Pitfalls of Insuring Production Risk*

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Abstract

We consider auctions for procurement contracts involving exogenous production risk and whose payment rule depends not only on actual production but also on self-reported expected production. We first establish a conflict between insurance provision and strategy-proofness. We then analyze equilibrium bidding behavior under several paradigms regarding bidders' ability to misreport their expected production: Payment rules that are manipulable could produce rents for strategic bidders which may overwhelm the benefits from reduced risk premiums thanks to insurance provision. We illustrate our results through simulations calibrated on a few offshore wind power auctions in France and estimate that public spending could have increased by 3% given that strategic bidders would benefit from overestimating their expected production by more than 10%. Such potential losses are 15 times greater than the potential benefits from reduced risk premiums under truthful reporting. We also introduce variants of the French rule with punishments intended to discourage misreporting, and find limited room for improving linear contracts. Various extensions of our baseline model are discussed.

Keywords: Auctions for Contracts; Contingent Auctions; Market Design; Gaming; Bid Manipulation; Public–Private Partnerships; Risk Premium; Renewable Energy; Wind Power.
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1 Introduction

The transition towards low-carbon economies has led many countries to support renewable energy sources of electricity (RES-E) on a large scale, especially wind and solar power. This support often involves subsidy contracts awarded to RES-E projects through auctions.[1] These can be regarded as standard procurement contracts through which public authorities buy green electricity, and which involve various risks for the producer. In general, when producers are more risk averse than the public decision-maker, designing Public–Private Partnerships such that producers bear a smaller share of these risks reduces risk premiums (Engel, Fischer and Galetovic (2013)), and thus in our case may help to develop RES-E at a lower cost (Cantillon, 2014). As an example, Engel, Fischer and Galetovic (2001) plead for least-present-value-of-revenue auctions where the franchise terms adjust to demand realizations: according to their estimates for a highway franchising project in a developing country, such contracts could reduce public spending by more than 20% compared to the widespread fixed term contracts where contractors bid on tolls.

RES-E are often subsidized through Feed-in-Tariffs (FiT) where producers receive a fixed subsidy for each MWh produced. Producers' revenue is thus proportional to the quantity produced, even though wind and solar electricity generation does not involve variable costs. Henceforth, FiT contracts make producers' revenues highly dependant on the quantity produced, which is in turn highly dependant on weather conditions. As argued by Cantillon (2014), economic theory calls for reducing producers' exposure to risks over which they have no control, such as the weather, while risks over which they have some control call for contractual arrangements that trade off the benefits of risk sharing with incentive provision. Incentivizing producers to make ex ante efforts to upgrade production (e.g. through turbine model selection) is the main rationale for using FiT contracts instead of capacity (or investment) subsidies: the latter fully eliminate both risk exposure and incentives to maximize production.[2] Nevertheless, once the RES-E capacity is built and connected to the electricity network, producers have no control over the quantity produced which they then view as an exogenous risk. For wind farm projects, this risk is not negligible since the standard deviation of the yearly production could represent at least 10% of the mean production (Newbery, 2012) but also and mainly because until recently wind power forecasting suffered from an important over-prediction bias.[3] Some countries – including Brazil, France and Germany – have departed from (standard) linear FiT and adopted contract designs (henceforth referred to as "payment rules") where wind farm revenue is made less sensitive to production variations within

[1] In 2019, an estimated 115 GW (resp. 60 GW) of solar PV (resp. wind power) capacity was installed worldwide. RES-E subsidies were awarded through auctions in 48 countries according to REN21's 2020 global status report (www.ren21.net/wp-content/uploads/2019/05/gsr_2020_key_findings_en.pdf).

[2] Huenteler et al. (2018) analyze the performance of wind farms and argue that the huge gap between US and China is driven by factors that are related to efforts made by the producers.

[3] See Lee and Fields (2020) for a survey.

an interval around the reported reference production. For instance, the payment rule for early offshore wind auctions in France was designed in a way that makes producers' yearly revenues almost insensitive to the annual quantity produced within +/- 10% around a *reference production* reported by the producers themselves. We presume that the rationale for such a risk sharing agreement was to lower the risk premiums producers include in their bids, and thus to reduce public spending.

However, such designs open the door to strategic behavior, in particular when letting producers freely self-report their reference production.[4] We formalize and analyze this pitfall through a model where a set of firms compete for a procurement contract in which the buyer's total payment is a function of the contractor's per-unit price bid, of its actual production (whose realization is determined after the auction) and of the reference production as reported in the contractor's bid. We call *linear contracts* the rules where the total payment is equal to the per-unit price bid times the actual production. The winning firm is selected on the sole criterion of its per-unit price bid, regardless of the reported reference production. We then consider two kinds of firms: those that are constrained to report their expected production truthfully and those that are entirely free – at no cost – to make any possible report. The former (resp. latter) firms are called truthful (resp. strategic).

We introduce the class of so-called *production-insuring payment rules* which we define as the rules such that the buyer's expected cost is the same as in the linear contract while the expected utility of any risk averse contractor is greater for any symmetric production distribution and any given per-unit price, and provided that the reference production matches the expected production. However, the buyer's expected cost depends on the chosen payment rule insofar as the per-unit price results from a competitive auction. Under truthful reporting, a production-insuring payment rule incurs (by definition) lower risk premiums compared to the linear contract. These will be reflected in lower equilibrium price bids placed by the firms, and consequently in a lower expected cost for the buyer.

Production-insuring payment rules seem to be a salient choice for risk neutral buyers facing risk averse firms as they certainly represent an improvement over the linear contract when all firms are truthful. Our research question is then to analyze the performance of such rules if we depart from the assumption that all bidders are necessarily truthful.

As a preliminary, we analyze the incentives of strategic firms to misreport their expected production. We formalize a fundamental conflict between insurance provision and strategy-proofness: for any given production-insuring payment rule and any given symmetric single-peaked distribu-

[4] E.g., in offshore wind farm auctions in France, the reference production was based on the firm's own data and calculation and there was thus no guarantee that this self-reported parameter would correspond to the expected production.

tion, risk neutral firms strictly benefit from stating a reference production greater than their actual expected production. We also impose additional structure to analyze the incentives to manipulate the payment rule under risk aversion and to derive some comparative statics. We show in particular that risk aversion reduces the incentive to overstate the reference production.

Such deceptive behavior gives a comparative advantage to strategic firms. Furthermore, a strategic firm overstating its reference production in its bid causes disappointment for the buyer when it wins the auction: the effective per-unit price, i.e. the average ex post subsidy paid per quantity produced, will be greater than the submitted price bid. With a production-insuring payment rule, the effective per-unit price and the submitted price bid only match when the winning firm reports its actual expected production as its reference production. Intuitively, the larger the misreporting, the larger the discrepancy between the effective subsidy and the bid.

We then analyze the auction game when firms differ only regarding their ability to misreport their reference production. We consider that all firms have the same production distribution, the same costs and the same payoff function (capturing possible risk aversion). We first derive the equilibria under complete information, depending on whether and how many firms are truthful or strategic. Second, we derive the (mixed strategy) equilibrium when each firm is, independently of the others, either truthful or strategic with some given probability. In all cases, we establish that the presence of strategic firms produces a lower equilibrium price compared to the case where all firms are truthful, but the buyer's expected cost does not necessarily decrease, quite the contrary.

Production-insuring payment rules not being strategy-proof leads to two kinds of pitfalls to which the linear contract is immune: a) Instead of evening out the firms' revenue (as would be the case under truthful reporting), a production-insuring payment rule could have exactly the opposite effect, as illustrated in Section 2, and those risks are borne ultimately by the buyer through an increased risk premium. b) Heterogeneity regarding the ability to misreport the reference production leads to non-competitive rents. Informally, these rents increase with the degree of heterogeneity: the highest buyer's expected cost is reached when a single strategic firm captures all the benefits from strategic misreporting. In the specific case where firms are risk neutral the comparison is unambiguous: for any symmetric single-peaked production distribution, the linear contract (strictly) outperforms any production-insuring payment rule provided that there is a positive probability of having a single strategic firm.

We then use our RES-E application to illustrate those effects quantitatively. We consider the production-insuring payment rule which was used in early offshore wind auctions in France and calibrate the production risk distribution based on wind production simulations. For any realistic degree of risk aversion, we find that the potential benefits from insurance provision are much lower in magnitude than the potential losses due to misreporting. Furthermore we show that the largest pitfall of production-insuring payment rules does not result from misreporting per se (since risk premiums are actually quite small) but rather from the non-competitive rents resulting from the possible heterogeneity in the way bidders (mis)report their reference production. According to our simulations with a coefficient of risk aversion equal to 1, the non-competitive rents accruing to a single strategic firm exceed 3% of the buyer's expected cost while the risk premiums barely exceed 0.3%.

On the whole, this first step of our analysis can be viewed as a strong warning against production-insuring rules: if the buyer is poorly informed about the distribution of production risk such that it can not screen the reference production, then departing from linear contracts to reduce risk premium seems quite a risky bet.

Last, we depart from our baseline model in two directions. First, we depart from production-insuring payment rules and adopt the perspective of a sophisticated buyer who anticipates firms' strategic behavior and can partially adapt its payment rule to the production risk. While only imposing that the payment rule should be homogeneous of degree 1, we establish that it is impossible to eliminate the risk premium with strategic bidders: for any given symmetric single-peaked production distribution and any form of risk aversion, we cannot design a payment rule such that strategic firms would be fully insured against production risk. Then, inspired by the payment rules that have been used in some countries to subsidize wind farms, we analyze, using numeric simulations, a class of payment rules that introduces on top of insurance provision some punishments consisting of payment cuts in case actual production is too far removed from the reported expected production. Heftier punishments reduce the incentives to misreport production, and then a fine-tuning of these punishments could allow strategy-proofness to be restored and eliminate non-competitive rents. However, such payment rules could exacerbate the risk associated with the lowest levels of actual production, producing effects on risk premiums and on the cost for the buyer that are not clear-cut.

Second, we discuss the relevance of our results beyond our limited framework and question more generally the benefits of departing from the linear contract: we start with a discussion on the (non)optimality of the linear contract when firms are risk neutral in the presence of both moral hazard and adverse selection, we then depart from the multiplicative payment rules we considered where the remuneration is proportional to the price bid; we consider moral hazard meaning that the winning firm can make some efforts ex post to upgrade its production distribution; we extend our analysis to environments where production involves variable costs on top of the initial investment cost; we briefly sketch how non-competitive rents would be modified if the asymmetry between firms comes not only from the heterogeneity in terms of truthful/strategic behavior but also in terms of cost and production distribution; last we discuss the case where misreporting is costly.

Links with the literature

Like Eso and White (2004), we consider an auction setup where bids incorporate risk premiums because the value of the good for sale, or equivalently the profit from the contract to be awarded, suffers from an exogenous risk. However, the connection goes no further because Eso and White (2004) do not consider contingent auctions but rather analyze –and compare– standard auction formats and how informational rents interact with risk aversion.

Contingent auctions This paper contributes to the theoretical literature on contingent auctions as surveyed by Skrzypacz (2013). Hansen's (1985) seminal contribution shows that royalty auctions leave lower informational rents to the winning bidder compared to cash-only auctions. More generally, DeMarzo et al. (2005) introduce the concept of "steepness", arguing that having "steeper" securities reduces informational rents. Intuitively, the ranking of securities with respect to the concept of "steepness" is related to risk sharing. In this vein, Abhishek et al. (2015) consider a model with risk averse bidders and argue that steeper securities are beneficial not only because they reduce informational rents but also because they provide more insurance and thus reduce risk-premiums.

The empirical literature on auctions and procurement is also taking a growing interest in auctions involving contingent contracts. Bhattacharya et al. (2018) consider auctions for oil tract contracts and analyze the trade-off between the benefits for having higher royalties (reducing both risk premiums and informational rents as argued above) and the losses resulting from inadequate incentives to drill (or not) the tracts in an efficient manner. They estimate that the optimal royalty rate is around 26% which is more than 50% higher than the one currently used in oil lease auctions. The analog of this issue in procurement is the analysis of the performance of Fixed Price (FP) contracts – where the contractor bears all the cost overruns – versus unit-price (UP) contracts that specify a percentage of the observable costs that accrue to the buyer. In procurement for transport infrastructure projects, Bolotnyy and Vasserman (2019) estimate that switching to a FP contract would more than double public spending compared to a UP scaling auction where producers are partially insured against cost overruns. For similar infrastructure projects, Luo and Takahashi (2019) show that UP contracts are chosen by project managers more often than FP contracts when the projects are more complex and thus more risky ex ante in terms of cost overruns, suggesting that they are regarded as an appropriate risk management instrument.

In our setup, linear contracts correspond to cash-only auctions or FP contracts in the sense that bidders perceive it as being the most risky. On the contrary, production-insuring payment rules correspond to risk sharing agreements as with royalty contracts (to share the stochastic benefits) or with UP contracts (to share the stochastic costs). The trade-off we analyze here is different from what has been previously covered by this strand in the literature, as we leave aside moral hazard to focus on an asymmetric information problem resulting in an opportunity to game the auction rule thanks to the insurance-provision feature of the contract. This leads us to another strand of the auction literature to which our work is related.

Bid manipulation/Gaming in auctions This paper contributes to the literature involving flaws in the bid evaluation process, either because some bidders have opportunities to "game" the auction rules or because the principal is corrupted and could deliberately misevaluate some bids in exchange for a bribe.

Various contributions have investigated the benefits of individual manipulations where bidders do not bid according to the "spirit" of the auction rules. We stress that such manipulations are often legal but may not be available to all bidders either due to a lack of sophistication/rationality or to a lack of information. These issues arise in complex environments, in particular when bids are multi-dimensional.[5] Yokoo et al. (2004) consider multi-object combinatorial auctions where bidders can benefit from using multiple identities to bid in the auction.[6] In scaling auctions, the score of a bid is computed based on ex ante estimates of the various underlying quantities. If bidders receive, ex ante, information about actual quantities, then they will benefit from skewing their bids (Athey and Levin, 2001).[7] In a related manner, Agarwal et al. (2009) discuss such incentives and mention other manipulations in sponsored search auctions for online advertising. Last, Ryan (2020) considers procurement auctions for coal power plants with a hedging instrument against the hard coal future price. Bids are evaluated through a score combining a price bid and an index of how much the firm wishes to be hedged against coal price variations. Ryan (2020) shows that some firms prefer not to use the hedging instrument in order to increase their score, having in mind their ability to renegotiate their contract in case of spikes in the price of coal. The main insight from this literature is that heterogeneity between bidders' abilities or opportunities in gaming opens the door to welfare inefficiencies by selecting – instead of the firms with the lowest cost – the best "manipulators" and/or to non-competitive rents accruing to those manipulators. In this perspective, our strategic bidders are the analog of the firms who benefit the most from ex post renegotiation in Ryan (2020) and of the firms who benefit the most from skewing their bids in Luo and Takahashi (2019).

[5] The standard auction formats (that prevail in auction textbooks, e.g. Krishna (2002)) are immune to individual gaming strategies, but not to collective manipulations which are referred to as collusion and have received considerable interest (see for Correia-da-Silva (2017) for a survey).

[6] Such false-name bidding activity is sometimes referred to as shill bidding, a term that is also used for manipulation by the seller consisting of bidding (possibly fraudulently) in the auction (Lamy, 2013) in order to increase the selling price.

[7] In Athey and Levin's (2001) bi-dimensional timber scaling auctions model, the optimal strategy of a risk neutral bidder consists of bidding zero on the species whose percentage has been underestimated by the seller and paying the Forest Service only for the overestimated species. Such extreme unbalanced bids are not observed in practice, partly due to risk aversion (Athey and Levin, 2001). Bajari et al. (2014) mention another explanation: the risk that a bid could be rejected when its skewness is too visible. Luo and Takahashi (2019) consider multidimensional UP contracts and argue that bidders form their bid portfolios to balance their risks.

In contrast to the literature on bid manipulations which take as exogenous which bidder(s) can "game" the auction rules, the literature on corruption in auctions typically endogenizes the set of bidders which are able to manipulate the bid evaluation process. Celentani and Ganuza (2002) is thus a kind of exception in the literature on corruption by considering a model where the dishonest principal that organizes the procurement is randomly matched to one of the firms who will later benefit from the opportunity to deliver a good at a lower quality than specified in its bid. This model is thus highly related to our bidding paradigm where there is a single strategic firm. On the contrary, in Compte et al. (2005), firms compete ex ante through bribes to be the favored bidder at the auction stage, while in Burguet and Che (2004) firms simultaneously submit a bid and a bribe.

The remainder of the paper is organized as follows. Section 2 introduces the payment rule used by the French government and some of its caveats. Section 3 presents our auction model with production risk. The manipulability of production-insuring contracts is analyzed in Section 4. Section 5 develops the equilibrium analysis of the auction game under several paradigms regarding how bidders (mis)report their expected production. We come back to our empirical application in Section 6: various estimates regarding the buyer's expected cost under French rules compared to the linear FiT are reported. The (possible) benefits from designs that do not fall into the class of production-insuring payment rules are investigated in Section 7. Section 8 discusses the relevance and robustness of our insights beyond our simple model through several extensions. Section 9 concludes. Details of our simulations and the proofs of our main results are presented in the Appendix while additional elements are available in an online Supplementary Appendix (henceforth the SA).

2 French offshore wind auctions

In 2011 and 2013, the French government auctioned up to 4 GW of capacity through six offshore wind farm projects.[8] For each retained project, the feed-in-tariff (FiT) contract specifies the yearly amount paid by the government to the winning firm as a function of its actual yearly production (in MWh). The French payment rule differs from standard FiT linear contracts where the payment is strictly proportional to total production: the yearly remuneration depends not only on the auction-determined price (per MWh) and the amount of electricity produced during the year, but also on how the latter compares to the ***reference production*** reported by the firms

[8]The auction and contract rules are provided (in French) by the French Energy Regulatory Commision for both auction rounds from 2011 and 2013: www.cre.fr/Documents/Appels-d-offres/Appel-d-offres-portant-sur-des-installations-eoliennes-de-production-d-electricite-en-mer-en-France-metropolitaine and www.cre.fr/Documents/Appels-d-offres/Appel-d-offres-portant-sur-des-installations-eoliennes-de-production-d-electricite-en-mer-en-France-metropolitaine2.

in their bids.

Formally, let p denote the price bid of the winning firm, q_0 the reported reference production and q_t the actual production in year t. According to the French payment rule, the firm's revenue for each year t can be expressed as $p \cdot R(q_t, q_0) = p \cdot q_t \cdot z(\frac{q_t}{q_0})$ where the function $z : \mathbb{R}_+ \to \mathbb{R}_+$ with $z(1) = 1$ is referred to as the correction factor. For a given price bid p, the solid (resp. dotted) line in Figure 1a depicts the yearly subsidy according to the French payment rule (resp. the linear contract) as a function of the actual production and on how it compares to q_0.

To hedge firms against variation of q_t, it is desirable to set the correction factor $z(\cdot)$ such that the payment is higher (resp. lower) than it would have been under the linear payment rule for the same per-unit price when the actual production stands below (resp. above) the reference production, i.e. $z(\frac{q_t}{q_0}) \geq 1$ (resp. ≤ 1) if $q_t < q_0$ (resp. $q_t > q_0$). The French payment rule is such that indeed $z(\frac{q_t}{q_0}) > 1$ in the range $[0.85 \cdot q_0, q_0]$ and symmetrically $z(\frac{q_t}{q_0}) < 1$ in the range $[q_0, 1.15 \cdot q_0]$.[9] The solid line in Figure 1b depicts the correction factor $z(\frac{q}{q_0})$ as a function of q_0 the reference production. For a given price p, firms wish to generate higher correction factors. If firms already knew ex ante their actual production q, then they would maximize their revenue by overestimating production by about 11%. Thanks to this strategic misreporting, the subsidy would increase by 10% compared to truthful reporting. This shift corresponds to the difference between the slopes of the dashed and the dotted lines depicted in Figure 1a. We expect firms overestimating incentives to extend to environments with production risk, at least when the risk is small.

When the production is risky and if $q_{max} > 0$ denotes the upper bound of the distribution f, then a firm reporting q_{max} for the reference production is guaranteed that any production outcome will generate a correction factor that is greater than 1. If q_t is symmetrically distributed, note on the contrary that the expected value of the correction factor under truthful reporting is equal to one. This illustrates that strategic risk neutral firms, which should report a reference production q_0 that maximizes $\mathbb{E}[z(\frac{q_t}{q_0})]$, should misreport their expected production. More generally, we expect that their optimal misreport consists of overestimating the expected production: it would more often generate a favorable correction factor $z(\frac{q_t}{q_0}) > 1$ (and less often a correction factor below 1). By optimizing their report q_0, firms benefit from the *effective feed-in-tariff* $p \cdot \mathbb{E}[q_t z(\frac{q_t}{q_0})]/\mathbb{E}[q_t]$ which is thus necessarily greater than $p \cdot \mathbb{E}[q_t z(\frac{q_t}{\mathbb{E}[q_t]})]/\mathbb{E}[q_t]$ the per-unit subsidy under truthful reporting (the latter being equal to p if q_t is symmetrically distributed[10]). The *effective feed-in-tariff* is bounded above by $p \cdot \max_{x \geq 0} z(x)$, a bound that is achieved when future production is perfectly known ex ante and firms optimize their report q_0.

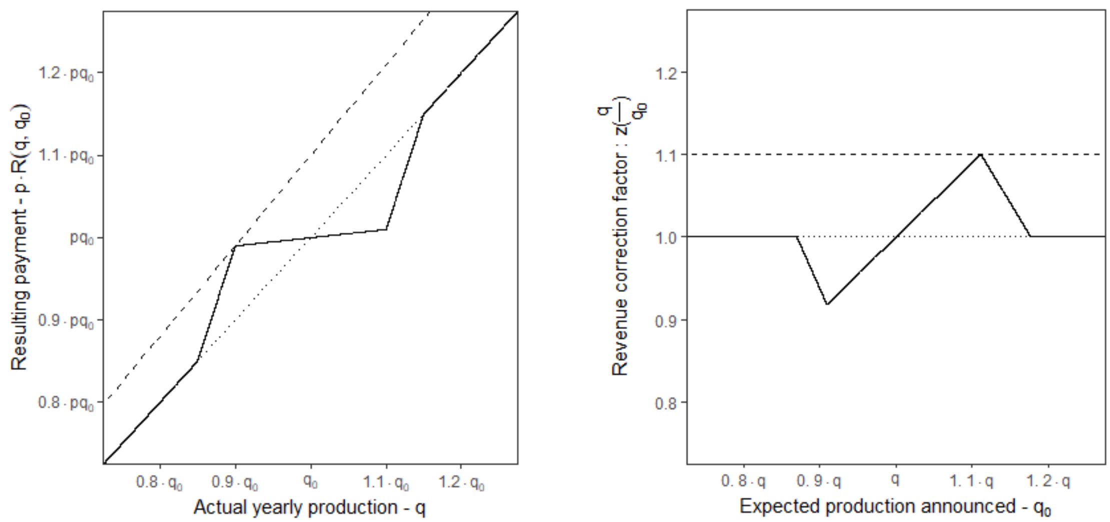
[9]More specifically, the French rule is defined such that the function $\epsilon \to (1+\epsilon) \cdot [z(1+\epsilon) - 1]$ is an odd function which is null outside the $[-0.15, 0.15]$ range and strictly negative for $\epsilon \in]0, 0.15[$.

[10]If q_t is symmetrically distributed, then we have $\mathbb{E}[\frac{q_t}{\mathbb{E}[q_t]}[z(\frac{q_t}{\mathbb{E}[q_t]}) - 1]] = 0$ since the function $\epsilon \to (1+\epsilon)z(1+\epsilon)$ is odd.

Figure 1: Payment rule in French offshore wind auctions

(a) Payment to the firm

(b) Correction factor z(.)

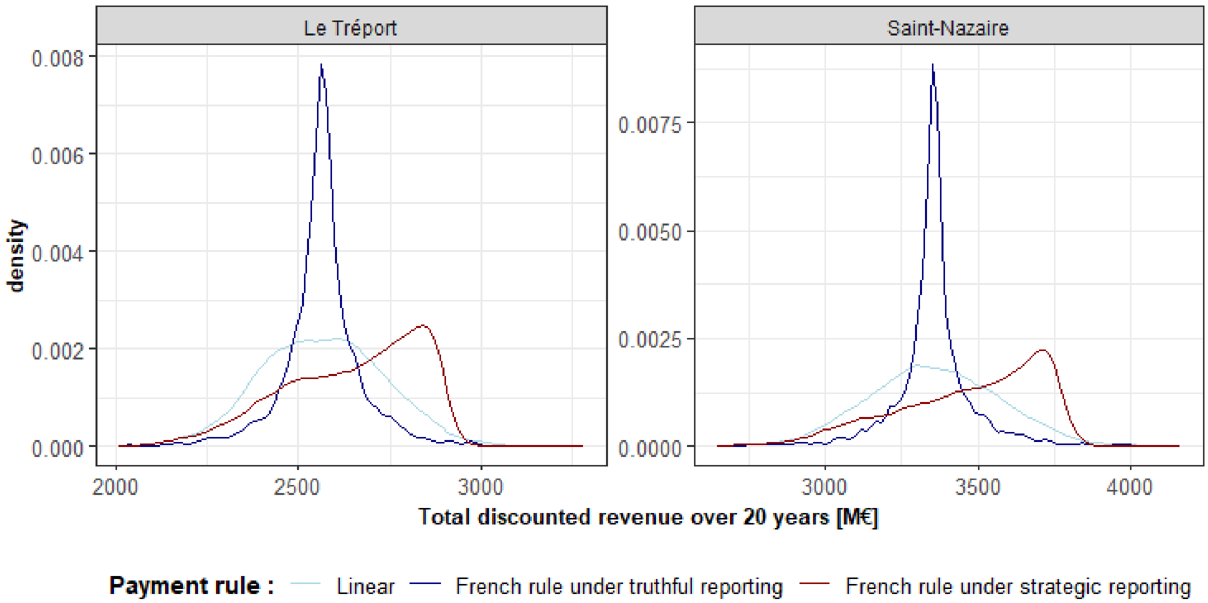


To obtain a first-order approximation of the magnitude of the incentives to misreport expected production and of its consequences on revenues, Appendix 1 provides a methodology to model the yearly production distribution of a wind farm project, and this from an ex ante perspective.

For three different scenarios and for a given price bid (equal to that awarded to the winning bidder in the corresponding project), Figure 2 depicts the PDF of the discounted revenue raised over 20 years for two offshore wind farm projects in Le Tréport and Saint-Nazaire. The scenarios correspond to the linear FiT and the French payment rule, first when all firms are truthful and then when all firms are strategic, i.e. formally when $q_0 = \mathbb{E}[q_t]$ and when $q_0 = q_0^* \in \operatorname{Arg\,max}_{q \in \mathbb{R}_+} \mathbb{E}[R(q_t, q)]$ respectively.[11] When firms report their expected production truthfully, we observe (as expected) that the revenue distribution is less spread out under the French rule than under the linear FiT. However, firms could benefit from a significant upward shift in their revenue distribution by strategically overestimating their expected production: for the five wind farms used in our simulations, we estimate that risk neutral firms' optimal report consists of overestimating their expected production by 11.9 to 12.5% which would increase their expected revenue by 3.2 to 3.6% (for any given price). But by doing so, they also increase the standard deviation of their revenue distribution by 72 to 85% compared to truthful reporting, which ends up being 10 to 13% greater than the standard deviation under the linear FiT. In

[11]Here, in order to simplify, we consider that the optimal reported reference production is that which would maximize the expected revenue, or equivalently the expected payoff of a risk neutral firm. More generally, the optimal (mis)report would depend on firms' risk aversion and also possibly on the price bid p, as explained later.

Figure 2: Firm's revenue distribution depending on the payment rule and the strategy regarding the reference production



overall terms, the French payment rule that was presumably insuring firms against production risk could have exactly the opposite effect.

To pursue the comparison with the linear FiT, we should also take into account the fact that the price bid should not be the same under both contracts. Assuming that the contracts are awarded through competitive auctions and that all bidders are strategic, the benefits from overstating production would be competed away in the auction. Suppose that p is the equilibrium price under the linear FiT once firms are risk neutral. Then let p^S denote the price bid that yields the same expected subsidy under the French rule with strategic reporting (formally, $p^S = p\mathbb{E}[q_t]/\mathbb{E}[R(q_t, q_0^*)]$). After this price rescaling, we find that the variance of $p^S \cdot R(q_t, q_0^*)$ is greater than the variance of $p \cdot q_t$ by 6.6 to 9.3% in the five wind farm projects included in our simulations. In other words, the alleged benefit from the French rule – insurance provision – can be largely offset by strategic reporting and is likely to fail to achieve its original objective of reducing firms' risk premiums. An in-depth analysis of risk premiums and of the expected equilibrium subsidy in this application is developed in Section 6.

3 The model

We develop a theory of auctions for production contracts when the quantity produced ex post is determined by exogenous conditions and when the payment rule has an insurance provision clause. Namely, we consider the following setup:

Production risk: A buyer wishes to contract with a firm to develop a risky project where the quantity produced ex post q is an exogenous random variable.[12] In particular, efforts made by the contractor have no influence on the distribution of q. We assume that the random variable q is distributed on $\mathbb{R}_+$ according to the PDF f with the expected value $\mathbb{E}_f[q] \equiv \bar{q} > 0$. Let F denote the corresponding (atomless) CDF. Throughout our theoretical analysis we often consider distributions that are symmetric and single-peaked and we let $\mathcal{F}_{sp}$ denote the corresponding set of distributions.[13]

The auction rule: The buyer selects the contractor through a first-price auction among $N \geq 2$ firms: each bidder submits a pair $(p, q_0) \in \mathbb{R}_+^2$ where p corresponds to a (per quantity) price bid and q_0 to the so-called *reference production*. The buyer selects the offer involving the lowest price bid p. When necessary for our equilibrium analysis, a tie-breaking rule will be specified. In particular, when two firms submit the same lowest price bid and if when winning one would make zero profit while the other's expected payoff would be strictly positive, then we always assume that the tie is broken in favor of the latter.

As clarified below, the buyer expects contractors to report the expected production $\bar{q}$ for q_0. If a firm reports a reference production $q_0 \neq \bar{q}$, then we will say that the firm misreports its expected production.

The class of contracts: The contract between the buyer and the winning firm specifies a remuneration rule as a function of the latter's bid (p, q_0) and of the actual production q. The remuneration rule takes the multiplicative form $p \cdot R(q, q_0)$ where the function $R : \mathbb{R}_+^2 \mapsto \mathbb{R}_+$ is called the *payment rule*.[14] Among these contracts, we call linear contracts those for which $R(q, q_0) = q$ for any q_0. In addition, we always assume that the payment rule satisfies the following technical restrictions: i) The function $q \mapsto R(q, q_0)$ is continuously non-decreasing[15] with $R(0, q_0) = 0$ for any $q_0 \in \mathbb{R}_+$; ii) The function $q \mapsto R(q, q)$ is strictly increasing with

[12] The variable q could also correspond to a measure for quality, or more generally to any kind of uni-dimensional verifiable measure characterizing the contractor's output.

[13] Formally, this means that $f(\bar{q}+x) = f(\bar{q}-x)$ for any $x \in [0, \bar{q}]$, $f(q) = 0$ for $q > 2\bar{q}$ and that f is non-decreasing on $[0, \bar{q}]$.

[14] Our analysis of firms' incentives to misreport their expected production holds for any given price p and our specific multiplicative form is imposed without loss of generality. On the contrary, it plays a role in Section 5 to derive the quantitative impact of strategic behavior on the buyer's expected cost. See Section 8 for a discussion.

[15] The non-decreasing property guarantees that the contractor does not wish to reduce production ex post. The continuity assumption is not mandatory for most of our results but allows us to avoid technicalities related to intermediate properties holding almost everywhere instead of everywhere.

$\lim_{q \to +\infty} R(q, q) = +\infty$; iii) The function $q_0 \mapsto R(q, q_0)$ is differentiable for any $q \in \mathbb{R}_+$; iv) Without loss of generality, we also make the normalization $R(q_0, q_0) = q_0$.[16]

We further say that a payment rule is ***homogeneous of degree 1*** if $R(\lambda \cdot q, \lambda \cdot q_0) = \lambda \cdot R(q, q_0)$ for any $\lambda, q, q_0 \geq 0$.

Firms' payoff: We assume that firms value their revenue according to an increasing differentiable concave utility function U with $\lim_{x \to +\infty} U(x) = +\infty$. Firms are risk neutral if U is linear and are risk averse (resp. strictly risk averse) if U is concave (resp. strictly concave). For some results, we consider CRRA utility functions, i.e. utility functions U such that $U'(x) = x^{-\gamma}$, where $\gamma \geq 0$ corresponds to the relative risk aversion coefficient. The firm's expected payoff conditional on winning the auction with the bid (p, q_0) is denoted by $\Pi(p, q_0) \equiv \mathbb{E}_f[U(p \cdot R(q, q_0))]$. If a firm loses the auction and thus does not sign any contract, its expected payoff is given by $U(C)$ where C corresponds to the fixed cost that is needed to develop the project. The cost C is sunk after signing the contract such that losing the auction can be viewed as offering the equivalent cash revenue C.[17]

Truthful/Strategic behavior: Each firm is either truthful, meaning it reports $\bar{q}$ for q_0, or strategic, meaning it reports a quantity q_0 belonging to the set $Q_0^*(p) \equiv \operatorname{Arg\,max}_{q_0 \in \mathbb{R}_+} \Pi(p, q_0)$ given its price bid p.[18] In other words, for a given price bid p, strategic firms face the menu of contracts $\{p \cdot R(q, q_0)\}_{q_0 \in \mathbb{R}_+}$ among which they pick the contract they prefer. We let $\Pi^S(p)$ (resp. $\Pi^T(p)$) denote the expected payoff of a strategic (resp. truthful) firm winning the auction at the price bid p, i.e., $\Pi^S(p) = \max_{q_0 \in \mathbb{R}_+} \Pi(p, q_0)$ (resp. $\Pi^T(p) = \Pi(p, \bar{q})$). Then, for a given distribution f, a given utility function U and a given contract price $p > 0$, we say that a payment rule is ***strategy-proof*** (resp. ***manipulable***) if firms do not benefit (resp. do strictly benefit) from misreporting their expected production, i.e., formally, if $\Pi^S(p) = \Pi^T(p)$ (resp. $\Pi^S(p) > \Pi^T(p)$). The linear contract is always strategy-proof since the contractor's payoff does not depend on q_0. If a firm reports $q_0 > \bar{q}$ (resp. $q_0 < \bar{q}$), then we say from now on it overstates (resp. understates) its reference production (compared to its expected production).

In the specific case of CRRA utility functions (which includes the case of risk neutral firms), then the ratio $\Pi^S(p)/\Pi^T(p)$ does not depend on p and we thus obtain that if a payment rule is manipulable (resp. strategy-proof) for a given price bid $p > 0$, then it is manipulable (resp.

[16]Since the function $q \mapsto R(q, q)$ is a bijection on $\mathbb{R}_+$, then we can always renormalize the variable q such that $R(q, q) = q$. Nevertheless, renormalizing the variable q in this way could be at the cost of losing the property $f \in \mathcal{F}_{sp}$. From this perspective, the assumption that $f \in \mathcal{F}_{sp}$ is not innocuous.

[17]An alternative specification would consist of letting the winning bidder's payoff be $\mathbb{E}_f[U(p \cdot R(q, q_0) - C)]$ and the losing bidder's payoff be $U(0)$. Such a specification would be equivalent to ours, thanks to a re-normalization of U that would not modify the concavity property. However, our specification is more convenient when dealing with CRRA utility functions.

[18]We assume implicitly that the payment rule is such that this set is not empty for any price p. This set is guaranteed to be non-empty if we specify the payment rule such that $R(q, q_0) = q$ for $q \geq 2q_0$, an extra assumption that we could add while remaining consistent with our analysis.

strategy-proof) for any price bid in $\mathbb{R}_+$. Thus for a given distribution f and a given CRRA utility function, we say that a payment rule is manipulable/strategy-proof without specifying any price bid.

We are interested in payment rules that provide insurance against production variability compared to the linear contract. From a positive perspective, the latter appears as a natural benchmark since it is both commonly used and strategy-proof. The theoretical status of the linear contract as an optimal contract when firms are risk neutral is discussed later in Section 8.

Definition 1. *A payment rule $R(q, q_0)$ is production-insuring if for any $f \in \mathcal{F}_{sp}$, any risk averse firm and any contract price $p > 0$,*

$$\mathbb{E}_f[U(p \cdot R(q, \bar{q}))] \geq \mathbb{E}_f[U(p \cdot q)] \tag{1}$$

and where the inequality is strict (resp. stands as an equality) if the firm is strictly risk averse (resp. risk neutral).

In words, the production-insuring payment rules correspond to the payment rules that make risk averse truthful firms better off without increasing the expected payment made to the firm and this in a robust way insofar as it should hold for any distribution $f \in \mathcal{F}_{sp}$.

Our model considers that all firms have the same investment cost C, the same utility function U and the same production distribution f. Thus it leaves out the usual adverse selection issues which would generate some trade-off between maximizing allocative efficiency and minimizing firms' informational rents. Moreover it also leaves out moral hazard.[19] We do not attempt to derive an optimal procurement as Laffont and Tirole (1986) and McAfee and McMillan (1987) did in models with risk neutral firms competing for a contract, but rather adopt a "positive" perspective: Our objective is to delineate a pitfall associated with production-insuring payment rules, motivated by the fact it has been used and it is quite tempting to use when the environment involves exogenous production risk. It can indeed be viewed as the natural class of rules that a naive buyer might adopt, assuming bidders would report their true reference production (as one could naively expect). Under such an assumption, the risk premium or equivalently the buyer's expected cost would indeed be reduced compared to the linear contract (as detailed in Section 5).

To evaluate the performance of a payment rule, the criterion we consider is to maximize the expected payoff of a risk neutral buyer. In our setup where all firms have the same production distribution, this criterion reduces to the buyer's expected cost (henceforth the BEC), i.e., $p \cdot \mathbb{E}_f[R(q, q_0)]$ where (p, q_0) corresponds to the winning bid), which depends on the payment rule $R(.,.)$ but also on whether firms are truthful or strategic.

[19] Both asymmetry between firms and moral hazard are briefly discussed in Section 8.

4 Strategic misreporting in production-insuring payment rules

We analyze firms' incentives to misreport their expected production when the payment rule is production-insuring. Intuitively, the magnitude of misreporting can be viewed as a proxy of the flaws resulting from the presence of strategic bidders as will be developed in our equilibrium analysis in Section 5.

Let us first characterize the payment rules that are production-insuring. For any payment rule and any pair $q, q_0 > 0$, we can express the term $R(q, q_0)$ as $q \cdot z_{q_0}(\frac{q}{q_0})$ where the function $z_{q_0} : \mathbb{R}_+ \to \mathbb{R}_+$ can be viewed as a correction factor with $z_{q_0}(1) = 1$. Definition 1 implies that $\mathbb{E}_f[z_{q_0}(\frac{q}{\bar{q}})] = 1$ for any $f \in \mathcal{F}_{sp}$. Lemma 1 (whose tedious proof is relegated to the SA) establishes in addition that a production-insuring payment rule would never deflate (resp. inflate) payments compared to the linear contract for production occurrences that are lower (resp. higher) than the reference production q_0: the correction factor is greater (resp. less) than one when production is lower (resp. higher) than q_0. Furthermore, the fact that these correction factors should compensate in expectation for any symmetric risk imposes a one-to-one relationship between $z_{q_0}(1+\epsilon)$ and $z_{q_0}(1-\epsilon)$.

Lemma 1. *A payment rule is production-insuring if and only if we have for any $q_0 > 0$ and $\epsilon \in]0,1]$, $z_{q_0}(1+\epsilon) \leq 1$, $z_{q_0}(1-\epsilon) \geq 1$, $(1+\epsilon) \cdot z_{q_0}(1+\epsilon) + (1-\epsilon) \cdot z_{q_0}(1-\epsilon) = 2$ and $\int_0^{\epsilon} z_{q_0}(1+t)dt < \epsilon$.*

We then obtain the fact that the payment rule used by the French government is production-insuring (see in particular Footnote 9). As a corollary of Lemma 1, we also obtain that if there is no risk relating to production, then overestimating (resp. underestimating) future production can never be detrimental (resp. beneficial) to the contractor under a production-insuring payment rule. Furthermore, the contractor would also strictly gain from slightly overestimating production since the correction factor $z_{q_0}(.)$ is strictly greater than 1 for some values in the left neighborhood of 1. Next we generalize this insight for any $f \in \mathcal{F}_{sp}$ and when the contractor is risk neutral.

Proposition 2. *For any $f \in \mathcal{F}_{sp}$, any production-insuring payment rule is manipulable if the contractor is risk neutral. Furthermore, the contractor weakly increases (resp. decreases) its expected payo by overestimating (underestimating) its expected production.*

Proposition 2 formalizes a fundamental conflict between insurance provision and strategy-proofness. We stress that the incentive to overestimate the expected production holds for any distribution in $\mathcal{F}_{sp}$. Nevertheless, this result holds only when the contractor is risk neutral. Risk aversion modifies the (mis)reporting incentives: in particular, underestimating production could be a way to hedge against the worst production outcomes. To get more intuition about this novel channel, think of the French payment rule where $R(q, q_0) = q$ if $q \leq 0.85 \cdot q_0$. If production of below $0.85 \cdot q_0$ may occur with positive probability, then, under truthful reporting, the worst production outcomes would not benefit from a correction factor greater than one. On the contrary, underestimating the reference production could be a way to increase the contractor's revenue for those worst outcomes. From an empirical perspective, this channel does not play a significant role under the French rule in our simulations. Nevertheless it prevents us from deriving the analog of Proposition 2 under risk aversion.

To obtain further insights into the way risk averse contractors wish to misreport their expected production, and in particular about the factors that drive the magnitude of overestimation, we impose more structure on our model. We consider a specific class of payment rules where the remuneration to the contractor is totally flat within a range around the reference production q_0, and matches the linear contract outside this range. We assume that the insurance range is large enough to fully insure the contractor under truthful reporting and that the PDF f is continuous on $\mathbb{R}_+$ and such that $x \mapsto \frac{1-F(x)}{f(x)}$ is decreasing on the interior of its support. Under such assumptions, we obtain the following results (whose tedious proofs are relegated to the SA): any optimal report of a risk averse (strategic) contractor is above the true expected production and below the optimal report of a risk neutral contractor (the latter does not depend on the contract price p and is then denoted q_0^{RN}). Formally, for any $q_0^* \in Q_0^*(p)$, we have $\bar{q} \leq q_0^* \leq q_0^{RN}$.

With the additional restriction that U is a CRRA utility function, we obtain that the set of optimal reports $Q_0^*(p)$ is a singleton which does not depend on p and derive the following comparative statics on the corresponding optimal report $q_0^* > \bar{q}$:

1. The lower is the coefficient of relative risk aversion γ, the higher is q_0^*.

2. Considering two production distributions F_1 and F_2, where F_1 is less risky than F_2 in the sense that $\frac{f_1(q)}{(1-F_1(q))} \leq \frac{f_2(q)}{(1-F_2(q))}$ for any $q \leq \bar{q}$, then the optimal report q_0^* is higher when the contractor faces the least risky distribution F_1 than when they face the most risky distribution F_2.

3. If the insurance range is larger for payment rule R_1 than for R_2 (which implies that $R_1(q, q_0) \geq R_2(q, q_0)$ if $q \leq q_0$), then a strategic contractor with $\gamma \geq 1$ reports a higher reference production q_0^* when facing R_1 than when facing R_2.

5 Auction prices and the buyer's expected cost

Through our equilibrium analysis, we characterize the bid pairs (p, q_0) submitted by firms and the resulting BEC depending on whether firms are truthful or strategic, and the number in each category. We assume throughout Sections 5 to 7 that the cost C, risk distribution F and utility function U are the same for all firms and are common knowledge. We first consider a complete information setup where strategic firms know whether their opponents are truthful or strategic. We first consider the case when all firms are truthful, then the case when several firms are strategic, and last when a single firm is strategic. Finally, we turn to an incomplete information setup where each firm is strategic (independently of the others) with a given probability α which is assumed to be common knowledge.

Firms' beliefs regarding whether their opponents are truthful or strategic do matter for strategic firms (and the specifications below are consistent with rational expectations), but they do not matter for truthful firms: in equilibrium, truthful firms bid the price that leads to zero surplus and this independently of their beliefs regarding their opponents.[20] Therefore, our analysis fits both the case where truthful firms are unaware of the possibility of misreporting their expected production (in which case it would be natural to assume that they believe that their opponents are also truthful) and the case where truthful firms are not able to misreport their expected production but are fully aware that some of their opponents could do so.

We stress that the results derived hereafter (unless specified otherwise) are not limited to production-insuring payment rules but hold for any payment rule R that fails to be strategy-proof.

Complete information

If all firms are truthful or if at least two firms are strategic, then the winning firm had to compete in the auction with at least one fully identical firm. In such cases, Bertrand competition leads to zero surplus for the firms and the equilibrium price is characterized by their indifference to winning or losing the auction (see formal details in the SA). Nevertheless, the BEC depends on the payment rule and the presence of strategic bidders, as both result in different levels of insurance provision, and therefore different risk premiums.

Case 1: all firms are truthful

If all firms are truthful, the equilibrium price, denoted p^T, is the unique solution of:

$$\Pi^T(p^T) \equiv \Pi(p^T, \bar{q}) = U(C) \tag{2}$$

and the BEC is equal to $p^T \cdot \mathbb{E}_f[R(q, \bar{q})]$, which reduces to $p^T \cdot \bar{q}$ if R is production-insuring and if $f \in \mathcal{F}_{sp}$. Let p^L denote the equilibrium price for the linear contract, then the corresponding BEC is equal to $p^L \cdot \bar{q}$ if $f \in \mathcal{F}_{sp}$.

[20]We ignore equilibria based on weakly dominated strategies where truthful firms submit a bid that would generate a negative surplus when winning because they expect to be outbid for sure by a strategic firm. Standard refinements (like trembling-hand perfect equilibrium, see Fudenberg and Tirole (1991)) allow those non-relevant equilibria to be eliminated.

When firms are risk neutral, we obtain from (2) that the BEC is equal to the contractor's cost C for any payment rule. On the contrary, the BEC depends on the payment rule under risk aversion.

Proposition 3. *Suppose all firms are truthful and $f \in \mathcal{F}_{sp}$. The equilibrium price and the buyer's expected cost are smaller under a production-insuring payment rule than under the linear contract. They are strictly smaller if firms are strictly risk averse, and equal if firms are risk neutral.*

Since U is concave, we obtain from (2) and Jensen's inequality that $p^T \cdot \mathbb{E}_f[R(q, \bar{q}))] \geq C$ for any payment rule R, or equivalently that: the BEC is necessarily greater than the firm's cost. If the payment rule fully insures the contractor so that the transfer is unchanged for any production outcome in the support of f, then the equilibrium price and the BEC are the same as in the risk neutral case: $p^T = \frac{C}{\bar{q}}$, and the cost for the buyer is C. On the contrary, if firms are strictly risk averse and the payment rule does not fully insure, a strict difference emerges between the BEC and C which corresponds to a risk premium. This is true in particular for the linear contract, for which we have $p^L \cdot \bar{q} > C$.[21] As formalized in Proposition 3, production-insuring payment rules reduce this risk premium compared to the linear contract.

Case 2: several firms are strategic

Consider now the case where at least two firms are strategic. The strategic firms' equilibrium price bid, denoted by p^S, is the unique solution of:

$$\Pi^S(p^S) \equiv \max_{q_0 \in \mathbb{R}_+} \Pi(p^S, q_0) = U(C) \tag{3}$$

while truthful firms (if any) submit price bids that are greater than p^S and thus irrelevant for the equilibrium outcome.[22] Strategic firms report a reference production $q^S \in Q_0^*(p^S) \equiv \operatorname{Arg\,max}_{q_0 \in \mathbb{R}_+} \mathbb{E}_f[U(p^S \cdot R(q, q_0))]$. If the latter set is not a singleton, multiple equilibria exist and they are equivalent in terms of firms' payoff but possibly produce different BEC, depending on the reference production (within $Q_0^*(p^S)$) submitted by the winning firm.

When firms are risk neutral, we obtain from (3) that the BEC is equal to C for any payment rule due to the absence of both risk premiums and positive surplus (the latter being competed away in the presence of several strategic firms). However, in such a case, the equilibrium price differs from that when all firms are truthful: we have $p^S = \frac{C}{\max_{q_0 \in \mathbb{R}_+} \mathbb{E}_f[R(q, q_0)]} \leq p^T$ (with a strict inequality if the payment rule is manipulable at price p^T). Proposition 4 generalizes this inequality to environments with risk averse firms.

[21] Here we use the strict version of the Jensen inequality which guarantees that $U(p^L \cdot \bar{q}) > \mathbb{E}_f[U(p^L \cdot q)]$ for any strictly concave function U, while from (2) the latter term is equal to $U(C)$.

[22] In equilibrium, a truthful firm would necessarily make a negative surplus by outbidding a strategic firm whose bid satisfies the zero surplus condition: formally, this comes from $\Pi^T(p) < \Pi^S(p^S) = U(C)$ for any $p < p^S$.

Proposition 4. *Suppose several firms are strategic. The equilibrium price is lower than the equilibrium price when all firms are truthful (p^T), and the inequality is strict for payment rules that are manipulable at price p^T. If the payment rule provides full insurance against production risk to a truthful firm, is homogeneous of degree 1 and if firms are strictly risk averse, then the buyer's expected cost is strictly greater with several strategic firms than with only truthful firms.*

The second part of Proposition 4 points out a particular case where the BEC is greater than in the environment where all firms are truthful because the ex post revenue becomes risky and then risk premiums (absent under truthful bidding) emerge. This illustrates the fact that when the winning firm is strategic, a lower equilibrium price does not necessarily imply a lower cost for the buyer: the BEC is equal to the product of the equilibrium price with the term $\mathbb{E}_f[R(q, q^S)]$. There are thus two effects at work with respect to the BEC when we move from case 1 to case 2, i.e., from competition between truthful firms to competition between strategic firms: on the one hand the equilibrium price decreases as firms' benefits from misreporting are competed away; on the other hand, the term $\mathbb{E}_f[R(q, q_0)]$ varies due to misreporting. Furthermore, given our equilibrium analysis in Section 4, we expect that $\mathbb{E}_f[R(q, q^S)] > \mathbb{E}_f[R(q, \bar{q})]$ and thus that these two effects will be conflicting[23]: formally, for any $f \in \mathcal{F}_{sp}$ and risk neutral firms, it will be the case for any production-insuring payment rule such that in equilibrium strategic firms overestimate their expected production, insofar as Proposition 2 shows that $\mathbb{E}_f[R(q, q_0)] \geq \mathbb{E}_f[R(q, \bar{q})] = \bar{q}$ for any $q_0 \geq \bar{q}$. Moreover, the further insights presented at the end of Section 4 reinforce our conjecture in favor of overestimation even in the risk averse case. On the whole, the zero surplus condition imposes that these two effects perfectly cancel each other out regarding the contractor's expected payoff, but they are not necessarily neutral regarding the BEC. We conjecture that strategic behavior will typically expose firms to higher risk and thus increase risk premiums, as will be confirmed by our simulations. Nevertheless, Example 1 in the SA exhibits a production-insuring payment rule where the equilibrium BEC with several strategic firms may be lower than when all firms are truthful.[24]

In a nutshell, when all firms are truthful any production-insuring payment rule outperforms the linear contract (Proposition 3). The presence of several strategic bidders lowers the equilibrium price even more, but through a deceptive effect which does not necessarily imply a lower BEC than under a linear contract. The last case considered below departs from perfect Bertrand competition

[23]On the contrary, under the less plausible hypothesis that $\mathbb{E}_f[R(q, q^S)] < \mathbb{E}_f[R(q, \bar{q})]$, then the BEC is unambiguously lower in case 2 than in case 1: under such circumstances, switching from case 1 to case 2 would be Pareto improving. When R is production-insuring and $f \in \mathcal{F}_{sp}$, note from Proposition 2 that $\mathbb{E}_f[R(q, q^S)] < \mathbb{E}_f[R(q, \bar{q})]$ holds only if $q^S < \bar{q}$, and the latter inequality is never satisfied if firms are risk neutral.

[24]In this example, the insurance provided by the payment rule is almost vanishing under truthful reporting while the payment rule is flat further away from the expected production $\bar{q}$ and provides insurance when firms are optimally misreporting their expected production.

and the single strategic firm benefits from a positive surplus. This novel channel acts in favor of strategy-proof payment rules.

Case 3: a single firm is strategic

In this third case under complete information, we consider that there is a single strategic firm. The equilibrium then takes the following form:[25] truthful firms bid $(p^T, \bar{q})$ exactly as in the equilibrium where all firms are truthful, while the strategic firm (knowing ties are broken in its favor) bids (p^T, q^{S-T}) where $q^{S-T} \in Q_0^*(p^T)$. The latter firm wins the auction and the BEC is then equal to $p^T \cdot \mathbb{E}_f[R(q, q^{S-T})]$. The difference $\Pi^S(p^T) - \Pi^T(p^T) \geq 0$ represents the surplus reaped by the strategic firm from misreporting its expected production. This surplus is strictly positive if the payment rule is manipulable at price p^T.

Proposition 5. *Suppose only one firm is strategic. The equilibrium price is the same as the equilibrium price when all firms are truthful (p^T). If firms are risk neutral, then the buyer's expected cost is equal to the sum of C and the non-competitive rent $p^T \cdot (\mathbb{E}_f[R(q, q^{S-T})] - \mathbb{E}_f[R(q, \bar{q})])$, the latter being null under the linear contract and strictly positive under a payment rule that is manipulable.*

If U is a CRRA utility function and if the payment rule is manipulable, then the buyer's expected cost is strictly higher than when several firms are strategic.

When comparing the BEC in case 3 and case 2, both the effect on the equilibrium price and the variation of $\mathbb{E}_f[R(q, q_0)]$ could be at work. However, when $q^S = q^{S-T} \neq \bar{q}$ which happens to be the case when the utility function is CRRA and R is manipulable, then only the price effect matters. Then, since $p^S < p^T$, the BEC is strictly greater when a single firm is strategic than when several firms are strategic.

When comparing case 3 with case 1, only the second effect matters. In addition, given Proposition 2 and as argued in case 2, we again expect that $\mathbb{E}_f[R(q, q^{S-T})] \geq \mathbb{E}_f[R(q, \bar{q})]$: formally, if R is production-insuring and $f \in \mathcal{F}_{sp}$, then the BEC increases when switching from the case where all firms are truthful to the case where a single firm is strategic provided that $q^{S-T} \geq \bar{q}$. Yet this overestimation hypothesis is supported by our analysis in Section 4. Thus the BEC presumably increases by a larger magnitude when only one firm (instead of several firms) become strategic.

In both case 2 and case 3 (but also in our incomplete information paradigm below), the equilibrium price is (weakly) lower than p^T. We then obtain the fact that the percentage increase of the BEC compared to case 1 is bounded above by $[\sup_{q,q_0}\{z_{q_0}(q/q_0)\} - 1]$. In the French rule, the latter bound is equal to 1/9 meaning that the BEC increase due to misreporting cannot exceed 12%.

[25] In order to avoid the well-known problem of the non-existence of an equilibrium in some discontinuous strategic games (Simon and Zame, 1990), we assume in this case that ties are broken in favor of the strategic firm.

Regarding the comparison between a production-insuring payment rule and the linear contract (for any $f \in \mathcal{F}_{sp}$), the ranking is ambiguous in general when there is a single strategic firm. However, if firms are risk neutral then the linear contract strictly outperforms any production-insuring rule when a single firm is strategic. We next consider an incomplete information setup where firms ignore whether their competitors are truthful or strategic.

Incomplete information

Consider now $N \geq 2$ firms each being strategic (resp. truthful) with probability α (resp. $1-\alpha$) independently of the other firms. Each firm knows its own status and the parameter $\alpha \in]0,1[$ but ignores other firms' status.

Proposition 6. ***Equilibrium under incomplete information***

Suppose each firm is strategic (resp. truthful) with probability α (resp. $1-\alpha$) independently of each other, where $\alpha \in]0,1[$ is common knowledge. If the payment rule is manipulable at p^T, then in equilibrium, all firms adopt the following strategy:

- *If the firm is truthful, it bids $(p^T, \bar{q})$.*
- *If the firm is strategic, it adopts a mixed strategy, consisting of bidding (p, q_0) with $q_0 \in Q_0^*(p)$ and the price bid p being distributed according to the CDF $G(p) = \max\{1 - \frac{1-\alpha}{\alpha}\left(\sqrt[N-1]{\frac{\Pi^S(p^T)-U(C)}{\Pi^S(p)-U(C)}} - 1\right), 0\}$. The upper (resp. lower) bound of the distribution G is equal to p^T (strictly greater than p^S).*

If for any price bid p in the support of G the set $Q_0^*(p)$ is a singleton, then the equilibrium is unique. On the contrary, if there are multiple optimal misreports, then any selection forms an equilibrium and the BEC would depend on the selection denoted next by $q_0^*(p)$ for any given price in the support of G.

In equilibrium, the expected surplus of a truthful (resp. strategic) firm is null (resp. is equal to $(1-\alpha)^{N-1}[\Pi^S(p^T) - \Pi^T(p^T)] > 0$). Intuitively, such positive surplus should translate into higher costs for the buyer. Note that in this incomplete information setup, the BEC is an expectation not only over the production distribution F but also over the probability for each firm to be strategic and over strategic firms' mixed strategy G. Thus the BEC differs from that under complete information through two effects: first, the probability of being in each state (none, several or a single strategic firm), second the bids submitted by each strategic firm which, independently of the realized state, do take into account the probability of facing competition from another strategic firm. To obtain further insights, we consider in the next proposition that firms are either risk neutral or risk averse with a CRRA utility function. In such cases, the set $Q_0^*(p)$ does not depend on p and is denoted Q_0^*.

Proposition 7. *Suppose that U is a CRRA utility function and consider a payment rule R that is manipulable. Under incomplete information, for all $\alpha \in]0,1[$:*

- *If $\mathbb{E}_f[R(q,q_0^*)] \geq \mathbb{E}_f[R(q,\bar{q})]$ for any $q_0^* \in Q_0^*$, then the buyer's expected cost is strictly lower than the highest buyer's expected cost when there is a single strategic firm under complete information, and it is strictly higher than the lowest buyer's expected cost under complete information.*[26]

- *If firms are risk neutral, then the buyer's expected cost is equal to the sum of C and the non-competitive rent*

$$N \cdot \alpha(1-\alpha)^{N-1} \cdot p^T \left(\mathbb{E}_f[R(q,q^{S-T})] - \mathbb{E}_f[R(q,\bar{q})] \right) > 0. \tag{4}$$

When firms are risk neutral, the expected non-competitive rents in (4) vanish in the two polar limit cases where α is equal to 0 or 1, which are actually covered by Propositions 3 and 4. Moreover for any intermediary value of α, the uncertainty about each firm being strategic or not moderates the expected extra cost for the buyer compared to the case of complete information with a single strategic firm case, where the extra cost is equal to $p^T(\mathbb{E}_f[R(q,q^{S-T}] - \mathbb{E}_f[R(q,\bar{q}])$. The maximum expected extra cost (over α) is reached for $\alpha = \frac{1}{N}$, that is when the probability of having exactly one strategic firm is the highest. We thus obtain that the increase in the BEC cannot be higher than half of the extra cost when there is a single strategic firm under complete information (this bound is reached for $N = 2$).[27]

When firms are risk averse, additional assumptions are needed to draw conclusions about the BEC. The condition $\mathbb{E}_f[R(q,q_0^*)] \geq \mathbb{E}_f[R(q,\bar{q})]$ for any $q_0^* \in Q_0^*$ is a very mild condition stating that the equilibrium with truthful firms outperforms any equilibrium with a single strategic firm under complete information. Such conditions, which were previously discussed for production-insuring payment rules, guarantees that the BEC under incomplete information lies somewhere in between the worst case and the best case under complete information.

We conclude that the rents captured by the firms are smaller with such "miscoordinated heterogeneity", but could still have a sizable effect of the same order of magnitude. In our simulations we consider the complete information case with a single strategic firm to evaluate a worst case scenario, while bearing in mind that the increase in the BEC would be mitigated under incomplete information.

[26] Formally, the highest BEC when there is a single strategic firm is equal to $p^T \cdot \max_{q_0 \in Q_0^*} \mathbb{E}_f[R(q,q_0^*)]$. The lowest BEC under complete information can be reached either with zero or several strategic firms.

[27] Conversely, in this worst case, the increase in the BEC cannot go lower than 36% of the extra cost when there is a single strategic firm (since $(1-1/N)^{N-1} > \exp(-1) > 0.36$, which results from a standard logarithm inequality).

Comments: Our equilibrium analysis is analogous to the analysis of first price auctions with two (possibly risk averse) symmetric bidders having binary valuations developed by Maskin and Riley (1985): being strategic (resp. truthful) in our procurement setup corresponds to having a high (resp. low) valuation in Maskin and Riley's (1985) auction setup.[28] There are nevertheless two differences: First we consider any number of bidders. Second, the ex post revenue of a strategic bidder, which is equal to $p \cdot R(q, q_0^*(p))$, where $q_0^*(p) \in Q_0^*(p)$, may no longer be linear in the price bid p insofar as the optimal report $q_0^*(p)$ could now depend on p. The latter difference matters when it comes to the analysis of other auction formats and to establishing a revenue ranking. If the set $Q_0^*(p)$ does not depend on the price bid p (let us use the shortcut notation Q_0^*), then the equilibrium analysis is straightforward in the second price auction (or equivalently the English auction): truthful (resp. strategic) firms bid $(p^T, \bar{q})$ (resp. (p^S, q_0) with $q_0 \in Q_0^*$). Then exactly as in Maskin and Riley (1985) when valuations are drawn independently, we can check the revenue equivalence between first-price and second-price auctions if firms are risk neutral, and that the first-price auction outperforms the second-price auction if firms are risk averse.[29] Note that the equivalence between first- and second-price auctions holds only under the complete information paradigm.

6 Performance analysis of the French rule

The French government used a production-insuring payment rule in the auctions for six offshore wind farm sites. These contracts were awarded separately through first-price sealed bid auctions: The firm asking for the lowest subsidy per MWh was declared the winning bidder.[30] It was then subsidized according to both this price and its reference production, the latter being the yearly production derived from the firm's self-reported average capacity factor.[31] From a practical perspective, unrealistic capacity factors would lead to disqualification. Nevertheless, France did not adopt explicit ranges for eligible capacity factors as other countries do. Our analysis leaves out the disqualification risk associated with misreporting. Such disqualification risk does not seem particularly relevant in our case since the optimal overestimation never exceeds 13%, which is of

[28] Doni and Menicucci (2012) extend the analysis to two asymmetric bidders when bidders are assumed to be risk neutral.

[29] On the contrary, if $Q_0^*(p)$ does depend on the price bid p, then the analysis under incomplete information is less straightforward: in particular, neither the bid pair (p^S, q^S) nor the pair (p^S, q^{S-T}) is a weakly dominant strategy for a strategic firm. The optimal reference production of a given strategic firm depends on its expectation on the price bid fixed by the auction rule in the case where it wins.

[30] These auctions were actually *scoring* auctions: in addition to the per-unit subsidy bid p, other criteria such as local environmental impact or carbon footprint were taken into account to determine the winning bid. We leave out such "multidimensional bidding" aspects given that they do not interfere with the production-insuring payment rule.

[31] The capacity factor is the power output divided by the maximum power capacity of the installation (the latter being a technical feature that is verifiable).

the same order of magnitude as the prediction bias observed in practice for wind farms (Lee and Fields, 2020).

A first slight difference with our theoretical framework is that we now explicitly consider multi-year contracts: the length is 20 years, during which the production-insuring payment rule $R(.,.)$ defined in Section 2 applies separately to each year, based on the expected yearly production q_0 reported freely by firms in their bid. A second difference is that we consider both a (fixed) investment cost IC occurring before production (which corresponds to C in our model), and (fixed) operating costs OC occurring each year. The values we use for our analysis are reported in Appendix 1. For a given bid (p, q_0), firms' expected payoff difference between winning and losing the auction can then be expressed as:

$$\mathbb{E}\left[U(\sum_{t=1}^{20}\frac{[p\cdot R(q_t,q_0)-OC]}{(1+r)^t})\right]-U(IC), \tag{5}$$

where the expectation is made w.r.t. the vector of yearly production $(q_1, \ldots, q_{20})$ and where r denotes firms' annual discount rate which is set equal to 5.7%.[32] Let $FC = IC + \sum_{t=1}^{20}\frac{OC}{(1+r)^t}$ denote firms' net present cost. Firms' risk aversion is captured through CRRA utility functions where we take γ between 0 and 15. For a given price bid p, a strategic firm reports an expected production $q_0^*(p)$ that maximizes the expression in (5). As a robustness check, we have also considered, in more general terms, the utility function $U(x) = \frac{(x-IC+w)^{1-\gamma}}{1-\gamma}$ where w should be interpreted as the firm's initial wealth. The results reported below correspond thus to $w = IC$. In the SA, we report results when the initial wealth is equal to the total net present cost of the firm, i.e., when $w = FC$.

When the payment rule is homogeneous of degree 1, as are the French rule and also the payment rules considered in Section 7, CRRA utility functions generate useful properties that are detailed in the SA. We show in particular that the equilibrium BEC (under our various bidding paradigms) is strictly proportional to firms' net present cost and does not change if we multiply actual production by a constant. These fundamental properties are established in Lemma 9 in the SA. In this section, it implies that the ratio between the equilibrium expected subsidy paid by the buyer and firms' net present cost FC remains unchanged if we multiply the investment and operation costs by the same constant.[33]

[32] Our choice is based on an estimation of the cost of capital for onshore wind projects in France made by Angelopoulos et al. (2016) which accounts for taxation and for compensation for other kinds of risks. Note that our analysis leaves out many kinds of risks, including cost overruns or delays that are not entirely under the control of the firms (e.g. connection to the grid). Those risks could generate much larger risk premiums but they are orthogonal to the design of the payment rule.

[33] These ratios would change if we modified the investment cost while fixing the operating costs, or analogously if we changed firms' interest rates. However, in the same way as having an initial wealth different to IC has little impact on our results, it would not change our insights.

As detailed in Appendix 1, we calibrate the distribution of the vector of yearly production $(q_1, \cdots, q_{20})$ based on historic production simulated by models developed by Staffell and Pfenninger (2016) and whose outputs are easily accessible through the site `www.renewables.ninja`. The calibration procedure considers a wide range of possible yearly production based on recombination of quarterly production values randomly drawn from historical data. On top of this meteorological risk, we also consider that the capacity factor of each site's wind resource suffers from a ***misevaluation risk*** through a multiplicative normally-distributed shock (with a standard deviation taken as $\sigma = 6.3\%$).

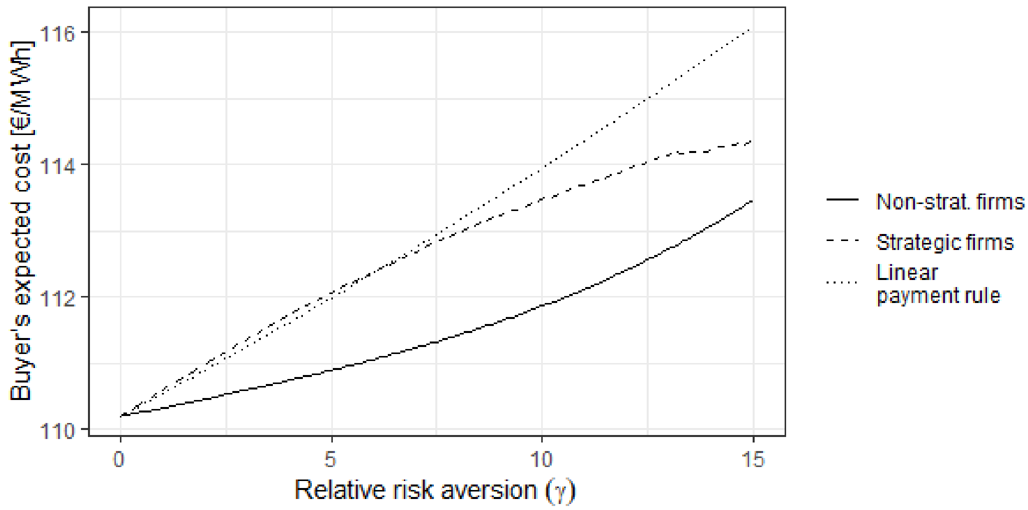
We evaluate performance in comparison to the linear contract. Let $BEC(p, q_0) := p \cdot \sum_{t=1}^{20} \frac{\mathbb{E}[R(q_t,q_0)]}{(1+r)^t}$ denote the buyer's expected cost as a function of the winning firm's bid (p, q_0). We compute equilibrium bids under the three complete information cases analyzed in Section 5: when all firms are truthful, when several firms are strategic, and last when a single firm is strategic. Note first that for each bidding paradigm, firms submit only bids (p, q_0) that lead to positive surplus, i.e., such that the expression in (5) is positive. This implies (by applying Jensen's inequality) that $BEC(p, q_0) \geq FC$. As shown in Section 5, if firms are risk neutral this inequality stands as an equality, except when there is a single strategic firm. Higher values for the equilibrium BEC are driven either by a risk premium (resulting from firms' risk aversion) or by a positive noncompetitive rent captured by a (single) strategic winning bidder. Since the linear FiT is strategy-proof, Bertrand competition prevails and firms make zero surplus.

Hereafter, all ranges presented correspond to the smallest and the largest result obtained among the five sites retained.[34] First, the risk premiums under a linear contract are notably small: for $\gamma = 1$ they are comprised between $0.29 - 0.36\%$, and fluctuate in the range $0.89 - 1.1\%$ for $\gamma = 3$. When all firms are truthful, the risk premium is reduced by a bit more than half under the French rule. However, these (limited) gains are entirely lost when all firms are strategic and this for any reasonable level of risk aversion, as depicted in Figure 3 which depicts the BEC divided by the expected quantity produced: only for unrealistic degrees of risk aversion ($\gamma > 6$) do we find that the French payment rule outperforms the linear contract under strategic reporting.

As shown in section 5, heterogeneity among firms regarding misreporting produces noncompetitive rents that inflate the BEC. Our simulations support the idea that such rents are of a larger order of magnitude than the risk premium reduction that the buyer could save in the most favorable case where all firms are truthful: with a single strategic firm, we find a BEC $3.3 - 3.6\%$ greater than under the linear FiT when firms are risk neutral, and $2.6 - 2.9\%$ greater when firm's risk aversion is up to $\gamma = 3$. Note that those figures are much lower than $\frac{1}{9} \approx 11.11\%$ the theoretical upper bound mentioned in Section 5. Nevertheless, for any intermediate risk aversion level,

[34] Detailed results are given in the SA. We have removed one site from our analysis because the recombination procedure is inadequate for this specific site.

Figure 3: Buyer's expected cost per quantity produced with homogeneous firms as a function of γ the relative risk aversion coefficient (Courseulles site)



the increase in BEC when a single firm is strategic is always more than four times greater than the cost reduction thanks to insurance provision when all firms are truthful. For $\gamma = 1$, this increase is more than 15 times greater than the potential cost reduction in the most favorable case where all firms are truthful.

On the whole, we conclude that the premiums associated with production risk were quite negligible which limits the benefits that the French payment rule could have brought thanks to insurance provision. Furthermore, those potential benefits relied crucially on the hypothetical assumption that all firms report their expected production truthfully, an assumption which conflicts with their incentives. Finally, the French rule opens the door to two kinds of pitfall: 1) Strategic firms increase the variability of their revenue by overestimating their production which nips in the bud the presumed benefits from a production-insuring rule if all firms are strategic; 2) Heterogeneity among firms regarding truthful/strategic behavior could produce noncompetitive rents. If all firms are strategic, we see from Figure 3 that the French rule and the linear FiT perform almost equally well for any realistic level of risk aversion. On the contrary, the second pitfall could increase the BEC by about 3%.

Last, we stress that our specification with a misevaluation risk (which tends to shrink over time thanks to improvements in capacity factor predictions, see Lee and Fields' (2020)) exacerbates the potential benefits from insurance provision but also reduces the incentives from overestimating production (as formalized at the end of Section 4) and thus the associated surplus captured by strategic firms. Keeping this in mind reinforces the conclusion above.

7 Beyond production-insuring payment rules

Our analysis so far provides strong arguments against the use of production-insuring payment rules: they are (typically) manipulable which then leads to non-competitive rents in the auction once firms are heterogeneous regarding their ability to misreport the reference production. However, our analysis does not claim that we should stick to the linear payment rule. We now adopt the perspective of a sophisticated buyer who anticipates that firms may strategically report the reference production q_0. We explore whether there are any payment rules $R(q, q_0)$, not necessarily production-insuring in the sense of Definition 1, that could bring a lower BEC in a manner that is robust to strategic behavior, i.e. for any of our bidding paradigms.

With this in mind, we first formalize the fact that no payment rule $R(q, q_0)$ that is homogeneous of degree 1 can fully eliminate risk premiums for strategic firms. The restriction to payment rules that are homogeneous of degree 1 excludes payment rules tailored to a specific distribution f, which would be inappropriate in the presence of asymmetric information regarding f.[35] In other words, we formalize the fact that it is impossible to fully insure strategic firms against production risk if the contract designer does not know the production distribution up to a homothetic transformation.

Proposition 8. *Consider a payment rule that is homogeneous of degree 1 and a contract price $p > 0$. If the contractor optimally (mis)reports its reference production, then it is not fully insured against production risk. Formally, $q_0 \in Q_0^*(p)$ necessarily implies that the variance of $p \cdot R(q, q_0)$ is strictly positive, which means that the contractor's revenue is risky.*

This results from the fact that if reporting q_0 ensures that the contractor is fully insured, the latter would strictly benefit from reporting a reference production slightly higher than q_0: the potential loss from moving some of the lowest production outcomes (provided this mass is small enough) outside the range where it is perfectly insured would be overcompensated by the benefits from raising the correction factor for production outcomes remaining in this range.

Even though there is no hope of fully insuring strategic contractors we attempt to find a better performing class of contracts, possibly by discouraging misreporting through "punishments" (defined hereafter). Inspired by rules adopted in some countries for RES-E auctions,[36] we consider the following class of homogeneous of degree 1 payment rules $R_{(w,\eta)}$ parameterized by the pair of coefficients $(w, \eta) \in [0, 1]^2$ and defined in the following way:

[35] Without the homogeneous of degree 1 restriction, an obvious strategy-proof payment rule for any $f \in \mathcal{F}_{sp}$ such that 0 does not belong to its support is that where $R(q, q_0) = \bar{q}$ if $q_0 = \bar{q}$ and $R(q, q_0) = q$ otherwise. To implement such a payment rule, the contract designer needs to know $\bar{q}$ exactly.

[36] In Brazil, e.g., features comparable to the "punishment" we study hereafter are implemented: the contractor must pay $1.06 \cdot p$ (where p is the per-unit price) for each quantity that it fails to deliver, while overproduction is sold on the spot market (and thus typically at a lower price than p).

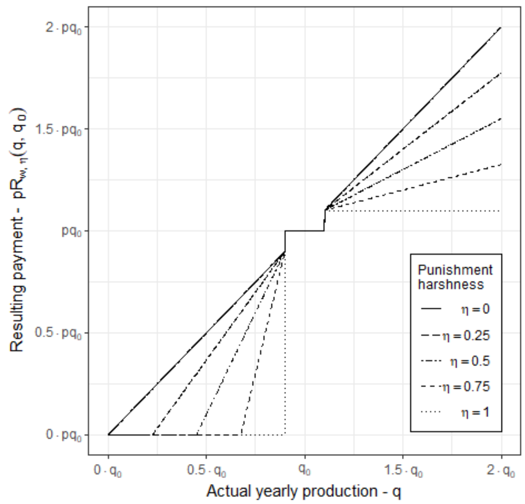


Figure 4: Simplified production-insuring payment rule with punishments

- $R_{(w,\eta)}(q, q_0) = q_0, \qquad \text{if } q \in [q_0(1-w), q_0(1+w)],$
- $R_{(w,\eta)}(q, q_0) = (1-\eta)\cdot q + \eta \cdot q_0(1+w), \qquad \text{if } q > q_0(1+w),$
- $R_{(w,\eta)}(q, q_0) = \max\{\frac{1}{1-\eta}\cdot q + (1-\frac{1}{1-\eta})\cdot q_0(1-w), 0\}, \qquad \text{if } q < q_0(1-w).$[37]

Figure 4 depicts such payment rules for $w = 0.15$ and various values for η. The parameters w and η capture respectively the width of a range around q_0 where firms are fully insured and the strength of the punishment when actual production lies outside this range. If $\eta = 0$, then the payment rule matches the linear payment rule outside the insured range and the payment rule $R_{(w,\eta)}$ is production-insuring for any $w > 0$. On the contrary, when $\eta > 0$ then payment to the firm decreases more rapidly (resp. increases more slowly) when production falls below (resp. goes above) the insured range. Then the expected value of the correction factor under truthful reporting may be strictly lower than one: the payment rule $R_{(w,\eta)}$ thus fails to be production-insuring when $\eta > 0$.[38] We thus circumvent the impossibility result in Proposition 2 and for any $f \in \mathcal{F}$, there may exist some $R_{(w,\eta)}$ differing from the linear contract but which are still strategy-proof. Intuitively, the risk of production outcomes falling outside the insured range, which would be "punished" by a correction factor below 1, deters firms from misreporting their expected production.

The main question we ask is whether fixing the parameters (w, η) appropriately may lower public spending in a way that is robust to some firms being strategic. We study this class of

[37]If $\eta = 1$, then we adopt the convention that $R_{(w,\eta)}(q, q_0) = 0$ if $q < q_0(1-w)$.

[38]If $\eta > 0$, then $\mathbb{E}_f[R(q,\bar{q})] < \bar{q}$ for any distribution $f \in \mathcal{F}_{sp}$ whose support is not a subset of $[q_0(1-w), q_0(1+w)]$.

payment rules through simulations of the complete information equilibria presented in Section 5. Throughout this section, we consider a single year contract as in our theoretical framework, a CRRA utility function with $\gamma = 1$ and two production distributions: first, a normal distribution where the standard deviation is equal to 20% of the mean (Figure 5) and, second, a uniform distribution on the interval $[0.5\bar{q}, 1.5\bar{q}]$ (Figure 6).[39] In Figures 5 and 6, the three panels (a), (b), and (c) depict the ratio between the BEC and the producer's cost, respectively in the equilibrium when all firms are truthful, when several firms are strategic, and last when only one firm is strategic. Next those three ratios are referred to as the performance ratios. We stress that all these performance ratios depend neither on the production cost C nor on the mean of the production distribution $\bar{q}$ (that were thus left unspecified). Panel (d) depicts the ratio between the reference production reported by a strategic firm q_0^* and the true expected production $\bar{q}$. If the payment rule is strategy-proof, then both strategic and truthful firms submit the bid pair $(p^T, \bar{q})$ and the performance ratios are identical in the various paradigms. In Figures 5 and 6 we report our results for the parameters (w, η) varying over the square $[0, 0.5]^2$, i.e., for values such that the performance ratios lie strictly above one since the BEC always includes a risk premium.[40] When there is a single strategic firm – panel (c) – the BEC also includes the positive surplus captured by the winner: note that the scale in the legend of panel (c) differs significantly from those for panels (a) and (b).

With truthful firms, the impact of both parameters on the performance ratio (or equivalently on the risk premium) is quite intuitive: the larger the insurance range and the lower the extent to which firms are punished, the lower is the risk premium, as shown in panel (a) in both Figures 5 and 6. The results are less straightforward in the presence of strategic firms.

Panel (d) in Figures 5 and 6 show that, overall, the larger the insurance range w the more strategic firms overestimate their expected production. This is consistent with the comparative statics regarding w that we derived in Section 4 (for $\eta = 0$). On the other hand, harsher punishments η lead firms to understate their expected production in an attempt to avoid outcomes falling below the lower bound of the insurance range. A surprising result is the discontinuity of the function mapping the payment rule parameters (w, η) into the optimal q_0^* that appears only for the uniform distribution. This discontinuity results from the existence of two local maximums, each moving in different directions with w and η. See Figure 7 for an illustration: the local maximum on the left (with the lowest q_0) consists of reporting a reference production slightly underestimated compared to expected production to insure oneself against low production outcomes. This

[39]Then the standard deviation is equal to $\sqrt{\frac{1}{12}} \approx 29$ % of the mean. The distributions thus differ mainly in the sharpness of the peak.

[40]The payment rule $R_{(w,\eta)}$ provides full insurance only for the uniform distribution and in the limit case where $w = 0.5$ such that production outcomes remain in the flat part under truthful reporting. The performance ratio is equal to one only in this limit case.

Figure 5: Auction outcome depending on payment rule for a normally distributed production

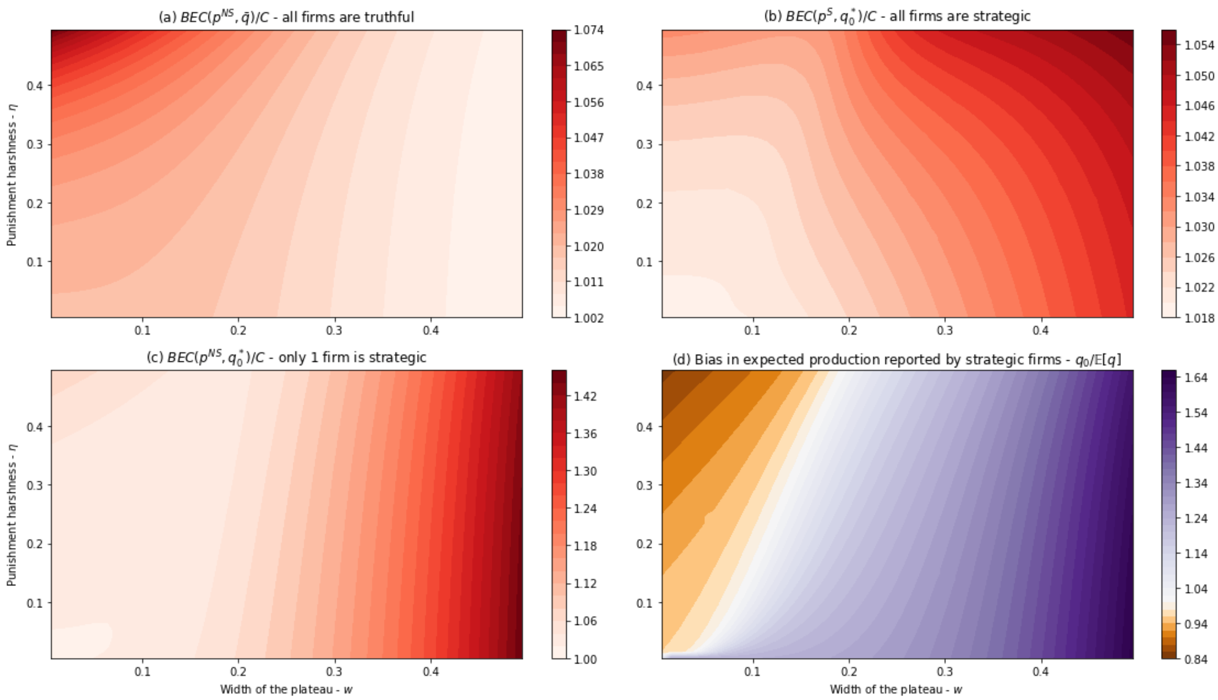
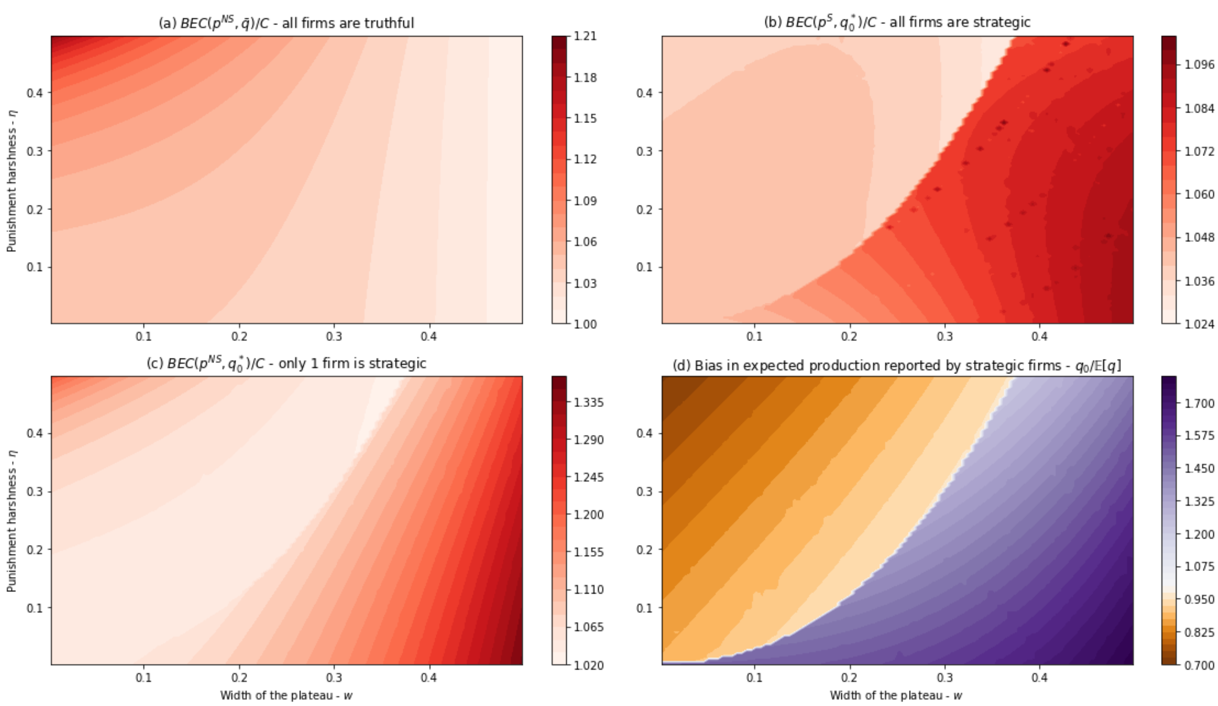


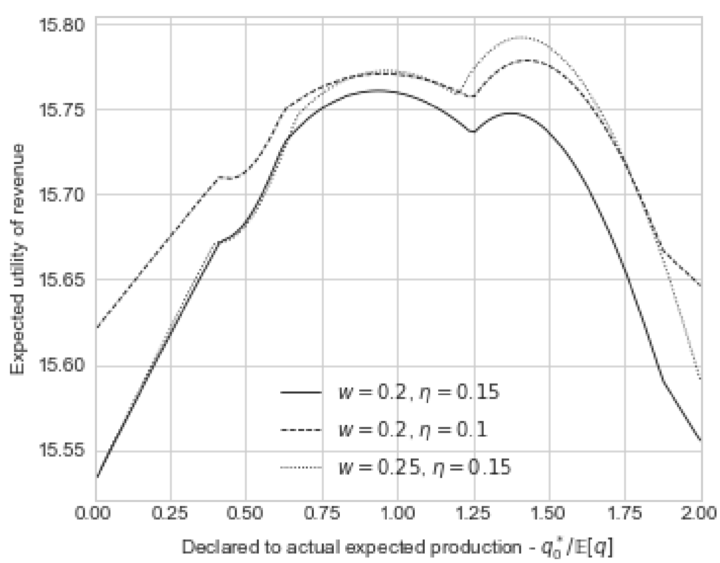
Figure 6: Auction outcome depending on payment rule for a uniformly distributed production



cautious strategy is the ***global*** maximum for small w and large η. The local maximum on the right consists of overestimating expected production to maximize the expected compensation the contractor obtains for "lower than expected" production outcome. This risky strategy corresponds to the ***global*** maximum for large w and small η. Switching from one side to another of the (w, η) discontinuity line, which corresponds roughly to the "white convex curve" in Figure 6d, generates a discontinuity in the risk premium as can been seen in Figure 6b.

A consequence of this discontinuity is that under the uniform distribution, optimal reporting is always either a strict overestimation or a strict underestimation when $(w, \eta) \neq (0, 0)$. Consequently, any payment rule $R_{(w,\eta)}$ differing from the linear contract is manipulable. On the contrary, such discontinuity does not exist under the normal distribution and we observe a (w, η) curve (close to the line $\eta = 0.2 \cdot w$) for which the payment rule is strategy-proof.

Figure 7: Producer's expected payoff as a function of $\frac{q_0}{\bar{q}}$ under the uniform distribution



Under the normal distribution and when there is at least one strategic firm, we see from Figures 5b and 5c that a higher w or a higher η are in all cases associated with a higher BEC: the linear contract $(w, \eta = 0)$ minimizes the BEC. The extra cost generated by using another payment rule $R_{(w,\eta)}$ is typically much larger when there is a single strategic firm: this reflects the fact that the surplus captured by the strategic firm is of a larger order of magnitude than the risk premium. But even in the absence of such surplus, i.e. for strategy-proof payment rules, departing from the linear contract increases the BEC: the intuition is that for any given $w > 0$, the punishment $\eta > 0$ needed to guarantee strategy-proofness is so large that it exacerbates the risk more than it is mitigated by the insurance range.

The picture is different and more subtle for the uniform distribution. The performance depends crucially on which side of the line of discontinuity the subject lies. On the right-hand side, for which strategic firms overestimate production, the impact of parameters w and η is similar to the case with the normal distribution. However, if we wish to minimize the BEC, we would rather focus on the range of parameters on the left-hand side of the discontinuity line where the BEC is much lower. Over this range and when there is at least one strategic firm, the BEC does not increase but rather decreases with w and η. The BEC-minimizing contract within the square $[0, 0.5]^2$ corresponds to the intersection of the discontinuity line with the line $\eta = 0.5$ where w is approximately equal to 0.375. For such a contract, compared to the linear contract, the BEC is lowered by 1.31% when several firms are strategic, by 1.37% when a single firm is strategic and by 1.16% when all firms are truthful. However, adopting such a payment rule might be risky: The contract designer would most likely not have sufficient information to precisely determine the optimal payment rule, and a slight mistake may result in producers switching to the risky strategy (i.e., moving to the right side of the discontinuity line), which would dramatically increase the BEC. For instance, when several firms are strategic, if firms' relative risk aversion coefficient γ is equal to 0.9, then the contract that was optimal with $\gamma = 1$ would instead underperform the linear contract by 2.56%.

In conclusion, payment rules with punishments may bring a better outcome than a standard linear payment rule in some cases. However, adopting such payment rules would remain risky as imprecise information about the production distribution or firms' preferences may lead the designer to choose an inadequate payment rule resulting in larger losses than the potential gains. From a robust mechanism design perspective (Bergemann and Morris, 2012), the linear contract seems a safe choice.

8 Discussion and extensions

Our baseline model leaves out aspects that are important in most procurement contracts. In particular, it assumes that the production distribution is independent of any effort provided by the firm, that the firms have fixed costs alone, that firms are perfectly symmetric in all dimensions (except for strategic behavior) and finally that the manipulation being studied is cost-free. Hereafter we comment on how our results would be affected by a modification of our model to account for moral hazard, for observable variable costs, for asymmetry between firms and last for costs incurred by strategic reporting of q_0. First of all, let us delineate the theoretical status of the linear contract by clarifying what would be the socially optimal contract when firms are risk neutral.

Optimal contracts under risk neutrality

Let us consider an environment with possibly asymmetric risk neutral firms. Each firm $i = 1, \dots, N$ is characterized by the cost function $C_i : \mathcal{F}_{sp} \mapsto \mathbb{R}_+ \cup \{+\infty\}$. After signing the contract with the buyer, the contractor chooses the production distribution which maximizes its expected payoff. The buyer is assumed to value production linearly and let $\bar{p} > 0$ denote the buyer's value per quantity produced. The (expected) social welfare when contractor i chooses distribution f is then equal to $\bar{p} \cdot \mathbb{E}_f[q] - C_i(f)$. Let (i^*, f^*) denote the corresponding welfare optimal allocation.[41]

If the payment rule takes the form $p \cdot q + b$ where firms bid on the fixed cash payment b in a second price auction, then bidding $b_i = -\max_{f \in \mathcal{F}_{sp}}\{p \cdot \mathbb{E}_f[q] - C_i(f)\}$ is a (weakly) dominant strategy for each firm i. When the buyer sets $p = \bar{p}$ the equilibrium allocation is socially optimal: the winning bidder is firm i^* and it chooses production distribution f^*, since the payment rule makes its payoff congruent with the social welfare. This design provides *marginal rewards* to the contractor which is the key ingredient to guarantee social optimality.[42] This efficient contract design corresponds to the so-called "cash auctions" in the contingent auction literature. Departure from this design (e.g., to share risk) is known to generate social inefficiencies either in terms of moral hazard (Laffont and Tirole (1986) and McAfee and McMillan (1987)) or in terms of adverse selection (Che and Kim, 2010).

The linear contract where firms bid on the unit price p (without cash payment b) is prone to such inefficiencies. In the second price auction bidding $\min\{p \geq 0 | \max_{f \in \mathcal{F}_{sp}}\{p \cdot \mathbb{E}_f[q] - C_i(f)\} \geq 0\}$ is a (weakly) dominant strategy for each firm i, and the equilibrium allocation (i^{eq}, f^{eq}) belongs to $\operatorname{Arg\,max}_{(i,f)}\{p^{eq} \cdot \mathbb{E}_f[q] - C_i(f)\}$ where p^{eq} denotes the equilibrium price. If $p^{eq} < \bar{p}$,[43] then the contractor has lower incentives to upgrade its production: informally, if the most efficient firm i^* wins the auction, then the equilibrium expected production will be lower than that under the optimal distribution f^*. Furthermore, there is no guarantee that i^* wins the auction: a firm with lower fixed costs but which is less efficient in upgrading production could outbid the most efficient firm i^*. However, assuming the equilibrium price p^{eq} is not far from $\bar{p}$, the linear contract would still be "approximately efficient" in terms of social welfare.[44,45]

[41] To simplify the discussion, we consider here that the set $\operatorname{Arg\,max}_{(i,f)}\{\bar{p} \cdot \mathbb{E}_f[q] - C_i(f)\}$ is a singleton.

[42] In a related manner, Rogerson (1992) shows that providing marginal rewards guarantees social optimality in a setup which includes ex ante private investments from the competing bidders. Hatfield, Kojima, and Kominers (2018) establishes a converse result and provides approximate versions.

[43] If $p^{eq} > \bar{p}$, then the buyer should prefer not to contract with the winning firm.

[44] From the equilibrium conditions, we have $p^{eq} \cdot \mathbb{E}_{f^{eq}}[q] - C_{i^{eq}}(f^{eq}) \geq p^{eq} \cdot \mathbb{E}_{f^*}[q] - C_{i^*}(f^*)$, which implies that the equilibrium social welfare $\bar{p} \cdot \mathbb{E}_{f^{eq}}[q] - C_{i^{eq}}(f^{eq})$ is greater than $\bar{p} \cdot \mathbb{E}_{f^*}[q] - C_{i^*}(f^*) - (\bar{p} - p^{eq}) \cdot [\mathbb{E}_{f^*}[q] - \mathbb{E}_{f^{eq}}[q]]$, i.e. the optimal social welfare minus the term $(\bar{p} - p^{eq}) \cdot [\mathbb{E}_{f^*}[q] - \mathbb{E}_{f^{eq}}[q]]$.

[45] In a related manner, Hatfield et al. (2018) shows that a mechanism providing approximately marginal rewards is approximately efficient (for any type realization). On contrary, our approximate efficiency claim relies on the assumption that bidders' equilibrium payoffs are close to marginal rewards, which corresponds in our case to p being close to $\bar{p}$.

Beyond multiplicative payment rules

Our analysis can be adapted straightforwardly to the class of additive payment rules where the remuneration takes the form $A \cdot R(q, q_0) + b$ with $A > 0$ and where b corresponds to the auction price while the winning bidder is determined by the offer with the lowest (possibly negative) bid. Our definition of production-insuring rules (that suits the multiplicative framework) also suits the additive setup if the corresponding linear benchmark now becomes the remuneration rule $A \cdot q + b$. In particular, Proposition 3 extends to this setup: production-insuring payment rules still constitute an improvement over the linear benchmark when firms are truthful. Furthermore, the same qualitative pitfalls hold when some firms are strategic: e.g. when firms are risk neutral and when there is a single strategic firm, the strategic firm captures the non-competitive rents $A \cdot (\max_{q_0} \mathbb{E}_f[R(q, q_0)] - \mathbb{E}_f[R(q, \bar{q})]) \geq 0$, an expression which differs from the one we have derived if $A \neq p^T$.[46] More generally, Definition 1 suits any remuneration rule taking the form $A(b) \cdot R(q, q_0) + B(b)$, with $A(b) > 0$, because it implies that $\mathbb{E}_f[U(A(b) \cdot R(q, q_0) + B(b))] \geq \mathbb{E}_f[U(A(b) \cdot q + B(b))]$ for any concave function U and any bid b. The sole difference from our analysis is qualitative: the exact expression of the BEC depends on how functions $A(.)$ and $B(.)$ are specified.

Moral hazard

Instead of inviting bidders to report their idiosyncratic reference production, another approach for the buyer would consist of setting the reference production, bearing in mind that the contractor will make ex post efforts to match its expected production to the reference production. As formalized below, our results in Section 4 could be reinterpreted from this moral hazard perspective: insurance provision would reduce the contractor's incentives to upgrade its expected production compared to the linear contract and then prevent to implement the socially optimal level of effort.[47]

Suppose that after signing the contract with the price $p > 0$ and the payment rule $R(q, q_0)$, the contractor chooses its expected production $\bar{q}$, which generates the cost $C(\bar{q})$. Let us assume that the contractor is risk neutral, the cost function $C : \mathbb{R}_+ \mapsto \mathbb{R}_+$ is increasing and strictly convex and that the distribution $F_{\bar{q}}$ belongs to $\mathcal{F}_{sp}$. Hence the level of effort $\bar{q}$ generates the private payoff $p \cdot \mathbb{E}_{f_{\bar{q}}}[R(q, q_0)] - C(\bar{q})$ for the contractor. Under the linear contract, the optimal level of effort

[46] From this narrow perspective, lowering A would reduce the buyer's expected cost. However, this is an artefact of our baseline model which leaves out moral hazard and adverse selection, both pleading in favor of setting $A = \bar{p}$, the buyer's value per quantity produced, as argued above.

[47] See Shavell (1979) for a seminal contribution on an insured agent's effort reduction in a model where the random variable is binary. Note also that Tirole (1997) criticized the contract proposed by Engel et al. (2001) on the grounds that hedging highway franchises against demand risk would kill the incentives to upgrade quality and then reduce demand.

for the contractor is equal to $[C']^{-1}(p)$.

For a given price p, if the buyer designs a production-insuring[48] payment rule $R(., q_0)$ where q_0 is set to the contractor's optimal level of effort under the linear contract, then the contractor's optimal level of effort can not be larger q_0. As a corollary, we obtain that for any price $p < \bar{p}$, where $\bar{p}$ is the buyer's value per unit, it is impossible to ensure that the contractor provides the socially optimal level of effort $\bar{q}^* := [C']^{-1}(\bar{p})$ while offering a payment rule that is production-insuring for this same level of effort. Formally, if $p < \bar{p}$ and if the buyer sets the reference production $\bar{q}^*$, then the contractor would strictly benefit from shirking, i.e. providing an effort strictly lower than $\bar{q}^*$. The formal proof is detailed in the SA. In other words, the reduced incentives to make efforts when $p < \bar{p}$ under the linear contract are reinforced under a production-insuring payment rule.[49]

Similarly to the results in Section 5, we expect at the auction stage that the equilibrium price would be lower under a production-insuring payment rule than under the linear rule but that this effect is deceptive, the extra cost from socially sub-optimal efforts being borne ultimately by the buyer.

Variable costs

In line with our case study of RES-E generation, we assume in our baseline model that there is no variable cost incurred by production. Other applications may however require an extension of this model. E.g., in procurement for infrastructure projects (studied by Bolotnyy and Vasserman (2019) and Luo and Takahashi (2019)), the analog of the production risk corresponds to the quantity of inputs needed for the project and those quantities (which are random variables from the perspective of the auction stage) do not solely shape the payment rule but also involve (physical) costs for the supplier. With a fixed cost to build the production capacity and then no variable costs associated with production, our renewable energy application is a kind of exception.

Suppose that actual production q leads to the variable cost $\tilde{C}(q)$ in addition to the fixed cost C. Our analysis can be adapted straightforwardly to this framework if we assume that these variable costs are observable ex post, or equivalently if the function $\tilde{C}(.)$ is known by the contractor: according to our notation, it would consist of replacing the payment rule $p \cdot R(q, q_0)$ by the function $p \cdot R(q, q_0) + \tilde{C}(q)$. In this more general setup, the analog of the linear FiT (resp. a production-insuring rule) consists first of reimbursing the observable variable costs $\tilde{C}(q)$ and then adding to this the linear transfer $p \cdot q$ (resp. a term $p \cdot R(q, q_0)$ where q_0 is the reported reference production and with $R(q, q_0) \geq q$ if and only if $q \leq q_0$). In particular, if the cost function $\tilde{C}$ is

[48] Here, the properties of a production-insuring payment rule as stated in Definition 1 will apply conditionally on the contractor providing a level of effort $\bar{q}$ matching the q_0 set by the buyer, rather than conditionally on the contractor reporting its true $\bar{q}$ as q_0.

[49] We also show under additional technical restrictions that the contractor has an incentive to reduce its effort even if $p = \bar{p}$.

linear, then the analog of the linear FiT remains a linear payment rule. From this point of view, departing from the commonly used unit price contracts to hedge against ex post risk would raise the same kind of issues.

Asymmetry between firms

In our baseline model, all firms have the same production distribution F, the same investment cost C and the same utility function U. Let us now discuss how our results from Section 5 change in the presence of asymmetries. Consider for simplicity two firms indexed by $i = 1, 2$ and characterized by the primitives C_i, f_i and U_i. We assume below complete information, meaning that all primitives (C_i, f_i and U_i, $i = 1, 2$) are common knowledge. Let us denote p_i^L the zero surplus bid of firm i under the linear contract. Without loss of generality, let us assume that firm 1 is dominant under a linear contract, i.e. $p_1^L < p_2^L$. Similarly, let us denote p_i^T (resp. p_i^S) the zero surplus bid of a truthful (resp. strategic) firm i under a given production-insuring contract and say that firm i is dominant under the truthful/strategic paradigm if it has the lowest zero surplus bid in the corresponding paradigm. Next we always make the implicit assumption that the production-insuring contract of interest is manipulable and that strategic firms overstate their reference production: for any given price p and any given winning firm, the BEC is higher if the winning firm is a strategic.

In equilibrium with a linear contract both firms bid p_2^L, the BEC is equal to $p_2^L \cdot \mathbb{E}_{f_1}[q]$ and the dominant firm wins and captures the surplus $(p_2^L - p_1^L) \cdot \mathbb{E}_{f_1}[q]$.[50] One noteworthy twist when switching to a production-insuring payment rule is that the winning firm might not be the same as under the linear contract: which firm is dominant depends not only on the contract but also on the truthful/strategic paradigm considered (in particular because bidder i's benefits from misreporting depend on the spread of its production distribution spread and its risk aversion). Given that the winning bidder's identity might change and given potential discrepancies between firms' expected production, let us now consider as our performance criterion the buyer's expected cost divided by the expected production, further referred to as the per-unit BEC.

If the two firms are homogeneous regarding truthful/strategic behavior and it is common knowledge, then we reach conclusions similar to those in Section 5. Given Propositions 3 and 4, we have $p_i^S < p_i^T \leq p_i^L$ with the last inequality being strict if firm i is strictly risk averse. We obtain thus that the equilibrium price bid when both firms are truthful (resp. strategic), which is equal to $\max\{p_1^T, p_2^T\}$ (resp. $\max\{p_1^S, p_2^S\}$), is lower than the equilibrium price bid under the linear contract. When firms are truthful, the price bid and the per-unit BEC match and we conclude then that the production-insuring contract outperforms the linear contract. When firms

[50] As before (see Footnote 25), we assume that ties are broken in favour of the firm that makes a strictly positive surplus.

are strategic the equilibrium price bid is lower than under the linear contract, but as before we cannot conclude on how the equilibrium per-unit BEC will be affected.

When a single firm is strategic, the picture is quite different in the presence of asymmetry. As developed below and as in Burguet and Perry (2007), the impact of the bid manipulation on buyer's cost depends crucially on whether it is the strategic firm or the truthful firm which is dominant. Next we compare the equilibrium per-unit BEC when a single firm is strategic with the case when both firms are truthful.[51]

If the strategic firm (say firm 1) is dominant under the truthful paradigm (i.e. $p_1^T < p_2^T$) then it still wins at price p_2^T and also benefits from misreporting q_0. The surplus due to strategic reporting and due to its dominant position 'are added to one another'. Hence the per-unit BEC increases when a single firm becomes strategic.

If the truthful firm (say firm 2) is dominant under the truthful paradigm (i.e. $p_2^T < p_1^T$), then we distinguish three different cases. Contrary to the model developed in Section 5, here the equilibrium depends on whether the truthful firm is aware or not that its competitor is strategic.

In one case the truthful firm is strongly dominant such that $p_2^T < p_1^S$, and aware that its competitor (firm 1) is strategic. Firm 2 then still wins the auction but gives up part of its surplus by bidding p_1^S, i.e. lower than its bid when both firms are truthful. In sharp contrast with the previous case, the presence of a strategic firm is here unambiguously beneficial to the buyer. In a second case, we assume that firm 2 does not know that firm 1 is strategic. Then firm 1 wins the auction by bidding slightly below p_1^T, while firm 2 presumes it can win the auction by bidding p_1^T. In this case, the presence of a single strategic firm is unambiguously detrimental. In a third case, the truthful firm is dominant under the truthful paradigm ($p_2^T < p_1^T$) but only slightly insofar as $p_2^T > p_1^S$ and we assume furthermore that firm 2 knows that firm 1 is strategic. Then the strategic firm is able to win the auction by bidding (slightly below) p_2^T. In this case there are two conflicting effect at work: On the one hand, the equilibrium price bid is lowered by the presence of a strategic firm which increases the competitive pressure on the price bid. Second, the deceptive effect associated to misreporting is at work. The overall effect is ambiguous.

The main insight we obtain is that bid manipulations can have a pro-competitive effect when bidders are asymmetric. However, this insight holds only when the strategic firm faces a dominant truthful firm such that manipulations reduce bidders' surplus.[52]

[51] In the special case where firms are risk neutral, then this corresponds to the comparison between the production-insuring contract and the linear contract.

[52] In an incomplete information model for the first price auction with favoritism, Burguet and Perry (2007) show surprisingly that the manipulation is beneficial to the buyer when the dishonest supplier is a strong bidder.

Costly manipulation

Our model can be viewed as one where the cost of falsification is binary, either zero for strategic bidders or infinity for truthful bidders. In practice, inflating q_0 involves some costs (because you need either to produce a fake justification for it, or to corrupt the agent in charge of the technical evaluation of the project). Following Maggi and Rodriguez-Clare (1995), let us briefly consider a simple model where the falsification cost is a smooth increasing function of the magnitude of the difference between the reported reference production and the (true) expected production $\bar{q}$. Under risk neutrality, then it is straightforward given Proposition 2 that the optimal report with such falsification costs would lie somewhere between $\bar{q}$ and q_0^* the optimal report without falsification costs. From this perspective, our results are a kind of upper bound to the increased BEC resulting from misreporting. Nevertheless, from a welfare perspective, falsification is also a wasteful activity.

9 Conclusion

We study procurement auctions with ex post risk. In such environments, it is tempting for the buyer to design risk sharing contracts. We have shown that a hedging instrument used in France to subsidize offshore wind farms suffered from large pitfalls: the cure is likely to produce a worse net result in terms of buyer's cost. In addition, reducing risk premiums seems a second order issue in this specific application, in contrast to environments where risks are cumulative.[53] Both our theoretical analysis and our numerical investigations support the insight that departing from linear contracts (that are non-manipulable) is a risky bet. However, the class of payment rules we have analyzed rely on two important restrictions. On the one hand, bidders are free to report any reference production. On the other hand, the hedging instrument is static: it does not use the fact that in some applications (including RES-E), the outcome can be modelled as a vector of independent draws from a common distribution.

These restrictions have been relaxed by some countries who used innovative RES-E subsidy designs. In Brazil, the analog of the reference production is certified by a third party based on wind measurements, while in Germany it is determined according to administrative rules independently of the specific characteristics of the project.[54] It may be thought that this would resolve the pitfalls we have identified when firms self-report their reference production. Nevertheless, if the reference

[53] In Engel et al. (2001), risk concerns demand for a highway and is related to future GDP growth. In Ryan's (2020) auctions for fossil power plants, risk concerns future coal prices. Spurred by the European Commission, many European countries have shifted their subsidy design for RES-E in the direction of Feed-in-Premium (FiP) where producers are free to sell their production on the market and then receive a premium per MWh as a revenue complement. In FiP contracts, risk concerns future electricity prices.

[54] See the report D4.1-BRA (2016) of the AURES project and Bichler et al. (2020) for details.

production is mis-estimated (in relative terms) across the competing projects (due to asymmetric information or if the third party can be corrupted by some bidders), then it would lead to the same kinds of inefficiencies. In Brazil, the payment rule is not additive across years but involves an instrument that smooths the revenue across years: e.g., if the outcome is low in the first year, then the producer is not penalized on a short term basis but could compensate this shortage by a high production outcome in a subsequent year. More generally, as argued in Thomas and Worrall (1990) with a repeated principal-agent setup with i.i.d. shocks, efficient risk sharing relies on dynamic contracts and repeated interactions allow asymmetric information to be reduced.[55] Dynamic contracts are a promising avenue for future research. Nevertheless, we emphasize that many procurement applications do not fit into a repeated screening setup.

[55] See Malin and Martimort (2016) and Krasikov and Lamba (2021) for more recent contributions on optimal dynamic contracts with risk aversion and cash constraints, respectively.

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Appendix 1: Modelling production risk and our assumptions on producers' costs

Our simulations of producers' equilibrium bidding behaviour and then of the corresponding expected public spending are based on a production distribution built from historic simulated data and this for each of the six offshore wind farm sites that were actually auctioned under the production-insuring payment rule we have presented in Section 2. The characteristics of those projects (name, location, size in MW) are listed in Table 1.

Hourly electricity productions of these farms are simulated for 19 years (from 2000 to 2018) using the model developed by Staffell and Pfenninger (2016) and this thanks to the website https://www.renewables.ninja/ to which the location and the characteristics of the turbines have been given as inputs. The production is simulated considering the full capacity of each farm.[56] In most cases, data needed to simulate production with the turbine type actually implemented by the winning bidder (most often the Adwen AD 8-180 turbine) was not available. For the six projects, we consider instead the Vestas V164 8000 turbine which seems the most closely related kind of turbine for such projects.

Historic hourly production obtained from the simulator is then aggregated at the quarterly level. Then we bootstrap our 19 years of aggregated quarterly data to generate the distribution of yearly production: quarters are randomly drawn and summed to generate yearly production points. This resampling approach to generate more than our 19 original years of production is relevant if there is no significant autocorrelation between quarterly aggregate production.[57]

At the bidding stage, firms do not have a perfect knowledge on their average capacity factor which does not depend solely on their technological choice (e.g., the size and the height of the turbine) but also on the local meteorological conditions which are estimated from measurement mats. In the past, such estimations has suffered from important bias: Lee and Fields' (2020) survey report an over-prediction of the median of the capacity factor distribution around 4%. The methodologies have been improved with the aim to reduce bias, but they still involve economically relevant errors: e.g. Jourdier and Drobinski (2017) show that the commonly used statistical model based on Weibull distributions lead to a mean absolute error around 4 or 5% of the average electricity production. In order to account for such noise in the estimation of the capacity factor,

[56] Staffell and Pfenninger's (2016) model is for an isolated turbine. Therefore, the production of each farm (which consists of many turbines) is likely to be slightly overestimated due wake effects.

[57] The Saint-Brieuc site suffers from significant autocorrelation between quarterly aggregate production. Therefore we do not further consider results related to this site which differ importantly from the other sites.

the distribution of the vector of yearly-production $(q_1, \ldots, q_{20})$ is build in the following way: each yearly-production q_t is the product of a yearly-dependent production drawn independently across years according to the bootstrapped distribution defined above with $1 + \epsilon$ where ϵ is a non-year-dependant noise distributed according to a centered normal distribution with the variance σ^2. We assume that $\sigma = 6.3\%$, which matches a mean absolute error of 5%. The noise ϵ for the capacity factor estimation is the main driver for the risk premiums relative to net present value of the subsidy contracts: contrary to weather risk, this additional risk is not averaged out over the 20 years of production.

Table 1: Characteristics on the wind farm projects (source : European Commission (2019) and French Energy Regulatory Commission (2011, 2013)

Site	Location (lat.,long.)	Capacity in MW	IC (CAPEX) M €	OC (OPEX/year) M €	FiT awarded €/MWh
Le Tréport	(50.1, 1.1)	496	2000	105	131
Ile d'Yeu	(46.9, -2.5)	496	1860	110	137
Fécamp	(49.9, 0.2)	497	1850	75	135.2
Courceulles	(49.5, -0.5)	448	1600	69	138.7
Saint-Brieuc	(48.8, -2.5)	496	2200	63	155
Saint-Nazaire	(47.2, -2.6)	496	1800	78	143.6

We consider throughout the paper that producers are fully homogeneous, meaning :

- Producers do not receive any private information on future production distribution which does not depend on the winning bidder's identity. The revenue distribution derived from any given contract is thus the same across all producers.
- Producers have the same costs made of two components: a fixed cost IC (reflecting the initial investment at the date $t = 0$) and a yearly operational cost OC (reflecting operation and maintenance for each year $t = 1, \cdots, 20$). Our assumptions for the cost for the various projects come from a reported of the European Commission.[58] are reported in Table 1.

Appendix 2: Proofs of our main theoretical results

Throughout the appendix we use the notation $\delta := \sup\{t \geq 0 | f(\bar{q}(1-t)) = 0\}$. For $f \in \mathcal{F}_{sp}$, note that the support of f corresponds then to the interval $[\bar{q}(1-\delta), \bar{q}(1+\delta)]$ and that $\delta \in]0, 1]$.

[58] https://ec.europa.eu/competition/state_aid/cases1/201933/265141_2088479_221_2.pdf

Proof of Proposition 2

Let us first show that if $q_0 \geq \bar{q}$, then $\mathbb{E}_f[R(q, q_0)] \geq \mathbb{E}_f[R(q, \bar{q})] = \bar{q}$ for any $f \in \mathcal{F}_{sp}$ (where the last equality comes from the assumption that $R(.,.)$ is production-insuring) or equivalently $\mathbb{E}_f[q \cdot z_{q_0}(\frac{q}{q_0})] \geq \bar{q}$. Take $q_0 \geq \bar{q}$ and let $\alpha := 1 - F(q_0) \leq \frac{1}{2}$.

Consider first the case where $\alpha = 0$, that is when q_0 is higher than any realization of q. Then $\mathbb{E}_f[R(q, q_0)] = \int_0^{q_0} q \cdot z_{q_0}(\frac{q}{q_0}) dF(q) \geq \int_0^{q_0} q dF(q) = \bar{q}$, since from Lemma 1 we have $\forall q \leq q_0$, $z_{q_0}(\frac{q}{q_0}) \geq 1$.

Consider now the complementary case where $\alpha > 0$. Let $G_{q_0} : \mathbb{R}_+ \to \mathbb{R}_+$ denote the function defined by:

$$\begin{aligned} &\text{for } q \geq q_0, \quad G_{q_0}(q) = \frac{1 + F(q) - 2F(q_0)}{2\alpha} \\ &\text{for } q \leq q_0, \quad G_{q_0}(q) = 1 - G_{q_0}(2q_0 - q). \end{aligned}$$

As a CDF, the function F is non-decreasing and then G_{q_0} is also non-decreasing. Since $f \in \mathcal{F}_{sp}$, we have $\forall q \geq 2\bar{q}$, $F(q) = 1$. Therefore $\forall q \geq 2q_0$ (which implies $q \geq 2\bar{q}$), $G_{q_0}(q) = 1$, and consequently $G_{q_0}(0) = 0$. Now let g_{q_0} denote the derivative of G_{q_0}, for $q \geq q_0$, $g_{q_0}(q) = \frac{f(q)}{2\alpha}$ and for $q \leq q_0$, $g_{q_0}(q) = g_{q_0}(q_0 + (q_0 - q))$. Then G_{q_0} is the CDF and g_{q_0} the PDF of a symmetric distribution with expected value q_0. We can then conclude that $\mathbb{E}_{g_{q_0}}[q \cdot z_{q_0}(\frac{q}{q_0})] = \mathbb{E}_{g_{q_0}}[q] = q_0$.

Let us define the function $H_{q_0} : \mathbb{R}_+ \to \mathbb{R}_+$ by $H_{q_0}(q) := F(q) - 2\alpha \cdot G_{q_0}(q)$, in such a way that $f(q) = H'_{q_0}(q) + 2\alpha \cdot g_{q_0}(q)$. Then we may write :

$$\begin{aligned} \mathbb{E}_f[q z_{q_0}(\frac{q}{q_0})] &= \int_0^{2\bar{q}} q z_{q_0}(\frac{q}{q_0}) dF(q) = \int_0^{2q_0} q z_{q_0}(\frac{q}{q_0}) dF(q) \\ &= \int_0^{2q_0} q z_{q_0}(\frac{q}{q_0}) H'_{q_0}(q) dq + 2\alpha \cdot \mathbb{E}_{g_{q_0}}[q z_{q_0}(\frac{q}{q_0})] = \int_0^{2q_0} q z_{q_0}(\frac{q}{q_0}) H'_{q_0}(q) dq + 2\alpha \cdot q_0 \end{aligned}$$

For $q \geq q_0$, $2\alpha g_{q_0}(q) = f(q)$ and therefore $H'_{q_0}(q) = 0$. Moreover, $\forall q \leq q_0$, $z(\frac{q}{q_0}) \geq 1$. We obtain therefore :

$$\begin{aligned} \mathbb{E}_f[q \cdot z_{q_0}(\frac{q}{q_0})] - 2\alpha \cdot q_0 &= \int_0^{q_0} q \cdot z_{q_0}(\frac{q}{q_0}) H'_{q_0}(q) dq \\ &\geq \int_0^{q_0} q \cdot H'_{q_0}(q) dq = \int_0^{q_0} q dF(q) - 2\alpha \int_0^{q_0} q dG_{q_0}(q) \\ &= \bar{q} - \int_{q_0}^{2\bar{q}} q dF(q) - 2\alpha \int_0^{q_0} q dG_{q_0}(q) \\ &= \bar{q} - 2\alpha \underbrace{\left(\int_{q_0}^{2\bar{q}} q dG_{q_0}(q) + \int_0^{q_0} q dG_{q_0}(q) \right)}_{= \mathbb{E}_{g_{q_0}}[q] = q_0} = \bar{q} - 2\alpha \cdot q_0. \end{aligned}$$

Finally, $\mathbb{E}_f[R(q,q_0)] \geq \bar{q} = \mathbb{E}_f[R(q,\bar{q})]$ (for any $q_0 \geq \bar{q}$). By symmetry, we can show that $\mathbb{E}_f[R(q,q_0)] \leq \bar{q}$ for any $q_0 \leq \bar{q}$.

To prove that the payment rule is manipulable, then for any given $f \in \mathcal{F}_{sp}$, let us build $q_0 > \bar{q}$ such that $\mathbb{E}_f[R(q,q_0)] > \bar{q}$. If $f \in \mathcal{F}_{sp}$, there are two possibilities: 1) f is a uniform distribution, 2) there exists a point $q' > \bar{q}$ such that $f(q'-t) > f(q'+t) > 0$ for any $t \in]0, q'-\bar{q}]$.

Consider first the case where f is a uniform distribution on its support $[(1-\delta)\bar{q}, (1+\delta)\bar{q}]$. Let $q' \equiv (1+\delta)\bar{q}$. For any realization q in the support of f, we have $z_{q'}(\frac{q}{q'}) \geq 1$. Furthermore, from Lemma 1, there is a subset of the interval $[\bar{q}, q']$ which has positive measure and on which $z_{q'}(\frac{q}{q'}) > 1$. Finally, we obtain that $\mathbb{E}_f[q \cdot z_{q'}(\frac{q}{q'})] > \mathbb{E}_f[q]$.

Consider now the case where there exists a point $q' > \bar{q}$ such that $f(q'-t) > f(q'+t) > 0$ for any $t \in]0, q'-\bar{q}]$. Since the latter interval is non-null, we know that for such q', $F(q') < 1$. To show that $\mathbb{E}_f[R(q,q')] > \bar{q} = \mathbb{E}_f[R(q,\bar{q})]$ using the same arguments as above, it is sufficient to show that $\int_0^{q'} q z_{q'}(\frac{q}{q'}) H'_{q'}(q) dq > \int_0^{q'} q H'_{q'}(q) dq$.

For $q \in [\bar{q}, q']$, we have $H'_{q'}(q) = f(q) - 2\alpha g_{q'}(q) = f(q) - f(2q'-q)$. Since f is non-increasing for $q > \bar{q}$ and $f(q'-t) > f(q'+t) > 0$ for any $t \in (0, q'-\bar{q}]$, then $\bar{q} < q < q' < 2q'-q$ implies $f(q) > f(2q'-q)$ and therefore $H'(q) > 0$ for any $q \in [\bar{q}, q']$. Moreover we know from Lemma 1 that there is a subset of $[\bar{q}, q']$ with positive measure in which $z_{q'}(\frac{q}{q'}) > 1$. We then obtain $\int_{\bar{q}}^{q'} q z_{q'}(\frac{q}{q'}) H'_{q'}(q) dq > \int_{\bar{q}}^{q'} q H'_{q'}(q) dq$ which further implies $\int_0^{q'} q z_{q'}(\frac{q}{q'}) H'_{q'}(q) dq > \int_0^{q'} q H'_{q'}(q) dq$ (since $z_{q'}(q) \geq 1$ and $H'_{q'}(q) = 2F(q') - 1 \geq 0$ for $q \leq q'$ given that $q' \geq \bar{q}$). **Q.E.D.**

Proof of Proposition 3

As shown in the SA, we have that p^L and p^T are characterized by the zero surplus conditions: $\mathbb{E}_f[U(p^L \cdot q)] = \mathbb{E}_f[U(p^T \cdot R(q,\bar{q}))] = U(C)$ and the function $p \mapsto \mathbb{E}_f[U(p \cdot R(q,\bar{q}))]$ is continuously increasing. Applying Definition 1, we have $\mathbb{E}_f[U(p^L \cdot R(q,\bar{q}))] \geq \mathbb{E}_f[U(p^L \cdot q)]$, the inequality being strict if firms are strictly risk averse and standing as an equality if firms are risk neutral. We then obtain the fact that $p^T \leq p^L$. Since $\mathbb{E}_f[R(q,\bar{q})] = \bar{q}$ for any production-insuring payment rule when $f \in \mathcal{F}_{sp}$, we then obtain the fact that $\mathbb{E}_f[p^T \cdot R(q,\bar{q})] \leq \mathbb{E}_f[p^L \cdot \bar{q}]$. The previous inequalities are strict if firms are strictly risk averse, and stands as equalities if firms are risk neutral.

Q.E.D.

Proof of Proposition 4

As shown in the SA, we have that p^S is characterized by the zero surplus condition: $\max_{q_0 \geq 0} \mathbb{E}_f[U(p^S \cdot R(q,q_0))] = U(C)$ and the function $p \mapsto \max_{q_0 \geq 0} \mathbb{E}_f[U(p \cdot R(q,q_0))]$ is continuously increasing.

In order to show that $p^S \leq p^T$, we proceed by contradiction. Suppose that on the contrary that $p^S > p^T$. Then we have $\Pi^S(p^S) = \max_{q_0 \geq 0} \mathbb{E}_f[U(p^S \cdot R(q,q_0))] \geq \mathbb{E}_f[U(p^S \cdot R(q,\bar{q}))] >$

$\mathbb{E}_f[U(p^T \cdot R(q,\bar{q}))] = \Pi^T(p^T)$. From (2) (resp. (3)), the last (resp. first) term is equal to $U(C)$ and we have thus raised a contradiction.

If the payment rule is manipulable at price p^T, then we have $\max_{q_0 \geq 0} \mathbb{E}_f[U(p^T \cdot R(q,q_0))] > \mathbb{E}_f[U(p^T \cdot R(q,\bar{q}))]$. Given (2), then the last term is equal to $U(C)$. If $p^S = p^T$ and given (3), then $\max_{q_0 \geq 0} \mathbb{E}_f[U(p^T \cdot R(q,q_0))] = U(C)$ and we have thus raised a contradiction. We have thus shown that if the payment rule is manipulable at price p^T, then $p^S < p^T$. Note that Proposition 2 establishes that if firms are risk neutral and if $f \in \mathcal{F}_{sp}$, all production-insuring payment rule are manipulable.

If the payment rule R^{full} provides full insurance against production risk to truthful bidders and is homogeneous of degree 1, then we obtain from Proposition 8 that a strategic bidder will not be fully insured against production risk: $\mathrm{Var}_f[R^{full}(q,q^S)] > \mathrm{Var}_f[R^{full}(q,\bar{q})] = 0$ if $q^S \in \mathrm{Arg\,max}_{q_0 \in \mathbb{R}_+} \mathbb{E}_f[U(p^S R(q,q_0))]$. From the zero surplus conditions (2) and (3), we have $\Pi^S(p^S) = \Pi^T(p^T)$. Since the payoff of the truthful firm is deterministic (under R^{full}), we have $\Pi^T(p^T) = U(p^T\bar{q})$.

$\mathbb{E}_f[U(p^S R(q,q_0^S))] = U(p^T\bar{q})$ since the payoff of the truthful bidder is certain thanks to full insurance by the payment rule.

If bidders are strictly risk averse then U is strictly concave, given $R^{full}(q,q^S)$ is not deterministic, we have that $U(\mathbb{E}_f[p^S R(q,q^S)]) > \mathbb{E}_f[U(p^S R(q,q^S))] = \Pi^S(p^S)$. Combined the previous equalities, we have then $U(\mathbb{E}_f[p^S R(q,q^S)]) > U(p^T\bar{q})$ which further implies that $p^S \cdot \mathbb{E}_f[R(q,q^S)] > p^T \cdot \bar{q}$, or equivalently that the BEC in the equilibrium with strategic firms is greater than the BEC in the equilibrium with truthful firms. **Q.E.D.**

Proof of Proposition 5

If U is a CRRA utility function (which includes the case where firms are risk neutral), then the set $Q_0^*(p)$ does not depend on p (as shown in the SA). Furthermore, we assume that the payment rule is manipulable and thus that $\bar{q} \notin Q_0^*(p)$, $\Pi^S(p^T) > \Pi^T(p^T) = U(C)$ and $p^S < p^T$. The proposition makes also the implicit assumption that strategic firms use the same optimal (mis)report $q_0^* = q^S = q^{S-T}$ both when several firms are strategic and when a single firm is strategic. Then we obtain for any manipulable payment rule that $p^T \cdot \mathbb{E}_f[R(q,q_0^*)] > p^S \cdot \mathbb{E}_f[R(q,q_0^*)]$, i.e. that the BEC when there is a single strategic firm is strictly greater than when there are several strategic firms. Furthermore, if U is linear, then $\Pi^S(p^T) > \Pi^T(p^T) = U(C)$ is equivalent to $p^T\mathbb{E}_f[R(q,q_0^*)] > p^T\mathbb{E}_f[R(q,\bar{q})] = C$. If the payment rule is linear, then we have under risk neutrality that $\Pi^S(p^T) = \Pi^T(p^T) = U(C)$ which is equivalent to $p^T\mathbb{E}_f[R(q,q_0^*)] = p^T\mathbb{E}_f[R(q,\bar{q})] = C$. **Q.E.D.**

Proof of Proposition 6

The equilibrium analysis is analogous to Maskin and Riley (1985): having a low (high) valuation corresponds here to being a truthful (strategic) firm. Note that the assumption that $\Pi^S(p^T) > \Pi^T(p^T)$ guarantees that strategic firms make positive surplus and the equilibrium involves a mixed strategy. On the contrary, if $\Pi^S(p^T) = \Pi^T(p^T)$, then all firms would submit the price bid p^T. As in Maskin and Riley (1985), we have in equilibrium that truthful bidders make no surplus ($\Pi^T(p^T) = U(C)$) and bid thus $(p^T, \bar{q})$ and that all firms when strategic adopts the same bidding strategy which involves no atoms but rather a mixed strategy where the upper bound of the price bid distribution, denoted by p_{max}, is equal to p^T (if $p_{max} < p^T$, then strategic bidders submitting a price bid around p_{max} would have a strictly profitable deviation by bidding just below p^T). Let $G(.)$ denote the CDF of the price bid of a strategic firm. In equilibrium, any price bid p made as part of a mixed strategy must generate the same expected payoff, and in particular the same expected payoff as bidding p^T (under the assumption that ties are broken in favor strategic firms). This translates into the distribution G satisfying:

$$[1-\alpha+\alpha(1-G(p))]^{N-1} \cdot [\Pi^S(p) - U(C)] = (1-\alpha)^{N-1} \cdot [\Pi^S(p^T) - U(C)]. \tag{6}$$

We then obtain $G(p) = 1 - \frac{1-\alpha}{\alpha}\left(\sqrt[N-1]{\frac{\Pi^S(p^T)-U(C)}{\Pi^S(p)-U(C)}} - 1\right)$ for any p in the support of G. Let p_{min} denote the lower bound of the support of G. p_{min} is characterized as the unique solution of $\Pi^S(p_{min}) = (1-\alpha)^{N-1} \cdot [\Pi^S(p^T) - U(C)] + U(C)$. For any $\alpha \in (0,1)$, we have $\Pi^S(p_{min}) - U(C) = (1-\alpha)^{N-1} \cdot [\Pi^S(p^T) - U(C)] > 0 = [\Pi^S(p^S) - U(C)]$, and then that $\Pi^S(p_{min}) > \Pi^S(p^S)$ which further implies that $p_{min} > p^S$. **Q.E.D.**

Proof of Proposition 7

The BEC can be written as

$$(1-\alpha)^N \cdot p^T \cdot \mathbb{E}_f[R(q,\bar{q})] + \int_{p_{min}}^{p_{max}} p \cdot \mathbb{E}_f[R(q, q_0^*(p))]dK(p) \tag{7}$$

where $q_0^*(p) \in Q_0^*(p) \equiv \operatorname{Arg\,max}_{q \geq 0} \Pi(p,q)$ and $K(p) := 1 - (1-\alpha+\alpha(1-G(p)))^N$ denotes the CDF of the price bid of the winning bidder. If U is a CRRA utility function, then $Q_0^*(p)$ does not depend on p (as detailed in the SA). Furthermore, if firms are risk neutral, $\mathbb{E}_f[R(q, q_0^*(p))]$ does not depend on the selection for $q_0^*(p)$ and is equal in particular to $\mathbb{E}_f[R(q, q^{S-T})]$. If firms are risk neutral, we have $C = p^T \cdot \mathbb{E}_f[R(q,\bar{q})]$ and we then obtain from 7 the fact that the BEC is equal to the cost C plus the term $N\alpha \cdot (1-\alpha)^{N-1}[p^T \cdot \mathbb{E}_f[R(q,q^{S-T})] - C] = N\alpha \cdot (1-\alpha)^{N-1} p^T \cdot \Big(\mathbb{E}_f[R(q,q^{S-T})] - \mathbb{E}_f[R(q,\bar{q})]\Big)$.

Consider now the case where U is a CRRA utility function and assume that $\mathbb{E}_f[R(q,q_0)] \geq \mathbb{E}_f[R(q,\bar{q})]$ for any $q_0 \in Q_0^*$.

From (7) and given that $p_{max} = p^T$, the BEC is strictly smaller than

$$(1-\alpha)^N \cdot p^T \cdot \mathbb{E}_f[R(q,\bar{q})] + (1-(1-\alpha)^N) \cdot p^T \max_{q_0 \in Q_0^*} \mathbb{E}_f[R(q,q_0) \leq p^T \max_{q_0 \in Q_0^*} \mathbb{E}_f[R(q,q_0)$$

and where the latter term corresponds to the BEC in an equilibrium under complete information and with a single strategic firm choosing the reference production that maximize the BEC among the (optimal) reports in the set Q_0^*.

From (7) and given that $p_{min} > p^S$, the BEC is strictly greater than

$$(1-\alpha)^N \cdot p^T \cdot \mathbb{E}_f[R(q,\bar{q})] + (1-(1-\alpha)^N) \cdot p^S \min_{q_0 \in Q_0^*} \mathbb{E}_f[R(q,q_0).$$

The BEC is thus strictly greater than the minimum of the BEC with truthful firms ($p^T \cdot \mathbb{E}_f[R(q,\bar{q})]$) and the lowest possible BEC with several strategic firms under complete information (which is reached when the strategic firms choose the reference production that minimize the BEC among the (optimal) reports in the set Q_0^*). **Q.E.D.**

Proof of Proposition 8

In this proof, we do not assume that f is symmetric. We introduce then the notation $q_{min} := \inf\{q \in \mathbb{R}_+ | f(q) > 0\}$ and $q_{max} := \sup\{q \in \mathbb{R}_+ | f(q) > 0\}$. Since f is atomless, then we have $q_{max} > q_{min}$.

Suppose the existence of a payment rule that is homogeneous of degree 1 and such that for $p > 0$ and $q_0^* \in Q_0^*(p)$, the contractor is fully insured against production risk, meaning $\mathrm{Var}_f[R(q,q_0^*)] = 0$ and let us establish a contradiction.

Note first that the payment rule being homogeneous of degree 1 implies that the function $z_{q_0}(\cdot)$ does not depend on q_0. Below we use then the shortcut notation $z(.)$.

Let $x^*_{min} := \frac{q_{min}}{q_0^*}$ and $x^*_{max} := \frac{q_{max}}{q_0^*}$. Since $q \to R(q,q_0^*)$ is continuous and nondecreasing, the contractor being fully insured against production risk when reporting q_0^* implies that there exists a constant $k \geq 0$ such that $R(q,q_0^*) = k$ for any realization $q \in [q_{min}, q_{max}]$, and thus that $z(x) = \frac{k}{q_0^*}\frac{1}{x}$, $\forall x \in]x^*_{min}, x^*_{max}[$. Note that $\Pi(p,q_0) > 0$ if q_0 belong to the support of f. We have then $\Pi(p,q_0^*) > 0$ and then $k > 0$.

If the firm reports a reference production $q_0 \geq q_0^*$, then we have that $x^*_{min} q_0 \geq q_{min}$ and the payment rule $q \mapsto R(q,q_0)$ is flat in the interval $]q_0 x^*_{min}, q_0 x^*_{max}[$ where it is equal to $k \cdot \frac{q_0}{q_0^*}$. For $q_0 \in [q_0^*, \frac{q_{max}}{q_{min}} q_0^*]$, the contractor's expected payoff is then given by:

$$\Pi(p,q_0) = \int_{q_{min}}^{q_{max}} U\left(pqz(\frac{q}{q_0})\right) dF(q) = \int_{q_{min}}^{x^*_{min} q_0} U\left(pqz(\frac{q}{q_0})\right) dF(q) + \int_{x^*_{min} q_0}^{q_{max}} U\left(pk\frac{q_0}{q_0^*}\right) dF(q)$$

$$= \int_{q_0^*}^{q_0} U\left(px_{min}^* q' \cdot z(x_{min}^* \frac{q'}{q_0})\right) f(x_{min}^* q') x_{min}^* dq' + U\left(pk\frac{q_0}{q_0^*}\right)[1 - F(x_{min}^* q_0)] \tag{8}$$

Since the function $q \mapsto R(q, q_0)$ is assumed to be continuous and non-decreasing, it is differentiable almost everywhere. As $z(x) = R(x \cdot q_0, q_0)/x \cdot q_0$ (for any $q_0 > 0$), the function z is also differentiable almost everywhere in $\mathbb{R}_+$ and let $z'(x)$ denote the corresponding derivative when it exists and let us adopt the convention $z'(x) = 0$ otherwise. Recall also that U is assumed to be differentiable and that F is an atomless CDF and is thus semi-differentiable. Let us adopt below the convention that f correspond to its right-derivative.

From (8), we then obtain the fact that the function $q_0 \mapsto \Pi(p, q_0)$ is semi-differentiable on the interval $[q_0^*, \frac{q_{max}}{q_{min}} q_0^*]$ and we have then the following expression for the right derivative:

$$U\left(px_{min}^* q_0 \cdot z(x_{min}^*)\right) x_{min}^* f(x_{min}^* q_0) - \int_{q_0^*}^{q_0} p[x_{min}^* \frac{q'}{q_0'}]^2 \cdot z'(x_{min}^* \frac{q'}{q_0'}) U'\left(px_{min}^* q' \cdot z(x_{min}^* \frac{q'}{q_0'})\right) f(x_{min}^* q') x_{min}^* dq'$$

$$+ \frac{pk}{q_0^*} U'\left(pk\frac{q_0}{q_0^*}\right)[1 - F(x_{min}^* q_0)] - U\left(pk\frac{q_0}{q_0^*}\right) x_{min}^* f(x_{min}^* q_0) \tag{9}$$

At the limit $q_0 = q_0^*$, (9) simplifies (the integral vanishes and $F(x_{min}^* q_0^*) = 0$) and the right derivative of $q_0 \mapsto \Pi(p, q_0)$ is then equal to

$$\frac{pk}{q_0^*} U'(pk) + [U(px_{min}^* q_0^* z(x_{min}^*) - U(pk)]\, x_{min}^* f(x_{min}^* q_0^*) = \frac{pk}{q_0^*} U'(pk) > 0$$

since by continuity of $q \mapsto R(q, q_0^*)$ at $q = q_{min} = x_{min}^* q_0^*$, we have $x_{min}^* q_0^* z(x_{min}^*) = k$. Therefore, starting from the reference production q_0^*, the contractor would strictly increase its expected payoff by increasing slightly its reference production, which stands in contradiction with $q_0^* \in Q_0^*(p)$. **Q.E.D.**

Supplementary Appendix (for online publication)

Proof of Lemma 1

"Only if" part For a given $q_0 > 0$ and a given $\epsilon \in]0,1]$, let $f^*_{q_0,\epsilon}$ denote the uniform distribution on the interval $[q_0(1-\epsilon), q_0(1+\epsilon)]$. We have that $f^*_{q_0,\epsilon} \in \mathcal{F}_{sp}$ and that $\bar{q} = q_0$.

Applying Definition 1 to the contract price $p = 1$ and when U is linear, we have that :

$$q_0 = \mathbb{E}_{f^*_{q_0,\epsilon}}[q] = \mathbb{E}_{f^*_{q_0,\epsilon}}[q \cdot z_{q_0}(\frac{q}{q_0})] = \int_{q_0(1-\epsilon)}^{q_0(1+\epsilon)} q \cdot z_{q_0}(\frac{q}{q_0}) \cdot \frac{dq}{2q_0\epsilon} = \frac{q_0}{2\epsilon}\int_{-\epsilon}^{\epsilon}(1+t)\cdot z_{q_0}(1+t)dt.$$

We then obtain the fact that $\int_0^\epsilon [(1+t)\cdot z_{q_0}(1+t) + (1-t)\cdot z_{q_0}(1-t)]dt = 2\epsilon$ for any $\epsilon \in [0,1[$. The left-hand side of this latter equation has a derivative (w.r.t. ϵ) almost everywhere in the interval $[0,1]$ and which is equal to $(1+\epsilon)\cdot z_{q_0}(1+\epsilon) + (1-\epsilon)\cdot z_{q_0}(1-\epsilon)$, and which should thus be equal to the derivative of the right-hand side. Since the function $z_{q_0}(.)$ is continuous (because the function $q \to R(q, q_0)$ is assumed to be continuous), we obtain that

$$(1+\epsilon)\cdot z_{q_0}(1+\epsilon) + (1-\epsilon)\cdot z_{q_0}(1-\epsilon) = 2 \tag{10}$$

for any $\epsilon \in [0,1]$.

In order to show that $z_{q_0}(1+\epsilon) \leq 1$ for any $\epsilon \in [0,1]$, let us proceed by contradiction. Suppose on the contrary that $z_{q_0}(1+\epsilon) > 1$ for some $\epsilon \in [0,1]$ and let then $\underline{\delta} := \inf\{\epsilon \in [0,1] | z_{q_0}(1+\epsilon) > 1\}$. Since $z_{q_0}(.)$ is continuous, we have then $\underline{\delta} < 1$ and we can also define $\overline{\delta} \in (\underline{\delta}, 1]$ such that $z_{q_0}(1+\epsilon) > 1$ for any $\epsilon \in]\underline{\delta}, \overline{\delta}[$. Since $z_{q_0}(\cdot)$ is continuous, we also have $z_{q_0}(1+\underline{\delta}) = 1$.

Consider then $f^*_{q_0,\overline{\delta}}$ the uniform distribution on $[q_0(1-\overline{\delta}), q_0(1+\overline{\delta})]$. Consider a continuous function U such that $U(x) = x$ for $x \leq q_0(1+\underline{\delta})$ and $U'(q) \in]0,1[$ being strictly decreasing for $q > q_0(1+\underline{\delta})$.[59] Note that U is then increasing and concave.

Given that the function $q \mapsto q \cdot z_{q_0}(\frac{q}{q_0})$ is non-decreasing and that $z_{q_0}(1+\underline{\delta}) = 1$ (which implies $z_{q_0}(1-\underline{\delta}) = 1$ given (10)), we have that $q \cdot z_{q_0}(\frac{q}{q_0}) \in [q_0(1-\underline{\delta}), q_0(1+\underline{\delta})]$ for any $q \in [q_0(1-\underline{\delta}), q_0(1+\underline{\delta})]$. Therefore using that $U(x) = x$ for $x \in [q_0(1-\underline{\delta}), q_0(1+\underline{\delta})]$, the symmetry of $f^*_{q_0,\overline{\delta}}$ around q_0, and making the change of variable $\epsilon = \frac{q}{q_0} - 1$ in (10) we obtain:

[59] How to build a function U satisfying such properties (which will guarantee then its existence) is left to the reader.

$$
\begin{aligned}
\int_{q_0(1-\underline{\delta})}^{q_0(1+\underline{\delta})} U(q\cdot z_{q_0}(\frac{q}{q_0}))dF^*_{q_0,\overline{\delta}}(q) &= \int_{q_0(1-\underline{\delta})}^{q_0(1+\underline{\delta})} q\cdot z_{q_0}(\frac{q}{q_0})dF^*_{q_0,\overline{\delta}}(q)\\
&= \int_{-\underline{\delta}}^{\underline{\delta}} q_0(1+\epsilon)\cdot z_{q_0}(1+\epsilon)dF^*_{q_0,\overline{\delta}}(q_0(1+\epsilon))\\
&= q_0\int_0^{\underline{\delta}}[(1+\epsilon)\cdot z_{q_0}(1+\epsilon)+(1-\epsilon)\cdot z_{q_0}(1-\epsilon)]dF^*_{q_0,\overline{\delta}}(q_0(1+\epsilon))\\
&= 2q_0\cdot[F^*_{q_0,\overline{\delta}}(q_0(1+\underline{\delta}))-\frac{1}{2}] = q_0\cdot[F^*_{q_0,\overline{\delta}}(q_0(1+\underline{\delta}))-F^*_{q_0,\overline{\delta}}(q_0(1-\underline{\delta}))]\\
&= \int_{q_0(1-\underline{\delta})}^{q_0(1+\underline{\delta})} q_0 dF^*_{q_0,\overline{\delta}}(q) = \int_{q_0(1-\underline{\delta})}^{q_0(1+\underline{\delta})} q dF^*_{q_0,\overline{\delta}}(q) = \int_{q_0(1-\underline{\delta})}^{q_0(1+\underline{\delta})} U(q) dF^*_{q_0,\overline{\delta}}(q).
\end{aligned}
$$

Note that the first and the last equalities use the assumption that U is linear on $[0, q_0\cdot(1+\underline{\delta})]$.

We obtain thus that the difference $\mathbb{E}_{f^*_{q_0,\overline{\delta}}}[U(q)] - \mathbb{E}_{f^*_{q_0,\overline{\delta}}}[U(q\cdot z_{q_0}(\frac{q}{q_0}))]$ resumes to

$$
\int_{q_0(1-\overline{\delta})}^{q_0(1-\underline{\delta})}[U(q)-U(q\cdot z_{q_0}(\frac{q}{q_0}))]\frac{dq}{2\overline{\delta}} + \int_{q_0(1+\underline{\delta})}^{q_0(1+\overline{\delta})}[U(q)-U(q\cdot z_{q_0}(\frac{q}{q_0}))]\frac{dq}{2\overline{\delta}}
$$

Thanks to the change of variable $\epsilon = 1-\frac{q}{q_0}$ and $\epsilon = \frac{q}{q_0}-1$ in the first and second integrals, respectively, we obtain:

$$
\begin{aligned}
\mathbb{E}_{f^*_{q_0,\overline{\delta}}}[U(q)] - \mathbb{E}_{f^*_{q_0,\overline{\delta}}}[U(q\cdot z_{q_0}(\frac{q}{q_0}))] &= \frac{q_0}{2\overline{\delta}}\int_{\underline{\delta}}^{\overline{\delta}}[U(q_0(1-\epsilon))-U(q_0(1-\epsilon)z_{q_0}(1-\epsilon))]d\epsilon\\
&+ \frac{q_0}{2\overline{\delta}}\int_{\underline{\delta}}^{\overline{\delta}}[U(q_0(1+\epsilon))-U(q_0(1+\epsilon)z_{q_0}(1+\epsilon))]d\epsilon. \quad (11)
\end{aligned}
$$

Let us show below that in the first (resp. second) integral the function U is applied to values where it is linear (resp. strictly concave).

For $\epsilon\in[\underline{\delta},\overline{\delta}]$, we have $z_{q_0}(1+\epsilon)\geq 1$. From (10), we obtain for any $\epsilon\in[\underline{\delta},\overline{\delta}]$ that $z_{q_0}(1-\epsilon)\leq 1$, which further implies that $q_0(1-\epsilon)z_{q_0}(1-\epsilon)\leq q_0(1-\epsilon)\leq q_0\leq q_0(1+\underline{\delta})$. In the first integral, the function U is thus applied only for values below $q_0(1+\underline{\delta})$ where the function U is defined such that $U(x)=x$ for $x\leq q_0(1+\underline{\delta})$. We have thus that $\forall\epsilon\in[\underline{\delta},\overline{\delta}]$:

$$
U(q_0(1-\epsilon)-U(q_0(1-\epsilon)z_{q_0}(1-\epsilon)) = q_0\cdot[(1-\epsilon)-(1-\epsilon)z_{q_0}(1-\epsilon)]. \quad (12)
$$

Since the function $\epsilon\mapsto q_0(1+\epsilon)z_{q_0}(1+\epsilon)$ is non-decreasing and $z_{q_0}(1+\underline{\delta})=1$ (from the way we have defined $\underline{\delta}$), then for $\epsilon\in[\underline{\delta},\overline{\delta}]$, we have that $q_0(1+\epsilon)z_{q_0}(1+\epsilon)\geq q_0(1+\underline{\delta})z_{q_0}(1+\underline{\delta}) = q_0(1+\underline{\delta})$.

Besides, we note that $q_0(1+\epsilon) \geq q_0(1+\underline{\delta})$. In the second integral, the function U is thus applied only for values above $q_0(1+\underline{\delta})$ where the function U is concave and with $U'(x) < 1$ (for $x \geq q_0(1+\underline{\delta})$). We have thus that $\forall \epsilon \in (\underline{\delta}, \overline{\delta}]$:

$$U(q_0(1+\epsilon)) - U(q_0(1+\epsilon)z_{q_0}(1+\epsilon)) \geq [q_0(1+\epsilon) - q_0(1+\epsilon)z_{q_0}(1+\epsilon)] \cdot U'(q_0(1+\epsilon)) > q_0(1+\epsilon) - q_0(1+\epsilon)z_{q_0}(1+\epsilon). \tag{13}$$

Finally, plugging (12) and (13) into (9) and using 10, we obtain:

$$\mathbb{E}_{f^*_{q_0,\overline{\delta}}}[U(q)] - \mathbb{E}_{f^*_{q_0,\overline{\delta}}}[U(q \cdot z_{q_0}(\frac{q}{q_0}))] > \frac{q_0^2}{2\overline{\delta}} \int_{\underline{\delta}}^{\overline{\delta}} \underbrace{[2 - (1-\epsilon)z_{q_0}(1-\epsilon) - (1+\epsilon)z_{q_0}(1+\epsilon)]}_{=0} d\epsilon = 0.$$

We have thus shown that $\mathbb{E}_{f^*_{q_0,\overline{\delta}}}[U(q)] > \mathbb{E}_{f^*_{q_0,\overline{\delta}}}[U(q \cdot z_{q_0}(\frac{q}{q_0}))]$, which stands in contradiction with the production-insuring assumption. On the whole we have shown that $z_{q_0}(1+\epsilon) \leq 1$ for any $\epsilon \in [0,1]$. From (10), we then obtain $z_{q_0}(1-\epsilon) \leq 1$ for any $\epsilon \in [0,1[$.

The remaining part of Lemma 1 to be shown is that z_{q_0} can not be equal (uniformly) to one in the neighborhood of one or equivalently (given that we have shown that $z_{q_0}(1+t) \leq 1$ for $t \in [0,1]$ and that z_{q_0} is continuous) that for all $\epsilon \in]0,1]$ we verify $\int_0^\epsilon z_{q_0}(1+t)dt < \epsilon$. Suppose that $z_{q_0}(t) = 1$ for any $t \in [-\epsilon, \epsilon]$ (with $\epsilon > 0$) and let us establish a contradiction. Consider a strictly concave payoff function U, the contract price $p = 1$ and the uniform distribution $f^*_{q_0,\epsilon}$. Since z_{q_0} is uniformly equal to 1 on the support of $f^*_{q_0,\epsilon}$, then we obtain that $\mathbb{E}_{f^*_{q_0,\overline{\epsilon}}}[U(q)] = \mathbb{E}_{f^*_{q_0,\overline{\epsilon}}}[U(q \cdot z_{q_0}(\frac{q}{q_0}))]$ which stands in contradiction with the production-insuring property.

"If" part

Consider first the case where U is linear. If Eq. (10) holds for any $q_0 > 0$ and $\epsilon \in [0,1]$, then for any contract price p and any symmetric distribution f with expected value $\bar{q}$ (such that the support of f is a subset of $[0, 2\bar{q}]$), using the change of variable $q = \bar{q}(1+\epsilon)$, we obtain below that Eq. (1) stands as an equality (note that it is the first and the last equality that uses that U is linear):

$$\begin{aligned}
\mathbb{E}_f[U(pqz_{\bar{q}}(\frac{q}{\bar{q}}))] = U\left(\mathbb{E}_f[pqz_{\bar{q}}(\frac{q}{\bar{q}})]\right) &= U\left(p\bar{q}\int_{-1}^{1}(1+\epsilon)z_{\bar{q}}(1+\epsilon)f(\bar{q}(1+\epsilon))d\epsilon\right) \\
&= U\left(p\bar{q}\int_{0}^{1}\left[(1+\epsilon)z_{\bar{q}}(1+\epsilon) + (1-\epsilon)z_{\bar{q}}(1-\epsilon)\right]f(\bar{q}(1+\epsilon))d\epsilon\right) \\
&= U\left(p\bar{q}\underbrace{\int_{0}^{1}2f(\bar{q}(1+\epsilon))d\epsilon}_{=1}\right) = U(p\mathbb{E}_f[q]) = \mathbb{E}_f[U(pq)].
\end{aligned}$$

Let us now consider the case where U is strictly concave. Consider the function $\varphi : \lambda \to U(p\bar{q}\lambda) + U(p\bar{q}(2-\lambda))$. If U is strictly concave, then $U'(p\bar{q}\lambda) < U'(p\bar{q}(2-\lambda))$ as long as $\lambda > 1$. We have thus that $\varphi'(\lambda) = p\bar{q}\left[U'(p\bar{q}\lambda) - U'(p\bar{q}(2-\lambda))\right] < 0$ for $\lambda > 1$.

Moreover, since f is symmetric and given (10), we have both following equations for any function U:

$$\mathbb{E}_f[U(p\cdot q)] = \int_0^1 \overbrace{\left[U(p\cdot\bar{q}(1+\epsilon)) + U(p\cdot\bar{q}(1-\epsilon))\right]}^{=\varphi(1+\epsilon)} dF(\bar{q}(1+\epsilon))$$
$$\mathbb{E}_f[U(p\cdot q\cdot z_{\bar{q}}(\frac{q}{\bar{q}}))] = \int_0^1 \underbrace{\left[U(p\cdot\bar{q}(1+\epsilon)z_{\bar{q}}(1+\epsilon)) + U(p\cdot\bar{q}(1-\epsilon)z_{\bar{q}}(1-\epsilon))\right]}_{=\varphi((1+\epsilon)z_{q_0}(1+\epsilon))} dF(\bar{q}(1+\epsilon))$$

In addition to (10), we also assume that $z_{q_0}(1+\epsilon) \leq 1$ for any $\epsilon \in [0,1]$ and that for any $\epsilon' \in]0,1[$, there exists a subset S of $[0,\epsilon']$ with positive measure such that $z_{q_0}(1+t) < 1$ for any $t \in S$. Moreover, since $q \mapsto q\cdot z_{q_0}(\frac{q}{q_0})$ is non decreasing, we have $(1+\epsilon)\cdot z_{q_0}(1+\epsilon) \geq 1$ for $\epsilon \in [0,1]$. For any $\epsilon \in [0,1]$, we have thus $1 \leq (1+\epsilon)z_{q_0}(1+\epsilon) \leq 1+\epsilon \leq 2$.

The function φ is strictly decreasing on $[1,2]$ and thus on the interval $[(1+\epsilon)z_{q_0}(1+\epsilon), 1+\epsilon]$ for any $\epsilon \in [0,1]$. Finally we have for any $\epsilon \in [0,1]$,

$$\varphi((1+\epsilon)z_{q_0}(1+\epsilon)) \geq \varphi(1+\epsilon). \tag{14}$$

Furthermore, for any $\epsilon' > 0$, there exists a subset S of $[0,\epsilon']$ with positive measure such that the inequality (14) is strict for any $\epsilon \in S$.

Since $f \in \mathcal{F}_{sp}$, then there exists $\epsilon' > 0$ such that the function $\epsilon \to f(\bar{q}(1+\epsilon))$ is strictly positive on $[0,\epsilon']$. Therefore, if we integrate the inequality (14) which is strict on a positive measure of $[0,\epsilon]$, we obtain the strict inequality:

$$\int_0^1 \varphi((1+\epsilon)z_{q_0}(1+\epsilon))dF(\bar{q}(1+\epsilon)) > \int_0^1 \varphi(1+\epsilon)dF(\bar{q}(1+\epsilon))$$

or equivalently $\mathbb{E}_f[U(p\cdot q\cdot z_{\bar{q}}(\frac{q}{\bar{q}}))] > \mathbb{E}_f[U(p\cdot q)]$.

Last, in the remaining case where U is concave, it is straightforward according to the arguments above (it is sufficient to integrate the weak inequality (14)) that the inequality (1) holds. On the whole, we have established that any payment rule associated with the correction factors $\{z_{q_0}(.)\}_{q_0>0}$ is production-insuring.

Comment: when U is concave, note that the inequality (1) holds for any symmetric distribution f (even if it is not single-peaked).

Q.E.D.

Appendix to the end of Section 4: results for a specific class of payment rules.

As a complement to the general results on optimal reporting derived in the case where the contractor is risk neutral, we further study a much more restricted setup to provide some insights about how a risk averse contractor reports its expected production depending on various parameters. The setup considered is as follows:

- The payment rule denoted R_w is parameterized by $w \in]0,1[$ and is such that $R_w(q, q_0) = q_0$ if $q \in [(1-w)q_0, (1+w)q_0]$ and $R_w(q, q_0) = q$ otherwise. In other words, the contractor is perfectly insured and its remuneration depends only on reported expected production q_0 as long as its actual production is no more than w% away from q_0. Beyond this interval, the remuneration is the same as under the linear contract.

- The production risk is distributed according to $F \in \mathcal{F}_{sp}$ which admits a continuous PDF f and whose support is $[(1-\delta)\bar{q}, (1+\delta)\bar{q}]$ with $\delta \leq w$. A direct consequence of this last restriction is that a truthful contractor would be fully insured: the whole support of its production distribution is included in the area where the payment does not depend on q.

To derive the optimal reporting of q_0, we consider the contractor's payoff in four separate cases regarding the chosen q_0 which cover all possible reported q_0 (given the assumption $\delta \leq w$):

1. q_0 is such that actual production never falls in the insured range;

2. q_0 is such that actual production always falls in the insured range;

3. q_0 is such that actual production sometimes falls in the insured range, sometimes above;

4. q_0 is such that actual production sometimes falls in the insured range, sometimes below;

Case 1 Actual production never falls in the insured range if q_0 is chosen such that either $(1+\delta)\bar{q} < (1-w)q_0$ or $(1-\delta)\bar{q} > (1+w)q_0$, i.e., for any q_0 outside the interval $[\frac{1-\delta}{1+w}\bar{q}, \frac{1+\delta}{1-w}\bar{q}]$. For such q_0, the contractor's expected payoff is $\mathbb{E}_f[U(pR(q, q_0)] = \mathbb{E}_f[U(pq)] \leq U(p\mathbb{E}_f[q]) = U(p\bar{q})$. The last inequality results from the concavity of U and implies that the case 1 never brings a better payoff to the contractor than truthful reporting.

Case 2 Actual production always fall in the insured range if q_0 is chosen such that $(1-w)q_0 \leq (1-\delta)\bar{q}$ and $(1+w)q_0 \geq (1+\delta)\bar{q}$, i.e., for $q_0 \in [\frac{1+\delta}{1+w}\bar{q}, \frac{1-\delta}{1-w}\bar{q}]$. In this interval, the firm's payoff is $\mathbb{E}_f[U(pR(q, q_0)] = U(pq_0)$, which is then maximized for the highest value of q_0 within this interval: $q_0 = \frac{1-\delta}{1-w}\bar{q} \geq \bar{q}$.

Case 3 This case corresponds to reported expected productions such that the upper bound of the insurance range is within the support of F: $(1-\delta)\bar{q} \leq (1+w)q_0 < (1+\delta)\bar{q}$, or equivalently $q_0 \in [\frac{1-\delta}{1+w}\bar{q}, \frac{1+\delta}{1+w}\bar{q}[$. The contractor's expected payoff can then be expressed as

$$\Pi(p, q_0) = \mathbb{E}_f[U(pR(q, q_0)] = F((1+w)q_0) \cdot U(p \cdot q_0) + \int_{(1+w)q_0}^{(1+\delta)\bar{q}} U(p \cdot q) dF(q).$$

Let us define the distribution F^* from the (atomless) CDF F, by replacing the smooth part on the interval $[(1-\delta)\bar{q}, (1+w)q_0]$ by an atom at q_0. Formally, $F^*(q) = 0$ for $q < q_0$, $F^*(q) = F((1+w)q_0)$ for $q \in [q_0, (1+w)q_0]$ and $F^*(q) = F(q)$ for $q \geq (1+x)q_0$. Equipped with this definition we have $\Pi(p, q_0) = \mathbb{E}_{f^*}[U(p \cdot q)] \leq U(p \cdot \mathbb{E}_{f^*}[q])$ where the latter inequality comes from the concavity of U. Therefore if we show that $U(p \cdot \mathbb{E}_{f^*}[q]) \leq U(p\bar{q})$ we would have shown that no q_0 in this interval brings a better expected payoff to the contractor than truthfully reporting $\bar{q}$.

We then want to show for any $q_0 \in [\frac{1-\delta}{1+w}\bar{q}, \frac{1+\delta}{1-w}\bar{q}]$ that $\mathbb{E}_{f^*}[q] \leq \bar{q}$, or equivalently that:

$$\int_{(1-\delta)\bar{q}}^{(1+w)q_0} q dF(q) \geq F((1+w)q_0) \cdot q_0. \tag{15}$$

First note that for $q_0 \leq (1-\delta)\bar{q}$, $\int_{(1-\delta)\bar{q}}^{(1+w)q_0} q dF(q) \geq \int_{(1-\delta)\bar{q}}^{(1+w)q_0} q_0 dF(q) = F((1+w)q_0) \cdot q_0$. Now, supposing $q_0 \geq (1-\delta)\bar{q}$ we can decompose the left-hand side in (15) as follows:

$$\int_{(1-\delta)\bar{q}}^{(1+w)q_0} q dF(q) = \int_{(1-\delta)\bar{q}}^{q_0} q dF(q) + \int_{q_0}^{2q_0-(1-\delta)\bar{q}} q dF(q) + \int_{2q_0-(1-\delta)\bar{q}}^{(1+w)q_0} q dF(q) \tag{16}$$

$$= \int_0^{q_0-(1-\delta)\bar{q}} [(q_0-\epsilon) \cdot f(q_0-\epsilon) + (q_0+\epsilon) \cdot f(q_0+\epsilon)] d\epsilon + \int_{2q_0-(1-\delta)\bar{q}}^{(1+w)q_0} q dF(q). \tag{17}$$

Where the two first parts of the integral are merged through a change of variable, resp. $\epsilon = q_0 - q$ and $\epsilon = q - q_0$. To characterize this first term in (17), consider $\epsilon \in [0, q_0 - (1-\delta)\bar{q}]$ and note that from the symmetry of f around $\bar{q}$ we have $f(q_0 - \epsilon) = f(2\bar{q} - q_0 + \epsilon)$. Moreover, knowing $q_0 < \frac{1+\delta}{1+w}\bar{q} < \bar{q}$ we obtain that $q_0 - \epsilon < q_0 + \epsilon < 2\bar{q} - q_0 + \epsilon$ and therefore since F is single-peaked we know that $f(q_0 - \epsilon) = f(2\bar{q} - q_0 + \epsilon) \leq f(q_0 + \epsilon)$. Thus we obtain:

$$\begin{aligned}(q_0-\epsilon) \cdot f(q_0-\epsilon) + (q_0+\epsilon) \cdot f(q_0+\epsilon) &= q_0(f(q_0-\epsilon) + f(q_0+\epsilon)) + \epsilon((f(q_0+\epsilon) - f(q_0-\epsilon)) \\ &\geq q_0(f(q_0-\epsilon) + f(q_0+\epsilon)).\end{aligned}$$

Then, plugging this inequality into (17) we obtain:

$$\int_{(1-\delta)\bar{q}}^{(1+w)q_0} qdF(q) \geq q_0 \underbrace{\int_0^{q_0-(1-\delta)\bar{q}} (f(q_0-\epsilon)+f(q_0+\epsilon))d\epsilon}_{=\int_{(1-\delta)\bar{q}}^{2q_0-(1-\delta)\bar{q}} f(q)dq} + \underbrace{\int_{2q_0-(1-\delta)\bar{q}}^{(1+w)q_0} qdF(q)}_{\geq q_0 \int_{2q_0-(1-\delta)\bar{q}}^{(1+w)q_0} f(q)dq}$$

$$\geq q_0 \int_{(1-\delta)\bar{q}}^{(1+w)q_0} f(q)dq = F((1+w)q_0)\cdot q_0$$

We have then establish the inequality (15), which implies (as detailed above) that no $q_0 \in [\frac{1-\delta}{1+w}\bar{q}, \frac{1+\delta}{1-w}\bar{q}]$ brings a better payoff to the contractor than reporting truthfully $\bar{q}$.

Case 4 This case corresponds to reported expected productions such that the lower bound of the insurance range is within the support of F: $(1-\delta)\bar{q} < (1-w)q_0 \leq (1+\delta)\bar{q}$, or equivalently $q_0 \in]\frac{1-\delta}{1-w}\bar{q}, \frac{1+\delta}{1-w}\bar{q}]$. We have already shown through the three previous cases that $q_0 = \frac{1-\delta}{1-w}\bar{q}$ brings a better payoff than any other $q_0 \notin [\frac{1-\delta}{1-w}\bar{q}, \frac{1+\delta}{1-w}\bar{q}]$, therefore the (globally) optimal report of expected production necessarily lies within the present interval.

The contractor's expected payoff on this interval and its derivative are expressed as:

$$\Pi(p,q_0) = \int_{(1-\delta)\bar{q}}^{(1-w)q_0} U(p\cdot q)dF(q) + (1-F((1-w)q_0))\cdot U(p\cdot q_0)$$

And its derivative with respect to q_0 is:

$$\frac{\partial \Pi(p,q_0)}{\partial q_0} = (1-w)\left[U((1-w)pq_0) - U(pq_0)\right] f((1-w)q_0) + (1-F((1-w)q_0))pU'(pq_0) \quad (18)$$

$$= p\cdot U'(pq_0)f((1-w)q_0)\left[\frac{1-F((1-w)q_0)}{f((1-w)q_0)} - \frac{1-w}{p}\cdot\frac{U(pq_0)-U(p(1-w)q_0)}{U'(pq_0)}\right] \quad (19)$$

Note that since $U'(pq_0)f((1-w)q_0) > 0$, $\frac{\partial \Pi(p,q_0)}{\partial q_0}$ has the same sign as the term in brackets in (19), that we further denote $M(q_0)$. Then, any interior optimum within this interval q_0^* must satisfy the FOC:

$$M(q_0^*) \equiv \frac{1-F((1-w)q_0^*)}{f((1-w)q_0^*)} - \frac{(1-w)}{p}\cdot\frac{U(pq_0^*)-U(p(1-w)q_0^*)}{U'(pq_0^*)} = 0 \quad (20)$$

Note that we know from the previous cases that if $\delta < w$, then reporting the lower bound of the interval $\frac{(1-\delta)}{1-w}\bar{q}$ brings a strictly better payoff to the contractor than the upper bound (the latter raising the same payoff as a linear contract, i.e., $\mathbb{E}_f[U(pq)]$). The latter is therefore ruled out as a global optimum.

Finally, if $\delta < w$, any optimal reporting $q_0^* \in Q_0^*(p)$ satisfies either $q_0^* = \frac{1-\delta}{1-w}\bar{q}$ or the first order condition (20). The set $Q_0^*(p)$ can be further characterized when assuming:

- The distribution F is such that the function $q \mapsto \frac{1-F(q)}{f(q)}$ is continuously decreasing.[60]
- The PDF f is continuous on $\mathbb{R}_+$, or to put it otherwise the distribution F is vanishing at the bounds of its support: $\lim_{q \to (1-\delta)\bar{q}} f(q) = 0$.

Let us first consider the case of a risk neutral contractor. In such a case, we use the notation $M^{RN}(q_0)$ for the function $M(q_0) = \frac{\partial \Pi(p,q_0)}{\partial q_0}$. If U is linear, then $U(pq_0) - U(p(1-w)q_0) = wpq_0U'(pq_0)$ and we have consequently:

$$M^{RN}(q_0) = \frac{1 - F((1-w)q_0)}{f((1-w)q_0)} - (1-w)wq_0.$$

From the first assumption above, $M^{RN}(q_0)$ is decreasing in q_0 for any $w \in]0,1[$, and therefore $M^{RN}(q_0^*) = 0$ admits at most one solution. Moreover, since F is symmetric and single peaked we have that $f(\bar{q}) \geq \frac{1}{2\delta\bar{q}}$. Therefore:

$$M^{RN}(\frac{1}{1-w}\bar{q}) = \frac{1 - F(\bar{q})}{f(\bar{q})} - w\bar{q} \leq \bar{q}(\delta - w) < 0.$$

Then there is a unique global optimal which necessarily belongs to the interval $]\frac{1-\delta}{1-w}\bar{q}, \frac{1}{1-w}\bar{q}[$. This optimum denoted next q_0^{RN} is characterized as the solution of $M^{RN}(q_0^{RN}) = 0$ and thus does not depend on p.

In the general case, for any risk averse contractor with the concave utility function U, we have $U(pq_0) - U(p(1-w)q_0) \geq wpq_0U'(pq_0)$ and therefore that $M(q_0) \leq M^{RN}(q_0)$ for any q_0. If $q_0 > q_0^{RN}$, then $M(q_0) \leq M^{RN}(q) < 0$ which implies that $q_0^* \notin Q_0^*(p)$. Overall, for any concave utility function U, any optimum $q_0^* \in Q_0^*(p)$ is below the optimum with a risk neutral contractor: $q_0^* < q_0^{RN}$. In other words, any risk averse strategic contractor always overestimate its production less than a risk neutral strategic contractor.

In addition, note that the second assumption above (the continuity of f) implies that $\lim_{q_0 \to \frac{1-\delta}{1-w}\bar{q}} \frac{1-F((1-w)q_0)}{f((1-w)q_0)} = +\infty$ which further implies that:

$$\lim_{q_0 \to \frac{1-\delta}{1-w}\bar{q}} M(q_0) = +\infty$$

[60] This assumption is stronger than most often needed, in order to cover any potential value taken by w: we actually only need the function $M(q_0)$ defined in Eq. (20) to be continuously decreasing in q_0 on the interval $]\frac{1-\delta}{1-w}\bar{q}, \frac{1+\delta}{1-w}\bar{q}[$.

and therefore that the derivative of the contractor's payoff is positive (and infinite) at the lower bound $\frac{1-\delta}{1-w}\bar{q}$. The potential corner solution $q_0^* = \frac{1-\delta}{1-w}\bar{q}$ is then ruled out and any global optimum necessarily satisfies $M(q_0^*) = 0$.

Last, we assume the contractor's utility function is a CRRA utility function. The first order condition (20) simplifies to:

$$M_F(q_0^*; w, \gamma) \equiv \frac{1 - F((1-w)q_0^*)}{f((1-w)q_0^*)} - (1-w)q_0^* \cdot K(w, \gamma) = 0 \tag{21}$$

where $K(w,\gamma) = \frac{1-(1-w)^{1-\gamma}}{1-\gamma}$. Note that $\forall \gamma \neq 1$, $K(0,\gamma) = 0$ and $\frac{\partial K(w,\gamma)}{\partial w} = \frac{1}{(1-w)^{\gamma}} > 0$, therefore $\forall (w,\gamma) \quad K(w,\gamma) \geq 0$. Moreover $\frac{1-F(q)}{f(q)}$ is strictly decreasing on $](1-\delta)\bar{q}, \bar{q}[$, then $M_F(\cdot; w, \gamma)$ is strictly decreasing as well. Then Eq. (21) admits a single solution on this interval. Overall, we obtain that $Q_0^*(p)$ is a singleton and does not depend on p. Let q_0^* denote the global optimum.

We now are able to derive the following comparative statics on q_0^* from (21):

1. $K(w,\gamma)$ is increasing in γ and then $M_F(q_0; w, \gamma)$ is decreasing in γ for every q_0. Therefore, the optimal report q_0^* decreases with γ: the more risk averse firms are, the less they overestimate their production.

2. Consider two distributions F_1 and F_2 (on the same support), with F_1 less risky than F_2 in the sense that $\forall q \leq \bar{q}$, $\frac{f_1(q)}{1-F_1(q)} < \frac{f_2(q)}{1-F_2(q)}$. Then $M_{F_1}(q_0; w, \gamma) > M_{F_2}(q_0; w, \gamma)$ for any $q_0 \in]\frac{1-\delta}{1-w}\bar{q}, \frac{1}{1-w}\bar{q}[$ (the interval where the optima are to be found), and consequently the solution to $M_{F_1}(q_0; w, \gamma) = 0$ is larger than the solution to $M_{F_2}(q_0; w, \gamma) = 0$: if production is less risky, then firms overestimate more their expected production.

3. Assuming $\gamma \geq 1$, $K(w,\gamma)$ is non-increasing in w, and therefore $(1-w)q_0 \cdot K(w,\gamma)$ is strictly decreasing in w. In addition, since $\frac{1-F(q)}{f(q)}$ is decreasing on $](1-\delta)\bar{q}, \bar{q}[$, we also have $\frac{1-F((1-w)q_0)}{f((1-w)q_0)}$ decreasing in w for $q_0 \in]\frac{1-\delta}{1-w}\bar{q}, \frac{1}{1-w}\bar{q}[$. Then $M_F(q_0; w, \gamma)$ is strictly decreasing in w on the interval containing q_0^*, and therefore the greater is w the greater is the solution to (20): the larger the insurance range is, the more firms overestimate their production if $\gamma \geq 1$.

Technical details for Section 5: The zero surplus condition when firms are homogeneous

To simplify the arguments, below we consider implicitly symmetric equilibria and that ties are resolved randomly with equal probabilities.[61] Nevertheless, we do not exclude equilibria in mixed strategies.

Let $S_p \subseteq R_+$ denote the support of the price bid of a firm characterizing a (possibly mixed) equilibrium, i.e., the set such that in equilibrium firms are indifferent between any bid $p \in S_p$. Let $\overline{p}$ denote the upper bound of S_p, with $\overline{p} > 0$. Suppose that there exists an equilibrium where firms' expected payoff π^*, raised by any bid $p \in S_p$, is strictly greater than $U(C)$. Let $P(b)$ denote the probability to win with the price bid p.

Assume the firm's payoff (conditional on winning) is continuous in p. Then the equilibrium strategy could not have any atom: slightly undercutting such an atom would incur a discrete positive change in the probability of winning but a negligible change in the firm's payoff conditional on winning (and such that it remains strictly superior to $U(C)$), and therefore lead to a strict increase in the firm's expected payoff. In the absence of any atom in the equilibrium strategy, $p \mapsto P(p)$ is continuous and we cannot have $P(\overline{p}) = 0$, because otherwise the expected payoff raised by some equilibrium bid in the neighborhood of $\overline{p}$ would be strictly lower than π^* (it would converge to zero as p tends to $\overline{p}$) which would raise a contradiction. So we must have $P(\overline{p}) > 0$, which is possible only if opponents bid $\overline{p}$ with a strictly positive probability. Thus we have an atom at $\overline{p}$ which raises a contradiction as argued above.

On the whole, we have shown that bidders' expected payoff cannot be strictly superior to and then should be equal to $U(C)$ (the payoff when losing the auction) in equilibrium with homogeneous bidders. Furthermore, we show below that there is a single price bid that is consistent with zero surplus, both under the "all truthful" and the "all strategic" paradigms. In other words, the set S_p is a singleton.

All truthful paradigm On the one hand, the function U is (strictly) increasing and concave and so we have $U'(x) > 0$ for any x. On the other hand $q \mapsto R(q, \bar{q})$ is continuously non-decreasing with $R(\bar{q}, \bar{q}) = \bar{q} > 0$ so that $R(q, \bar{q}) > 0$ on a positive measure of the support of f. Therefore the function $p \mapsto \mathbb{E}_f[U(p \cdot R(q, \bar{q}))]$ is strictly increasing. Furthermore, the function $p \mapsto \mathbb{E}_f[U(p \cdot R(q, \bar{q}))]$ is continuous and is equal to $U(0)$ for $p = 0$ and goes to infinity when p goes to infinity. The zero surplus condition $\mathbb{E}_f[U(p \cdot R(q, \bar{q}))] = U(C)$ has thus a solution which is unique.

All strategic paradigm Let us show below that the function $H : \mathbb{R}_+ \mapsto \mathbb{R}_+$ defined by $H(p) :=$

[61] The zero surplus condition extends to asymmetric ones. In particular, there exists asymmetric equilibria where two firms bid competitively while other firms submit non-competitive offers.

$\max_{q_0 \geq 0} \mathbb{E}_f[U(p \cdot R(q, q_0))]$ is strictly increasing on R_+. This function is well-defined since we have assumed that the sets $\mathcal{Q}_0^*(p)$ are non-empty for any $p > 0$. As in the previous case with truthful bidders, the function $q \mapsto R(q, \bar{q})$ is strictly positive on a positive measure of the support of f. This property hold then for the function $q \mapsto R(q, q_0^*(p))$ where $q_0^*(p) \in \mathcal{Q}_0^*(p)$ (because if $R(q, q_0^*(p)) = 0$ almost everywhere on the support of f, then the firm would raise its expected payoff by reporting $\bar{q}$ instead of $q_0^*(p)$ which would raise a contradiction). Take $p' > p > 0$. We have then $\mathbb{E}_f[U(p' \cdot R(q, q_0^*(p)))] > \mathbb{E}_f[U(p \cdot R(q, q_0^*(p)))]$. Then from the optimality of $q_0^*(p')$ when the price bid is p', we have $\mathbb{E}_f[U(p' \cdot R(q, q_0^*(p')))] \geq \mathbb{E}_f[U(p' \cdot R(q, q_0^*(p)))]$. We have thus shown that H is (strictly) increasing on $\mathbb{R}_+$.

Furthermore, H is continuous (since it is a maximum of continuous functions) and is equal to $U(0)$ for $p = 0$ and goes to infinity when p goes to infinity.[62] The zero surplus condition $H(p) = U(C)$ has thus a solution which is unique.

Properties with CRRA utility functions

For a given payment rule $R(.,.)$ and a given utility function U, let us use the notation $Q_f^*(p) := \operatorname{Arg\,max}_{q_0 \geq 0} \mathbb{E}_f[U(p \cdot R(q, q_0))]$. For a set $S \subseteq \mathbb{R}$ and $\lambda \in \mathbb{R}$, we let $\lambda \times S := \{x \in \mathbb{R} | \exists s \in S \quad \text{such that} \quad \lambda \cdot s = x\}$.

For a given production distribution f (with the corresponding CDF F) and $\lambda > 0$, we let denote $f_\lambda(.)$ the PDF (with the corresponding CDF F_λ) such that $f_\lambda(q) = \lambda \cdot f(\lambda \cdot q)$ (or equivalently $F_\lambda(q) = F(\lambda \cdot q)$) for any $q \in \mathbb{R}_+$. The distribution f_λ corresponds to a homothetic transformation of the distribution f. The mean of f_λ is then equal to $\frac{\bar{q}}{\lambda}$.

Let BEC_f^T, BEC_f^S and BEC_f^{S-T} denote the BEC in the paradigms where all firms are truthful, all firms are strategic and a single firm is strategic while the other firms are truthful, respectively. We have that $BEC_f^T = p^T \cdot \mathbb{E}_f[R(q, \bar{q})]$. When all firms are strategic (resp. one firm is strategic while the others are truthful), the BEC in equilibrium depends implicitly on how the optimal report is selected in the set $Q_f^*(p^S)$ (resp. $Q_f^*(p^T)$). Next we let $q^S(f) \in Q_f^*(p^S)$ (resp. $q^{N-S}(f) \in Q_f^*(p^T)$) the corresponding selection such that $BEC_f^S = p^S \cdot \mathbb{E}_f[R(q, q^S)]$ (resp. $BEC_f^{S-T} = p^T \cdot \mathbb{E}_f[R(q, q^{S-T})]$).

Lemma 9. *Suppose that the utility function U is a CRRA utility function and consider a production distribution f on $\mathbb{R}_+$.*

1. *Then the set $Q_f^*(p)$ does not depend on p for any $p > 0$ and there is thus a selection rule such that neither $q^S(f)$, $q^{S-T}(f)$, $\frac{p^T}{C}$, $\frac{p^S}{C}$ nor the performance ratios $\frac{BEC_f^k}{C}$, $k = T, S, S-T$, depend on C.*

[62] We have that $\mathbb{E}_f[U(p \cdot R(q, \bar{q}))]$ goes to infinity when p goes to infinity, while the optimality of $q_0^*(p)$ implies that $H(p) \geq \mathbb{E}_f[U(p \cdot R(q, \bar{q}))]$ for any p.

2. *If the payment rule R is homogeneous of degree 1, then $Q^*_{f_\lambda}(p) = \frac{1}{\lambda} \times Q^*_f(p)$ for any $p, \lambda > 0$ and there is thus a selection rule such that neither $\lambda \cdot q^S(f_\lambda)$, $q^{S-T}(f_\lambda)$, $\frac{p^T}{\lambda}$, $\frac{p^S}{\lambda}$ nor the performance ratios $\frac{BEC^k_f}{C}$, $k = T, S, S-T$, depend on λ.*

Lemma 9 involves various ratios between the BEC and the producer's cost. Lemma 9 says that those (performance) ratios depend neither on C nor on λ under various bidding paradigms: This non-dependence holds when all firms are truthful, when all firms are strategic and also if a single firm is strategic while its competitors are truthful. In particular, in the two first cases where firms are homogeneous, it means that risk premiums does not depend on C and λ. In the third case, the ratio capture both a risk premium and a non-competitive rent.

Proof of Lemma 9

If U is a CRRA utility function, then $U(p \cdot R(q, q_0)) = p^{1-\gamma} \cdot U(R(q, q_0))$. For any $p > 0$, we have then $Q^*_f(p) = Q^*_f(1)$.

Let us now consider the ratios between the cost for the buyer and the cost for the firm under our various bidding paradigms. With a CRRA utility function, (2) and (3) can be rewritten respectively as

$$(\frac{p^T}{C})^{1-\gamma} \cdot \mathbb{E}_f[U(R(q, \bar{q}))] = 1$$

and

$$(\frac{p^S}{C})^{1-\gamma} \cdot \mathbb{E}_f[U(R(q, q^S(f)))] = 1$$

with $q^S(f) \in Q^*_f(p^S) = Q^*_f(1)$ where the set $Q^*_f(1)$ does not depend on C. Next we pick a selection rule such that $q^S(f)$ does not depend on C.

We obtain that the ratios $\frac{p^T}{C}$ and $\frac{p^S}{C}$ do not depend on C and finally that the ratios $\frac{BEC^k_f}{C}$, $k = T, S, S-T$ do not depend on C. We have show part 1.

Consider now that R is homogeneous of degree 1. We have then $\mathbb{E}_{f_\lambda}[U(p \cdot R(q, q_0))] = \int_0^\infty U(p \cdot R(q, q_0)) f_\lambda(q) dq = \int_0^\infty U(p \cdot R(q, q_0)) f(\lambda q) d(\lambda q) = \int_0^\infty U(p \cdot R(\frac{q}{\lambda}, q_0)) f(q) dq = \mathbb{E}_f[U(p \cdot R(\frac{q}{\lambda}, \lambda \cdot \frac{q_0}{\lambda}))] = \frac{1}{\lambda^{1-\gamma}} \cdot \mathbb{E}_f[U(p \cdot R(q, \lambda q_0))]$ where the last equality uses the homogeneity of degree 1 assumption and that U is a CRRA utility function. Since $\mathbb{E}_{f_\lambda}[U(p \cdot R(q, q_0))] = \frac{1}{\lambda^{1-\gamma}} \cdot \mathbb{E}_f[U(p \cdot R(q, \lambda \cdot q_0))]$, we then obtain $Q^*_f(p) = \lambda \times Q^*_{f_\lambda}(p)$.

Let us show that the equilibrium prices p^T and p^S are linear in λ. Below we explicit in our notation the dependence in λ and in particular use the notation $\bar{q}_\lambda$ (for the mean of f_λ) and p^T_λ and p^S_λ (for the equilibrium prices for f_λ). According to our notation, we have thus $\bar{q}_\lambda = \frac{\bar{q}}{\lambda}$, $p^T = p^T_1$ and $p^S = p^S_1$. Since $Q^*_f(p) = \lambda \times Q^*_{f_\lambda}(p)$ (for any $\lambda > 0$), for any given $p > 0$ and given f, we can pick a selection $q^*_\lambda(p)$ in the sets $Q^*_{f_\lambda}(p)$ such that $q^*_\lambda(p) = \frac{q^*_\lambda(p)}{\lambda}$. Next we have $q^S(f_\lambda) = q^*_\lambda(p^S_\lambda)$

and $q^S(f_\lambda) = q^*_\lambda(p^S_\lambda)$.

If we apply (2) for both f and f_λ, we obtain that for any λ:

$$\mathbb{E}_f[U(p^T \cdot R(q,\bar{q}))] = U(C) = \mathbb{E}_{f_\lambda}[U(p^T_\lambda \cdot R(q,\bar{q}_\lambda))] = \mathbb{E}_f[U(p^T_\lambda \cdot R(\frac{q}{\lambda},\frac{\bar{q}}{\lambda}))] = \mathbb{E}_f[U(\frac{p^T_\lambda}{\lambda} \cdot R(q,\bar{q}))].$$

The equality $\mathbb{E}_f[U(p^T \cdot R(q,\bar{q}))] = \mathbb{E}_f[U(\frac{p^T_\lambda}{\lambda} \cdot R(q,\bar{q}))]$ implies then that $p^T_\lambda = \lambda \cdot p^T$.

Similarly, if we apply (3) for both f and f_λ, we obtain that for any λ:

$$U(C) = \mathbb{E}_{f_\lambda}[U(p^S_\lambda \cdot R(q, q^*_{0,\lambda}(p^S_\lambda)))] = \mathbb{E}_f[U(p^S_\lambda \cdot R(\frac{q}{\lambda}, \frac{q^*_0(p^S_\lambda)}{\lambda}))] = \mathbb{E}_f[U(\frac{p^S_\lambda}{\lambda} \cdot R(q, q^*_0(p^S_\lambda)))]$$

and

$$U(C) = \mathbb{E}_f[U(p^S \cdot R(q, q^*_0(p^S)))] = \mathbb{E}_f[U(p^S \cdot R(q, q^*_0(p^S_\lambda)))]$$

where the last equality comes from the fact that $q^*_0(p^S) = q^*_0(p^S_\lambda)$ because the optimal report $q^*_0(p)$ does not depend on p. Finally, this implies that $p^S_\lambda = \lambda \cdot p^S$.

We conclude the proof by noting that the buyer's expected cost can be written expressed in the following way in the three bidding paradigms:

- $p^T_\lambda \cdot \mathbb{E}_{f_\lambda}[R(q,\bar{q}_\lambda)] = p^T_\lambda \cdot \mathbb{E}_f[R(\frac{q}{\lambda},\frac{\bar{q}}{\lambda})] = p^T \cdot \mathbb{E}_f[R(q,\bar{q})]$ if all firms are truthful,
- $p^S_\lambda \cdot \mathbb{E}_{f_\lambda}[R(q, q^*_{0,\lambda}(p^S_\lambda))] = p^S_\lambda \cdot \mathbb{E}_f[R(\frac{q}{\lambda}, \frac{q^*_0(p^S_\lambda)}{\lambda})] = p^S \cdot \mathbb{E}_f[R(q, q^*_0(p^S_\lambda))] = p^S \cdot \mathbb{E}_f[R(q, q^*_0(p^S))]$ (the last equality results from the fact that $q^*_0(p)$ is independent of p), if all firms are strategic,
- $p^T_\lambda \cdot \mathbb{E}_{f_\lambda}[R(q, q^*_{0,\lambda}(p^T_\lambda))] = p^T_\lambda \cdot \mathbb{E}_f[R(\frac{q}{\lambda}, \frac{q^*_0(p^T_\lambda)}{\lambda})] = p^T \cdot \mathbb{E}_f[R(q, q^*_0(p^T_\lambda))] = p^T \cdot \mathbb{E}_f[R(q, q^*_0(p^T))]$ (the last equality results from the fact that $q^*_0(p)$ is independent of p), if a single firm is strategic while the other firms are truthful.

Q.E.D.

Remark: Under the multi-year contracts used in France and in presence of operating costs, we could extend Lemma 9.

Formally, let us denote the producer's total (discounted) cost over the life time of the plant by $TC := IC + \sum_{t=1}^{20} \frac{OC}{(1+r)^t}$. Let us generalize the definition of BEC^k_f, for the bidding paradigm $k = NS, S, S-T$, to our multi-period setup. BEC^k_f corresponds then to the expected (discounted) total subsidy paid by the buyer to the contractor in the paradigm k. We have e.g. that $BEC^T_f = \sum_{t=1}^{20} \frac{p^T \cdot \mathbb{E}_{f_\lambda}[R(q,\bar{q})]}{(1+r)^t}$.

Lemma 9 extends to this framework in the following way:

If the utility function U is a CRRA utility function, then the set of optimal reports $q^*_0(p)$ remains the same if we simultaneous multiply the price bid p and the operation cost OC by the same constant.

Then the ratios $\frac{BEC_f^k}{TC}$, for $k = S, NS, S-T$ remain the same if we multiply both the investment cost and the operation costs by the same constant.[63] Note that if the investment and operation costs are multiplied by different constants, then there would be a wealth effect that would complicate the analysis.

Last, if we also assume that the payment rule $R(.,.)$ is homogeneous of degree 1, then the ratios $\frac{BEC_f^k}{TC}$, for $k = S, NS, S-T$ remain the same after a homothetic transformation of the distribution f, i.e., does not depend on λ.

Example 1

Let us build a production-insuring rule $R(.,.)$ and a distribution f such that the cost to the buyer under truthful reporting is greater than under strategic reporting.

Take $\epsilon \in (0,1)$. For each $q_0 > 0$, let us define the function $R(., q_0) : \mathbb{R}_+ \to \mathbb{R}_+$ recursively in the following way: for $q \in [\frac{5}{6}q_0, \frac{7}{6}q_0]$, we let $R(q, q_0) := q_0 + (1-\epsilon)\cdot(q - q_0)$ so that payment is almost equivalent to the linear contract for ϵ small, but with a slightly smaller slope; for $q \in [(\frac{1}{2}+\epsilon)q_0, \frac{5}{6}q_0[$ we let $R(q, q_0) := R(\frac{5}{6}q_0, q_0)$, for $q \in]\frac{7}{6}q_0, (\frac{3}{2}-\epsilon)q_0]$ we let $R(q, q_0) := R(\frac{7}{6}q_0, q_0)$ so that payment is flat in these two intervals; for $q \in [0, \frac{1}{2}q_0[$ and for $q \geq \frac{3}{2}q_0$ we let $R(q, q_0) := q$, then the payment is equivalent to the linear contract on these intervals; finally we define $R(.,.)$ in $[\frac{1}{2}q_0, (\frac{1}{2}+\epsilon)q_0[$ and in $[(\frac{3}{2}-\epsilon)q_0, \frac{3}{2}q_0[$ so that payment is continuous in q: on the first segment $R(q, q_0) := q(\frac{1}{3\epsilon} + \frac{1}{6}) + q_0(\frac{5}{12} - \frac{1}{6\epsilon})$, and on the second segment $R(q, q_0) := q(\frac{1}{3\epsilon} + \frac{1}{6}) + q_0(\frac{5}{4} - \frac{1}{2\epsilon})$.

For the distribution f, take the uniform distribution on $[1-\delta, 1+\delta]$ where $\delta < \frac{1}{6}$. Under truthful reporting, we have that the equilibrium price p^T is characterized by $\int_{1-\delta}^{1+\delta} U(p^T \cdot (1-\epsilon)q) = U(C)$. Under strategic reporting, we have that the firm overestimates its production by reporting $q^* > \bar{q}$ in order to benefit from the payment being largely inflated in lower flat areas.

Through simulations with $\delta = 1/6$, a CRRA utility function with $\gamma = 1$ and $\epsilon = 0.01$, we find the optimal reporting of q_0 being 1.6605. For such reporting, the lower bound of the distribution (relative to the average realization $\bar{q}$), $1-\delta$, is slightly below 1/2 (0.044), while the upper bound is slightly below 5/6 (0.77). Then most of the support of the distribution stands on the flat part of the payment rule, which results in a smaller risk premium. With the firm's cost being 1, the buyer's expected cost drops from 1.0045 when firms are truthful to 1.0009 when firms are strategic.

[63] If this constant is equal to $\alpha > 0$, then there exists an equilibrium (in the three paradigms we consider) where the corresponding equilibrium price is multiplied by α and the optimal report remains unchanged.

Model with moral hazard

We know from Proposition 2 that $q_0 < \bar{q}$ implies that $\mathbb{E}_{f_{\bar{q}}}[R(q,q_0)] \leq \bar{q}$ if $R(.,.)$ is production-insuring. For any $p > 0$, if the buyer sets a reference production $q_0 \geq [C']^{-1}(p)$ (or equivalently $p \leq C'(q_0)$ since C is convex), i.e. the optimal level of effort for the contractor under the linear contract, then for any $\bar{q} > q_0$, we have

$$p \cdot \left(\mathbb{E}_{f_{\bar{q}}}[R(q,q_0)] - q_0\right) \leq p(\bar{q} - q_0) \leq C'(q_0)(\bar{q} - q_0) < C(\bar{q}) - C(q_0) \tag{22}$$

where the last inequality comes the strict convexity of C.

For any price p and any reference production q_0, let $\Pi(p, q_0, \bar{q}) \equiv \mathbb{E}_{f_{\bar{q}}}[p \cdot R(q,q_0)] - C(\bar{q})$ denote the contractor's expected payoff as a function of its effort $\bar{q}$. Note that $\Pi(p, q_0, q_0) = pq_0 - C(q_0)$ (given the definition of a production-insuring payment rule). From (22), we obtain then that

$$\Pi(p, q_0, \bar{q}) < \Pi(p, q_0, q_0) \tag{23}$$

if $\bar{q} > q_0 \geq [C']^{-1}(p)$. We have thus shown that the contractor's optimal level of effort can not be larger than q_0, when the latter is set greater or equal to the optimal level of effort under the linear contract.

Remark: Under additional restrictions (presented below), we show that $\frac{\partial \Pi(p,q_0,\bar{q})}{\partial \bar{q}}|_{\bar{q}=q_0} < 0$ guaranteeing that the contractor's optimal level of effort is actually strictly smaller than under the linear contract.

Since C is convex, then for any price $p < \bar{p}$, the optimal level of effort under the linear contract $[C']^{-1}(p)$ is lower than the socially optimal level of effort $\bar{q}^* = [C']^{-1}(\bar{p})$. Finally we obtain that for any $p < \bar{p}$, if the production of reference is set strictly above $[C']^{-1}(p)$, then the contractor will provide a lower level of effort. In particular the level of effort $[C']^{-1}(\bar{p})$ can not be implemented this way if $p < \bar{p}$.

Strict incentives to shirk with production-insuring payment rules:

Under additional restrictions (presented below), this impossibility result is extended to the case where $p = \bar{p}$.

Consider a production-insuring payment rule $R(., q_0)$ where q_0 is set by the buyer. Once q_0 is fixed, we can assume without loss of generality that $R(.,.)$ is homogeneous of degree 1, which implies that for any $\lambda > 0$, $\frac{d\mathbb{E}_{f_{\bar{q}}}[R(\lambda q, \lambda q_0)]}{d\lambda} = \mathbb{E}_{f_{\bar{q}}}[R(q,q_0)]$, or equivalently

$$\mathbb{E}_{f_{\bar{q}}}\left[q \cdot \frac{\partial R}{\partial q}(\lambda q, \lambda q_0)\right] + q_0 \cdot \mathbb{E}_{f_{\bar{q}}}\left[\frac{\partial R}{\partial q_0}(\lambda q, \lambda q_0)\right] = \mathbb{E}_{f_{\bar{q}}}[R(q,q_0)]. \tag{24}$$

From the homogenous of degree 1 property, we can also write $R(q,q_0) = q \cdot z(\frac{q}{q_0})$. Below we assume implicitly that all the derivatives we use are well-defined. Let us assume a change in $\bar{q}$ is associated with a homothetic transformation of the distribution: $F_{\bar{q}}(q) = F_1(\frac{q}{\bar{q}})$ for any $q \in \mathbb{R}_+$ which implies that $\bar{q} f_{\bar{q}}(q) = f_1(\frac{q}{\bar{q}})$. After the change of variable $\epsilon = \frac{q}{\bar{q}}$, we have then

$$\mathbb{E}_{f_{\bar{q}}}\left[\frac{\partial R}{\partial q_0}(q, \bar{q})\right] = -\int_0^2 \epsilon^2 \cdot z'(\epsilon) f_1(\epsilon) d\epsilon.$$

Note that the latter expression does not depend on $\bar{q}$. Proposition 2 implies here that $\mathbb{E}_{f_{\bar{q}}}\left[\frac{\partial R}{\partial q_0}(q, \bar{q})\right] \geq 0$. In our case, it corresponds thus to

$$-\int_0^2 \epsilon^2 \cdot z'(\epsilon) f_1(\epsilon) d\epsilon \geq 0 \tag{25}$$

Let us assume that the inequality is strict.

From the structure regarding the distributions $F_{\bar{q}}$, we have then: $\mathbb{E}_{f_{\bar{q}}}[R(q, q_0)] = \int R(q, q_0) f_{\bar{q}}(q) dq = \int R(q \cdot \bar{q}, q_0) f_{\bar{q}}(q \cdot \bar{q}) d[q \cdot \bar{q}] = \int R(q \cdot \bar{q}, q_0) f_1(q) dq = \mathbb{E}_{f_1}[R(\bar{q} \cdot q, q_0)]$. This further implies that $\frac{d\mathbb{E}_{f_{\bar{q}}}[R(q,q_0)]}{d\bar{q}} = \frac{d\mathbb{E}_{f_1}[R(\bar{q} \cdot q, q_0)]}{d\bar{q}} = \mathbb{E}_{f_1}[q \cdot \frac{\partial R}{\partial q}(q \cdot \bar{q}, q_0)]$, which when multiplied by $\bar{q}$ gives $\bar{q} \frac{d\mathbb{E}_{f_{\bar{q}}}[R(q,q_0)]}{d\bar{q}} = \mathbb{E}_{f_1}[\bar{q} \cdot q \cdot \frac{\partial R}{\partial q}(q \cdot \bar{q}, q_0)] = \mathbb{E}_{f_{\bar{q}}}[q \cdot \frac{\partial R}{\partial q}(q, q_0)]$. Applying $\lambda = 1$ in (24) and replacing the first term thanks to the previous equality, we get the general result in (26).

$$\bar{q} \cdot \frac{d\mathbb{E}_{f_{\bar{q}}}[R(q, q_0)]}{d\bar{q}} + q_0 \cdot \mathbb{E}_{f_{\bar{q}}}\left[\frac{\partial R}{\partial q_0}(q, q_0)\right] = \mathbb{E}_{f_{\bar{q}}}[R(q, q_0)] \tag{26}$$

We then can derive that for any q_0 set by the buyer, for a level of effort $\bar{q} = q_0$ we get from (26) that:

$$\frac{d\mathbb{E}_{f_{\bar{q}}}[R(q, q_0)]}{d\bar{q}}|_{\bar{q}=q_0} = 1 - \mathbb{E}_{f_{\bar{q}}}\left[\frac{\partial R}{\partial q_0}(q, \bar{q})\right] < 1 \tag{27}$$

where the strict inequality comes from the strict version of (25). Therefore for any price p, we get the following inequality on the derivative of its payoff $\Pi(p, q_0, \bar{q}) \equiv \mathbb{E}_{f_{\bar{q}}}[pR(q, q_0)] - C(\bar{q})$ at the reference production q_0:

$$\frac{d\Pi(p, q_0, \bar{q})}{d\bar{q}}|_{\bar{q}=q_0} = p \frac{d\mathbb{E}_{f_{\bar{q}}}[R(q, q_0)]}{d\bar{q}} - C'(q_0) < p - C'(q_0). \tag{28}$$

For all $q_0 \geq [C']^{-1}(p)$, which includes $q_0 = \bar{q}^*$ as long as $p \leq \bar{p}$, we know that the last term in (28) is negative and thus we have shown that the contractor has a strict incentive to shirk. This precludes in particular the buyer from setting a payment rule that both is production insuring and incentivize to provide the socially optimal level of effort, unless the buyer accepts to pay a price p higher than its value $\bar{p}$.

More detailed results on the performance of the French rule.

For 5 wind farm sites and 5 level of relative risk aversion (including risk neutrality), Table 2 reports the performance ratio

$$\frac{p \cdot \sum_{t=1}^{20} \frac{\mathbb{E}[R(q_t,q_0)]}{(1+r)^t}}{IC + \sum_{t=1}^{20} \frac{OC}{(1+r)^t}} \tag{29}$$

for different equilibrium values for the bid pair (p, q_0) of the winning bidder: first we consider the equilibrium under the linear FiT, second we consider the equilibrium under the French payment rule according to our three bidding paradigms of interest. The performance ratio is necessary above (or equal to) one: otherwise the winning bidder would have preferred to lose the auction which would raise a contradiction with the pair (p, q_0) being an equilibrium bid. Under the linear FiT or if bidders are homogeneous (either all truthful or all strategic), then our performance ratio minus one corresponds to the risk premium that the buyer have to concede to firms to insure them against production risk (and which vanishes if $\gamma = 0$).

Table 3 does the same exercise when the equilibrium bid pairs (p, q_0) in (29) are computed with the utility function $U(x) = \frac{[x-IC+w]^{1-\gamma}}{1-\gamma}$ with the initial wealth w being equal to the total net present cost $IC + \sum_{t=1}^{20} \frac{OC}{(1+r)^t}$ (instead of taking implicitly $w = IC$ in Table 2). Given Table 1, the initial wealth used for the computations in Table 3 are then about twice larger than in our main specification: this makes firms less risk averse in absolute terms and thus reduce the risk premium. This is consistent with what we obtain in the columns 3 to 5. E.g., under the linear FiT and for $\gamma = 1$, the risk premiums are about 50% larger in Table 2 than in Table 3. However, if a bidder is less risk averse (as it is the case with a larger initial wealth), then he/she is more prone to bias his/her report (i.e., here to overestimate even more the expected production): due the corresponding effect on the noncompetitive rents, the performance ratio may be worse in Table 3 than in the corresponding estimates in Table 2 for some specification (it is actually the case for large values of γ, e.g. for $\gamma = 10$ in Fécamp). Overall, due to these two opposite effects in the case with a single strategic producer, we obtain that the performance ratios are very close in column 6 of Table 2 and 3.

Table 2: Performance ratio with $U(x) = \frac{x^{1-\gamma}}{1-\gamma}$.

Site	γ	Linear FiT	The French payment rule		
			All truthful	All strategic	a single strategic bidder
Courseulles	0	1.000	1.000	1.000	1.035
	1	1.003	1.001	1.004	1.036
	3	1.009	1.003	1.010	1.038
	5	1.016	1.006	1.016	1.038
	10	1.033	1.014	1.028	1.038
Fécamp	0	1.000	1.000	1.000	1.036
	1	1.003	1.001	1.003	1.037
	3	1.009	1.003	1.010	1.038
	5	1.015	1.006	1.016	1.039
	10	1.032	1.013	1.028	1.039
Le Tréport	0	1.000	1.000	1.000	1.033
	1	1.003	1.001	1.004	1.034
	3	1.010	1.004	1.011	1.036
	5	1.017	1.008	1.018	1.038
	10	1.037	1.019	1.033	1.040
Saint-Nazaire	0	1.000	1.000	1.000	1.036
	1	1.003	1.001	1.004	1.037
	3	1.009	1.003	1.010	1.038
	5	1.016	1.006	1.016	1.039
	10	1.033	1.014	1.028	1.039
Noirmoutier	0	1.000	1.000	1.000	1.035
	1	1.004	1.001	1.004	1.036
	3	1.011	1.004	1.012	1.038
	5	1.019	1.007	1.019	1.039
	10	1.039	1.019	1.032	1.038

Table 3: Performance ratio with $U(x) = \frac{[x-IC+w]^{1-\gamma}}{1-\gamma}$ with the initial wealth w being equal to the total net present cost of the project.

Site	γ	Linear FiT	The French payment rule		
			All truthful	All strategic	a single strategic bidder
Courseulles	0	1.00000	1.00000	1.00000	1.03501
	1	1.00202	1.00072	1.00237	1.03571
	3	1.00612	1.00218	1.00693	1.03688
	5	1.01030	1.00372	1.01117	1.03770
	10	1.02115	1.00807	1.02032	1.03844
Fécamp	0	1.00000	1.00000	1.00000	1.03560
	1	1.00197	1.00069	1.00227	1.03627
	3	1.00598	1.00209	1.00664	1.03737
	5	1.01006	1.00356	1.01080	1.03822
	10	1.02065	1.00771	1.02002	1.03906
Le Tréport	0	1.00000	1.00000	1.00000	1.03251
	1	1.00207	1.00085	1.00231	1.03335
	3	1.00625	1.00259	1.00677	1.03483
	5	1.01052	1.00439	1.01099	1.03602
	10	1.02163	1.00943	1.02082	1.03819
Saint-Nazaire	0	1.00000	1.00000	1.00000	1.03563
	1	1.00226	1.00082	1.00266	1.03643
	3	1.00686	1.00250	1.00777	1.03773
	5	1.01159	1.00426	1.01248	1.03860
	10	1.02390	1.00930	1.02262	1.03920
Noirmoutier	0	1.00000	1.00000	1.00000	1.03456
	1	1.00212	1.00079	1.00244	1.03533
	3	1.00641	1.00238	1.00706	1.03658
	5	1.01077	1.00404	1.01146	1.03758
	10	1.02203	1.00864	1.02086	1.03846