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Auctioning vs. Grandfathering in Cap-and-Trade Systems with Market Power and Incomplete Information

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Summary

We compare auctioning and grandfathering as allocation mechanisms of emission permits when there is a secondary market with market power and the firms have private information. Based on real-life cases such as the EU ETS, we consider a multi-unit, multi-bid uniform auction, modelled as a Bayesian game of incomplete information. At the auction each firm anticipates his role in the secondary market, which affects the firms' valuation of the permits (that are not common across firms) as well as their bidding strategies and it precludes the auction from generating a cost-effective allocation of permits, as it would occur in simpler auction models. Auctioning tends to be more cost-effective than grandfathering when the firms' costs are asymmetric enough, especially if the follower has lower abatement costs than the leader and uncertainty about the marginal costs is large enough. If market power spills over the auction, the latter is always less cost-effective than grandfathering. One central policy implication is that the specific design of the auction turns out to be crucial for cost-effectiveness. The chances of the auction to outperform grandfathering require that the former is capable of diluting the market power that is present in the secondary market.

Keywords: Cap-and-Trade Systems, Auctions, Grandfathering, Market Power, Bayesian Games of Incomplete Information

JEL Classification: D44, Q58, L13

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Auctioning vs. grandfathering in cap-and-trade systems with market power and incomplete information*

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September 30, 2013

Abstract

We compare auctioning and grandfathering as allocation mechanisms of emission permits when there is a secondary market with market power and the firms have private information. Based on real-life cases such as the EU ETS, we consider a multi-unit, multi-bid uniform auction, modelled as a Bayesian game of incomplete information. At the auction each firm anticipates his role in the secondary market, which affects the firms' valuation of the permits (that are not common across firms) as well as their bidding strategies and it precludes the auction from generating a cost-effective allocation of permits, as it would occur in simpler auction models. Auctioning tends to be more cost-effective than grandfathering when the firms' costs are asymmetric enough, especially if the follower has lower abatement costs than the leader and uncertainty about the marginal costs is large enough. If market power spills over the auction, the latter is always less cost-effective than grandfathering. One central policy implication is that the specific design of the auction turns out to be crucial for cost-effectiveness. The chances of the auction to outperform grandfathering require that the former is capable of diluting the market power that is present in the secondary market.

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1 Introduction

Most economists tend to favour auctioning of emission permits while business tend to prefer a grandfathering scheme, as noted for example by Hepburn *et al.* (2006). Until very recently, auctioning has been the exception rather than the rule, while grandfathering has been, by far, the most widespread method used to distribute emission permits. Nevertheless, the situation is changing and it could change even more dramatically in the coming future.

For the European Union Emission Trading System (EU ETS), considered to be the largest environmental market in the world, the role of auctioning is becoming increasingly relevant. The 2008 revision of the European Emission Trading Directive established as a fundamental change for the third trading period, starting in 2013, the mandate that auctioning of allowances will be the default method for allocating allowances. From 2013 onwards all allowances not allocated for free must be auctioned and auctioning will progressively replace grandfathering as the main method in all EU-ETS sectors except aviation. It is expected that roughly half of the allowances will be auctioned. This is in sharp contrast to the first trading period (2005-2007) in which a 5% limit was set to the amount of allowances that could be auctioned. Moreover, only four countries used auctions at all and only Denmark used up the 5% limit. The situation in the second trading period (2008-2012) was not very different, with no more than 4% of all the allowances auctioned. The arguments posed by the European Commission (EC) to support the introduction of auctions in the third period are that auctioning "best ensures the efficiency, transparency and simplicity of the system, creates the greatest incentives for investment in a low-carbon economy and eliminates windfall profits".[1]

The world first CO_2 cap-and-trade system to require the widespread use of auctions was the Regional Greenhouse Gas Initiative (RGGI). This programme began in 2009, it includes the 10 northeastern US states as well as Eastern Canada and it covers CO_2 emissions from electricity generators. As noted by Burtraw *et al.* (2009), the RGGI proposal represents a substantial break with the past since, instead of giving the permits away for free, the RGGI states decided to auction close to 90 percent of their permit budgets. The increasing role of auctioning supported by these examples is an important motivation to analyze the role of auctions as an allocation mechanism for emission permits.

In this paper, we try to get some insight into the properties of auctioning versus grandfathering. Specifically, we start from the EC's argument to support the introduction of auctioning on the grounds of efficiency. The efficiency of an environmental policy requires a) enforcing the "right" (efficient) amount of emissions (considering both the abatement costs and the externalities caused by pollution) and b) distributing those emissions among emitters in a cost-effective way. In this paper, we disregard the former issue by assuming that the amount of permits is exogenously decided and we focus on the second dimension,

[1] See http://ec.europa.eu/clima/policies/ets/cap/auctioning/faq_en.htm, section "Why are allowances being auctioned?".

i.e., the right way of distributing permits among polluting firms. Summing up, our central research question is: can auctioning distribute permits in a more cost-effective way than grandfathering? So, we focus on cost-effectiveness, which is a necessary (although not sufficient) condition for efficiency.

It is well known that, under perfect competition and full information, the initial allocation of permits only matters for the distribution of the gains from trade, but it is irrelevant for the final allocation and, hence, for cost-effectiveness (see, for example, Tietenberg 2006). Nevertheless, as first noted by Hahn (1984), if there is market power, the initial distribution of permits does matter for the sake of cost-effectiveness. Indeed, the cost-effective allocation will be reached only when, in the initial allocation, the leader receives exactly the amount of permits that he would receive under perfectly competitive pricing. So, on the grounds of cost-effectiveness, the EC's argument for auctioning only makes sense under the implicit recognition that there is not a perfect market for permits since, otherwise, no efficiency gains could be made by changing the allocation method.

Sturn (2008) notes that whether market power actually constitutes a problem in an emission trading system has to be analyzed for each market separately. Market power is probably not one of the main issues in the EU ETS since the number of involved facilities is very large, but it may constitute a serious problem for future international emissions trading system within the framework of the Kyoto Protocol and for some regional emissions markets. Montero (2009) and Muller *et al.* (2002) stress that market power issues are more likely to show up in markets where countries -rather than individual entities- are the relevant players, as is the case of the Kyoto Protocol. On the other hand, it can be argued that, even in a cap-and-trade system with a large number of participants (as the EU ETS), it is not unrealistic to assume that the market is not perfectly competitive since there might be information asymmetries, collusive behavior, interaction with other markets and other imperfections. For example, Karl-Martin *et al.* (2008) claim that "loopholes in EU emissions trading law foster tacit collusion that impacts oligopolistic product markets" (p. 347). Specifically, they state that "permits might be diverted from their intended use as a vehicle for tacit collusion in two basically different manners: by increasing permit prices or by coordinating the firms' emissions" (p. 357-358). Hinterman (2011) focuses on the power sector and considers a case in which there is market power in both the power and the permit market. In an application to the EU ETS, he concludes that the largest electricity producers in Germany, the UK and the Nordpool market could have found it profitable to manipulate the permit price upwards and he claims that this could explain the elevated allowance price level during the first 18 months of the EU ETS. For each individual market, the higher or lower severity of those failures will determine how imperfect the market is and, therefore, the room for efficiency improvements.

Apart from market power, we consider an additional element to make the comparison between grandfathering and auctioning non-trivial, which is incomplete information. If information were complete, and more specifically, if the environmental planner could observe or make a perfect forecast of firms' behaviour, then, he could compute the cost-effective solution and implement it.[2] Under those conditions there would be no room for further improvements since grandfathering would readily provide the minimum-cost allocation. That is clearly not the case in real life. For example, Ellerman *et al.* (2010) claim that, during the first period of the EU ETS, "the task of setting a cap that was at or close to business-as-usual (BAU) emissions was made enormously more difficult by poor data. The problem was that no member state government had a good idea of the exact emissions within the ETS sectors ... and the data problem was even worse in the new member states of the eastern Europe". Moreover, "the problems created by poor data were not limited to cap-setting; they extended into the allocation of allowances to installations, which required installation-level emissions data ... Not surprisingly, since allocations to these installations depended on the data submitted, industrial firms were forthcoming, although there has always been a suspicion that the intended use of the data imparted an upward bias to these data" (p. 37-38). We capture this reality by means of a Bayesian model in which firms have private information about their technology and the effects of external events on their BAU emissions.

To the best of our knowledge, the question of how cost-effective an auction is as compared to grandfathering (under market power) has not been addressed in formal terms, although some related informal discussions and experimental studies have been conducted (see Ledyard and Szakaly-Moore (1994), Godby (1999, 2000), Muller *et al.* (2002)). In a theoretical paper, Antelo and Bru (2009) compare auctioning and grandfathering in a permit market with a dominant firm, when the government is concerned both about cost-effectiveness and public revenue, but one of our main building blocks, incomplete information, is absent in their work. Montero (2009) also uses a deterministic approach and, as a consequence, both Antelo and Bru (2009) and Montero (2009) conclude that, in a setting in which the auction is followed by a secondary market, it is optimal for the leader not to take part in the auction and acquire all the permits in the secondary market. The rationale under this somewhat counterintuitive result is that, for the leader, it is optimal not to bid in order to keep the price low and then buy the permits in the market at a lower price than the competitive one by acting as a monopsonist. Although we get some related result, we conclude below that, under incomplete information, it is not necessarily optimal for the leader to refrain from participating in the auction.

Our paper builds on two strands of literature. The first, pioneered by Hahn (1984), focuses on cap-and-trade systems under market power. An overview of this literature can be found in Montero (2009). The second strand refers to auction theory. This literature typically focuses on the optimal bidding strategies, on how auctioned goods are allocated to bidders and what revenue the auctioneer can expect to get from the auction. Specifically, we are concerned about multi-unit multi-bid auctions, in which more than one

[2] That is, for example, what Antelo and Bru (2009) conclude in a complete-information model.

unit is being auctioned (multi-unit) and bidders can bid for more than one unit[3] (multi-bid). In most of the literature on multi-unit multi-bid auctions, common-value is assumed, that is, the value of each auctioned unit is constant both across units and across bidders. Under such assumption efficiency is not a relevant question since any allocation of units across bidders is efficient. In much simpler settings, such as single-unit auctions, the resulting allocation is also efficient. For a large range of auction formats it is always the case that the bidder with the highest valuation is the one who gets the unit on sale.

In our model, the common-value assumption fails to hold for two reasons. First, bidders -polluting firms- at the time of bidding anticipate that there will be some firm exerting market power in the secondary market. Moreover, each firm anticipates his role, either as a price setter or taker. This heterogeneity across firms implies that the value attached to permits is not common to them. Moreover, we realistically assume that marginal abatement cost is not constant, what implies that, for each bidder, the value of one additional permit is not constant across units either. Thus, efficiency of the auction allocation turns out to be a relevant question in our setting since efficiency results that holds true for simpler auctions do not trivially extend to this setting.[4]

We present a simple model in which two firms receive an initial allocation of emission permits (either by means of grandfathering or auctioning) and then interact in a secondary market[5] in which one of the firms acts as a leader and the other one as a follower. As is usual in auction theory, we model incomplete information by assuming that the agents have random and privately observed types. In our framework, these types determine the relative position of the abatement-cost functions. For technical simplicity some of the results are derived under uniform distribution and three alternative scenarios. In the first one, the types are mutually independently distributed, whereas in the other two scenarios they are positively correlated. In the second case the leader is assumed to have ex-ante lower marginal abatement costs than the follower and the opposite assumption is imposed in the third scenario.

In this setting, we compare auctioning and grandfathering in terms of cost-effectiveness. A rather natural argument to support the hypothesis that an auction could improve cost-effectiveness with respect to grandfathering is that the auction could work in such a way as to reduce the chances of the leader to exert its market power. To check the validity of this argument, we start analyzing a case in which both the leader and the follower act non-strategically in the auction although they are capable of anticipating that, in the secondary market, the leader will act strategically and the follower will be a price taker. So,

[3] More precisely, bidders can submit multiple quantity-price pairs, in short, a demand function.

[4] As another example, a classical result in single-unit auctions that does not extend to the multi-unit multi-bid case is the revenue equivalence theorem. See Krishna (2002) for a detailed discussion on this regard. Examples of multi-unit multi-bid non-common value auctions are presented in de Castro and Riascos (2009) and Engelbrecht-Wiggans and Kahn (1998). These papers do not address efficiency and they do not justify the value of the units on sale on the basis of a post-auction market as we do. Nyborg and Strebulaev (2001) present a model to analyze ECB money markets, considering both an auction and some secondary market. Though, their model is fundamentally different to ours, apart from the application, because the auctioneer participates in the secondary market with selling and buying prices which are ex-ante announced.

[5] For the sake of clarity, we will commonly refer to the secondary market (where firms can trade permits among themselves) to differentiate it from the initial allocation, which can be seen as a primary market. This is a slight abuse of terminology since only auctioning (not grandfathering) can be considered as a market.

in this case, the auction has the effect of making the firms more symmetric in some sense. The rationale behind this assumption is that the leader's ability to set the price in the secondary market could be absent (or, at least, weaker) in the auction, first, because the auctioneer has the duty to guarantee that all the participants in the auction are treated evenly while it is not so in the secondary market, and second, because the anonymity of the bidders make it more difficult to emit effective price signals.

This ability of the auction to neutralize market power is just a working hypothesis, not an essential feature of the auction, at least from a theoretical perspective. Thus, for the sake of completeness, we also analyze a case in which the auction preserves the roles (leader and follower) assumed in the secondary market. In standard auction theory,[6] the role-preserving auction is a relatively unexplored problem within a multi-unit multi-bid framework. With respect to the standard approach in the literature, the main complexities we deal with are non-common value and the existence of a post-auction market. Theoretical papers on multi-unit multi-bid auctions typically assume common value and no secondary market (see Wang and Zender (2002) or Alvarez and Mazón (2012)). More general settings, as the one by de Castro and Riascos (2009) do not fully characterize the equilibrium as we do, but just optimal responses. Since we are faced with a rather complex and novel model, to tackle it we restrict ourselves to continuous strategies and a subset of the parameter space that guarantees interior solutions.

Our main results fall into two categories. First, some of the results refer to the existence, uniqueness and characterization of the equilibrium under the auction. Second, we compare auctioning and grandfathering in terms of cost-effectiveness. Under the technical requirements we impose, existence and uniqueness is always guaranteed. As another general result, in all the cases that we study, the auction equilibrium is never cost-effective, because the leader will either over-bid or under-bid to place him in the most advantageous position for the secondary market.

In the auction with non-strategic bidders, we conclude that, it the firms are asymmetric enough in terms of marginal abatement costs, the firm with the higher cost is prone to bid more aggressively and get all the permits in the auction, what tends to generate more cost-effective results than grandfathering. If the firms are similar enough to each other, permits are shared among both firms in the auction, but the follower is generally under-assigned and the leader is over-assigned with respect to the cost-effective allocation. The comparison of expected cost is partially carried out with a numerical exploration. The results reveal that, in the auction, the leader tends to be over-assigned as compared to the cost-effective allocation and, as a consequence, the auction generally does worse than grandfathering in terms of expected cost when the types are independently distributed or the leader's marginal cost is ex-ante lower than the follower's. Contrarily, if the follower has access to a more efficient abatement technology, and additionally, the variability of the types is large in terms of the cap, then it is the auction that outperforms grandfathering, since the allocation

[6] By this, we refer to the game-theoretic approach that characterizes auctions as Bayesian games of incomplete information.

generated by the auction is closer to the cost-effective one than that resulting from grandfathering.

The role-preserving auction delivers bad news for auctioning. If the auction preserves the leader and follower roles, it is always dominated by grandfathering. Moreover, the dominance is not only in terms of expected cost, as it was under the non-strategic auction, but in a stronger manner: for each possible realization of the types, the auction leads to larger realized cost than grandfathering, what implies first-order stochastic dominance of grandfathering with respect to auctioning. There is even more, we prove the strong result that the auction is optimal ex-post for the leader, in the sense that the leader can play in such a way that he enjoys the same profit that he would get if he could observe not only his own type, but also his rival's type at the time of bidding. We also conclude that the leader always gets less permits than what would be cost-effective, which is in the same line as the result in Antelo and Bru (2009) and Montero (2009) regarding the absence of the leader in the auction, but our result is more general in the sense that the leader's allocation is lower than the optimal amount, but not necessarily zero.

As a general policy implication, we conclude that the mere fact of auctioning the permits instead of allocating them by means of grandfathering is not a panacea, at least in terms of cost-effectiveness. The specific design of the auction turns out to be crucial and, specifically, if the auction inherits the leader and follower roles from the secondary market, the results are prone to be worse rather than better. If, on the other hand, the auction is capable of diluting market power, then there are chances that it could render better results than grandfathering.

We organize our work as follows. In Section 2 we present the main elements of the model, including the structure of the secondary market and how we model grandfathering. In section 3 we analyze the case in which the firms act non-strategically in the auction. Section 4 deals with a role-preserving auction. Section 5 presents some conclusions and discussion.

2 The model

2.1 Basic setting

There are two polluting firms, labelled as $i \in \{F, L\}$, that are subject to a cap-and-trade system. $\bar{Q}$ emission permits are issued and distributed between the firms by some allocation procedure (either auctioning or grandfathering). The number of permits is assumed to be given and we only care about the distribution of those permits among firms. Therefore, for our purposes, $\bar{Q}$ can be treated as a parameter since it is not an endogenous variable. Each firm i receives an initial allocation of permits, denoted as q_{i0}, with $q_{L0} + q_{F0} = \bar{Q}$, and then the permits are traded in a secondary market in which L acts as a leader and F as a follower.[7] Since in real-world examples the number of permits to be assigned is typically very large,

[7] For easiness of exposition, we consider only two firms. While including more than one leader would imply a qualitative complication, the model would be qualitatively similar with a competitive fringe instead of a single follower, since the leader

as a reasonable approximation we take it to be continuous variable.[8]

To meet the environmental legal requirements, each firm has two options: first, to use permits and, second, to do some abatement effort to reduce its emissions. For the sake of analytical tractability, we assume that the cost of the latter option is given by a quadratic total abatement cost function (TC), that gives rise to a linear marginal abatement cost (MC):

$$TC_i\left(e_i\right) = K_i - \alpha_i e_i + \frac{\beta}{2} e_i^2, \tag{1}$$

$$MC_i\left(e_i\right) = -TC_i' = \alpha_i - \beta e_i,$$

where e_i represents the effective emissions of firm i. In this standard specification, apart from a fixed-cost term K, total and marginal costs depend on two parameters, α and β, that represent the intercept and the slope of MC respectively. We allow for heterogeneity across firms by making the fixed cost and the intercept firm-specific. An alternative way to do the same would be to make the slope firm-specific instead (or, of course, make all three parameters firm-specific). The insight we get is similar but the calculus become much more cumbersome when β is not constant across firms.

Moreover, to account for incomplete information, we assume that α_i is a random variable that, as is usual in auction theory, we refer to as the *type* of firm i.[9] We assume that the distribution of both types is common knowledge. At the beginning of the game each firm observes its own type but only knows the distribution of the rival's type. In our framework, the interpretation of this assumption is that a firm itself is the one that has more accurate information about its own technology and the effect of random shocks (due to climatic, environmental or technological reasons) on the firm's results. We assume that both α_L and α_F are a priori distributed in the closed interval $[\theta, \theta + \sigma]$, where θ, $\sigma > 0$. Thus, the distribution is characterized by two parameters, θ and σ; the former captures the size whereas the later accounts for variability in the types.

We assume that, without the cap-and-trade system, the firms would emit the laissez-faire or BAU emissions, e_i^{BAU}, i.e., the amount of emissions that would minimize TC_i. By making the marginal abatement cost equal to zero, we get $e_i^{BAU} = \frac{\alpha_i}{\beta}$.

After the initial allocation is made, the types are publicly revealed. Then the firms engage in the secondary market and trade allowances with full information. To assume that the types are known in the secondary market but not in the auction amounts to the fact that transactions in the secondary market are far more frequent than auctions, and thus, it is realistic to assume that in the secondary market the

is only concerned about the aggregate behaviour of the followers.

[8] See Wilson (1979) or, more recently, Alvarez and Mazon (2012) and Wang and Zender (2002).

[9] Following standard auction theory, the auction will be modelled as a Bayesian game of incomplete information. The pair of types, (α_F, α_L), are the fundamental random variables of the model ("types"). With a slight abuse of notation, we denote indistinctly a random variable and an arbitrary realization of it.

agents handle more information. So, the timing of the game is the following:

1. Each player i observes his own type (realization of α_i)
2. The planner initially allocates the permits. We consider two cases:

Option A: Grandfathering (for free based on BAU emissions)

$$\textit{Option B}\text{: Auctioning} \begin{cases} \text{2.B.1. Each player submits a bid} \\ \text{2.B.2. Planner collects bids and sets opt-out price} \\ \text{2.B.3. Bidders pay the price and get the permits} \end{cases}$$

3. The types are revealed to everyone

$$\text{4. Secondary market} \begin{cases} \text{4.1. The leader sets the price} \\ \text{4.2. The follower decides its demand} \\ \text{4.3. The market clears} \end{cases}$$

For the sake of comparison, we compute the cost-effective allocation $\left(e_L^{CE}, e_F^{CE}\right)$, which follows from equating marginal abatement costs across firms and imposing the market-clearing condition $e_L + e_F = \bar{Q}$:

$$e_L^{CE} = \tfrac{\alpha_L - \alpha_F + \beta\bar{Q}}{2\beta}, \qquad e_F^{CE} = \tfrac{\alpha_F - \alpha_L + \beta\bar{Q}}{2\beta}, \tag{2}$$

where CE stands for "cost-effective". Note that, when both firms are identical ($\alpha_F = \alpha_L$), it is optimal that each firm gets $\frac{\bar{Q}}{2}$ permits, and if $\alpha_i > \alpha_j$ it is optimal that firm i receives more permits than j.

2.2 The secondary market

Denote as q_{i1} the amount of permits that firm i holds after trading in the secondary market, that has to coincide with his realized emissions.[10] Therefore, the amount of permits sold (if $q_{i0} > q_{i1}$) or bought (if $q_{i1} > q_{i0}$) in the secondary market by firm i is $|q_{i0} - q_{i1}|$. The aim of both firms is to maximize their profits, considering both the revenue or the expenses due to permits trading and abatement costs, i.e.,

$$\Pi_i = p_1 \left(q_{i0} - q_{i1}\right) - TC_i, \tag{3}$$

where p_1 is the price of permits in the secondary market. The difference between both firms' behavior is that the follower chooses its net demand while taking p_1 as given, whereas the leader takes into account the effect of his behavior on the market price. We restrict ourselves to interior solutions in the secondary market, i.e., we require both q_{L1} and q_{F1} to be positive and lower than $\bar{Q}$ in equilibrium. Besides its tractability, assuming that the post-market holdings of permits are positive for every firm is fairly realistic. Moreover, to avoid meaningless solutions, we require $q_{i1} \leq e_i^{BAU}$ for all i, i.e., no firm will hold more permits than their BAU emissions and, hence, some abatement effort is required in equilibrium. Proposition 1 identifies

[10] We do not consider the possibility that some firm buys more permits than needed just to withdraw them from the market and pushing the price upwards. This is guaranteed under the technical condition (4), that we impose below.

sufficient conditions for these requirements to hold and states the solution to the secondary market under those conditions.

Proposition 1 *If the following condition holds*

$$\frac{3}{2}\theta \geq \beta\bar{Q} \geq \sigma, \tag{4}$$

the number of permits hold by each firm in the secondary-market equilibrium is given by

$$q_{L1}^{*} = \frac{\alpha_L - \alpha_F}{3\beta} + \frac{\bar{Q} + q_{L0}}{3}, \tag{5}$$

$$q_{F1}^{*} = \frac{\alpha_F - \alpha_L + \beta\left(2\bar{Q} - q_{L0}\right)}{3\beta}, \tag{6}$$

and it is guaranteed that, for any initial allocation, $q_{i1} \in [0, \min\{\bar{Q}, e_i^{BAU}\}]$ *holds w.p.1 for* $i \in \{F, L\}$. *The resulting profits are given by*

$$\begin{aligned}
\pi_L\left(q_{L0}, \boldsymbol{\alpha}\right) &= \Theta_L + \frac{\alpha_L + 2\alpha_F - 2\beta\bar{Q}}{3} q_{L0} + \frac{\beta}{6} q_{L0}^2, && (7)\\
\pi_F\left(q_{F0}, \boldsymbol{\alpha}\right) &= \Theta_F + \frac{2\alpha_L + 7\alpha_F - 2\beta\bar{Q}}{9} q_{F0} - \frac{5\beta}{18} q_{F0}^2, && (8)
\end{aligned}$$

where $\boldsymbol{\alpha} := (\alpha_F, \alpha_L)$ *and* Θ_L *and* Θ_F *are two terms that depend on the parameters of the model as well as the types but are independent of the initial allocation.*

In the rest of the paper we restrict ourselves to the parameter space defined by (4). From the results in Proposition 1, it is important to underline the fact that the equilibrium reached in the secondary market depends on the initial allocation. Moreover, as first noted by Hahn (1984), the only case in which the secondary market renders the cost-effective solution is that in which the leader initially receives exactly the amount of permits that corresponds to the cost-effective allocation. If this is the case, the secondary market is superfluous in the sense that no transaction will be made. In any other event, the role of the secondary market will be relevant. Indeed, using (2) in (5), it is easy to check that, if $q_{L0} < e_L^{CE}$, then $e_L^{CE} > q_{L1} > q_{L0}$. Symmetrically, if $q_{L0} > e_L^{CE}$ then $e_L^{CE} < q_{L1} < q_{L0}$. In words, if the leader receives initially less permits than in the cost-effective allocation, in the secondary market he will act as a monopsonist and will buy less permits than what would be cost-effective. If, on the contrary, he receives more permits than e_L^{CE}, he will act as a monopolist and will sell less permits than required to reach cost-effectiveness.

Summing up, the initial allocation of permits is crucial to determine the equilibrium of the secondary market and its cost-effectiveness. The secondary market turns out to be relevant as far as the initial allocation is different from the cost-effective one. We claim that this is generally the case. Under grandfathering, if the planner had perfect information (in our framework, if the values of α_F and α_L were perfectly known), then it would be possible to compute the cost-minimizing solution and, by allocating the right amount of permits to each firm, cost-effectiveness would be achieved with certainty and the secondary market would be redundant. Nevertheless, it is reasonable to think that the planner does not have perfect information about the firms' technology and the way in which random shocks affect the firms' result. Consistent with this fact, we assume that the planner allocates the permits under incomplete information, what prevents him from allocating the cost-effective amount to each firm. Under auctioning, as it is discussed in the introduction, in a multi-unit, multi-bid, non-common-value auction as the one we deal with, the resulting allocation is not necessarily efficient, what in our framework means that it is not cost-effective. This is consistent with our findings below.

For the analysis of the auction it is also important to notice that, according to Proposition 1, π_L is strictly convex in q_{L0} while π_F is strictly concave in q_{F0}.

In Corollary 1 we show that total cost can be expressed as a function of the amount of permits initially assigned to the follower.

Corollary 1 *The aggregated abatement cost can be written as the following quadratic function of* q_{F0} :

$$TC\left(q_{F0},\boldsymbol{\alpha}\right) := TC_L + TC_F = \Theta + \frac{\alpha_L - \alpha_F - \beta\bar{Q}}{9}q_{F0} + \frac{\beta}{9}q_{F0}^2, \tag{9}$$

where Θ *is a term that depends on the parameters and the types but not on the initial allocation.*

We include $\boldsymbol{\alpha}$ as an argument of TC in (9) in order to emphasize its dependence on the types. Since we focus on cost-effectiveness, TC will be our comparison criterion to assess grandfathering and auctioning as alternative allocation mechanisms. From (9) it can be noticed that calculating expected total cost under grandfathering is rather simple since q_{F0} is exogenously given (decided by the planner) and, therefore, α_L and α_F are the only stochastic variables, while the computation is much more complex under auctioning, since q_{F0} comes out as an equilibrium result determined by the firms' strategies, which, in turn, are driven by the realized types.

An implication of Corollary 1 is that the total cost entailed by an allocation system can be assessed just by checking how close the initial allocation is to the cost-effective one. In the special case $\alpha_L = \alpha_F$ it is immediate to conclude, once again, that the cost-minimizing distribution involves $q_{L0} = q_{F0} = \frac{\bar{Q}}{2}$. Using (9) allows us to skip computing the secondary-market effect to evaluate an allocation system, since such effect is already incorporated in (9). We only need to care about the initial allocation. In other words, all the information we need about the secondary market is contained in (7), (8) and (9).[11] For notational

[11] As a matter of fact, to evaluate grandfathering we only need (9) since the initial allocation is exogenously given. For the auction, we also need the profit functions, (7) and (8) to derive the optimal bidding functions.

simplicity we define the following monotone linear transformation of TC:

$$h(\delta, \boldsymbol{\alpha}) := \frac{9}{\bar{Q}} \left[TC \left(q_{F0}, \boldsymbol{\alpha} \right) - \Theta \right] = \delta^2 \beta \bar{Q} + (\alpha_L - \alpha_F - \beta \bar{Q}) \delta, \tag{10}$$

which is a function of $\delta := q_{F0}/\bar{Q}$, that is, the proportion of permits initially assigned to F. For simplicity, and with a slight abuse of terminology, we will refer to h as "cost", though it actually is a monotone linear transformation of it. This is innocuous since we are using costs only to determine the relative position of auctioning and grandfathering, i.e., to ascertain which method is more cost-effective, and the relative position is not altered by a monotone transformation.[12]

2.3 Grandfathering

We assume that, under grandfathering, permits are allocated based on BAU emissions, $e_i^{BAU} = \frac{\alpha_i}{\beta}$, and it is important to note that, since α_i is a random variable, so are the BAU emissions. In practice, grandfathering is usually applied by allocating permits based on observed past emissions. Our claim is that the observed emissions in a given period are the result of firms' decisions in that specific period while using all the private information they had, including their abatement technologies and the effects of random shocks. In terms of our model, under grandfathering the planner would use a specific past observed realization of $\frac{\alpha_i}{\beta}$. But, in general, this past value will not coincide with the present BAU emissions since those emissions depend on random events and privately observed information. In other words, the planner cannot perfectly determine the BAU emissions and will use some proxy for it. We assume that the allocation is based on average historical emissions or, equivalently, on the best prediction of e_i^{BAU}, which is its expected value, $E\left\{e_i^{BAU}\right\} = \frac{E\{\alpha_i\}}{\beta}$.[13] Therefore, each firm i receives an initial endowment of permits given by a fraction of $\bar{Q}$ proportional to $E\left\{e_i^{BAU}\right\}$. Specifically, the follower receives $q_{F0}^G = \delta^G \bar{Q}$ and the leader receives $q_{L0}^G = \left(1 - \delta^G\right) \bar{Q}$, where G stands for grandfathering and

$$\delta^G := \frac{E\left\{\alpha_F\right\}}{E\left\{\alpha_L\right\} + E\left\{\alpha_F\right\}}. \tag{11}$$

As a particularly simple case, consider that $E\left\{\alpha_L\right\} = E\left\{\alpha_F\right\}$, which implies $\delta^G = \frac{1}{2}$. Using (10) and

[12] Note that $h\left(\delta, \boldsymbol{\alpha}\right)$ is proportional to the difference between TC and Θ. From (9) we can interpret Θ as the total cost associated to a situation in which the follower receives no permits ($q_{F0} = 0$), which we can take as a comparison benchmark. So, a positive (negative) value of h means that the realized cost is higher (lower) than that in the benchmark situation.

[13] The notion of "expected BAU emission" might seem weird since BAU is commonly used to denote an observed value. To put it in simple terms, assume that the planer introduces a cap-and-trade system in period t and allocates permits based on past emissions, say $e_i\left(t-1\right)$. Since the cap-and-trade system was not in place in period t, this observed value can be seen as the BAU emissions in $t-1$. But the BAU emissions in t need not be equal to $e_i\left(t-1\right)$ due to uncertainty, and such value is unknown at the time of allocating the permits for period t. Our approach is that taking past values can be seen as a prediction for $e_i^{BAU}\left(t\right)$ and the most natural value for that prediction is the expected value. An additional empirical argument to take BAU emission as random is that data about past emissions are not always readily available. See the Ellerman *et al.* (2010) quotation in the introduction.

taking expected values, we get total cost under grandfathering and its (unconditional) expected value:

$$h(\delta^G, \boldsymbol{\alpha}) = \tfrac{2(\alpha_L - \alpha_F) - \beta\bar{Q}}{4}, \qquad E\{h(\delta^G, \boldsymbol{\alpha})\} = -\tfrac{\beta\bar{Q}}{4}. \tag{12}$$

3 Auction with non-strategic bidders

Assume now that the permits are auctioned. In the secondary market we have assumed the existence of one leader and one follower. Auction theory in itself does not impose any behavioural assumption in this regard. In other words, there is nothing in the mere concept of auction that prevents us to keep or to change those roles in the auction.[14] Our analysis tries to account for this generality. In this section we assume that both L and F act non-strategically in the auction (i.e., both act as price-takers). We start with this case since it seems the more favourable scenario for the auction. In Section 4 we consider the case in which the auction is role-preserving, i.e., it keeps the roles assumed in the secondary market. The aim of this paper is not to discuss which of these assumptions is more realistic, but to illustrate the theoretical predictions generated by each of them.

Since there are multiple units to be auctioned and every bidder can request more than one unit, we are faced with a multi-unit multi-bid auction. Moreover, due to the asymmetry between firms, and to the fact that MC_i is not constant, it is a non-common value auction. As usual in auction theory, a strategy for firm i is a mapping from the support of firm i's type into the set of feasible bids. Specifically, in our model, a strategy for firm i is a demand function of the form $q_i^b(\alpha_i, p_0)$, where the required amount, q_i^b, depends on the price, p_0, and firm i's type, but not on the rival's type, and b stands for "bid". Since the total amount of auctioned permits is $\bar{Q}$, we further assume that the demanded quantity submitted by the bidders must lie in $[0, \bar{Q}]$, that is, firms are not individually allowed to submit a demanded quantity either negative or larger than $\bar{Q}$ at any price. Denote as $v_i\left(q_{i0}, \alpha_i\right) := E\{\pi_i\left(q_{i0}, \boldsymbol{\alpha}\right) \mid \alpha_i, q_{i0}\}$ the value function of firm i at the auction, i.e., the expected value that i assigns to get q_{i0} permits in the auction conditional on his own type, where π_i is given by (7) or (8).[15] Then, i's best strategy is defined as

$$q_i^{b*}(\alpha_i, p_0) = \underset{q_{io} \in [0, \bar{Q}]}{\arg\max} \, \{v_i\left(q_{i0}, \alpha_i\right) - p_0 q_{i0}\}, \tag{13}$$

i.e., for each firm, the optimal bid is the demand function that maximizes his value function net of the cost incurred to get q_{i0} permits in the auction. An equilibrium in the auction is a pair of best strategies, q_F^{b*},

[14] In fact, many -and very important- real life auctions, such as Treasury auctions, do have both price-taker and price-setter players acting simultaneously.

[15] From the value function it is particularly easy to notice that the auction we are faced with is non-common-value. A common-value auction would require $v_i\left(q_{io}, p_0\right) = f\left(\boldsymbol{\alpha}\right) q_{i0}$, where $f\left(\boldsymbol{\alpha}\right)$ is an arbitrary function of the types that is common for both bidders, i.e., the marginal valuation of permits should be constant across units and across players. Using the definition of $v_i\left(q_{io}, p_0\right)$ and inspecting (7) and (8), it is obvious that this is not the case in our model.

q_L^{b*}, and a stop-out price p_0^* that satisfies $p_0^* = max\{p_0 \mid q_F^{b*}(\alpha_F, p_0) + q_L^{b*}(\alpha_L, p_0) \geq \overline{Q}\}$ for all (α_F, α_L). In words, this latter condition says that there is no a higher price than p_0^* such that all the permits are awarded while both firms follow their best strategies. The latter inequality allows for excess demand at the stop-out price, (which, as we show below, occurs at some equilibria). If so, a standard pro-rata formula is used, i.e., each player i receives a proportion $\frac{q_i^b}{q_i^b+q_j^b}$ of the permits. Based on the observed features of real auctions of permits we assume a uniform auction format, what means that all the awarded units pay the stop-out price, p_0^*.[16] Proposition 2 characterizes the optimal bidding functions and the types of equilibria.

Proposition 2 *There exist three threshold values p_{Fu}, p_{Fd} and p_L, where $p_{Fu} > p_{Fd}$, such that the optimal bidding functions of F and L are given, respectively, by*[17]

$$q_F^{b*}(\alpha_F, p_0) = \begin{cases} 0 & \text{if} \quad p_0 \geq p_{Fu}, \\ \frac{2E\{\alpha_L|\alpha_F\}+7\alpha_F-2\beta\bar{Q}-9p_0}{5\beta} & \text{if} \quad p_{Fd} < p_0 < p_{Fu}, \\ \bar{Q} & \text{otherwise}, \end{cases} \tag{14}$$

$$q_L^{b*}(\alpha_L, p_0) = \begin{cases} 0 & \text{if} \quad p_0 \geq p_L \\ \bar{Q} & \text{otherwise.} \end{cases} \tag{15}$$

Additionally, the auction has a unique equilibrium that belongs to one of the following three types:

type 1: $q_L^{b*}(\alpha_L, p_0^*) = 0$ *and* $q_F^{b*}(\alpha_F, p_0^*) = \bar{Q}$, *with* $p_0^* = p_{Fd}$;

type 2: $q_L^{b*}(\alpha_L, p_0^*) = \bar{Q}$ *and* $q_F^{b*}(\alpha_F, p_0^*) = 0$, *with* $p_0^* = p_L$;

type 3: $q_L^{b*}(\alpha_L, p_0^*) = \bar{Q}$ *and* $q_F^{b*}(\alpha_F, p_0^*) \in [0, \bar{Q}]$, *with* $p_0^* = p_L$.

Moreover, type-1 equilibrium occurs iff $\xi < -1$, type-2 equilibrium occurs iff $\xi > 1$ and type-3 equilibrium occurs iff $-1 \leq \xi \leq 1$, where

$$\xi := \frac{6\alpha_L - 14\alpha_F + 12E\{\alpha_F \mid \alpha_L\} - 4E\{\alpha_L \mid \alpha_F\}}{5\beta\bar{Q}}.$$

Regarding the follower's bidding function, in the interior-solution range q_F^{b*} is decreasing in the price, as expected. Moreover, it is increasing both in α_F and the expected value of α_L. Since α_F shifts the follower's abatement cost, it is reasonable that the higher α_F the more F is willing to pay for the permits. Regarding α_L, although this parameter affects L's, and not F's cost, the follower forecasts that a higher value of α_L will make the permits more valuable in the secondary market, what would make him also more willing to pay in the auction. Finally, q_F^{b*} depends negatively on the total amount of issued permits, $\bar{Q}$, since the more permits are issued the easier it will be to get cheaper permits in the secondary market.

[16] An alternative common format is the discriminatory auction, in which every awarded unit pays its bid. See, e.g., chapter 12 of Krishna (2002) for a detailed explanation.

[17] We omit the arguments of the bidding functions when there is no ambiguity.

As for the leader's strategy, since v_L is strictly convex in q_{L0}, its problem only has corner solutions: L will demand all the permits if the price is high enough and none in the opposite case. The interpretation of this result is that it is optimal for the leader to position himself in the best possible situation to exert its market power in the secondary market (by acting either as a monopolist of a monopsonist). As discussed above, such market power cannot be exerted when the initial allocation is the cost-effective one. Therefore, the leader is interested in placing himself as far as possible from the cost-effective allocation. This can be done either by demanding too few or too many permits. It is optimal to do the former if the price is high enough and to do the latter if the price is low enough.

These bidding functions give rise to three types of equilibria. In a type-1 equilibrium, F demands $\bar{Q}$ and L demands nothing, so F receives all $\bar{Q}$ permits, i.e., $\delta^A = 1$, where A stands for "auction". Type-2 equilibrium is just the opposite case; F demands zero, L demands $\bar{Q}$ and, therefore, $\delta^G = 0$. Finally, in type-3 equilibria the leader demands $\bar{Q}$ and the follower demands a positive quantity. The third case implies that there is an excess demand and rationing is required, with $\delta^A \in \left[0, \frac{1}{2}\right]$.

Note that type-1 equilibrium resembles Antelo and Bru's (2009) Proposition 1, which states that, in a complete-information model, for the leader it is always optimal to bid zero in the auction. We show that, under incomplete information, this is a possible result, but there are more possibilities depending on the parameter configuration. In fact, it could even be just the opposite if a type-2 equilibrium holds. Note, however, that our results in Proposition 2 are not fully comparable to Antelo and Bru's since they consider that the leader acts strategically in the auction, as we do in Section 4.

To get some additional insight into the properties of the equilibrium, from now on, we assume that the conditional expectation of the rival's type conditional on the own type is a linear function, denoting its coefficients as follows:

$$E\{\alpha_i \mid \alpha_j\} = \mu_j + \lambda_j \alpha_j, \tag{16}$$

where $\{i,\ j\}$ is an arbitrary enumeration of $\{L, F\}$. Moreover, we assume that α_L and α_F are jointly uniformly distributed on a support that satisfies (16), as stated in Assumption 1.

Assumption 1 *Consider the $\alpha_F\alpha_L$ plane. The support of the pair (α_F, α_L) is a square whose lower-left and upper-right corners are (θ, θ) and $(\theta + \sigma, \theta + \sigma)$ respectively. Within that square, we consider three different probability distributions for $(\alpha_F,\ \alpha_L)$:*

- *Case 1 ("Independent types"): uniform on the whole square. In this case we have*

$$\mu_L = \mu_F = \theta + \frac{\sigma}{2}, \qquad \lambda_F = \lambda_L = 0. \tag{17}$$

- *Case 2 ("L-ex ante efficient"): uniform on the lower diagonal triangle, that is, uniform on all points* *satisfying $\alpha_L \leq \alpha_F$. Therefore,*

$$\mu_F = \frac{\theta}{2}, \qquad \mu_L = \frac{\theta + \sigma}{2}, \qquad \lambda_F = \lambda_L = \frac{1}{2}. \tag{18}$$

- *Case 3 ("F-ex ante efficient"): uniform on the upper diagonal triangle, that is, uniform on all points satisfying $\alpha_F \leq \alpha_L$. Thus,*

$$\mu_F = \frac{\theta + \sigma}{2}, \qquad \mu_L = \frac{\theta}{2}, \qquad \lambda_F = \frac{1}{2}. \tag{19}$$

In case 1 we assume that the types are independently distributed whereas, in cases 2 and 3 the types are positively correlated. In case 2 we say that L is ex-ante (more) efficient (than F) in the sense that the abatement cost function of L is below that of F with probability one (w.p.1). In case 3 $\alpha_F \leq \alpha_L$ holds w.p.1 and we say that F is ex-ante efficient.[18] Below we analyze each of these cases separately.

3.1 Independent types (case 1)

We analyze now the likelihood of the three types of equilibria and the comparison of those equilibria with grandfathering when the types are independently distributed as stated in the first case of Assumption 1. We still restrict ourselves to the case in which the secondary market equilibrium is interior and both firms exert a positive abatement effort, that is, we assume that (4) holds. The following notation is used below. Consider the support of the pair (α_F, α_L). Let us define the diagonal of the support as the set $D := \{(\alpha_F, \alpha_L) \;/\; \alpha_F = \alpha_L = \theta + a\sigma, \; a \in [0, 1]\}$. In words, the diagonal is the set of realizations of the types such that both firms' costs functions are identical. Additionally, let $\kappa := \frac{\beta \bar{Q}}{\sigma}$. Notice that κ is a ratio that depends positively on a measure of the market size given by the total amount of permits ($\bar{Q}$) weighted by the impact of each permit in the marginal abatement cost (β) and it depends negatively on the variability of the types (σ). Note also that (4) implies $\kappa \geq 1$. Denote as Ω_l the range of the types under which a type-l equilibrium takes place, being $l \in \{1, 2, 3\}$.

Proposition 3 *Assume that both firms act non-strategically in the auction, the firms types are mutually independent and (4) holds. Then in D there are only type-3 equilibria. Moreover, the probabilities of type-1*

[18] The implication of $\alpha_i \geq \alpha_j$ is that the marginal abatement cost function of firm i is higher than that of firm j, i.e., $MC_i(e) \geq MC_j(e)$ for any given value of e. To fix ideas, we mostly stick to one possible interpretation of this condition, namely, that firm i has access to a more efficient abatement technology than j does. This is not the only interpretation, though. For example, firm i's MC function could be higher simply for a matter of size: it produces more output and, hence, it is harder for him to cut down emissions. Since we are not dealing with the output market, but only with emissions, the former interpretation fits more naturally in our setting, but the latter is also possible.

and type-2 equilibria are the same and given by

$$\Pr(\Omega_1) = \Pr(\Omega_2) = \begin{cases} \frac{25}{42}\left(1 - \frac{\kappa}{2}\right)^2 & \text{if } \kappa < 2 \\ 0 & \text{otherwise.} \end{cases} \tag{20}$$

Moreover, conditional on Ω_1 and Ω_2, the auction entails lower expected costs than grandfathering, i.e.,

$$E\{h(\delta^A, \boldsymbol{\alpha}) \mid \Omega_1\} < E\{h(\delta^G, \boldsymbol{\alpha}) \mid \Omega_1\}, \qquad E\{h(\delta^A, \boldsymbol{\alpha}) \mid \Omega_2\} < E\{h(\delta^G, \boldsymbol{\alpha}) \mid \Omega_1\} \blacksquare$$

According to Proposition 3 there is always a positive probability of a type-3 equilibrium to arise, which can be computed as $\Pr(\Omega_3) = 1 - 2\Pr(\Omega_1)$. Moreover, if $\kappa \geq 2$ holds, $Pr(\Omega_3) = 1$. If, on the contrary, $\kappa < 2$, all three types of equilibrium can arise with positive probability, although that type-3 equilibrium is always the most likely one. Indeed, by taking in (20) $\kappa = 1$, which is the lowest value consistent with (4), we get $Pr(\Omega_3) > 0.7$. Figure 1 shows which equilibrium arises for every pair in the support of types whenever $\kappa < 2$, i.e., when all three types of equilibria are possible.

Proposition 3 also states that the auction outperforms grandfathering, on average, in the range where type-1 and type-2 equilibria arise. To understand this result, it is important to notice that, although δ^G does no depend on the realization of the types (specifically, in case 1, $\delta^G = \frac{1}{2}$), to make a meaningful comparison between grandfathering and auctioning under type-1 or type-2 equilibria, we need to evaluate the expected value of $h\left(\delta^G, \boldsymbol{\alpha}\right)$ conditional on the set of realizations of $\boldsymbol{\alpha}$ such that each equilibrium takes place. As illustrated in Figure 1, a type-1 (resp. type-2) equilibrium tends to arise when α_F is well above α_L (α_L is well above α_F). In this case, F's (L's) marginal cost of abatement is higher enough than L's (F's) and, therefore, a situation in which F (L) holds all the permits is prone to be closer to the cost-effective allocation than a situation in which both firms receives $\frac{\bar{Q}}{2}$.

By direct comparison between the possible allocations resulting from the auction and the cost-effective one given in (2), it is obvious that, under a type-1 equilibrium, the leader will receive less permits in the auction than it is cost-effective (and, therefore, will act as a monopsonist in the secondary market) w.p.1 and, under a type-2 equilibrium, he will receive more permits than what is cost-effective (and, hence, he will be a monopolist in the secondary market) w.p.1. Corollary 2 shows that, in the case in which a type-3 equilibrium holds w.p.1 (i.e., $\kappa \geq 2$) the leader becomes over-assigned with respect to the cost-effective allocation w.p.1 (and, hence, we will act, again, as a monopolist).

Corollary 2 *If $\kappa \geq 2$, L gets over-assigned in the auction with respect to his cost-effective allocation of permits w.p.1.*

As discussed above, under type-1 and type-2 equilibria, auctioning is more cost-effective than grandfathering on average. To make a general assessment of auctioning relative to grandfathering, we need to evaluate costs under all three possible types of equilibria, weighted by their respective probabilities. Unfortunately, under type-3 equilibrium no general analytical statements can be made due to the complex analytical form of expected cost.[19] So, we now proceed with some numerical analysis.

We evaluate total abatement costs under auctioning and grandfathering for each combination of parameter values, $(\theta, \beta\bar{Q}, \sigma)$.[20] For each parameter combination we generate 1,000 random realizations of the pair of types[21]. For each realization we compute the corresponding equilibrium at the auction and the associated realized costs under auctioning and grandfathering. We check, first, how different realizations of the types determine the relative cost of both allocation methods. Then, we average across realization to have an estimation of the expected cost of each system.

We explore exhaustively the parameter space defined by (4). A first result is that variations in θ are irrelevant for the cost comparison as far as it is large enough to ensure that the set defined by (4) is non-empty. The reason is that modifying the value of θ is a change of origin that affects equally both firms' marginal costs but not the difference between them. Once the value of θ is fixed, the set of parameter values consistent with (4) is bounded, which easies the exploration. So, we just present the results for a specific value, $\theta = 10$, and we explore a grid of values of the pair $(\beta\bar{Q}, \sigma)$ such that (4) is respected.

Figure 2 shows an illustration of the relative performance of auctioning and grandfathering in terms of cost for different realizations of the pair of types, given a specific combination of the parameters. The upper (resp. lower) panel displays the combinations such that auctioning renders lower (higher) cost than grandfathering. The main conclusion is that those cases in which the difference between the marginal cost of both firms is large enough tend to favour auctioning while, if the firms' marginal costs are similar enough, grandfathering is less costly than the auction. Moreover, when it is the leader's marginal cost which is above the follower's ($\alpha_L > \alpha_F$) the range under which auctioning beats grandfathering is larger than in the opposite case ($\alpha_F > \alpha_L$).

From these results we can get two insights. First, auctioning is preferable when the firms are asymmetric enough in terms of costs. To understand this result, it is useful to identify two effects that we can label as "information effect" and "market power effect". Regarding the former, note that by means of the bids, the auction incorporates more information on the realized types (that are privately observed), whereas grandfathering only uses average values. This effect is prone to favour the auction. As for the latter effect, bidding gives the leader the opportunity to distort the market equilibrium to some extent, to its own benefit, what is prone to put the auction at a disadvantage. When the types are very close to each other,

[19] The main technical difficulty arises from the fact, under a type-3 equilibrium, there is rationing and therefore, the permits are distributed according to the relative demand of both players, which is a ratio involving stochastic variables (α_L, α_F) in the denominator.

[20] Recall that, although $\bar{Q}$ is not properly a parameter, we treat it as such since it is exogenously fixed. Nevertheless, in terms of cost, only the product $\beta\bar{Q}$ turns out to be relevant, rather than β and $\bar{Q}$ separately.

[21] The number of realizations is chosen to have a sample that is relatively dense in the support of types. We have tried with different sample sizes and the results remain basically unchanged.

the cost-effective allocation involves allocating similar amounts of permits to both firms (in the limit, if $\alpha_L = \alpha_F$, the optimal allocation requires $\delta = \frac{1}{2}$) and, so, grandfathering is prone to generate an allocation that is very close to the first best (recall that grandfathering renders a constant value $\delta^G = \frac{1}{2}$). In this case, the lack of information on the realized types is not a big problem because the average is a good enough proxy and then the market power effect dominates. The opposite happens when the marginal costs are very different from each other. In this case, the average is a poor proxy for the realized values and it is likely that the auction performs better than grandfathering, because the potential gain of using more precise information can be higher than the loss due to the market power distortion.

The second insight is that the chances for the auction to render a good result in terms of costs are better when the firm with the lower marginal abatement costs is not the same that acts as a leader. The intuition of this result is that, if L enjoys a cost advantage, this would reinforce his leadership, what be would use to bias the market result for his own profit and this distortion would weaken the beneficial information effect. The situation is more balanced when the follower can counterbalance its disadvantageous position by having lower costs than the leader.

Then we move on to compare expected costs, computed as the average across realizations. Our numerical analysis reveals that, for all the parameter values satisfying (4), grandfathering outperforms the auction in expected terms. Since Proposition 3 states that, in type-1 and type-2 equilibria auctioning outperforms grandfathering, it has to be case, first, that grandfathering outperforms auctioning on average in type-3 equilibria, what is confirmed by our numerical results. Moreover, recall that the probability of type-1 and type-2 equilibria is always smaller than that of a type-3 equilibrium. As we have discussed in subsection 2.2, the fact that auctioning entails higher cost than grandfathering means that on average, the former renders allocations that are further away from the cost-effective distribution than the latter. This fact is illustrated in Figure 3, which depicts those distances for each realization of the pair of types, under the same combination of parameter values considered in Figure 2. In this example, the vast majority of the equilibria are type-3, and the basic message of that figure is to confirm the theoretical result (see Corollary 2) that, in the auction, L gets over-assigned (or, equivalently, F under-assigned) with respect to the cost-effective allocation whenever a type-3 equilibria occurs.

In terms of sensitivity analysis, the difference between auction and grandfathering increases with κ. In short, a small variability of the types (as measured by σ in terms of the market size) with respect to the amount of permits tends to favour grandfathering over the auction. The reason is that a small variability implies that the average will be a good proxy for the actual value of the types and, therefore, the grandfathering allocation will be very close to the cost-effective one.

3.2 Non-independent types (cases 2 and 3)

We consider now cases 2 and 3 in Assumption 1. In both of these cases, the types are positively correlated. This is a reasonable event to consider since it might well be the case that different firms are affected similarly by external shocks. For example, it is commonly believed that, in the first years of the EU ETS, the cap was too mild in the sense that too many permits where distributed. The evolution of the energy markets and the weather caused an excess of permits or, in other words, meeting the environmental requirements turned out to be easier than expected for most facilities. This is not to say that the effect of these conditioning factors were exactly the same for all the firms, since there were clear asymmetries among them, but it seems safe to state that, on average, those effects worked in the same direction. Propositions 4 and 5 contain our main analytical findings for these cases.

Proposition 4 *If both firms act non-strategically in the auction, (4) holds and $\alpha_L \leq \alpha_F$ holds w.p.1 a type-1 equilibrium occurs with positive probability if and only if $\kappa < 2$ and it never happens in the diagonal. A type-2 equilibrium occurs with positive probability if $\kappa < \frac{6}{5}$ and, moreover, if a type-2 equilibrium does not occur for some pair (α_F, α_L), it does not hold either for any pair (α_F, α'_L) with $\alpha'_L < \alpha_L$. A type-3 equilibrium always occurs with positive probability.*

Proposition 5 *If both firms act non-strategically in the auction, (4) holds and $\alpha_F \leq \alpha_L$ holds w.p.1 a type-1 equilibrium occurs with positive probability if and only if $\kappa < \frac{6}{5}$ and, moreover, if this type of equilibrium does not hold for some pair (α_F, α_L), it does not hold either for any pair (α_F, α'_L) with $\alpha'_L > \alpha_L$. A type-2 equilibrium occurs with positive probability if and only if $\kappa < 2$, and always outside the diagonal. A type-3 equilibrium always occurs with positive probability.*

Consider first case 2 (L efficient). The relative position of the realizations of types that leads to the different equilibria are depicted in Figure 4 panel a. The numerical analysis for the case of L efficient (omitted for the sake of brevity) shows qualitatively identical results to the case with independent types.

Regarding case 3 (F efficient), Figure 4 panel b shows the relative position of the realizations of the types leading to each possible equilibrium. Next, we perform some numerical analysis for this case. Figure 5 shows that, unlike the two previous cases, there are parameter values for which the expected cost under auctioning is smaller than under grandfathering. Those points are displayed in green in the graph. The implication of this result is that, as discussed above, it is favourable for the auction that the agent endowed with market power is not the one with the lowest, but the highest cost, since any cost advantage would make him more capable to exploit his market power. Another message we can get from this analysis is that auctioning tends to do better, as compared to grandfathering, when the variability of types, as measured by σ, is large enough in terms of $\beta\bar{Q}$, which is in line with the analysis done for the independent-types case.

Figure 6 illustrates a case in which the auction leads to lower expected cost. To ease the comparison with the case of independent types, we take as an example $(\sigma, \beta\bar{Q}) = (6, 8)$ and $\theta = 10$. As in the case with independent types, L is still over-assigned in the auction with respect to the cost-minimizing allocation (the red line), but now the allocations resulting from the auction (represented by green dots) are, on average, closer to being cost-effective than those resulting from grandfathering (the blue line).

4 Role-preserving auction

In this section we analyze another setting for the auction in which the leader acts strategically while the follower still acts as a price taker. This case is based on the belief that, if one firm has market power in the secondary market, due to its size or dominant position, it is likely that this power has a reflection in the auction. To capture this notion, we assume a Stackelberg-like setting in which the follower acts as a price-taker, whereas the leader is capable of predicting the follower's strategy and reacting optimally to it.

This section brings up some additional technical complexity. It conveys a strategic bidder in a multi-unit multi-bid non-common-value auction. To the best of our knowledge, this is in the frontier of multi-unit auction theory. For the sake of tractability, we restrict ourselves to continuous strategies and interior solutions, which implies that, in equilibrium, both the leader and the follower requires an amount of permits between 0 and $\bar{Q}$, in such a way that $q_F^b + q_L^b = \bar{Q}$ and rationing is ruled out. We also keep the distributional assumptions made above: the conditional expectations are linear and, when needed, we will also assume a uniform distribution.

Given that F is still non-strategic in the auction, his behavior is the same as in Section 3. So, the follower's problem is (13) and his best strategy as defined in (14).[22] On the other hand, the leader's best strategy is a bid function $q_L^{b*}(\alpha_L, p_0)$ that represents a best response to F's strategy. To model the leader's problem, define total demand in the auction as $\Phi(\boldsymbol{\alpha}, p_0) := q_L^b(\alpha_L, p_0) + q_F^b(\alpha_F, p_0)$, from which the opt-out price can be obtained by imposing the market-clearing condition $\Phi(\boldsymbol{\alpha}, p_0^*) = \bar{Q}$ and solving for p_0^* we get $p_0^* = \Phi^{-1}\left(\boldsymbol{\alpha}, \bar{Q}\right)$.[23] Therefore, the leader's problem is

$$\underset{q_L^b(\alpha_L, p_0)}{\arg\max}\ v_L\left(q_{L0}, \alpha_L\right) - E\left\{\Phi^{-1}\left(\boldsymbol{\alpha}, \bar{Q}\right) \times q_{L0} \mid \alpha_L\right\}. \tag{21}$$

Notice that, unlike the non-strategic case, L's best strategy depends on F's (through $\Phi(\boldsymbol{\alpha}, p_0)$). Moreover, L does not take the price as given, but he plays by predicting the equilibrium price that will result from his and F's demand. The stop-out price, p_0^*, is again the highest market-clearing price when both firms play their corresponding best strategies.

[22] Specifically, since we disregard corner solutions in this section, the relevant part of (14) is that involving interior solution.

[23] For Φ^{-1} to be a well-defined function we require that Φ is invertible in p_0. This turns out to be case because both q_F^b and q_L^b are decreasing in p_0. (14) reveals that the former is decreasing and Proposition 6 shows that q_L^b also is.

An important feature of this case is that the leader is capable of making an ex-post optimal bid, i.e., a bid that gives him the maximum possible profit for any realization of the types, as stated in the following proposition:

Proposition 6 *Under any of the three cases considered in Assumption 1 there exists a non-empty set of the parameters* $\left(\theta, \sigma, \beta\bar{Q}\right)$ *such that there is a unique equilibrium in which the leader's best strategy is*

$$q_L^{b*}\left(\alpha_L, p_0\right) = m_0 + m_1\bar{Q} + m_2\alpha_L + m_3 p_0, \tag{22}$$

where $m_0 \leq 0$*,* $m_1 \leq 0$*,* $m_2 \geq 0$ *and* $m_3 \leq 0$ *depend only on* β *and* λ_L*. Moreover, the equilibrium price of the auction for any* $\boldsymbol{\alpha} = (\alpha_L, \alpha_F)$ *is the solution to*

$$\max_{\{p_0\}} \quad \pi_L\left(\bar{Q} - q_F^b\left(\alpha_F, p_0\right), \boldsymbol{\alpha}\right) - p_0 \times \left[\bar{Q} - q_F^b\left(\alpha_F, p_0\right)\right] \tag{23}$$

and the equilibrium of both the auction and the secondary market are interior w.p.1.

To understand this proposition, it is important to notice that (23) is an artificial auxiliary problem that selects the best price in the auction for the leader for any given pair (α_L, α_F). We say that it is artificial because it is written as if L could know the realization of α_F. This would be an ideal situation for the leader since he would not be affected by incomplete information. Proposition 6 states that there exists a bidding function for the leader such that the equilibrium price of the auction will replicate the solution to problem (23). It is important to underline that the bidding function depends only on known information for the leader (α_F is absent). This is what Wang and Zender (2002) refer to by saying that the auction allocation is ex-post optimal for the leader in the sense that the leader can play in such a way that the ultimate equilibrium will be the one that the leader would choose if he had full information. In other words, if the leader happened to know the value of α_F, he would not change his strategy. Note also that, although this is a remarkably strong result for the leader, the bidding function used to get that result is rather standard in the sense that it is a linear function and, as expected, it is linearly decreasing in the price and the total amount of issued permits and increasing in L's type.

Proposition 7 shows that, in the conditions described above, the auctioning solution is less cost-effective than the grandfathering solution w.p.1 what, as stated in Corollary 3, implies first-order stochastic dominance (FOSD) of grandfathering over auctioning.

Proposition 7 *In cases 1, 2 and 3 described in Assumption 1, under the relevant conditions for interior solutions, the amount of permits that the leader receives in equilibrium is lower than his cost-effective allocation and lower than the amount that he would receive under grandfathering; and the clearing price of* *the auction is lower than the price of the secondary market, i.e.,*

$$q_{L0}^{A} < e_{L}^{CE}, \qquad q_{L0}^{A} < q_{L0}^{G}, \qquad p_{0}^{A} < p_{1}^{A}.$$

Moreover, the total cost of abatement when the permits are auctioned is higher than under grandfathering, i.e.,

$$h(\delta^{A}, \boldsymbol{\alpha}) > h(\delta^{G}, \boldsymbol{\alpha}) \qquad \forall \boldsymbol{\alpha}.$$

Corollary 3 *Under the conditions described in Proposition 7, the cumulative probability distribution (CPD) of TC under the grandfathering allocation first-order-stochastically dominates the corresponding CPD under the auction.*

The second part of Proposition 7 is remarkably strong since it states that, in any event, auctioning will always be beaten by grandfathering from the point of view of cost. It deserves to be stressed that this is not only true in expected terms, but it is also true for every feasible realization of the types (as far as interior solution is guaranteed). The main message of this result is that introducing an auction such that the leader in the secondary market is also so in the auction can only worsen the results in terms of costs as compared to grandfathering. Moreover, under interior solution, this result holds with certainty. The reason is that the leader will have strong incentives to use its leadership to distort the market to own advantage and such distortion will result in a cost increase.

A clear-cut policy implication is that, with imperfect competition in the secondary market, switching from grandfathering to auctioning is likely to worsen the situation (in terms of cost-effectiveness) if it cannot be avoided that the market power spills over to the auction. Corollary 3 translate this result in the standard concept of FOSD.[24]

The first part of Proposition 7 clarifies how the auction behaves with respect to the cost-effective allocation. The leader will always receive less permits from the auction than the cost-effective amount, e_{L}^{CE}, and, therefore, will act as a monopsonist in the secondary market. Under grandfathering, the leader might receive more or less permits than what would be cost-effective, depending on the realizations of the types (and, if by chance both types were equal to its average, then grandfathering would render the cost-effective solution) but in the event that it receives less than e_{L}^{CE}, it would always be closer to the cost-effective solution than the auctioning solution. The leader understates his demand in the primary market to keep the price low. When he demands permits in the secondary market, the price increases to some extent, but it will we always lower than the price that would prevail under perfect competition. This result can be seen as a generalization of the result that Antelo and Bru (2009) get in a framework of

[24] As a matter of fact, the result in Proposition 7 is even stronger than FOSD since the latter does not preclude the possibility that the cost under auctioning is lower than under grandfathering for some (small enough) range of the parameter values, what is discarded in Proposition 7.

perfect information in the sense that, with a dominant firm and a secondary market, "it is optimal for the dominant firm to abstain from the initial auction" (Prop 1, p. 325). Under incomplete information, we get a softer result in the sense that the leader tends to demand less than socially optimal, but the demanded amount is no necessarily zero.

5 Conclusions and discussion

This paper compares the two most common allocation mechanisms of emission permits, auctioning and grandfathering, under two central assumptions: the existence of a secondary market with market power and the presence of incomplete information. On the one hand, we claim that these two elements together make the comparison between both methods non-trivial. On the other hand, it is rather realistic to assume that both elements are present to some extent in important real-life examples such as the Kyoto Protocol or the EU ETS.

One reason to be interested in this comparison is that there seems to be a current tendency (notably in the EU ETS) to shift from grandfathering to auctioning. This paper offers some insights into what we can really expect the auction do in a relatively adverse scenario: market power and incomplete information. Within a simple model, we study the optimal bidding strategies as well as the equilibria and we characterize the conditions under which auctioning does better or worse than grandfathering in terms of aggregate abatement cost.

The chances of auctioning to outperform grandfathering come essentially from the fact that, by means of the bids, the auction incorporates information that are only privately observable and, hence, could not be used by the planner to implement a centralized allocation. On the other hand, the risk of the auction is that a firm with market power can use such power to distort the equilibrium in its own benefit. The final balance depends on the relative strength of these two forces.

One central conclusion of our analysis is that we cannot expect that an auction "per se" has the property of providing more cost-effective allocations of permits. Indeed, the design of the auction and, specifically, its ability to preserve or dilute market power is a crucial element for the comparison. If the auction is capable of removing market power, then there is a chance that the results under the auction will be more cost-effective than under grandfathering. This is more likely to happen when the firms turn out to be very asymmetric in terms of cost, especially if the firm with cost advantage is not the same that enjoys market power. In this case, the additional information used by the auction tips the scales in its favour. In expected terms, the chances for the auction to outperform grandfathering increase when the follower's costs are well below the leader's and the variability of the types is large enough in terms of the number of permits to be distributed. If, on the contrary, the auction reproduces the leader and follower roles, one can only expect that this would result in more costly outcomes than grandfathering.

The aim of this paper is to offer some general insights about cap-and trade systems and not about one specific market such as the EU ETS (in which, moreover, it is not clear enough that market power is one of the main issues). Nevertheless, for the sake of motivation, it has been useful for us to take as a starting point the EC's argument to support auctioning on the grounds of efficiency (although we have focused on the milder criteria of cost-effectiveness by taking the cap as given). Although our analysis is strongly focused on cost-effectiveness, it can also provide some clues about the plausibility of the other EC's arguments to support auctioning: transparency, simplicity, more incentives for abatement investments and eliminate windfall profits.

The transparency argument makes sense as far as auctioning automatically incorporates more information than grandfathering since the bids contain privately observed data that typically will not be accessible to the environmental authorities. Moreover, auctioning has the advantage of treating facilities more evenly whereas, in the two first phases of the EU ETS, grandfathering has been applied through the National Allocation Plans, which inevitably have introduced some across-countries and across-facilities asymmetries in the permit allocation.

Regarding simplicity, it is by no means obvious that auctioning is simpler than grandfathering. From the planner's point of view, auctioning incorporates a clearer market-based dimension to the allocation procedure, what frees to some extent the environmental authorities from the responsibility of making direct allocations. But, on the other hand, it entails some additional complexities in the setup of the system, such as choosing the design of the auction (e.g., uniform or discriminatory), creating the auction platforms or deciding about the destiny of the revenues. From the facilities' point of view, it requires more frequent interaction between the participants and the authorities and probably some additional training to be able to bid properly.

Concerning the introduction of incentives for abatement investments, according to our results, this will be probably more true for firms without market power, which will typically bear higher costs and, hence, will have stronger incentives to improve their abatement technologies. Finally, the elimination of windfall profits is supported, to some extent, by the mere fact that firms will have to pay for the permits and, therefore, it is no longer the case that operators charge their customers the cost of allowances they have received for free. Nevertheless, the fact that allowances are not free of charge does not fully eliminate the possibility of windfall profits in the form of speculative operations. We conclude that, in most cases, the allocation resulting from an auction will be further away from the cost-effective one than that resulting from grandfathering. This implies that the marginal abatement costs will be more different across facilities, hence creating a room for windfall profits. What can probably be argued is that windfall profits will be smaller on average and concentrated on fewer hands, specifically in the hands of those firms that enjoy some market power. Summing up, our analysis seems to support the EC's arguments of transparency and more incentives for abatement investments, but not those of simplicity and the elimination of windfall profits. Obviously, these thoughts must be taken as a preliminary and incomplete informal discussion, not as a fully-fledged analysis, which is left for future work.

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6 Appendix 1: proofs

6.1 Proof of Proposition 1

Assume initially that the solution is interior (what we check below). The optimal behaviour of the follower is derived by solving problem (3) for $i = F$ while taking p_1 as given. From the first-order condition (FOC) we get the follower's net demand for permits:

$$q_{F1}^{d}(p_1) = \frac{1}{\beta}(\alpha_F - p_1), \tag{24}$$

where d stands for "demand". To get the leader's demand we solve problem (3) for $i = L$ including as constraints the market clearance condition, $q_{L1} + q_{F1} = \bar{Q}$ and the follower's demand, (24). The (interior) solution to this problem is given by (5). Using the market clearing condition and (24), we get the equilibrium price in the secondary market,

$$p_1^* = \frac{\alpha_L + 2\alpha_F - \beta\left(2\bar{Q} - q_{L0}\right)}{3}, \tag{25}$$

and using (25) in (24) we get the equilibrium number of permits for the follower, given by (6). Using (5), (6) and (25) in the expressions for F's and G's profits and rearranging we get (7) and (8) where Θ_L and Θ_F include the terms that do not depend on the initial allocation.

To show that the solution satisfies $q_{i1} \in [0, \min\{\bar{Q}, e_i^{BAU}\}]$ w.p.1, note first that $0 \leq q_{F1} \leq \bar{Q}$ ensures $0 \leq q_{L1} \leq \bar{Q}$ and using (24) we get $0 \leq q_{F1} \leq \bar{Q} \iff \alpha_F \geq p_1 \geq \alpha_F - \beta\bar{Q}$, which using (25) can be written as $-\frac{1}{\beta}(\alpha_L - \alpha_F) + 2\bar{Q} \geq q_{L0} \geq -\frac{1}{\beta}(\alpha_L - \alpha_F) - \bar{Q}$. Since $q_{L0} \in [0, \bar{Q}]$, the previous inequalities are ensured for any initial allocation iff $-\frac{1}{\beta}(\alpha_L - \alpha_F) + 2\bar{Q} \geq \bar{Q}$ and $0 \geq -\frac{1}{\beta}(\alpha_L - \alpha_F) - \bar{Q}$ hold at the same time. The intersection of these inequalities is: $\bar{Q} \geq \frac{1}{\beta}|\alpha_L - \alpha_F|$ and, since the maximum value of the right-hand side is σ/β, we have

$$\beta\bar{Q} \geq \sigma. \tag{26}$$

Firm i makes a strictly positive abatement effort iff $q_{i1} \leq e_i^{BAU} = \frac{\alpha_i}{\beta}$, i.e., $\alpha_i - \beta q_{i1} \geq 0$. If we particularize this inequality for $i = F$, using (24), we have $p_1 \geq 0$ what, using (25), can be written as $\alpha_L + 2\alpha_F \geq \beta(2\bar{Q} - q_{L0})$. Since $q_{L0} \in [0, \bar{Q}]$ and the minimum value for each type is θ, the latter equality is guaranteed under (4). For $i = L$, using (5), condition $\alpha_L - \beta q_{L1} \geq 0$ can be written as

$$2\alpha_L + \alpha_F \geq \beta(\bar{Q} + q_{L0}). \tag{27}$$

The most adverse values for the fulfilment of (27) are $\alpha_L = \alpha_F = \theta$, $q_{L0} = \bar{Q}$. To ensure that (27) holds w.p.1 we plug those values to get $\theta \geq \frac{2}{3}\beta\bar{Q}$, which combined with (26) gives (4).

6.2 Proof of Corollary 1

Total cost can be computed by plugging (5) and (6) in (1).[25] Substituting q_{L0} by $\bar{Q}-q_{F0}$ and rearranging, we get (9), where Θ includes the terms that do not depend on the initial allocation.

6.3 Proof of Proposition 2

Using (8), $v_F\left(q_{F0},\alpha_F\right)$ can be written as

$$v_F\left(q_{F0},\alpha_F\right)=E\left\{\Theta_F\mid\alpha_F\right\}+\frac{1}{9}\left(2E\{\alpha_L\mid\alpha_F\}+7\alpha_F-2\beta\bar{Q}\right)q_{F0}-\frac{5}{18}\beta q_{F0}^2.$$

Since v_F is strictly concave in q_{F0} for every α_F, an interior solution to F's problem (if it exists) follows easily from the first-order condition, which can be solved to get

$$q_F^b=\tau_F\left(q_{F0},\alpha_F\right):=\frac{2E\{\alpha_L\mid\alpha_F\}+7\alpha_F-2\beta\bar{Q}-9p_0}{5\beta},\tag{28}$$

where, for simplicity of exposition, we have denoted as $\tau_F\left(q_{F0},\alpha_F\right)$ the right-hand side of the previous equality. Since the submitted demand must lie in $[0,\bar{Q}]$ and given the concavity of v_F on q_{F0}, it is $q_F^b=0$ and $q_F^b=\bar{Q}$ whenever $\tau_F\left(p_0,\alpha_F\right)\le 0$ and $\tau_F\left(p_0,\alpha_F\right)\ge\bar{Q}$, respectively. Notice also that $\tau_F\left(p_0,\alpha_F\right)$ is strictly decreasing in p_0 for every α_F, thus p_{Fu} and p_{Fd} are defined by $\tau_F(p_{Fu},\alpha_F)=0$ and $\tau_F(p_{Fd},\alpha_F)=\bar{Q}$ respectively. Thus, we have

$$p_{Fu}=\frac{2E\{\alpha_L\mid\alpha_F\}+7\alpha_F-2\beta\bar{Q}}{9}\quad,\qquad p_{Fd}=\frac{2E\{\alpha_L\mid\alpha_F\}+7\alpha_F-7\beta\bar{Q}}{9}.$$

Now, consider L's problem, which is $max_{q_{L0}}\{v_L\left(q_{L0},\alpha_L\right)-p_0q_{L0}\}$ where

$$v_L\left(q_{L0},\alpha_L\right)=E\{\pi_L\left(q_{L0},\boldsymbol{\alpha}\right)\mid\alpha_L,q_{L0}\}=E\left(\Theta_L\mid\alpha_L\right)+\frac{\alpha_L+2E\{\alpha_F\mid\alpha_L\}-2\beta\bar{Q}}{3}q_{L0}+\frac{\beta}{6}q_{L0}^2.$$

Clearly $v_L\left(q_{L0},\alpha_L\right)$ is strictly convex in q_{L0} for every α_L, and therefore the leader's problem only has corner solutions, i.e., $q_L^b\in\{0,\bar{Q}\}$ with $q_L^b=\bar{Q}\iff v_L\left(\bar{Q},\alpha_L\right)\ge v_L\left(0,\alpha_L\right)$. Given that $v_L\left(0,\alpha_L\right)=E\left\{\Theta_L\mid\alpha_L\right\}$, L chooses $q_{L0}=\bar{Q}$ whenever $v_L\left(\bar{Q},\alpha_L\right)\ge E\left\{\Theta_L\mid\alpha_L\right\}+p_0\bar{Q}$ holds. Denote as p_L the maximum value of p_0 such that this inequality holds, i.e., $p_L=\frac{v_L\left(\bar{Q},\alpha_L\right)-E\{\Theta_L\mid\alpha_L\}}{\bar{Q}}$. Using the expression for v_L we get

$$p_L:=\frac{\alpha_L+2E\{\alpha_F\mid\alpha_L\}}{3}-\frac{1}{2}\beta\bar{Q}.\tag{29}$$

Since the support of α_L and α_F is $[\theta,\theta+\sigma]$, we know $p_L>\theta-\frac{1}{2}\beta\bar{Q}>0$, where the latter inequality follows from (4). Thus, demanded quantity is not smaller than supply at some positive price (p_L), which

[25] Alternatively, using (3) it can be obtained as $TC=-\left(\pi_L+\pi_F\right)$, by noting that $q_{F0}+q_{L0}=q_{F1}+q_{L1}=\bar{Q}$.

guarantees the existence of an equilibrium in the auction. Uniqueness follows from the fact that each firm's demand is non-increasing in p_0 for every possible pair (α_F, α_L). Since $p_{Fu} > p_{Fd}$ and $p_L > 0$ hold w.p.1, there are just three possible cases.

- The first case is $p_L < p_{Fd}$. The stop-out price cannot be $p_0 > p_{Fd}$ because there would be excess supply (i.e., some units would not be awarded). Since all the permits would be awarded for any $p_0 \leq p_{Fd}$, the opt-out price must be p_{Fd}, F gets all the permits and L gets nothing. This corresponds to type-1 equilibrium.

- The second case is $p_{Fu} < p_L$. For any $p_0 > p_L$ there would be excess supply and all the permits would be awarded for any $p_0 \leq p_L$. Therefore, the opt-out price must be p_L and L gets all the permits, which corresponds to type-2 equilibrium.

- The third case is $p_{Fd} \leq p_L \leq p_{Fu}$, which corresponds to type-3 equilibrium, in which permits are shared between F and L. The equilibrium price is p_L, at which F and L demand $\tau_F(p_L, \alpha_F) \in \left[0, \bar{Q}\right]$ and $\bar{Q}$, respectively and rationing is required.

Straightforward algebra leads to $p_L < p_{Fd} \iff \xi < -1$, $p_{Fu} < p_L \iff \xi > 1$ and $p_{Fd} \leq p_L \leq p_{Fu} \iff -1 \leq \xi \leq 1$.

6.4 Proof of Proposition 3

Under independent types, the conditions given in Proposition 2 for type-1 and 2 equilibria collapse to

$$\text{type 1:} \qquad \xi < 1 \Leftrightarrow 3\alpha_L - 7\alpha_F + 4\theta + 2\sigma + \frac{5}{2}\beta\bar{Q} < 0, \tag{30}$$

$$\text{type 2:} \qquad \xi > 1 \Leftrightarrow 7\alpha_F - 3\alpha_L - 4\theta - 2\sigma + \frac{5}{2}\beta\bar{Q} < 0. \tag{31}$$

respectively. For any pair in D, (30) and (31) become

$$(2-4a)\sigma + \tfrac{5}{2}\beta\bar{Q} < 0, \qquad (4a-2)\sigma + \tfrac{5}{2}\beta\bar{Q} < 0,$$

none of which, under (4), holds for any admissible a. Thus, we only have type-3 equilibria in D. Notice that the pair $(\alpha_F, \alpha_L) = (\theta + \sigma, \theta)$ satisfies (30) if $\kappa \leq 2$, which is allowed under (4). In addition, the equality of (30) is a straight line with positive slope in the plane $\alpha_F\alpha_L$, let us denote it by L_1. Thus, in the support of (α_F, α_L), under $\kappa \leq 2$, the subset satisfying (30) is the triangle below L_1, which does not contain the diagonal (see Figure 1 for illustration). If $\kappa > 2$, that subset is empty. An analogous analysis shows that, under $\kappa \leq 2$, the support region for type-2 equilibrium is the triangle above the line defined by the equality of (31), this region does not contain the diagonal and is empty if $k > 2$ (see Figure 1).

Since the types are assumed uniformly distributed, the probabilities of Ω_1 and Ω_2 are proportional to the corresponding areas, which can be easily computed based on Figure 1. For type-1 equilibrium we have

$$E\{h(\delta^A, \boldsymbol{\alpha}) \mid \Omega_1\} = E\{h(1, \boldsymbol{\alpha}) \mid \Omega_1\} = E\{\alpha_L - \alpha_F \mid \Omega_1\} = \frac{1}{3}\left(-\frac{1}{3} - \frac{31}{21}\kappa\right)\sigma \tag{32}$$

where the last equality follows directly from the computation of the expected values of α_L and α_F conditional on Ω_1. In addition, using (12) and $\kappa\sigma = \beta\bar{Q}$, we know that, under grandfathering, the expected cost is given by $E\{h(\delta^G, \boldsymbol{\alpha}) \mid \Omega_1\} = E\{h(1/2, \boldsymbol{\alpha}) \mid \Omega_1\} = \frac{1}{2}E\{\alpha_L - \alpha_F \mid \Omega_1\} - \frac{1}{4}\kappa\sigma$.

Therefore, direct comparison of expected costs under A and G leads to

$$E\{h(\delta^A, \boldsymbol{\alpha}) \mid \Omega_1\} < E\{h(\delta^G, \boldsymbol{\alpha}) \mid \Omega_1\} \iff E\{\alpha_L - \alpha_F \mid \Omega_1\} < \frac{1}{2}\kappa\sigma$$

and using the value of $E\{\alpha_L - \alpha_F \mid \Omega_1\}$ computed in (32) we get $E\{h(\delta^A, \boldsymbol{\alpha}) \mid \Omega_1\} \leq E\{h(\delta^G, \boldsymbol{\alpha}) \mid \Omega_1\}$ iff $\kappa > \frac{49}{62}$, which holds for the relevant range of κ, i.e., $[1, 2]$.

For type-2 equilibria the expected cost under auctioning is $E\{h(\delta^A, \boldsymbol{\alpha}) \mid \Omega_2\} = E\{h(0, \boldsymbol{\alpha}) \mid \Omega_2\} = 0$. Under grandfathering we have $E\{h(\delta^G, \boldsymbol{\alpha}) \mid \Omega_2\} = E\{h(1/2, \boldsymbol{\alpha}) \mid \Omega_2\} = \frac{1}{2}E\{\alpha_L - \alpha_F \mid \Omega_2\} - \frac{1}{4}\kappa\sigma$. Now, the corresponding conditional expectation is $E\{\alpha_L - \alpha_F \mid \Omega_2\} = \frac{1}{3}\left(\frac{1}{3} + \frac{31}{21}\kappa\right)\sigma$ and, using this value, $E\{h(\delta^G, \boldsymbol{\alpha}) \mid \Omega_2\} = \frac{\sigma}{252}(14 - \kappa)$. Therefore, for any value of κ compatible with (4) we conclude

$$E\{h(\delta^G, \boldsymbol{\alpha}) \mid \Omega_2\} > 0 = E\{h(\delta^A, \boldsymbol{\alpha}) \mid \Omega_2\}.$$

6.5 Proof of Corollary 2

Our strategy to prove the corollary is to show that, provided that $\kappa \geq 2$ holds, for any arbitrary realization $\boldsymbol{\alpha} := (\alpha_F, \alpha_L)$, we get $\delta^A < \delta^{CE} = \frac{\alpha_F - \alpha_L + \beta\bar{Q}}{2\beta\bar{Q}}$, where the last equality comes directly from (2).

Under a type-3 equilibrium, the auction allocation is given by $\delta^A := \frac{\tau_F(q_{F0}, \alpha_F)}{\tau_F(q_{F0}, \alpha_F) + \overline{Q}}$, where $\tau_F(q_{F0}, \alpha_F)$ is defined in (28). Using this expression for δ^A we get

$$\delta^A < \delta^{CE} \iff \beta\tau_F(q_{F0}, \alpha_F) \leq \frac{\delta^{CE}}{1 - \delta^{CE}}\beta\bar{Q}. \tag{33}$$

Now, we evaluate $\tau_F(q_{F0}, \alpha_F)$ in the equilibrium price, p_0^*, that, under a type-3 equilibrium is equal to p_L, where p_L is given by (29). Using the expression for δ^{CE} together with (16) and, using (17), (33) can be written as

$$\delta^A < \delta^{CE} \iff \frac{7\alpha_F - 3\alpha_L - 4\theta - 2\sigma}{5} < \frac{3(\alpha_F - \alpha_L) + \beta\overline{Q}}{2(\beta\overline{Q} + \alpha_L - \alpha_F)}\beta\overline{Q}.$$

Notice that we can write $\alpha_i = \theta + r_i\sigma$ for $i \in \{F, L\}$, where r_i is uniformly distributed in $[0, 1]$, so that there is a one-to-one mapping between α_i and r_i. Additionally, use the definition of κ to write $\beta\overline{Q} = \kappa\sigma$. By doing these substitutions in the latter inequality we get rid of θ and σ to obtain

$$\delta^A < \delta^{CE} \iff 7r_F - 3r_L - 2 < \frac{3(r_F - r_L) + \kappa}{\kappa - (r_F - r_L)} \times \frac{5}{2}\kappa. \tag{34}$$

To check that this inequality holds for any pair (α_F, α_L) or, equivalently, for any pair (r_F, r_L), we distinguish two cases. Consider first $r_F \geq r_L$. Notice that $7r_F - 3r_L - 2 \leq 3(r_F - r_L) + 2$ and that

$$\frac{3(r_F - r_L) + \kappa}{\kappa - (r_F - r_L)} \geq \frac{3(r_F - r_L) + 2}{\kappa - (r_F - r_L)}$$

where we have used $\kappa \geq 2$. Thus, a sufficient condition for (34) to hold is

$$3(r_F - r_L) + 2 < \frac{3(r_F - r_L) + 2}{\kappa - (r_F - r_L)} \times \frac{5}{2}\kappa. \tag{35}$$

If $r_F \geq r_L$, the left-hand side of (35) is positive and we can divide both sides by $3(r_F - r_L) + 2$ and rearrange to get $\frac{3}{2}\kappa > r_L - r_F$, which trivially holds when $\kappa \geq 2$ and $r_F \geq r_L$.

Consider now $r_F < r_L$. Notice that the right-hand side in (34) increases with κ, so it suffices to prove the inequality for $\kappa = 2$. Plugging this value of κ and rearranging we get

$$-7r_F^2 - 3r_L^2 + r_F + 7r_L + 10r_F r_L - 14 < 0. \tag{36}$$

A sufficient condition for (36) to hold is that both of the following inequalities hold:

$$\begin{aligned} r_F + 7r_L - 8 &\leq 0 & (37)\\ -7r_F^2 - 3r_L^2 + 10r_F r_L - 6 &< 0 & (38) \end{aligned}$$

since, if both (37) and (38) hold, (36) follows from the sum of both of them. Clearly, (37) holds since r_F, $r_L \in [0, 1]$. To prove (38) define $s := \frac{r_F}{r_L}$, where $s \in [0, 1]$ and rewrite (38) as $(-7s^2 - 3 + 10s)r_L^2 - 6 < 0$. For any r_L, the expression inside the parenthesis attains its maximum at $s = 5/7$. For that value of s, the latter inequality becomes $\frac{4}{7}r_L^2 - 6 < 0$, which clearly holds true for any $r_L \in [0, 1]$.

6.6 Proof of Proposition 4

As shown in Proposition 2, the condition for a type-1 equilibrium to arise is $\xi < -1$. Using (16) and (18), in the diagonal this condition can be written as $5\kappa \leq 4a - 6$, which clearly does not hold for any admissible value of a. In addition, the most favourable pair of realizations for a type-1 equilibrium is $\alpha_F = \theta + \sigma$ and

$\alpha_L = \theta$, under which the condition $\xi < 1$ becomes $\kappa < 2$. Thus, there is a positive probability to get a type-1 equilibria if and only if this latter inequality holds, and the realizations under which it takes place are in the lower-right corner of the support of firms types.

Now consider the condition for type-2 equilibria, $\xi > 1$. Under realizations in D, and after some algebra, this condition becomes $5\kappa \leq 2(3-2a)$, which is in contradiction with (4) if and only if $a > \frac{1}{4}$. On the other hand, for $a = 0$, which is the most favourable case, the inequality becomes $\kappa < \frac{6}{5}$, which is the required condition for this type of equilibrium to arise with positive probability.

To prove that a type-3 equilibrium always arises with positive probability, we evaluate ξ in $(\alpha_F, \alpha_L) = (\theta+\sigma, \theta+\sigma)$ and using (18) we get $\xi = \frac{-2\sigma}{5\beta Q}$ which clearly belongs to $(-1, 1)$ under (4) and, by continuity, this is true for some non-empty interval around $(\theta+\sigma, \theta+\sigma)$.

6.7 Proof of Proposition 5

Using (16) and (19) we conclude that the condition for a type-1 equilibrium to occur, $\xi < -1$, in the diagonal takes the form $\kappa \leq \frac{2(1+2a)}{5}$, which does not contradict (4) iff $a \geq \frac{3}{4}$. So, the most favourable situation is $a = 1$, under which the previous inequality becomes $\kappa \leq \frac{6}{5}$. In addition, if $\xi < -1$ does not hold for some pair (α_F, α_L), it does not hold neither for any pair (α_F, α'_L) with $\alpha'_L > \alpha_L$. Thus, there is a positive probability of type 1 equilibria if and only if $\kappa \leq \frac{6}{5}$ holds. Under the latter inequality, the realizations of the firms types under which there is a type 1 equilibrium are in the upper-right corner of the triangle.

The condition for a type-2 equilibrium to arise in the diagonal is $5\kappa \leq -2(1+2a)$, which does not hold for any admissible value of a. In addition, the most favourable realization for a type-2 equilibrium to occur are $\alpha_F = \theta$ and $\alpha_L = \theta + \sigma$, under which the inequality becomes $\kappa \leq 2$.

To prove that a type-3 equilibrium always arises with positive probability, we evaluate ξ in $(\alpha_F, \alpha_L) = (\theta, \theta)$ and using (19) we get $\xi = \frac{2\sigma}{5\beta Q}$ which clearly belongs to $(-1, 1)$ under (4) and, by continuity, this is true for some non-empty interval around (θ, θ).

6.8 Proof of Proposition 6

Assume initially that the solution is interior (what we check below). The first step is to derive the solution of problem (23). The first-order condition (FOC) of this problem is

$$-\frac{d\pi_L}{dq_{L0}} \cdot \frac{\partial q_F^{b*}}{\partial p_0} - \left[\bar{Q} - q_F^{b*}(p_0, \alpha_F)\right] + p_0 \frac{\partial q_F^{b*}}{\partial p_0} = 0,$$

where, under interior solution, we know $q_F^{b*} = \tau_F(q_{F0}, \alpha_F)$ -see (28)-. Using the expressions for π_L and $\tau_F(q_{F0}, \alpha_F)$ and rearranging, FOC can be written as

$$\frac{2}{5}\tau_F(q_{F0}, \alpha_F) - \frac{8\bar{Q}}{5} + \frac{3(\alpha_L + 2\alpha_F)}{5\beta} - \frac{9}{5\beta}p_0 = 0.$$

Using again the expression for $\tau_F(q_{F0}, \alpha_F)$ and (16) we get

$$\frac{2\mu_F}{5\beta} + \frac{(2\lambda_F + 7)\alpha_F}{5\beta} - \frac{2\bar{Q}}{5} - \frac{9}{5\beta}p_0 - 4\bar{Q} + \frac{3(\alpha_L + 2\alpha_F)}{2\beta} - \frac{9}{2\beta}p_0 = 0$$

which, solving for p_0 and simplifying, provides the solution of (23):

$$p_0^* = \frac{4\mu_F}{63} + \frac{2(2\lambda_F + 22)\alpha_F}{63} + \frac{15\alpha_L}{63} - \frac{44}{63}\beta\bar{Q}. \tag{39}$$

Assume now the leader's strategy is linear (we argue below that this is necessarily the case) and takes the form $q_L^{b*}(p_0, \alpha_L) = m_0 + m_1\bar{Q} + m_2\alpha_L + m_3 p_0$. The second step is to show that there exist values of the coefficients m_0, m_1, m_2, m_3 such that the market clearing condition $q_F^{b*}(p_0, \alpha_F) + q_L^{b*}(p_0, \alpha_L) = \bar{Q}$ has p_0^* as a solution. This means that, when L and F bid $q_F^{b*}(p_0, \alpha_F)$ and $q_L^{b*}(p_0, \alpha_L)$ respectively, p_0^* arises as a clearing price for the auction. Using the expressions for $q_F^{b*}(p_0, \alpha_F)$ and $q_L^{b*}(p_0, \alpha_L)$ in the market clearing condition, substituting (39) for p_0 and collecting terms, we get the following equation:

$$\frac{\mu_L(4\beta m_3 + 18)}{63\beta} + m_0 + \frac{18\lambda_L + \beta m_3(5\lambda_L + 44) + 9}{63\beta}\alpha_F + \frac{\beta(7m_2 + m_3) - 3}{7\beta}\alpha_L + \frac{63m_1 - 44\beta m_3 + 54}{63}\bar{Q} = \bar{Q}.$$

For this equation to hold for any arbitrary pair (α_L, α_F), we need that the, in the left-hand side, the constant term and the coefficients associated to α_F and α_F are equal to zero and the coefficient associated to $\bar{Q}$ is equal to one. From those conditions we get a system of four equations which has, as a unique solution, $m_0 = \frac{-3\lambda_L}{\beta(\lambda_L+11)} \leq 0$, $m_1 = \frac{-3\lambda_L}{\lambda_L+11} \leq 0$, $m_2 = \frac{6\lambda_L+21}{4\beta(\lambda_L+11)} \geq 0$, $m_3 = \frac{-(18\lambda_L+9)}{4\beta(\lambda_L+11)} \leq 0$, where the signs follow from the fact that, under Assumption 1, λ_L only can be equal to 0 (in case 1) or 1/2 (in cases 2 and 3). The fact that $q_L^{b*}(p_0, \alpha_L)$ is necessarily linear comes from the fact that both $q_F^{b*}(p_0, \alpha_F)$ and p_0^* are linear and hence, in the systems of equations set above, any non-linear term must be zero to ensure that the market-clearing condition holds for any pair (α_L, α_F).

Plugging (39) in the bidding function, we find the equilibrium allocation in the auction:

$$q_{L0}^{A*} = \frac{\beta\bar{Q} + 3\alpha_L - 2\mu_L - (2\lambda_L + 1)\alpha_F}{7\beta}, \qquad q_{F0}^{A*} = \frac{2\mu_L + (2\lambda_L + 1)\alpha_F + 6\beta\bar{Q} - 3\alpha_L}{7\beta}. \tag{40}$$

The third step is to show that $q_F^{b*}(p_0, \alpha_F)$ and $q_L^{b*}(p_0, \alpha_L)$ constitute an equilibrium of the game. By construction, p_0^* is an equilibrium price and q_F^{b*} is the best strategy for F for the same arguments used in Section 3. So, we only have to show that $q_L^{b*}(p_0, \alpha_L)$ is the best strategy for L, what amounts to proving that the value of q_{L0}^{A*} given in (40) solves (21). To prove this, note that, for a specific value of α_F, solving (23) in terms of p_0 is totally equivalent to solving it in terms of q_{L0}. Therefore, we conclude that (22) provides an allocation for L that maximizes π_L for any possible value of α_F, what implies that it also maximizes it on average and, therefore, he have solved (21). The equilibrium is unique since both $q_F^{b*}(p_0, \alpha_F)$ and $q_L^{b*}(p_0, \alpha_L)$ are unique.

If is only left to prove that there exists a set of parameters such that the solution is interior.

Using (5), (6), (25), (39) and (40), and rearranging, we conclude that the occurrence of an interior solution w.p.1 requires that the following conditions hold:

$$\begin{aligned}
\Pr\left(-13\beta\bar{Q} \leq 2\mu_F + (2\lambda_F + 8)\alpha_F - 10\alpha_L \leq 8\beta\bar{Q}\right) &= 1, & (41)\\
\Pr\left(-6\beta\bar{Q} \leq 2\mu_F + (2\lambda_F + 1)\alpha_F - 3\alpha_L \leq \beta\bar{Q}\right) &= 1, & (42)\\
\Pr\left(13\beta\bar{Q} \leq 10\alpha_L + (13 - 2\lambda_F)\alpha_F - 2\mu_F\right) &= 1, & (43)\\
\Pr\left(44\beta\bar{Q} \leq 4(\mu_F + (\lambda_F + 11)\alpha_F) + 15\alpha_L\right) &= 1. & (44)
\end{aligned}$$

The first condition guarantees interior solution for quantities in the secondary market[26] $(0 \leq q_{i1} \leq \bar{Q})$ and the second does the same for the auction $(0 \leq q_{i0} \leq \bar{Q})$. The third and fourth conditions ensure that the price is non-negative in the secondary market and the auction respectively $(p_1 \geq 0,\ p_0 \geq 0)$.

If we include the assumption of uniform distribution and we restrict ourselves to the three cases considered in Assumption 1, using the relevant expressions for μ_L and λ_L conditions (41) to (44), collapse to the following equations:

Case 1 (independent types): $2\sigma \leq \beta\bar{Q} \leq \frac{63\theta}{44} + \frac{\sigma}{22}$;

Case 2 (L efficient): $2\sigma \leq \beta\bar{Q} \leq \frac{63\theta}{44}$;

Case 3 (F efficient): $\sigma \leq \beta\bar{Q} \leq \frac{63\theta}{44} + \frac{\sigma}{22}$.

If θ is large enough with respect to σ, the sets defined by these conditions are clearly non-empty.

6.9 Proof of Proposition 7

The first part is readily proved by comparing the relevant expressions for prices and quantities and doing some straight-forward algebra. The strategy to prove the second part is to show that $h(\delta^A, \boldsymbol{\alpha}) > h(\delta^G, \boldsymbol{\alpha})$ for all the relevant values of the parameters. In turn, this is done by minimizing $h(\delta^A, \boldsymbol{\alpha}) - h(\delta^G, \boldsymbol{\alpha})$ in terms of α_L and α_F and showing that the minimum value is positive, what implies that it is positive for any combination of α_L and α_F. First, note that in all three cases $h(\delta^A, \boldsymbol{\alpha}) - h(\delta^G, \boldsymbol{\alpha})$ is a continuous and

[26] Notice that condition (4) guarantees interior solution in the secondary market for any initial allocation of permits, whereas (41) guarantees it only for the auction allocation considered in this section. Furthermore, we write the conditions in terms of probabilities and not in terms of parameters, as in (4). In order to present these conditions in terms of parameters, it suffices to consider the most adverse realizations for each inequality.

bounded function defined on a compact set and, therefore, we can use the Weierstrass theorem to state that there exists a minimum in the relevant interval. Although the strategy of the proof is the same for all three cases in Assumption 1, the development is slightly different for each case and so we consider them separately.

CASE 1: α_L and α_F are not correlated. Using (10), (12), (17) and (40), the difference between total cost under auctioning and grandfathering can be written as

$$h(\delta^A,\boldsymbol{\alpha}) - h(\delta^G,\boldsymbol{\alpha}) = \frac{1}{196\beta\bar{Q}}\left[-24\alpha_F^2 - 48\alpha_L^2 + 88\alpha_L\alpha_F - 2\alpha_F\left(20\theta + 10\sigma + 25\beta\bar{Q}\right)\right. \\ \left. +2\alpha_L\left(4\theta + 2\sigma + 5\beta\bar{Q}\right) + 4\left(2\theta+\sigma\right)^2 + 25\beta^2\bar{Q}^2 + 20\beta\bar{Q}\left(2\theta+\sigma\right)\right],$$

the sign of which is determined by the term in square brackets, which we denote as $\Delta_1(\alpha_L,\alpha_F)$. For the relevant values of the parameters we have $\frac{\partial\Delta}{\partial\alpha_L} > 0$ and $\frac{\partial\Delta}{\partial\alpha_F} < 0$, what implies that $\Delta(\alpha_L,\alpha_F)$ reaches a minimum at $(\alpha_L,\alpha_F) = (\theta,\theta+\sigma)$. Using these values, we get $\Delta_1(\theta,\theta+\sigma) = -40\sigma^2 - 30\sigma\beta\bar{Q} + 25\beta^2\bar{Q}^2$, which is always positive under the interior solution condition $2\sigma < \beta\bar{Q}$.

CASE 2: $\alpha_L \leq \alpha_F$. In this case we have $E\{\alpha_L\} = \theta + \frac{\sigma}{3}$, $E\{\alpha_F\} = \theta + \frac{2\sigma}{3}$, what implies $\delta^G = \frac{3\theta+2\sigma}{6\theta+3\sigma}$ and, using (10), (12), (18) and (40), the difference of total cost between both systems can be written as

$$h(\delta^A,\boldsymbol{\alpha}) - h(\delta^G,\boldsymbol{\alpha}) = \frac{1}{49\beta\bar{Q}X^2}\left\{X^2\left(-10\alpha_F^2 - 12\alpha_L^2 + 23\alpha_L\alpha_F\right) + \alpha_F\left[-X^2\left(3\theta + 32\beta\bar{Q}\right) + 49\beta\bar{Q}XY\right]\right. \\ \left. +\alpha_L\left[X^2\left(\theta + 27\beta\bar{Q}\right) - 49\beta\bar{Q}XY\right] + \beta^2\bar{Q}^2\left[225\theta\left(\theta+\sigma\right) + 44\sigma^2\right] + X^2\left(\theta^2 + 5\theta\beta\bar{Q}\right)\right\}$$

where $X := (6\theta + 3\sigma)$, $Y = (3\theta + 2\sigma)$. Denote as $\Delta_2(\alpha_L,\alpha_F)$ the term in curly brackets, what determines the sign of the whole expression. Now we solve the problem of minimizing $\Delta_2(\alpha_L,\alpha_F)$ subject to $\alpha_L \geq \theta$, $\alpha_F \leq \theta + \sigma$ and $\alpha_L \leq \alpha_F$. We conclude that there are two candidates that satisfy the first-order Kuhn-Tucker conditions. The first candidate is $\alpha_L = \theta$, $\alpha_F = \theta + \sigma$ and the second one is $\alpha_L = \alpha_F = \theta + \sigma$.[27] For the first candidate we have

$$\Delta_2(\theta,\theta+\sigma) = \sigma X\left[\beta\bar{Q}\left(-45\theta + 2\sigma\right) - 10\sigma X\right] + \beta^2\bar{Q}^2\left(225\theta\left(\theta+\sigma\right) + 44\sigma^2\right) > 0,$$

where the inequality comes from the fact that $\Delta_2(\theta,\theta+\sigma)$ is increasing in $\beta\bar{Q}$ for any $\beta\bar{Q} > 2\sigma$ (which is a required condition to guarantee interior solution) and replacing $\beta\bar{Q}$ by 2σ we get $\Delta_2(\theta,\theta+\sigma) > \sigma^2\left(334\theta\sigma + 98\sigma^2\right) > 0$. Analogously, for the second candidate we have

$$\Delta_2(\theta+\sigma,\theta+\sigma) = \sigma X^2\left[\sigma - 5\beta\bar{Q}\right] + \beta^2\bar{Q}^2\left(225\theta\left(\theta+\sigma\right) + 44\sigma^2\right) > 0$$

where, again, the inequality comes from the fact that $\Delta_2(\theta+\sigma,\theta+\sigma)$ is increasing in $\beta\bar{Q}$ for any $\beta\bar{Q} > 2\sigma$

[27] The second is a candidate only if σ and $\beta\bar{Q}$ are high enough as compared to θ.

and replacing $\beta\bar{Q}$ by 2σ we get $\Delta_2(\theta+\sigma,\theta+\sigma) > \sigma^2\left(576\theta^2+95\sigma^2+414\theta\sigma\right) > 0$.

CASE 3: $\alpha_F \leq \alpha_L$. In this case we have $E\{\alpha_L\} = \theta + \frac{2\sigma}{3}$, $E\{\alpha_F\} = \theta + \frac{\sigma}{3}$ and, therefore, $\delta^G = \frac{3\theta+\sigma}{6\theta+3\sigma}$. Using (10), (12), (19) and (40), the difference of total cost between auctioning and grandfathering can be written as

$$\begin{aligned} h(\delta^A,\boldsymbol{\alpha}) - h(\delta^G,\boldsymbol{\alpha}) &= \tfrac{1}{49\beta\bar{Q}X^2}\left\{X^2\left(-10\alpha_F^2 - 12\alpha_L^2 + 23\alpha_L\alpha_F\right)\right. \\ &\quad +\alpha_F\left[49\beta\bar{Q}XZ - X^2\left(3\theta+3\sigma+32\beta\bar{Q}\right)\right] + \alpha_L\left[X^2\left(\theta+\sigma+27\beta\bar{Q}\right) - 49\beta\bar{Q}XZ\right] \\ &\quad \left. + (\theta+\sigma)\left(5\beta\bar{Q} + (\theta+\sigma)\right) + \beta^2\bar{Q}^2\left[49Z(X-Z)-6\right]\right\} \end{aligned}$$

where $X := (6\theta+3\sigma)$, $Z = (3\theta+\sigma)$. Denote as $\Delta_3(\alpha_L,\alpha_F)$ the term in curly brackets, what determines the sign of the whole expression. We conclude that the only candidate that satisfies the Kuhn-Tucker first-order conditions to minimize $\Delta_3(\alpha_L,\alpha_F)$ subject to $\alpha_F \geq \theta$, $\alpha_L \leq \theta+\sigma$ and $\alpha_F \leq \alpha_L$ is $\alpha_L = \theta+\sigma$, $\alpha_F = \theta$. Evaluating $\Delta_3(\alpha_L,\alpha_F)$ for this candidate we get

$$\begin{aligned} \Delta_3(\theta+\sigma,\theta) &= -10\sigma^2X^2 + \beta\bar{Q}\sigma X(45\theta+47\sigma) + \beta^2\bar{Q}^2\left(225\theta(\theta+\sigma)+44\sigma^2\right) \\ &> \sigma^2\left[X(45\theta+47\sigma-10X) + (225\theta(\theta+\sigma)+44)\right] > 0, \end{aligned}$$

where the first inequality comes from the fact that $\Delta_3(\theta,\theta+\sigma)$ is increasing in $\beta\bar{Q}$ and then we can use $\beta\bar{Q} = \sigma$ to obtain a lower bound.

6.10 Proof of Corollary 3

Consider an arbitrary value of the (monotone transformation of) total cost h, say $\widetilde{h}$. For grandfathering, denote as $\Phi^G\left(\tilde{h}\right) := \left\{\boldsymbol{\alpha} \;/\; h(\delta^G,\boldsymbol{\alpha}) \leq \tilde{h}\right\}$ the set of values of the types, (α_L,α_F), such that the cost under grandfathering is not larger than $\tilde{h}$. Similarly, define $\Phi^A\left(\tilde{h}\right) := \left\{\boldsymbol{\alpha} \;/\; h(\delta^A,\boldsymbol{\alpha}) \leq \tilde{h}\right\}$ for the auction. From Proposition 7 we know that, for any realization of the types, we have $h(\delta^G,\boldsymbol{\alpha}) \leq h(\delta^A,\boldsymbol{\alpha})$. In particular, this will be the case for those types contained in $\Phi^A\left(\tilde{h}\right)$. Then, we conclude that $\Phi^A\left(\tilde{h}\right)$ is included in $\Phi^G\left(\tilde{h}\right)$ or, in other words, $F^A\left(\tilde{h}\right) \leq F^G\left(\tilde{h}\right)$ for any value of $\tilde{h}$, where F^A and F^G are the distribution functions of h under auctioning and grandfathering respectively, what implies FOSD of G over A.

7 Appendix 2: Figures

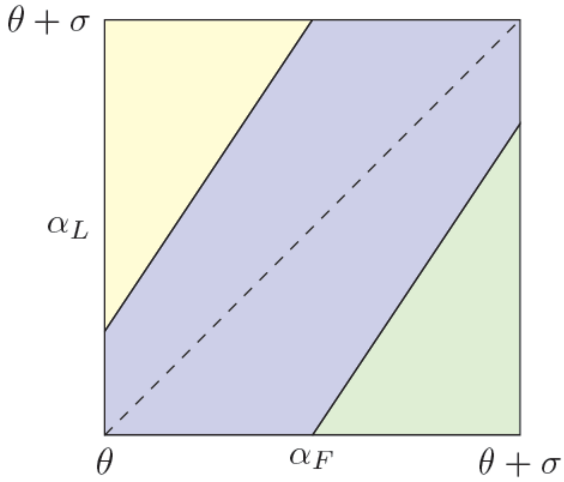

Figure 1: Equilibria for independent types when $\kappa < 2$. Type-1, 2 and 3 equilibria arise in green, yellow and blue regions respectively.

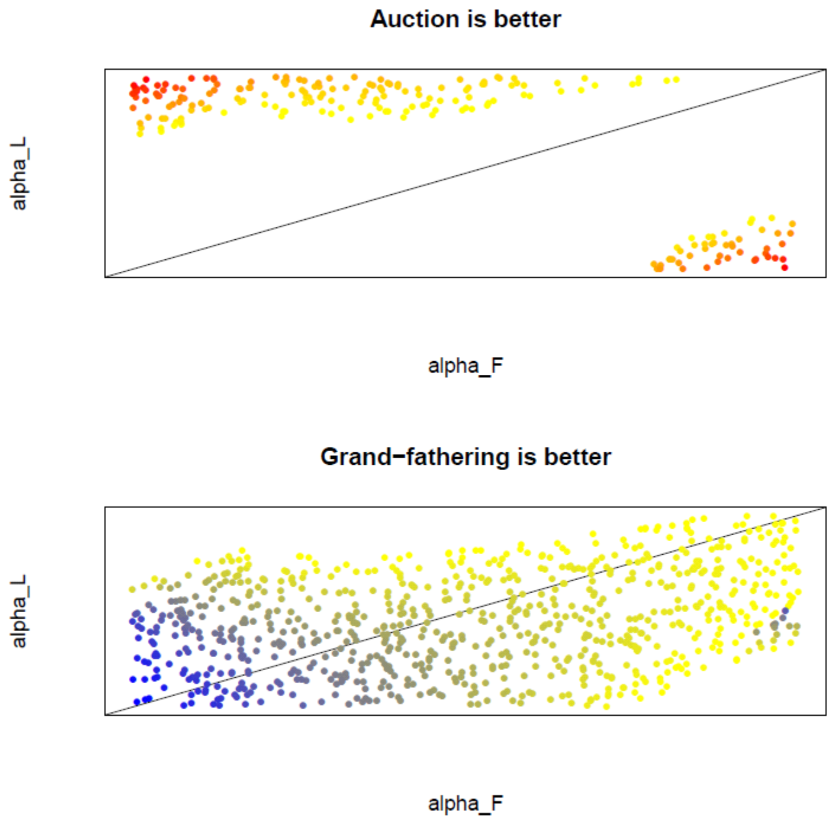

Figure 2: Realized Costs with $(\sigma, \beta\bar{Q}) = (6, 8)$ and $\theta = 10$. Each dot corresponds to a realization of $\boldsymbol{\alpha}$ and it is displayed in the upper (resp. lower) panel if, for that realization, total cost under auctioning is smaller (higher) than that under grandfathering. In the upper panel the colours ranges from yellow to red, where yellow means both costs are roughly similar to each other and red means a larger difference from one to another. In the lower panel the colours range from yellow to blue, where yellow means again similar costs.

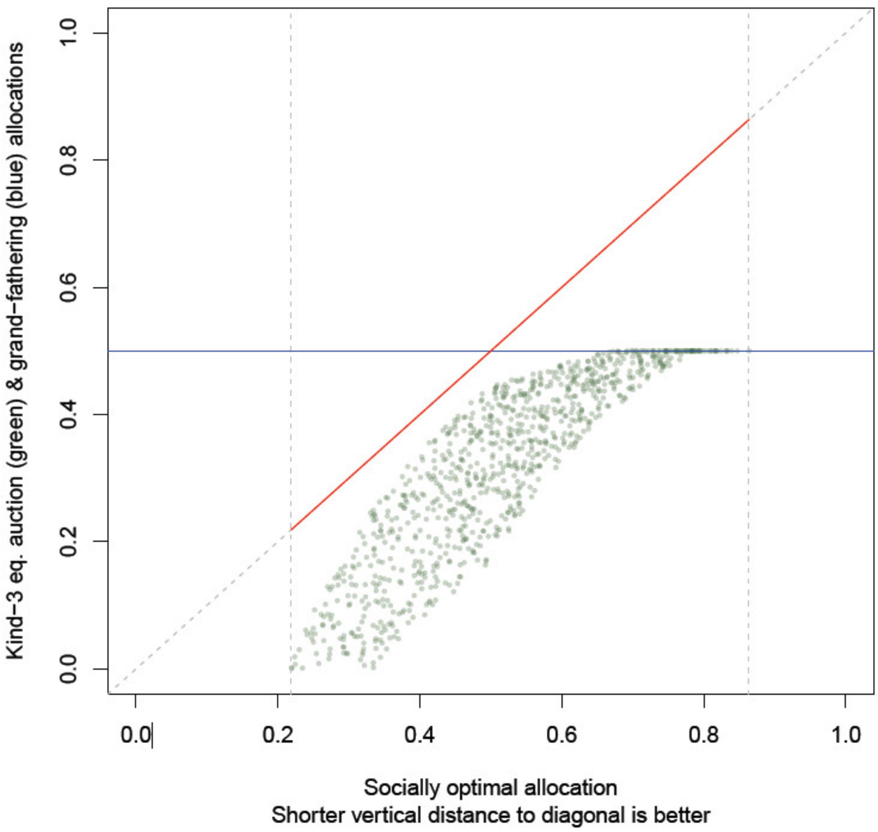

Figure 3: Allocations in terms of $\delta := \frac{q_{F0}}{\bar{Q}}$, with independent types and $(\sigma, \beta\bar{Q}) = (6, 8)$ and $\theta = 10$. The green points represent auction vs. cost minimizing allocations for each realization of $\boldsymbol{\alpha}$, thus the closer those points are to the diagonal (red line), the more cost-effective the auction allocation is. The blue line represents the grandfathering allocation (which is constant and equal to 1/2). Grandfathering is cost-effective if $\delta^{CE} = \frac{1}{2}$ (which corresponds to $\alpha_L = \alpha_F$) and L gets over-assigned (resp. under-assigned) if $\delta^{CE} > \frac{1}{2}$ ($\delta^{CE} < \frac{1}{2}$). In the vast majority of the realizations, $\delta^A < \delta^{CE}$, i.e., auctioning allocates more permits to the leader than what is cost-effective.

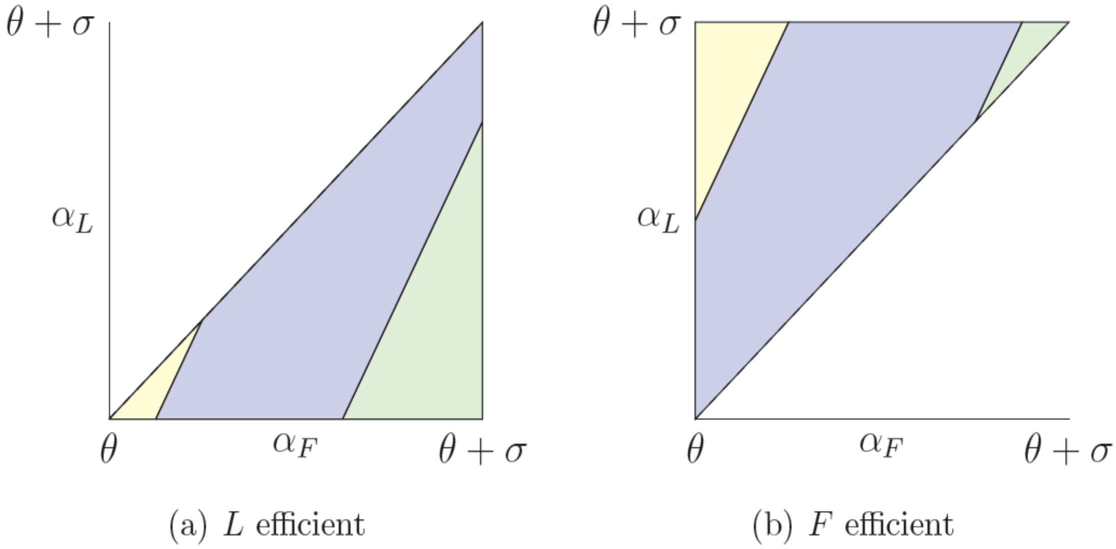

Figure 4: Equilibrium configuration for cases 2 and 3 when κ takes a value to enable all three types of equilibria. Type-1, 2 and 3 equilibria arise in green, yellow and blue regions respectively.

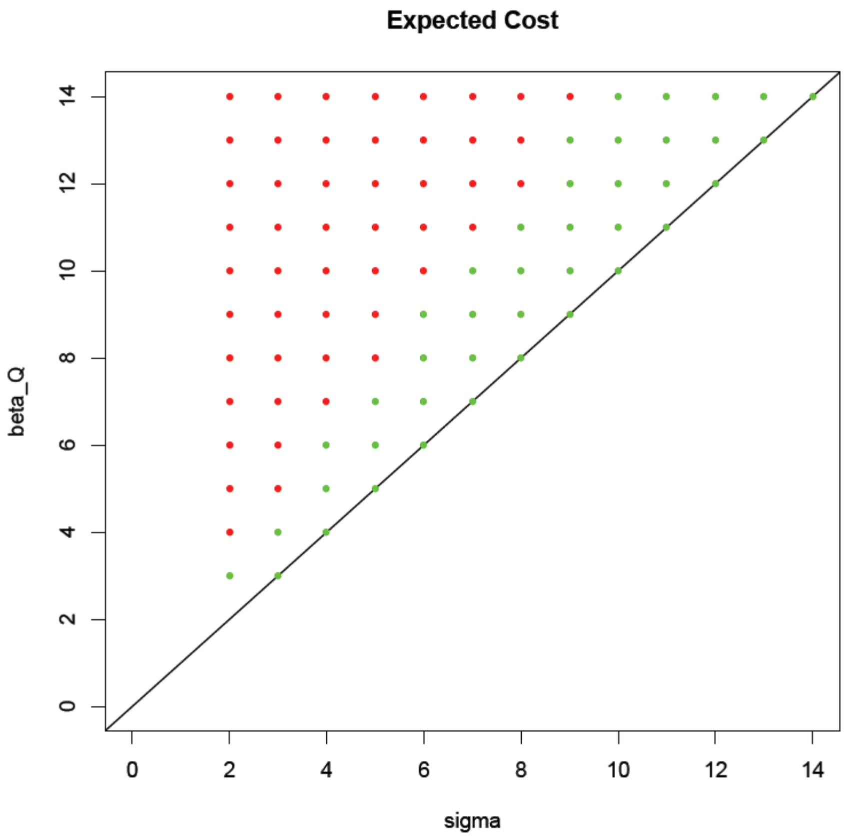

Figure 5: Expected costs under auctioning (A) and grandfathering (G) in case 3. For each realization, we compute expected cost under A and G and we average across 1,000 random realizations. A red (green) dot indicates that G (A) entails lower expected cost. In cases 2 and 3 all the dots would be red.

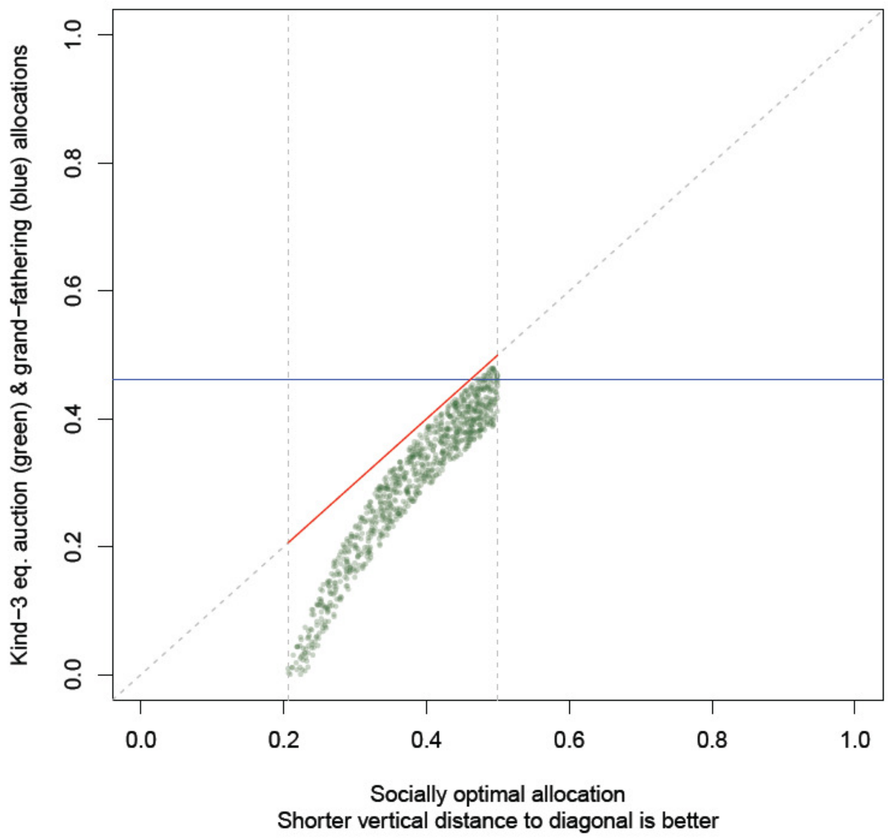

Figure 6: Allocations for type-3 equilibria in case 3 with $(\sigma, \beta\bar{Q}) = (6, 8)$ and $\theta = 10$. The interpretation is the same as Figure 3.

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