoly with $n+1$ electric power generators is $\beta_0^*(n,c,0) = \beta_j^*(n,c,0) = \xi_0(n,c)$, where*

$$\xi_0(n,c) := \frac{n-c-1+\sqrt{(n-c-1)^2+4nc}}{2nc}.$$

Moreover, the following inequalities hold,

$$\frac{1}{c+1} < \xi_0(n,c) < \xi_0(n+1,c) < \frac{1}{c} \quad \text{and} \quad \frac{\partial \xi_0}{\partial c}(n,c) < 0.$$

One of the statements of Proposition 1 is that $\xi_0(n,c)$ increases in n: as the number of electric power generators increases, the optimal strategy is to offer more electric power (at lower prices). Moreover, as the parameter c increases, marginal costs increase and thus, electric power generators exert higher market power (the value of $\xi_0(n,c)$ decreases in c). In a more simple setting, Delbono and Lambertini [40] get these results, which in turn were previously reported in [38].

Proposition 2. *Optimal profits of the symmetric $n+1$ private generators are,*

$$\pi^*(n,c,0) = (\alpha+\varepsilon)^2\cdot\frac{(1-c\xi_0)^2}{2\xi_0(2-c\xi_0)}, \tag{9}$$

The following properties hold:

(i) $\pi^*(n,c,0) > \pi^*(n+1,c,0)$.
(ii) $\arg\max_{c>0}\pi^*(n,c,0) = \widetilde{c}(n)$ *where* $\widetilde{c}(n) := -(n+1)+2\sqrt{n(n+1)}$, *and*

$$\max_{c>0}\pi^*(n,c,0) = \pi^*(n,\widetilde{c}(n),0) = (\alpha+\varepsilon)^2\cdot\frac{\widetilde{c}(n)(\widetilde{c}(n)+1-n)^2}{2(\widetilde{c}(n)+n+1)(-\widetilde{c}(n)+3n-1)}.$$

(iii) $\widetilde{c}(n) < \widetilde{c}(n+1)$ *and* $\pi^*(n,\widetilde{c}(n),0) > \pi^*(n+1,\widetilde{c}(n+1),0)$.

Statement (i) in Proposition 2 asserts that the ability to exert market power decreases as the number of generators increases: this is the competitive effect. Moreover, (ii) states that at $\widetilde{c}(n)$ the maximum profit level is reached, for each $n \in \mathbb{N}$. In other words, there is a critical value of the cost parameter c which allows electric power generators to exert a maximum market power. In the region $(0,\widetilde{c}(n))$ the cost effect (the negative impact on marginal cost of an increase in c) is lower than the market power effect (the ability to set higher prices as c increases). The contrary holds in the region $(\widetilde{c}(n),\infty)$. Finally, statement (iii) remarks that an increase of n makes that the maximum level of profits is reached at a higher $\widetilde{c}(n)$ (although it is lower as n increases). The intuition behind is that the larger the number of generators, the higher the level of inefficiency that can be assumed by generators in the sense that a maximum profit level can still be achieved. It seems that, when a negative input shock takes place, a relatively large n protects consumers from market power, but generators still may reach positive profits (although they are lower as n increases). This calls for attention about the present negative price shock in the European electric power market. Indeed, some EU member states are suffering extremely high electric power prices in the day-ahead market. On the one hand, it is due to the fact that electric power generation oligopolies are narrow. On the other hand, it may reveal some level of anticompetitive practises followed by generators. In this context, it is interesting to investigate the extent to which a SOG may mitigate market power and the success of collusion.

To illustrate the benchmark case, where $n+1$ generators compete, we present Fig. 2 to highlight the effect of the costs parameter c in the profits. We take $\alpha = 10$. In this case, $\widetilde{c}(10) = 9.976$ and $\widetilde{c}(4) = 3.944$. Then, for all positive $c \neq \widetilde{c}(10)$ one has $\pi^*(10,c,0) < \pi^*(10,\widetilde{c}(10),0) = 1.191$, and for all positive $c \neq \widetilde{c}(4)$ one has $\pi^*(4,c,0) < \pi^*(4,\widetilde{c}(4),0) = 2.786$.

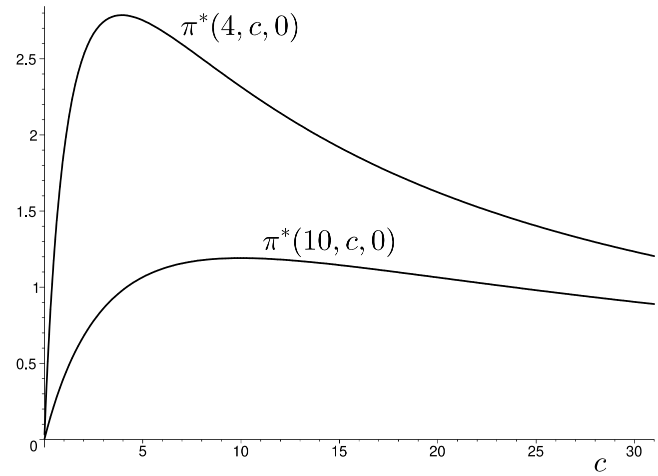

Fig. 2. Optimal profits of 5 and 11 private generators (including the fully privatized one).

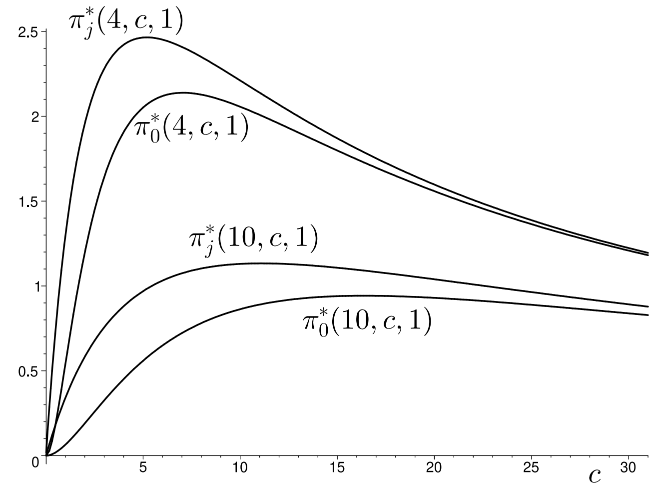

Fig. 3. Optimal profits for the SOG and the n PEGs (for $n = 4$ and $n = 10$).

2.2. Mixed oligopoly

Here we consider that the generator S remains as a SOG competing against n PEGs. In this case $\lambda = 1$.[12] As we stated above, we assume that generator S maximizes own profits plus consumer surplus.[13] Next proposition characterizes the optimal strategies in the mixed oligopoly environment.

Proposition 3. *The optimal strategies for the state-owned generator S and the n private generators are*

$$\beta_0^*(n,c,1) = \frac{1+2n\xi_1}{c+cn\xi_1},$$
$$\beta_j^*(n,c,1) = \xi_1,$$

where $\xi_1 \equiv \xi_1(n,c)$ is the unique positive value satisfying

$$n(n-1)c^2\xi_1^3 + ((2n-1)c^2 + (4n-n^2)c)\xi_1^2 + (c^2 + (3-2n)c - 2n)\xi_1 - (1+c) = 0.$$

Moreover, one has

(i) $\xi_0(n,c) < \xi_1(n,c)$.
(ii) $\beta_j^*(n,c,1) < \beta_j^*(n+1,c,1)$ *and* $\beta_0^*(n,c,1) < \beta_0^*(n+1,c,1)$.
(iii) $\beta_j^*(n,c,1) < \frac{1}{c} < \beta_0^*(n,c,1) < \frac{2}{c}$.
(iv) $\frac{\partial \beta_0^*}{\partial c}(n,c,1) < \frac{\partial \beta_j^*}{\partial c}(n,c,1) < 0$.

Proposition 3 states that, when the generator S is state-owned, private generators behave more competitively, $\xi_0(n,c) < \xi_1(n,c)$, whereas when n increases this competitive effect is enhanced. Moreover, the generator S behaves as an output expanding firm ($\beta_r^*(n,c,1) < \beta_0^*(n,c,1)$). Finally, an increase in c has a higher impact in the optimal strategy of the private generators. This can be due to the fact that, when a negative shock in costs takes place, private generators try to capture more market share in order to increase profitability.

It is interesting to note that as n increases, the strategic behavior of the state-owned generator S does not mimic the private generators, since

$$\lim_{n\to+\infty} \beta_0^*(n,c,1) = \frac{2}{c} \neq \frac{1}{c} = \lim_{n\to+\infty} \beta_j^*(n,c,1).$$

In other words, the SOG is always more competitive than the PEGs. Thus, consumer surplus is higher when the generator S remains under public hands.

Proposition 4. *Optimal profits of the state-owned generator S and the n private generators are*

$$\pi_0^*(n,c,1) = (\alpha+\epsilon)^2 \cdot \frac{(1-c\xi_1)^2(1+2n\xi_1)}{2c\xi_1^2(2-c\xi_1)^2(1+n\xi_1)^2},$$
$$\pi_j^*(n,c,1) = (\alpha+\epsilon)^2 \cdot \frac{(1-c\xi_1)^2}{2\xi_1(2-c\xi_1)}$$

The following properties hold:

(i) $\pi_j^*(n,c,1) > \pi_j^*(n+1,c,1)$ *and* $\pi_0^*(n,c,1) > \pi_0^*(n+1,c,1)$.
(ii) $\max_{c>0} \pi_j^*(n,c,1) > \max_{c>0} \pi_j^*(n+1,c,1)$ *while* $\arg\max_{c>0} \pi_j^*(n,c,1) < \arg\max_{c>0} \pi_j^*(n+1,c,1)$. *The same property holds for the optimal profit of generator S.*
(iii) $\pi_j^*(n,c,1) > \pi_0^*(n,c,1)$.
(iv) $\max_{c>0} \pi_j^*(n,c,1) > \max_{c>0} \pi_0^*(n,c,1)$ *while* $\arg\max_{c>0} \pi_j^*(n,c,1) < \arg\max_{c>0} \pi_0^*(n,c,1)$.

This proposition states that private generators are better off than the SOG regardless of the number of generators n. Moreover, when the number of generators increases, the maximum profits a generator may attain decrease. Finally, the ability to exploit market power decreases as c increases (see Fig. 3). The intuition is that an increase in n and the presence of a SOG increase competition. The former is a common wisdom. The latter gives us an interesting insight: as electric power market usually comprises a reduced number of generators, the presence of a SOG mitigates market power and, eventually, may deter the incentives to collude because it acts as a competitive fringe.

3. Collusion in the electric power market

In this section, we introduce collusion by assuming that PEGs agree to collude. When the generator S is privatized, collusion comprises $n+1$ generators, whereas when the generator S remains under public hands, we assume that this generator does not take part in the collusive agreement, acting as a fringe. Consequently, whenever $\lambda = 0$ and generator S becomes fully privatized, the $n+1$ generators maximize joint profits. Conversely, whenever $\lambda = 1$ generator S remains fully public, it maximizes its profits plus the consumer surplus, and the n PEGs maximize joint profits.

[12] In a duopoly model with a public and a private firm can be found in [25], where the authors state that a welfare maximizer fully state-owned firm provides the highest social welfare.

[13] We note that the mixed duopoly model with differentiated products studied in [26] is somehow a particular case of our model for the case $\lambda = 1$, $n = 1$, and $c = 1$, but including a parameter γ to capture the degree of product differentiation.

3.1. Collusion in a private oligopoly

When the generator S is privatized ($\lambda = 0$), the $n+1$ electric power generators maximize expected joint profits,

$$\max_{\substack{\beta_i \geq 0 \\ i=0,1,\ldots,n}} \int_\Omega \sum_{i=0}^{n} \pi_i(\beta)\, f(\varepsilon)\, d\varepsilon. \tag{10}$$

The first order conditions in (10) provide the strategic behavior of the $n+1$ generators, and the corresponding best response functions,

$$\beta_i(\beta_{-i}) = \frac{1 - \sum_{\substack{j=0 \\ j\neq i}}^{n} \beta_j(1 - c\beta_j)}{1 + c\left(1 + \sum_{\substack{j=0 \\ j\neq i}}^{n} \beta_j\right)}, \quad i \in \{0, 1, \ldots, n\}.$$

that satisfy the appropriate second order sufficient conditions. Since private generators are symmetric, the above best responses come down to

$$\beta_i = \frac{1 - n\beta_i + cn\beta_i^2}{1 + c + nc\beta_i}.$$

Solving this equation, one gets the optimal collusive strategy provided in the proposition below.

Proposition 5. *The symmetric optimal collusive strategy in a private oligopoly with $n+1$ electric power generators is $\beta_0^C(n,c,0) = \beta_j^C(n,c,0) = \chi_0(n,c)$, where*

$$\chi_0(n,c) := \frac{1}{c+n+1}.$$

Moreover, one has $\chi_0(n,c) > \chi_0(n+1,c)$ and $\frac{\partial \chi_0}{\partial c}(n,c) < 0$.[14]

It is interesting to note that for all $c > 0$, the optimal strategy for the $n+1$ generators when they compete in a private oligopoly, $\xi_0(n,c)$, is increasing in n. The contrary holds for the optimal collusive strategy, $\chi_0(n,c)$. Moreover, one has $\chi_0(n,c) < \xi_0(n,c)$. Indeed, when generators follow a collusive behavior they exert a higher market power than that under a competitive environment. Furthermore, the larger the number of generators, the lower the market power exerted by them.

Expected optimal collusive price and total electric power are, respectively,

$$p^C(n,c,0) = (\alpha+\varepsilon)\cdot\frac{c+n+1}{c+2(n+1)}, \qquad Q^C(n,c,0) = (\alpha+\varepsilon)\cdot\frac{n+1}{c+2(n+1)}.$$

Proposition 6. *Expected optimal collusive profits of the symmetric $n+1$ private electric power generators are*

$$\pi_0^C(n,c,0) = \pi_j^C(n,c,0) = (\alpha+\varepsilon)^2\cdot\frac{1}{2(c+2(n+1))}.$$

Moreover, one has $\pi_i^C(n,c,0) > \pi_i^C(n+1,c,0)$ and $\frac{\partial \pi_i^C}{\partial c}(n,c,0) < 0$.

The above proposition states that collusive profits decrease with the number of generators. Moreover, as the parameter c increases, profitability decreases despite the fact that $\frac{\partial \chi_0}{\partial c}(n,c) < 0$ (i.e., generators try to exploit market power as c increases). In other words, the cost effect is larger than the market power effect.

3.2. Collusion in a mixed oligopoly

When the generator S remains under public hands ($\lambda = 1$), then the n private generators may collude whereas the SOG S acts as a fringe, introducing some degree of competition in the market. Now, the joint profit maximization program of the n private generators is,

$$\max_{\substack{\beta_j \geq 0 \\ j=1,\ldots,n}} \int_\Omega \sum_{j=1}^{n} \pi_j(\beta)\, f(\varepsilon)\, d\varepsilon, \tag{11}$$

whereas S maximizes the profit maximization program (3) by letting $\lambda = 1$. The strategic behavior for the n private generators and SOG S arises from the first order conditions in (11) and (3), providing the best response functions,

$$\beta_0(\beta_j) = \frac{1 + 2\sum_{j=1}^{n}\beta_j}{c\left(1 + \sum_{j=1}^{n}\beta_j\right)}, \qquad \beta_j(\beta_r) = \frac{1 + \beta_0 - \sum_{\substack{r=1 \\ r\neq j}}^{n} \beta_r(1 - c\beta_r)}{1 + c\left(1 + \sum_{\substack{r=0 \\ r\neq j}}^{n} \beta_r\right)},$$

$j, r \in \{1, \ldots, n\}$.

The symmetry across the n private generators makes that in equilibrium $\beta_j = \beta_r$ for all $j, r \in \{1, \ldots, n\}$. Then, the above best responses come down to

$$\begin{aligned} \beta_0(\beta_j) &= \frac{1 + 2n\beta_j}{c + cn\beta_j}, \\ \beta_j(\beta_0, \beta_j) &= \frac{1 + \beta_0 - (n-1)\beta_j(1 - c\beta_j)}{1 + c + c\beta_0 + c(n-1)\beta_j}, \end{aligned} \tag{12}$$

which yield the optimal strategies reported in the following proposition.

Proposition 7. *The optimal collusive strategies for the n PEGs and the strategy for the SOG are*

$$\begin{aligned} \beta_0^C(n,c,1) &= \frac{1 + 2n\chi_1(n,c)}{c + cn\chi_1(n,c)} = \frac{(n+c)\chi_1(n,c) - 1}{1 - c\chi_1(n,c)}, \\ \beta_j^C(n,c,1) &= \chi_1(n,c), \end{aligned}$$

where $\chi_1(n,c)$ is the unique positive value satisfying $u_2\chi_1^2(n,c) + u_1\chi_1(n,c) + u_0 = 0$ with $u_2 := nc^2 + (n+2)nc$, $u_1 := c^2 + c - 2n$ and $u_0 := -(1+c)$, that is, $\chi_1(n,c) = \frac{-u_1 + \sqrt{u_1^2 - 4u_2u_0}}{2u_2}$.

Moreover, one has:

(i) $\chi_0(n,c) < \chi_1(n,c) < \frac{1}{c}$.

(ii) $\beta_j^C(n+1,c,1) < \beta_j^C(n,c,1) < \frac{n+1}{n}\beta_j^C(n+1,c,1)$ *and* $\beta_0^C(n+1,c,1) > \beta_0^C(n,c,1)$.

(iii) $\beta_j^C(n,c,1) < \beta_0^C(n,c,1)$ *and* $\dfrac{\partial \beta_0^C}{\partial c}(n,c,1) < \dfrac{\partial \beta_j^C}{\partial c}(n,c,1) < 0$.

In this case, the optimal collusive price and total quantity of electric power traded are,

$$p^C(n,c,1) = (\alpha+\varepsilon)\cdot\frac{1 - c\chi_1}{n\chi_1(2 - c\chi_1)},$$

$$Q^C(n,c,1) = (\alpha+\varepsilon)\cdot\frac{-nc\chi_1^2 + (2n+c)\chi_1 - 1}{n\chi_1(2 - c\chi_1)}.$$

Proposition 7 states that PEGs behave more aggressively when the generator S remains under public hands. Moreover, when n increases they exert a higher market power because the SOG acts as an output expanding firm. The intuition is that PEGs try to maintain a high price lowering production in response to the SOG's strategy.

Proposition 8. *Optimal collusive profits of the n PEGs and profits for the SOG are, respectively,*

$$\pi_0^C(n,c,1) = (\alpha+\varepsilon)^2\cdot\frac{(c(n+c+2)\chi_1 - (2+c))(1 - (n+c)\chi_1)}{2n^2\chi_1^2(2 - c\chi_1)^2},$$

$$\pi_j^C(n,c,1) = (\alpha+\varepsilon)^2\cdot\frac{(1 - c\chi_1)^2}{2n^2\chi_1\left(2 - c\chi_1\right)}.$$

The following properties hold:

(i) $\pi_j^C(n,c,1) > \pi_j^C(n+1,c,1)$ *and* $\pi_0^C(n,c,1) > \pi_0^C(n+1,c,1)$.

(ii) $\max_{c>0}\pi_j^C(n,c,1) > \max_{c>0}\pi_j^C(n+1,c,1)$ *while* $\arg\max_{c>0}\pi_j^C(n,c,1) < \arg\max_{c>0}\pi_j^C(n+1,c,1)$.

(iii) $\max_{c>0}\pi_0^C(n,c,1) > \max_{c>0}\pi_0^C(n+1,c,1)$ *and* $\arg\max_{c>0}\pi_0^C(n,c,1) > \arg\max_{c>0}\pi_0^C(n+1,c,1)$.

[14] This result was previously given in [38], although in our setting we explicitly include uncertainty.

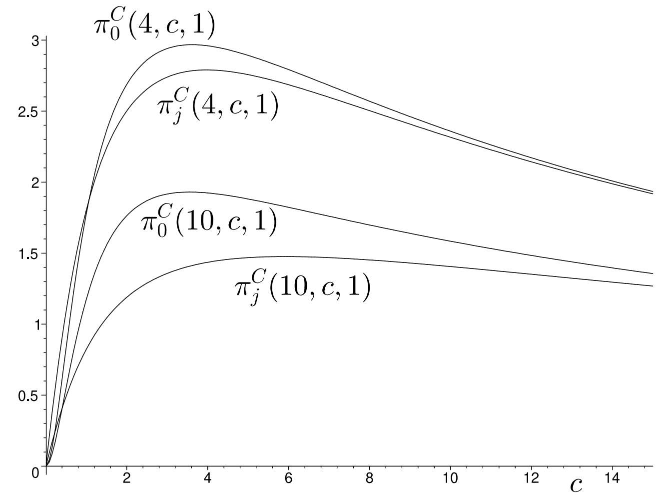

Fig. 4. Optimal collusive profits for the SOG and the n PEGs (for $n = 4$ and $n = 10$).

The effect of n is well-known. As the number of PEGs increases, profits decrease. In addition, PEGs' profits are larger than those of the SOG. Moreover, these effects are reinforced by the output expansion behavior of the SOG. Finally, as n increases profits decrease for all generators (see Fig. 4).

3.3. Consumer surplus implications

Once we have presented the four scenarios, it is interesting to point out the implications for consumer surplus. We shall denote by $CS^*(n,c,0)$ and $CS^*(n,c,1)$ the consumer surplus under the two competitive scenarios described in Section 2, that follow from (8) by considering either ξ_0 or ξ_1, accordingly. For the collusive cases one has

$$CS^C(n,c,0) = (\alpha+\varepsilon)^2 \cdot \frac{(n+1)^2}{2(c+2(n+1))^2},$$

for collusion with $n+1$ generators, whereas when the generator S remains under public hands

$$CS^C(n,c,1) = (\alpha+\varepsilon)^2 \cdot \frac{(nc\chi_1^2 - (2n+c)\chi_1 + 1)^2}{2n^2\chi_1^2(2-c\chi_1)^2}.$$

By comparing these four scenarios, it can be checked that the following chain holds:

$$CS^*(n,c,1) > CS^*(n,c,0) > CS^C(n,c,1) > CS^C(n,c,0).$$

Moreover, one has

$$CS^*(n,c,0) - CS^C(n,c,0) > CS^*(n,c,1) - CS^C(n,c,1).$$

Not surprisingly, the highest consumer surplus is obtained under the mixed oligopoly in the absence of collusion. Moreover, when the n PEGs collude and S remains under public hands the decrease in the consumer surplus is low. Moreover, the difference between the consumer surplus under competition and collusion is larger with a private oligopoly. It means that, even when PEGs collude, the presence of a public generator mitigates the losses in the consumer surplus. Conversely, electric power prices evolve according to the following chain:

$$p^*(n,c,1) < p^*(n,c,0) < p^C(n,c,1) < p^C(n,c,0).$$

Indeed, the lowest price is achieved under mixed oligopoly, whereas the highest one emerges under collusion when the generator S is privatized. Finally, the price difference between collusion and competition is larger when the SOG is privatized,

$$p^C(n,c,0) - p^*(n,c,0) > p^C(n,c,1) - p^*(n,c,1).$$

4. Collusion sustainability

In the previous section, we considered that PEGs perfectly colluded. In this section, we study collusion sustainablity under the two different scenarios, namely the mixed oligopoly and the private oligopoly. As we will see, if the objective of the government is to protect consumers from high electric power prices, the decision of privatization strongly depends on the cost parameter c and the number of PEGs.

In the case of wholesale electric power markets, coordination can be possible as market interaction takes place each hour, so it is possible to mimic competitors strategies and, as the same time, cheating from an anticompetitive agreement is easy to detect. Therefore, it is interesting to check if coordination among electric power generators when submitting price-quantity bids can be sustainable over time. Moreover, the incentives to cheat from a coordinated strategy is low, because demand for electric power is stable, demand is highly inelastic, and the technology mix does not change in the short and medium run. Thus, there is no reason to expect that extra profits derived by the collusive agreement are going to decrease. Indeed, when input prices tend to increase, as it was the case in the year 2021 and the year 2022, the ability of electric power generators to increase price-cost margins is higher when they coordinate their strategies.

We let electric power generators compete repeatedly over an infinite horizon with complete information (i.e., all generators observe the whole history of actions) and discount the future according to a common discount factor $\mu \in (0,1)$. At any stage, the profit function is $\pi_j(\beta)$ defined in Section 2.[15] Time is assumed to be discrete and dates are denoted by $t = 1, 2, \ldots$ In this framework, a pure strategy for a electric power generator j is an infinite sequence of functions $\left\{\beta_j^t\right\}_{t=1}^{\infty}$ with $\beta_j^t : \sum^{t-1} \mapsto \mathcal{Q}$ where $\sum^{t-1}$ is the set of all possible histories of actions (continuous supply function choices) of each electric power generator up to $t-1$, where $\mathcal{Q}$ is the set of the continuous supply function choices available to each generator. We follow Friedman [41] grim trigger strategies such that electric power generators adhere to a collusive agreement until there is a defection, in which case they revert forever to the static Nash equilibrium described in the competitive oligopoly under the two scenarios (namely, Propositions 1 and 3). Hence, for $j \in \{1,\ldots,n\}$, $\{\beta_j^t\}_{t=1}^{\infty}$ can be specified as follows: $\beta_j^1 := \beta_j^C(n,c,\lambda)$ and, for $t = 2, \ldots,$

$$\beta_j^t := \begin{cases} \beta_j^C(n,c,\lambda) & \text{if } \beta_j^\tau = \beta_j^C(n,c,\lambda) \text{ for all } \tau \in \{1,\ldots,t-1\}, \\ \beta_j^*(n,c,\lambda) & \text{otherwise.} \end{cases} \tag{13}$$

Electric power generators producing according to $\beta_j^C(n,c,\lambda)$ in each period can be sustained as a subgame perfect Nash equilibrium (SPNE, hereinafter) of the repeated game with the strategy profile (13) if and only if the condition

$$\pi_j^C(n,c,\lambda) \geq \pi_j^D(n,c,\lambda) - \mu\left(\pi_j^D(n,c,\lambda) - \pi_j^*(n,c,\lambda)\right) \tag{14}$$

is satisfied for all $j \in \{1,\ldots,n\}$, where $\pi_j^D(n,c,\lambda)$ denotes the profits obtained by an electric power generator j in an optimal deviation from the collusive strategy $\beta_j^C(n,c,\lambda)$, whilst the rest of generators remains under the cooperative strategy profile. As μ approach zero the difference between collusive profits and those under deviation become equal, so the incentives to defect from collusion disappear. The contrary holds when μ approaches one. Solving this inequality we can find a critical level of μ as a function of n and c for each scenario. When μ exceeds this critical level, the inequality (14) holds. We denote by $\hat{\mu}(n,c,\lambda)$ this critical value of the discount factor that supports $\beta_j^C(n,c,\lambda)$ as a SPNE of the repeated game. First, we need to obtain the strategy profile $\beta_j^D(n,c,\lambda)$.

[15] Notice that when S is privatized $j \in \{0,\ldots,n\}$, whereas when S remains under public hands $j \in \{1,\ldots,n\}$.

In the pure private oligopoly ($\lambda = 0$), the strategy profile for the deviating generator $r \in \{0, 1, \dots, n\}$ is $\beta_r^D(n,c,0)$, obtained by maximizing its expected profit whenever the rest of generators $j \neq r$ take the collusive strategies $\beta_j^C(n,c,0)$ given in Proposition 5, so that

$$\beta_r^D(n,c,0) = \frac{c + 2(n+1) - 1}{c^2 + (2c+1)(n+1)}.$$

Hence, one can derive the corresponding expression for the profit $\pi_r^D(n,c,0)$ and the cutoff $\hat{\mu}(n,c,0)$ for the discount factor. Particularly, one has

$$\pi_r^D(n,c,0) = (\alpha+\varepsilon)^2 \cdot \frac{(c+n+1)^2}{2(c+1)(2n+c+2)(2n+c+1)}.$$

In the second scenario, we have a mixed oligopoly ($\lambda = 1$) with n private generators and the SOG. In this case, the optimal response of generator S in each period when it remains under public hands simply consists of maximizing its current profits plus the consumer surplus. Notice that we assume that generator S is miopic, in the sense that, as it has observed a collusive strategy during the previous history, there is no reason to change its strategy. Analogously, the strategy profile $\beta_j^D(n,c,1)$ for the generator $j \in \{1, \dots, n\}$ that deviates, is obtained by maximizing its expected profit whenever the rest of the generators take the collusive strategies described in Proposition 7. Then,

$$\beta_j^D(n,c,1) = \frac{\chi_1(c(n-1)\chi_1 + 1 - 2n)}{c(n-1)(c\chi_1 - 2)\chi_1 - 1}.$$

One can derive the corresponding expressions for the profit $\pi_j^D(n,c,1)$ and the cutoff $\hat{\mu}(n,c,1)$ for the discount factor. One has

$$\pi_j^D(n,c,1) = (\alpha+\varepsilon)^2 \cdot \frac{(1-c\chi_1)^2}{2\chi_1(c\chi_1-2)(c(n-1)\chi_1+1)(c(n-1)\chi_1+1-2n)}.$$

The effect of the privatization on the behavior of generators' optimal deviation strategy and on the profits they obtain after the deviation has occurred, is as follows: for every $n \in \mathbb{N}$ and $c > 0$, one has:

(i) $\beta_j^D(n,c,1) > \beta_j^D(n,c,0)$, and
(ii) $\pi_j^D(n,c,1) < \pi_j^D(n,c,0)$.

These statements follow from the interaction of three different forces. Firstly, we know from the previous section that generators obtain larger profits in the collusive allocation when S has been privatized and thus, it participates in the agreement. Secondly, we also know that when S remains under public hands, its aggressive behavior reduces the profits of the PEGs in the Nash equilibrium. These two forces go in opposite directions in order to help collusion sustainability for the privatization case compared to the case when S is state-owned. Finally, all else being equal, the increase in the deviation profits due to the privatization tends to increase $\hat{\mu}(n,c,0)$ compared to $\hat{\mu}(n,c,1)$. We next show that privatization reduces the incentives to collude because the latter two effects dominate the first one. The next proposition summarizes these ideas, whereas Fig. 5 illustrates the evolution of the cutoffs for the case of $n = 4$ and $\alpha = 10$.

Proposition 9. *Let $n \in \mathbb{N}$, $c > 0$ and consider $\hat{\mu}(n,c,\lambda)$ as defined above. For all $c > 0$ and for all n collusion is harder to sustain when there is a pure private oligopoly, i.e.,*

$$\hat{\mu}(n,c,0) > \hat{\mu}(n,c,1).$$

Proposition 9 states that the privatization of S always yields to a less aggressive (namely, less competitive) behavior by the private generator which deviates from the collusive allocation than when S remains state-owned. As a consequence, the profits obtained after deviation in the latter case are smaller. The intuition is fairly simple. When S remains under public hands, it always behaves more aggressively than private generators, forcing the private generator that deviates to behave more aggressively as well. As a consequence, the deviation profits are smaller. To summarize, and interestingly enough, we prove

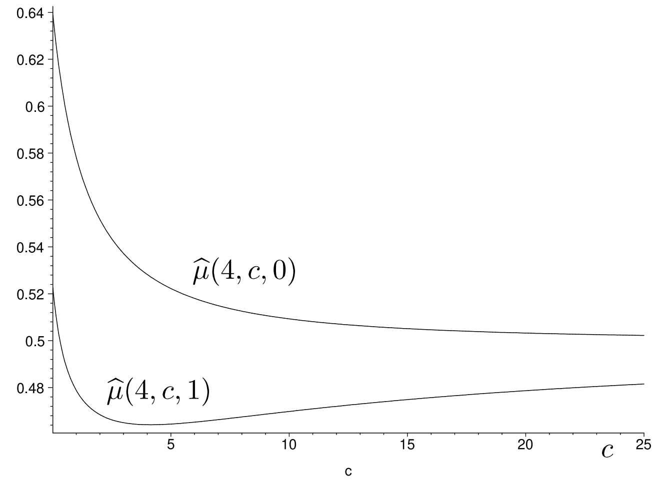

Fig. 5. Impact of parameter c in collusion sustainability with and without SOG.

that it is precisely the aggressive behavior of a SOG that might provide additional incentives to collude in order to enable private generators to obtain larger profits.

Moreover, as c increases there are more incentives to preserve collusion both under a private and mixed oligopoly. This is because as costs increase the ability to exert abuse of market power also increases, and price-cost margin is large: i.e., the market power effect is larger than the costs effect. Although this feature arises under both scenarios, under the mixed oligopoly, this feature is lower because of the output expansion behavior of the S generator: namely, the competitive effect.

Regarding the effect of c on generators' profits, we can easily observe that when all generators collude (including S), deviation profits decrease with c. However, when S remains under public hands and thus, it does not collude, deviation profits have an inverse U-shape form with respect to c. This fact is explained by the interaction of two forces going in opposite directions. On the one hand, as c increases, the aggressiveness of the SOG is smaller which, all else being equal, increases PEGs' profits. On the other hand, we also have that the direct effect of a larger c implies a higher production cost. Consequently, only when c is small enough, the deviation profits in absence of privatization are significantly larger than those obtained when all generators collude. This explains the third force mentioned above.

5. Running the model: the EU electric power market

In this section, we challenge our theoretical results by assessing how the rocketing of fossil inputs prices and the share of green technologies in the technology mix are affecting the EU country members electric power market. In our simulation, we use data at EU-27 level as reported by Ember Group in 2021. We take gas and coal as the most important pollutant inputs in the technology mix (combined-cycle plants and traditional thermal power plants). The generation costs of these plants are more sensitive to input prices. On the one hand, the tight supplies from Russia during the year 2021 and the occupation of Ukrainian territories from the Putin's administration since February 2022, has made gas in the EU pricier. On the other hand, this soaring European wholesale gas prices are encouraging more companies to switch to carbon-heavy coal to generate electric power, just as the region tries to wean nations off the polluting fuel. This shift has led to further increases in European coal and carbon prices in recent months, although they have lagged the spike in gas prices, causing short-term marginal costs to shift in favor of using coal to generate electricity (see [42,43]).

According to Eurostat, the highest shares of electricity produced in power plants comes from renewable energy sources, followed by nuclear power plants, gas-fired plants and coal-fired power plants. Other

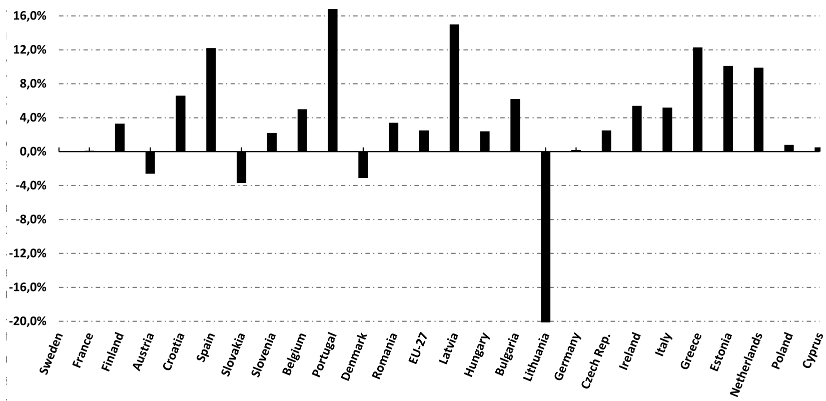

Fig. 6. Renewable sources variation (percentage of GW) by country: 2019–2021.

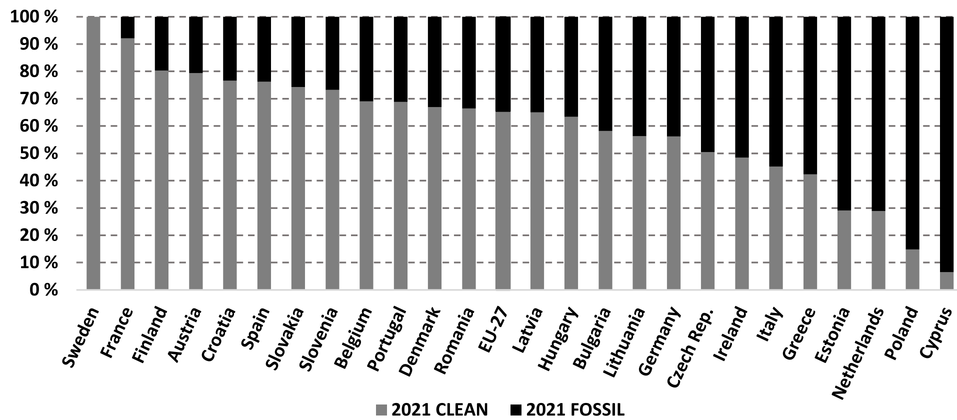

Fig. 7. Technology mix in 2021: green vs. pollutant.

sources such as oil and non-renewable wastes account for minimum shares. In general, EU country members are increasing the percentage of clean inputs in the electricity technology mix. Fig. 6 reports the shift from polluting sources to clean sources between 2019 and 2021, whereas Fig. 7 reports the monthly weights of clean and fossil inputs in the technology mix.[16]

5.1. Characterization of the parameter c

In order to conduct our simulation, we assume that the parameter c varies according to the evolution of input prices, which includes both clean and pollutant sources. As clean sources, we include renewable sources as well as nuclear power, as it has been stated by the EU energy policy.[17] Although European Commission has labeled nuclear and gas as sustainable sources as a way to become climate-neutral by 2050 [44], we include gas as a fossil source because it causes GHG emissions. Let us define the following function in order to characterize the evolution of the cost parameter c,

$$c = \omega_F \cdot c_F + \omega_c \cdot c_c + \varepsilon,$$

where w_F and w_c stand for the weight that fossil and clean sources have in the technology mix, respectively. Accordingly, c_F and c_c are the prices of the pollutant and clean sources, whereas ε includes other generation costs. As we focus on the effect that the negative shock of gas and coal prices has on final electric power prices, we abstract from the effect that ε may have on c. Moreover, as clean sources (nuclear and renewables) enter the technology mix at almost zero costs, the cost parameter specification becomes $c = \omega_F \cdot c_F$. The weight ω_F is the monthly averaged level of pollutant inputs in the electric power technology mix in 2021, as reported in Fig. 7. In order to obtain numerical values for c_F, let us define $c_F = \mu_{gas} \cdot p_{gas} + \mu_{co} \cdot p_{co}$, where μ_i and p_i, $i \in \{gas, co\}$, stand for the monthly weighted average and market prices of gas and coal, respectively, during the period under study.

According to the International Energy Agency (IEA, hereinafter) (IEA, 2021), gas and coal account for more than 90% of the total amount of fossil inputs in the electricity mix. Moreover, natural gas was responsible for 38.9% of total electricity production in 2020, up from 23.1% in 2010, whereas coal was responsible for 19.9% of total production, down from 45.2% in 2010. We take the above IEA percentages to average the parameter μ_i as follows: 2/3 comes from the gas price and the rest 1/3 from the coal price. Finally, to produce a generalized fossil input price for electric power generation, we use the monthly evolution of the gas and coal prices during the year 2021 up to July 2022. We take the Dutch Title Transfer Facility (TTF) for the gas price, p_g, as it is the leading European benchmark price (see Trading Economics). For the coal price, p_{co}, we take the standard GC Newcastle (see Trading Economics).[18] Fig. 8 reports the evolution of gas and coal prices during the period under study.

[16] Luxemburg and Malta are excluded because of the reduced amount of energy traded with respect to the rest of the EU country members

[17] This decision comes from the fact that nuclear power does not cause GHG emission to the atmosphere (see, for instance, Reuters).

[18] We take the price of the last working day each month.

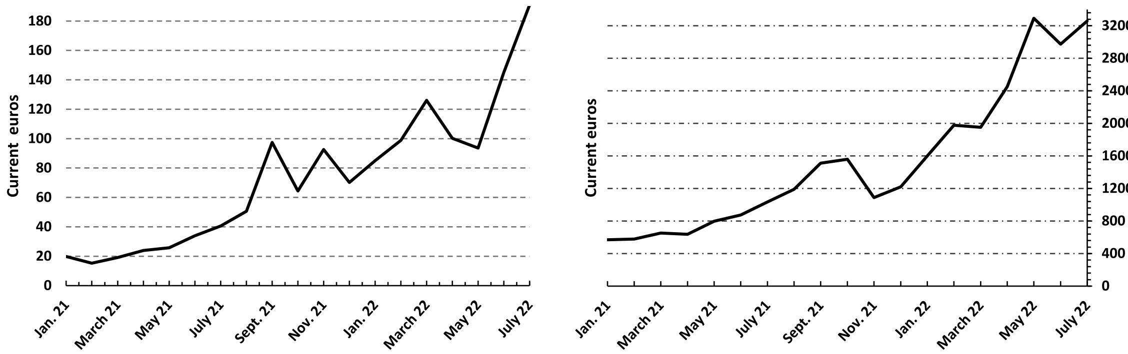

Fig. 8. (Left) Gas price MWh; (Right) Coal price MWh.

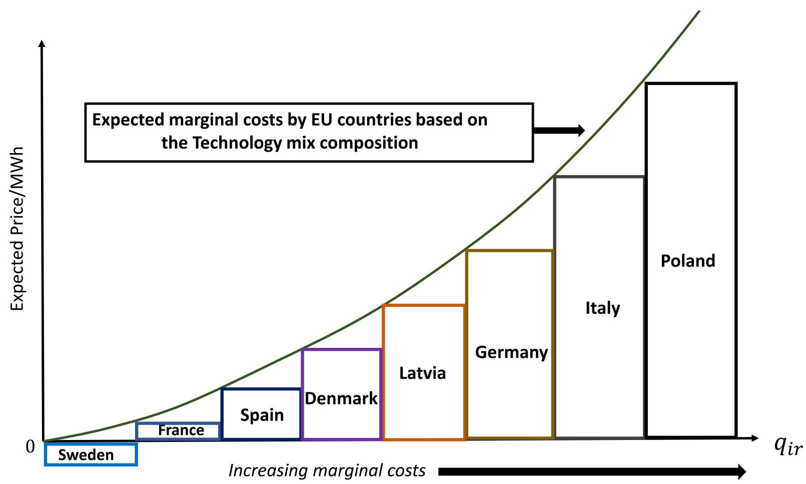

Fig. 9. Expected marginal costs according to technology mix.

5.2. The sample

In our simulation, we take as representative EU countries those where the volume of electric power generated is among the top 10 in the group over the last 10 years. Moreover, we take into account differences in terms of the technology mix, the number of competitors and the existence of SOG. The final selection comprises Sweden, France, Spain, Denmark, Latvia, Germany, Italy, and Poland. In line with Fig. 1, we highlight in Fig. 9 the expected position of each country in terms of marginal costs according to the composition of the technology mix. Moreover, in Fig. 10, it is shown the dominant source by country in the year 2021.

Regarding the importance of the state-owned firms, a study by the OECD estimates that 22% of the world's largest firms are under state control, being the highest percentage in decades [45]. In electric power generation, the upsurge of state-owned enterprises is related with public policy obligations. Indeed, a public firm may mitigate the market power exerted by private generators by pushing down wholesale electric power prices and provide supply security. As [46] states, and also in the reports cited therein, for most of the countries considered in our sample, the aggregates provided in the OECD database are fairly constant over time, suggesting only minor changes in public ownership.

In Germany, and Spain though, public authorities do not hold shares in the largest electric power generator's equity, so they can be considered as a private wholesale electric power market (which in our model means that $\lambda = 1$). In Italy, the dominant player in the entire Italian electric power market remains the Enel group, which was privatized in 1999. It has a slightly downward market share, falling from 37.6% in 2018 to 36% of volumes sold in 2019. The Italian market includes a constellation of several generators, some of them with a low market share (see Statista, accessed May 26th 2022). Contrary to these situations, in France, despite the fact that the liberalization started in 1999, the state-owned generator Électricité de France (EDF) still dominated the market in 2020 with a market share of roughly 80% (see Eurostat, accessed May 14th 2022). In Sweden, a few major generators dominate the market. The state-owned generator Vattenfall generates nowadays slightly over 40% of the total power (see Energy Policies of IEA Countries: Sweden 2019 Review, accessed May 16th 2022). In Denmark, Ørsted (previously Dong Energy) has consolidated its role as the largest Danish generation company, with a market share around 50%. The Danish Government holds the majority of Ørsted shares and it also owns power production facilities and projects in Germany, Sweden, the Netherlands, Norway and the United Kingdom. Generation in Denmark also includes several competitors including the Swedish Vattenfall (see Statista, accessed May 7th 2022).

In Latvia, the state-owned electric utility company Latvenergo Group succesfully maintained the position of electricity sales leader in the Baltic States accounting for one third of the total Baltic market share in the last years. Although since 2015 the liberalization process started and the market was opened to competition, most of the Latvian households have chosen Latvenergo as their electricity trader. The company generates about 70% of the country's electricity (see Latvenergo annual report, accessed May 6th 2022). Poland started a liberalization process in 2004, when this country entered the EU. The former state-owned entities were organized into four vertically integrated groups and nowadays are partially privatized. These groups are PGE Polska Grupa Energetyczna (PGE), Tauron Polska Energia (Tauron), Enea and Energa. They combine generation, distribution and trading (including supply) activities although in pursuit of compliance with the Internal Market in the Second Energy Package unbundling regime, Distribution

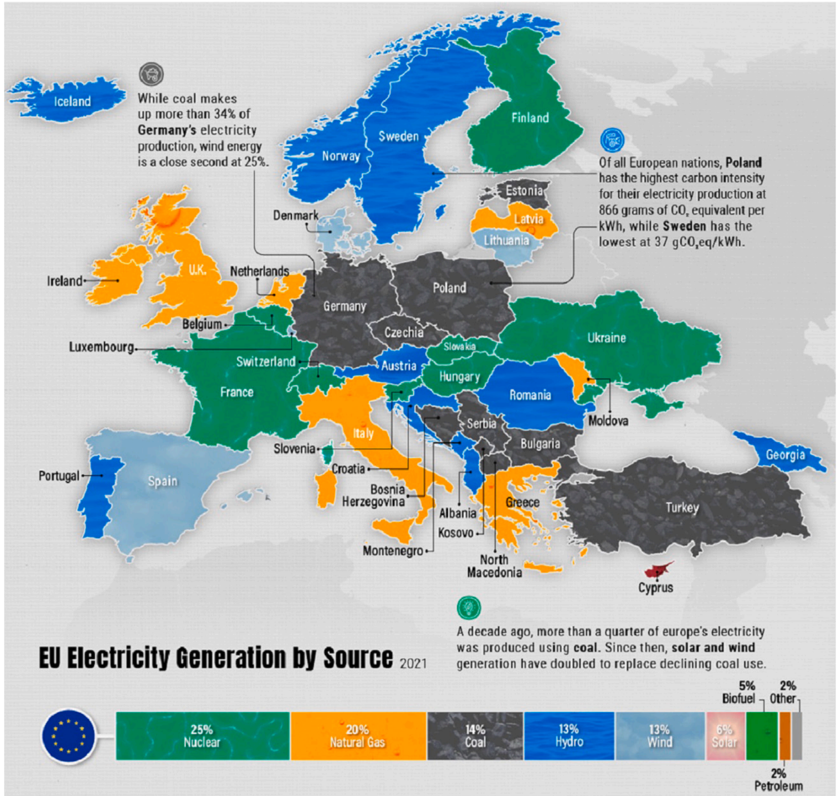

Fig. 10. Dominant source in the technology mix by country. *Source:* Electricity Maps, IEA, BP Statistical Review of World Energy, Eurostat, Government of Iceland.

Table 1
Competitive framework.

Country	Generators with SMS[a]	Clean sources	SOG
EU-25	4	65.5%	Yes/No
Sweden	3	99.9%	Yes
France	2	92.1%	Yes
Spain	5	76.2%	No
Denmark	5	66.9%	Yes[b]
Latvia	3	65.0%	Yes
Germany	5	56.2%	No
Italy	5	45.2%	No
Poland	4[c]	6.5%	Yes

[a] Significant Market Share (generators that produce at least 10% of the electric power during the years 2020 and 2021);
[b] 50.1% of equities in public hands;
[c] Poland has 4 semi-privatized generators, so we include three private generators and one public generator as an approximation.

System Operators (DSO) were legally unbundled on 1 July 2007 (see Lexology, accessed May 24th 2022). For our purposes, we consider that this market is composed by three privatized generators plus one SOG. Table 1 describes the electric power market in those EU country members included in our sample.

5.3. Simulation

We use the characterization of the parameter c and the information enclosed in Table 1 to study the extent to which fossil prices impact marginal costs and our equilibrium results.[19]

[19] From January to July 2022 we use the technology mix reported in 2021 because the technology composition is not updated yet.

Fig. 11 shows that the larger the amount of pollutant sources in the technology mix, the higher the value of the c parameter. As we will see, this fact has a direct impact in final electric power prices and the consumer surplus. Moreover, the magnitude also depends on the number of competitors and the presence of a SOG.

First, in order to highlight our findings in Section 3.3, we present differences in the consumer surplus due to variations in c. We distinguish between two groups. In the first group (Sweden, Spain, Denmark and Germany, see Fig. 12), we include those countries that have a relative clean technology mix with respect to the EU mean (see Fig. 7). The second group (France, Latvia, Poland and Italy, see Fig. 13) consists of those countries whose technology mix composition strongly depends on fossil inputs (i.e., it is below the EU mean). Overall, despite the fact that consumer surplus is always larger under competition than under collusion, the effect of a higher level of c yields to significant decreases in their levels.

In the first group (the green oriented), it can be observed that, regardless of the presence of a SOG and the number of private generators, the effect of a relative clean technology mix is strongly enough to produce significant differences in the consumer surplus between competition and collusion. The case of France is an exception because, as there is only one private generator, collusion is not possible so that the consumer surplus is the same.

In the second group (those countries which have a pollutant oriented technology mix), the level of consumer surplus is lower than in the first group, both under competition and collusion. Moreover, their differences are also lower compared to the first group. It comes from the fact that generators in the fossil oriented group exert higher market power when they compete. Consequently, the extra losses of consumer surplus when they collude are lower. In order to clarify this fact, we present in Fig. 14 the convergence of consumer surplus of our sample as c increases. In our context, we define convergence as consumers' surpluses getting closer to each other.

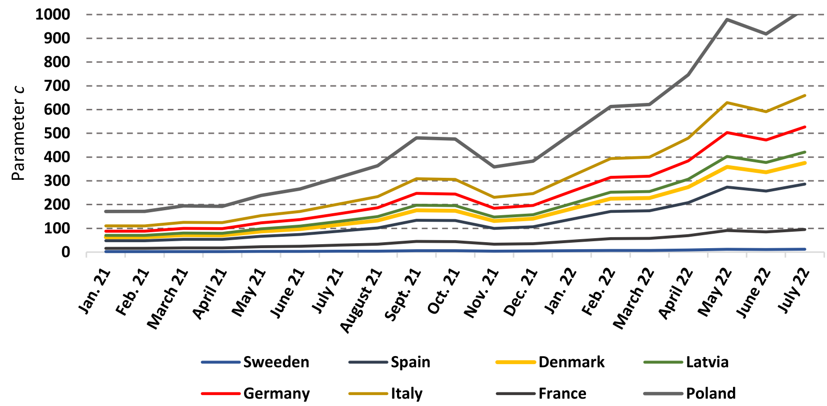

Fig. 11. Evolution of the level of c by the EU country members in the sample period.

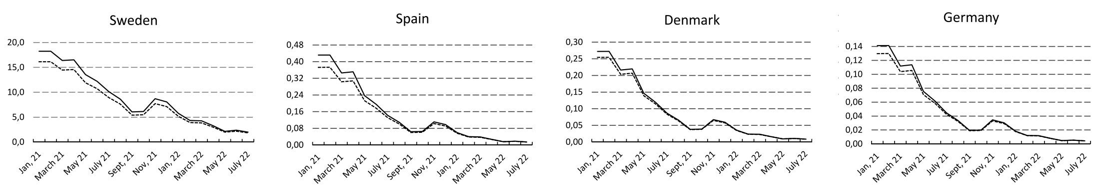

Fig. 12. EU countries members above mean. Solid line: Consumer surplus under competition. Dashed line: Consumer surplus under collusion.

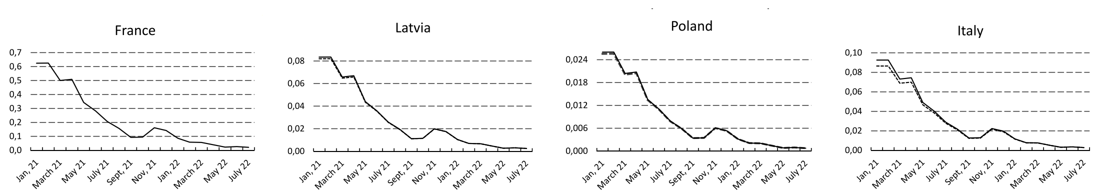

Fig. 13. EU country members below mean. Solid line: Consumer surplus under competition. Dashed line: Consumer surplus under collusion.

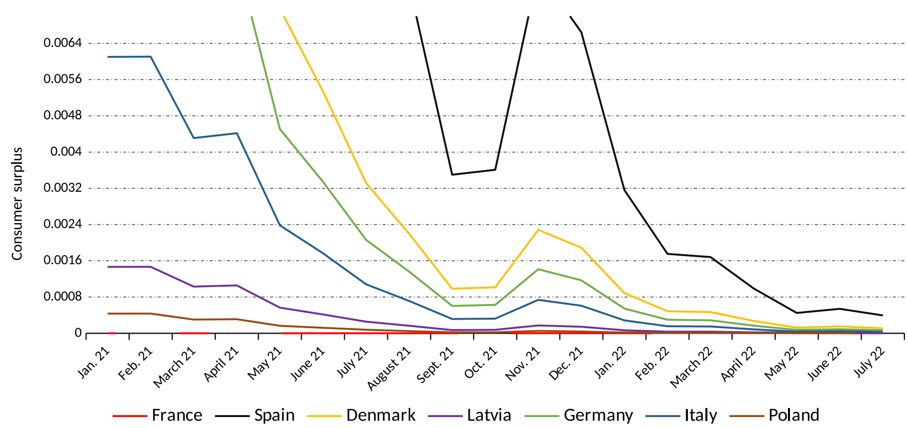

Fig. 14. Consumer surplus convergence among EU country members.

To illustrate our findings, Fig. 14 shows that the larger the c the later the convergence. In other words, when the technology mix is dominated by pollutant sources it is more difficult the convergence. Each line represents the difference between consumer surplus under competition and collusion. Sweden does not appear because convergence occurs very slowly (the range is out of the scope of the figure). Moreover, the case of France is an exception because collusion coincides with competition. The intuition behind is that as long as the technology mix becomes cleaner, losses in consumer surplus decrease, no matter the presence of a SOG and the number of private generators. However, as c increases there is convergence but it occurs slowly as the technology mix is cleaner. The policy implication of a cleaner technology mix is that it might prevent collusion and, when it does not, the damage in the consumer surplus is moderate because the ability to exert market power abuse is smaller. Besides, the presence of a SOG and its output expansion behavior has a lower impact as c increases.

Finally, we present in Fig. 15 the evolution of the discounts factors as c changes. In the first group (the green oriented), the evolution of the

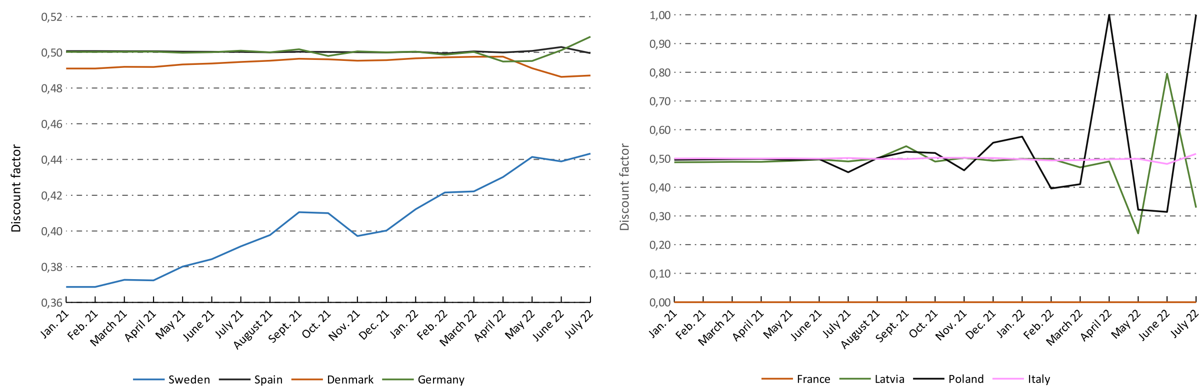

Fig. 15. Evolution of the discount factor in the sample period by countries.

cutoff of the discount factor is relatively stable, whereas in the second group (the fossil oriented) this variability strongly depends on c.

6. Conclusions

In this paper, we have presented a mixed oligopoly model where electric power generators compete in supply functions. We are interested in the effects that a greener-oriented technology mix has in the ability to exert market power by private electric power generators. The SOG can be either fully privatized or remains under public hands. In this setting, we investigate collusion among private generators, its sustainability over time and how it affects consumer surplus. Our results suggest that those countries where electric power generation is provided by a few companies, the state should maintain the SOG because it may mitigate market power. Even though collusion is easier to sustain when the state maintains the SOG, the extra benefits from collusion and the negative effects on consumer surplus are lower. It occurs because the output expansion behavior of the SOG makes the punishment harder when a private generator deviates from collusion. Moreover, the positive effect of the SOG is reinforced as the parameter c decreases, which in our setting is means that the amount of cleaner sources domains the pollutant ones in the technology mix. The main contribution of the model is to address the problem of abuse of market power, ownership of generators and the effect of the composition of the technology mix on market outcomes. However, the model has the weakness of not being able to specify differences in cost functions by country. This issue needs to be studied in a future work.

We also run a simulation of our model in order to highlight the effect that the continuous increase of pollutant input prices (gas and coal) has in generators' costs. Our simulation results suggest that in those countries where electric power generation is green oriented consumer surplus is less affected when private generators collude. Besides, we observe that when c increases, the effect of a SOG tends to disappear; i.e., the cost effect is larger than the output expansion behavior. The intuition behind is that it is more effective to promote green technologies that imply lower costs (renewable sources and nuclear power) than maintaining a SOG in the market (which may be costly for the government).

To analyze a real-world electric power systems, further research is required. Possible extensions include a dynamic model with entry that could explain the SOG. For example, the regulator could commit to either privatize the SOG or not and, later, private generators could decide to enter incurring in an entry cost. In this setting, entry could only occur if the government commits to privatization. Additionally, incorporating spillovers in the case of a privatization policy affecting the production cost, or cross-ownership would probably also enrich our analysis.[20] We believe that those are subjects for future research.

[20] A recent study of cross-ownership and the issue of environmental concerns measured by Corporate Social Responsibility can be found in [47].

CRediT authorship contribution statement

Marc Escrihuela-Villar: Writing – review & editing, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Carlos Gutiérrez-Hita:** Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **José Vicente-Pérez:** Visualization, Validation, Supervision, Software, Resources, Project administration, Investigation, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Carlos Gutierrez-Hita reports financial support was provided by Spain Ministry of Science and Innovation. Jose Vicente-Perez reports financial support was provided by Valencia Department of Education Culture and Sport. Carlos Gutierrez-Hita reports financial support was provided by Valencia Department of Education Culture and Sport.

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Appendix A. Proofs of selected results

Proof of Theorem 1. Given $(n, c, \lambda) \in \mathbb{N} \times (0, +\infty) \times [0, 1]$, the optimal supply functions $\beta_0^*(n, c, \lambda)$ and $\beta_r^*(n, c, \lambda)$ in (6) are obtained by combining the equations in (5).

Next we prove that the equilibrium given in (6) is unique. For that purpose we define the polynomial $P_{n,c,\lambda}(x) := a_3x^3 + a_2x^2 + a_1x + a_0$. On the one hand, if $n = 1$, then $a_3 = 0$ and so $P_{n,c,\lambda}(x)$ is a convex parabola since $a_2 = c^2 + (2 + \lambda)c > 0$. Hence, as $P_{n,c,\lambda}(0) = a_0 < 0$, Bolzano's Theorem guarantees that $P_{n,c,\lambda}$ has a unique positive real root.

On the other hand, if $n > 1$, since $a_0 < 0$ and $a_3 > 0$, then $P_{n,c,\lambda}$ has at least one positive real root. By the classical Descartes' Rule of Signs, the maximum number of positive real roots of $P_{n,c,\lambda}$ coincides with the variations of sign of the sequence of coefficients a_3, a_2, a_1, a_0. We observe that the problematic case in which $a_1 > 0$ and $a_2 < 0$ does not hold, since $a_1 \geq 0$ implies $a_2 > a_1$. This follows from the fact that $\inf\{a_2 - a_1 : a_1 \geq 0, n \geq 2, c \geq 0, \lambda \in [0,1]\} = 6 + 3\sqrt{2} > 0$, which can be numerically checked. Thus, $P_{n,c,\lambda}$ has at most one, and so a unique, positive real root. □

Proof of Proposition 1. The optimal strategies follow from Theorem 1 by taking $\lambda = 0$. In this case, one can write $P_{n,c,0}(x) = \left(ncx^2 + (1 + c - n)x - 1\right)\cdot((n-1)cx + 2 + c)$, whose unique positive root is $\xi_0(n,c)$. The identity $\beta_0^*(n,c,0) = \beta_r^*(n,c,0)$ follows as a consequence of the expression of $\beta_0^*(n,c,0)$. The inequalities $\frac{1}{c+1} < \xi_0(n,c) < \xi_0(n+1,c) < \frac{1}{c}$ were proved in [27, Proposition 1(a)]. Finally, it can be checked that

$$\frac{\partial \xi_0}{\partial c}(n,c) = -\frac{(n-1)\sqrt{(n-c-1)^2+4nc} + (n-1)^2 + c(n+1)}{2nc^2\sqrt{(n-c-1)^2+4nc}} < 0,$$

which concludes the proof. □

Proof of Proposition 2. The expression for the optimal profits of the symmetric $n+1$ private generators in (9) follows from the definition of profit by considering the optimal strategies in Proposition 1.

(i) We first observe that $\pi_r^*(n,c,0) > \pi_r^*(n+1,c,0)$ holds if and only if

$$2\xi_0(n+1,c)(2-c\xi_0(n+1,c))(1-\xi_0(n,c))^2 > 2\xi_0(n,c)(2-c\xi_0(n,c))(1-c\xi_0(n+1,c))^2,$$

and this inequality holds as $\xi_0(n+1,c) > \xi_0(n,c)$, $1-c\xi_0(n,c) > 1-c\xi_0(n+1,c)$ and finally, $(2-c\xi_0(n+1,c))(1-c\xi_0(n,c)) > (2-c\xi_0(n,c))(1-c\xi_0(n+1,c))$.

(ii) For $\tilde{c}(n) := -(n+1) + 2\sqrt{n(n+1)}$, it can be checked that

$$\frac{\partial \pi_r^*}{\partial c}(n,\tilde{c}(n),0) = 0, \quad \frac{\partial \pi_r^*}{\partial c}(n,c,0) > 0 \ \ \forall c < \tilde{c}(n), \quad \text{and} \quad \frac{\partial \pi_r^*}{\partial c}(n,c,0) < 0 \ \ \forall c > \tilde{c}(n).$$

(iii) The inequality $\tilde{c}(n) < \tilde{c}(n+1)$ can be easily obtained. Finally, it can be numerically checked that $\pi_r^*(n,\tilde{c}(n),0) > \pi_r^*(n+1,\tilde{c}(n+1),0)$ for all $n \in \mathbb{N}$. □

Proof of Proposition 3. The optimal strategies follow from Theorem 1 by taking $\lambda = 0$. In this case, $P_{n,c,1}(x) = n(n-1)c^2x^3 + ((2n-1)c^2 + (4n-n^2)c)x^2 + (c^2 + (3-2n)c - 2n)x - (1+c)$ whose unique positive root is denoted by $\xi_1(n,c)$.

(i) In order to prove that $\xi_0(n,c) < \xi_1(n,c)$ we just need to observe that $P_{n,c,1}(\xi_0(n,c)) < 0$, and the conclusion will follow from Bolzano's Theorem. Further computations show that

$$P_{n,c,1}(\xi_0(n,c)) = \frac{1+n}{2cn^2} \times \left((c^2 + (n+2)c + 1 - n) - (1+c)\sqrt{(n-c-1)^2+4nc}\right) < 0,$$

being this inequality equivalent to $-4cn^2 < 0$.

(ii) To show that $\xi_1(n,c) < \xi_1(n+1,c)$, we just need to show that $P_{n+1,c,1}(\xi_1(n,c)) < 0$. We observe that $P_{n+1,c,1}(\xi_1(n,c)) = P_{n+1,c,1}(\xi_1(n,c)) - P_{n,c,1}(\xi_1(n,c)) = \xi_1(n,c) \cdot G(\xi_1(n,c))$ where $G(x) = 2nc^2x^2 + (2c^2 + (3-2n)c)x - 2(1+c)$. The unique positive root of $G(x)$ is

$$\tilde{\xi}_0(n,c) := \frac{n - c - 1.5 + \sqrt{(n-c-1.5)^2 + 4n(c+1)}}{2nc}.$$

Since $\xi_1(n,c) < \tilde{\xi}_0(n,c)$ (as further computations show that $P_{n,c,1}(\tilde{\xi}_0(n,c)) > 0$), then $G(\xi_1(n,c)) < 0$, and so our claim holds. The second inequality $\beta_0^*(n,c,1) < \beta_0^*(n+1,c,1)$ is equivalent to $nc\xi_1(n,c) < (n+1)c\xi_1(n+1,c)$, and this follows from the fact that $\xi_1(n,c) < \xi_1(n+1,c)$.

(iii) One has $\xi_1(n,c) = \beta_r^*(n,c,1) < \frac{1}{c}$ as it can be easily checked that $P_{n,c,1}(\frac{1}{c}) > 0$. The inequalities $\frac{1}{c} < \beta_0^*(n,c,1) < \frac{2}{c}$ are straightforward.

(iv) In order to compute $\frac{\partial \xi_1}{\partial c}(n,c)$, we use the fact that $P_{n,c,1}(\xi_1(n,c)) = 0$ and employ implicit differentiation. Thus, we get

$$\frac{\partial \xi_1}{\partial c}(n,c) = -\frac{H_{n,c,1}(\xi_1(n,c))}{P'_{n,c,1}(\xi_1(n,c))},$$

where $H_{n,c,1}(x) := 2nc(n-1)x^3 + ((4n-2)c + 4n - n^2)x^2 + (2c + 3 - 2n)x - 1$. On the one hand, it follows from the proof of Theorem 1 that $P'_{n,c,1}(\xi_1(n,c)) > 0$. On the other hand, it can be numerically checked that $H_{n,c,1}(\xi_0(n,c)) \geq 1 > 0$ and, as $H_{n,c,1}$ has a unique positive root by reasoning as in the proof of Theorem 1, then one necessarily has $H_{n,c,1}(\xi_1(n,c)) > 0$. Consequently, $\frac{\partial \beta_r^*}{\partial c}(n,c,1) = \frac{\partial \xi_1}{\partial c}(n,c) < 0$. Finally, we observe that

$$\frac{\partial(\beta_0^* - \beta_r^*)}{\partial c} = \frac{\partial(\beta_0^* - \beta_r^*)}{\partial \xi_1} \cdot \frac{\partial \xi_1}{\partial c} = \frac{-nc^2\xi_1^2 + 2nc\xi_1 + 1 - n}{(1-c\xi_1)^2} \cdot \frac{\partial \xi_1}{\partial c} < 0$$

since $\frac{\partial \xi_1}{\partial c} < 0$ and $-nc^2\xi_1^2 + 2nc\xi_1 + 1 - n > 0$ (this inequality is equivalent to $J_{n,c}(\xi_1) > 0$ where $J_{n,c}(x) := -nc^2x^2 + 2ncx + 1 - n$, and it holds since $J_{n,c}(x) > 0$ if and only if $\frac{n-\sqrt{n}}{nc} < x < \frac{n+\sqrt{n}}{nc}$ and $\frac{n-\sqrt{n}}{nc} < \xi_0(n,c) < \xi_1(n,c) < \frac{1}{c} < \frac{n+\sqrt{n}}{nc}$). Hence, $\frac{\partial \beta_0^*}{\partial c}(n,c,1) < \frac{\partial \beta_r^*}{\partial c}(n,c,1)$. □

Proof of Proposition 4. The expressions for the optimal profits follow from the definition of profit by taking into account the optimal strategies in Proposition 3.

(i) The proof of $\pi_r^*(n,c,1) > \pi_r^*(n+1,c,1)$ follows the same lines than that of Proposition 2(i), whereas the proof of $\pi_0^*(n,c,1) > \pi_0^*(n+1,c,1)$ is a consequence of $\xi_1(n,c) < \xi_1(n+1,c)$ (see Proposition 3).

(ii) It can be checked that the first order condition $\frac{\partial \pi_r^*}{\partial c}(n,c,1) = 0$ holds for the value $\bar{c}(n)$ implicitly defined by the equation

$$3\xi_1(n,\bar{c}(n))^2 - \bar{c}(n)\xi_1(n,\bar{c}(n))^3 + 2\frac{\partial \xi_1}{\partial c}(n,\bar{c}(n),1) = 0.$$

Then, one numerically gets $\bar{c}(n) < \bar{c}(n+1)$ and $\pi_r^*(n,\bar{c}(n),1) > \pi_r^*(n,\bar{c}(n),1)$. The same argument applies with the optimal profit of firm S.

(iii) One has that $\pi_r^*(n,c,1) > \pi_0^*(n,c,1)$ is equivalent to

$$(nc\xi_1^2 + c\xi_1 - 1)(nc\xi_1^2 + (c-2n)\xi_1 - 1) < 0.$$

Let $K(x) := ncx^2 + cx - 1$ and $L(x) := ncx^2 + (c-2n)x - 1$. Since $L(1/c) = -n/c < 0$ and $\xi_1 < 1/c$, then $L(\xi_1) < 0$. Now, as $K(\xi_0) \geq 0$ and $\xi_0 < \xi_1$, then $K(\xi_1) > 0$. Thus, the conclusion follows.

(iv) Last statement also follows numerically. □

Further details of all the remaining proofs are available from the authors upon request.

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.energy.2024.133813.

Data availability

Data will be made available on request.

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