Horizontal Subcontracting and Intermittent Power Generation

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Abstract

Intermittent power sources enable firms to reduce costs by horizontally subcontracting generation. Dispatchable units serve as a strategic device, even when *never* used, since their availability credibly limits the price paid for subcontracting. Security of supply measures motivated by too low plant profitability therefore underestimate firms' unilateral incentive to install dispatchable units. If dispatchable generation is costly, firms can implement monopoly profits by signing option contracts *before* generation conditions reveal, to the benefit of consumers.

Keywords: subcontracting, intermittency, security of supply, dispatchable units

JEL-code: D43, L13, L14

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1. Introduction

A typical characteristic of important renewable energy sources, like wind or solar, is their intermittent component. Power generation from these sources only follows from favorable exogenous weather conditions like wind speed or sunlight. These conditions are outside the control of the supplier and to an important extent unpredictable. The intermittent characteristic of these renewable energy sources is, therefore, fundamentally distinct from conventional, dispatchable generating units that can be called on when needed and economically justified (Joskow, 2011).

At least two consequences have resulted from the introduction of intermittent power generation. First, it has *increased* the need for flexible back-up facilities to ensure security of supply. As an example, the New York Independent System Operator (2010) estimates that the addition of 1 MW of wind only removes 0.2-0.3 MW of existing dispatchable resources to still meet adequate reserve criteria. Second, intermittent energy sources typically have low to zero marginal generation costs and often enjoy priority of dispatch. As a consequence, they have *reduced* the capacity factor, the ratio of actual over potential generation, of conventional, dispatchable units. For example in Spain, where 20% of power production comes from an intermittent source like wind, the capacity factor of Combined Cycle Gas Turbine (CCGT) plants dropped from 40% in 2004 to 11% in 2013 (Red Eléctrica de España, 2014). Similarly, in Denmark, another frontrunner in intermittent power, wind farms generated 33% of total electricity consumption during 2013 at the expense of conventional power plants (Energinet, 2014).

The *direct* effect is that residual load profiles of conventional power plants have decreased considerably and therefore diminished profitability at the plant level. Low plant profitability *appears* to undermine firms' incentives to maintain or install dispatchable units. Gas-fired plants are mothballed due to their high maintenance costs. Accordingly, public interventions, e.g. capacity payments, have been proposed or implemented to guarantee sufficient returns from adequate capacity needed to secure supply. For instance, National Grid in the UK published capacity auction results of 2.2 £ per MW per hour, to be delivered in 2018 and beyond (National Grid, 2014). In the Northeast of the United States, PJM's reliability pricing model returned a price of about 5 $ per MW of capacity per hour in 2017/2018 (PJM, 2014).

Our analysis uncovers an *indirect* effect as well. In a world with intermittent power sources, firms have *strategic* incentives to install dispatchable units. The indirect returns from dispatchable units may contribute to the security of adequate supply. In particular, since weather conditions are location-specific, not all intermittent units are always available. For instance, one firm can be wind-abundant, while at the same time its rival is windless and needs to rely on its expensive dispatchable units. In such a framework, horizontally competing firms can gain from subcontracting. The (prime) *contractor* outsources generation from expensive coal or gas-fired plants by purchasing low-cost power from the rival's intermittent units (the *subcontractor*). If a firm cannot generate power from its intermittent source, but only has access to its dispatchable units, its willingness to pay for outsourcing equals at most its opportunity cost. Accordingly, the ability to dispatch conventional coal or gas-fired plants credibly puts an upper bound on the subcontracting price.

As a result, dispatchable units, even if *never* used for power generation, serve as credible protection against hold-up and reduce subcontracting costs. An exclusive measure of plant profitability, such as the capacity factor, is therefore insufficient to assess a firm's returns from dispatchable capacity.

Importantly, the subcontracting terms alter firms' equilibrium behavior. We find that consumers are bad off (little competition) if and only if subcontracting is expensive. The intuition stems from two distinct effects. First, by scheduling large amounts of power, a firm may not cover the subcontracting costs in the event it has no wind power available. Second, a firm could also choose to contract less sales in advance. By doing so, it can benefit from significant subcontracting revenues in the event it has wind power available whenever its rivals do not.

This effect is most apparent if firms compete in prices, where the low-price firm serves the whole market. Since the high-price firm sells zero output, it never contracts power from the low-price rival. However, it benefits from significant subcontracting payments in the event the low-price firm has no wind power available. In equilibrium, firms set high prices such that they are indifferent between serving the market or earning subcontracting revenues. Likewise, a supply function framework also reveals that subcontracting softens competition. Firms apply relative markups which exceed the inverse price elasticity of residual demand. Interestingly, consumers can be worse off if firms compete in prices or supply functions rather than quantities.

Moreover, we analyze an option contract that can serve as a device to increase industry profits. For instance, firms can design subcontracting payments in an agreement signed *before* they learn about wind availability, after which they compete non-cooperatively. To see this, let dispatchable units be non-expensive. Firms then prefer a lower industry output in order to increase profits. Accordingly, they raise subcontracting payments up to the contractor's opportunity cost of in-house generation. Such an agreement is clearly detrimental to consumer welfare. In contrast, suppose now that dispatchable units are expensive to use. A firm that contracts much sales in advance would then incur large subcontracting costs in the event it is windless. Consequently, firms guarantee sufficient returns by selling less power at higher prices. However, the availability of zero-cost wind power generation does not validate high prices if firms are profit maximizers. In other words, the industry profits can be augmented by lower prices. This is achieved by setting the subcontracting terms below the contractor's opportunity cost. Such an option contract is advantageous to both producers and consumers.

We also show that the subcontracting terms can be helpful for the purpose of colluding. Clearly, if the subcontracting terms enable firms to maximize industry profits, subcontracting coincides with—and therefore facilitates—tacit collusion. If not, collusive firms make deviation from the tacitly agreed upon outcome less attractive by raising the subcontracting payment up to the contractor's opportunity cost. As a result, the deviating firm has less to win. Interestingly, it is impossible for a third party like an antitrust authority to distinguish collusive from competitive behavior on the basis of the subcontracting terms.

Related literature — Our paper relates to the literatures on horizontal subcontracting and power markets design with intermittent generation.

A number of papers explain horizontal subcontracting—the selling and buying positions between rivalry firms—by asymmetries or convexities in their production functions. Signing subcontracts to shift production from one firm to the other can therefore result in production efficiencies.

Kamien, Li, and Samet (1989) study two price-bidding firms with convex costs that compete for a contract. Production costs are reduced when the winner contracts part of the output to the rival losing bidder. If the winner determines the terms of the subcontract, there is fierce competition for the contract and firms make zero profits in equilibrium. Conversely, if the loser determines the terms of the subcontract, firms set higher prices and make positive profits.[3]

Spiegel (1993) relies on convex upstream and downstream cost asymmetries across firms to rationalize horizontal subcontracting between rival firms. He studies ex ante and ex post subcontracts, signed before and after firms engage in quantity competition, respectively. Interestingly, only ex post agreements between horizontally subcontracting firms realize full production efficiency. To enhance welfare, subcontracts should generate sufficient production efficiencies.

Our contribution to the subcontracting literature is fourfold. First, in our setting, the motivation for subcontracting between firms originates from production technologies that are only intermittently available. This framework enables us to analyze a state-contingent option contract, signed ex ante, i.e. before firms learn about generation conditions. Firms anticipate that the agreed upon subcontracting terms alter equilibrium behavior, and hence, the option contract is a device to maximize each firm's expected profits. Interestingly, because firms are ex ante symmetric, their preferences are equal with regard to the option contract. The optimal option contract therefore maximizes each firm's expected profits *non-cooperatively*, so that our analysis does not require the assumption of joint profit maximization as in Spiegel (1993).

[3] See Marion (forthcoming) for an empirical approach to study the effects of subcontracting.

Second, our paper stresses the importance for firms to have access to dispatchable units, even when they are never used. Namely, when a firm contracts power from the rival, having excess capacity available avoids hold-up by the subcontractor. As such, we link the subcontracting literature with the hold-up literature.

Third, we uncover the incentives for collusion with subcontracting. Repeated interaction is common in the power industry, so that firms may choose to design the option contract such that collusion is maximally sustained.

Finally, our framework examines—and compares—both price *and* quantity competition in order to obtain welfare insights. As in Kamien et al. (1989), we capture that the low-price firm suffers from a reduction in subcontracting revenues by competing fiercely. We add to their analysis by showing that, due to this effect, quantity competition can outperform price or supply function competition with regard to consumer surplus.[4] Subcontracts that sufficiently favor the outsourcing firm increase consumer welfare.

Our paper also relates to the literature on power market design. Ambec and Crampes (2012) study the optimal energy mix with reliable and intermittent energy sources. To sustain a power system with intermittent power generation, ideally, consumers need to be priced state-contingently. Alternatively, policies should keep reliable production sufficiently profitable in order to secure supply. Structural or financial measures can then moderate the surplus appropriated to intermittent generating technologies. Joskow and Tirole (2007) consider the lack of demand response in power markets and assess the consequences in terms of optimal investment and reliability. When a price cap is imposed or the system operator undertakes out-of-market actions to secure the stability of the grid, capacity payment mechanisms can induce more efficient investment in capacity.[5]

[4] See also Fauli-Oller and Sandonis (2002), who study price and quantity competition with patent licensing and royalties. In a similar fashion, a firm can increase its licensing revenues by setting a high price.

[5] Gowrisankaran et al. (2014) empirically assess the social cost of solar power generation in a setting of welfare maximization based on Joskow and Tirole (2007). They disentangle the cost of unpredictability, the cost of varying availability and the

Our analysis reveals the important distinction between profitability at the *firm* level, as opposed to profitability at the *plant* level. Firms are willing to install dispatchable facilities that operate few or even zero hours per year, because it limits the subcontracting costs paid to the rival. Thus, the revenues generated by peaking plants need not cover the investment and variable costs. Plant profitability is not a necessary condition for profit maximization. Firms can profit from holding *idle* generating capacity.

Several papers explain how firms can benefit from holding idle capacity. For instance, incumbent firms can be willing to install excess capacity in order to deter entry (see Dixit 1979). In a dynamic setting, Maskin and Tirole (1988) find that holding excess capacity can sustain collusion because it discourages the rival from triggering a price war. Our analysis, in contrast, shows that firms attain monopoly profits by jointly *divesting* idle dispatchable units. Maintaining unused dispatchable units is only profitable from a unilateral perspective. That is, dispatchable units provide a firm with an alternative to the subcontract, and hence, it credibly limits the outsourcing price paid to the rival.

Other applications — Our set-up applies specifically the power generation industry. Of course, other industries can also be characterized by comparable subcontracting agreements. While there is often a common logic, one-to-one comparisons with our analysis should be taken with the necessary caution. We provide one example from the cargo industry and another from the banking industry.

Cargo companies (for maritime shipping or transport by air or road) sign binding contracts with their clients to ship goods on time. However, transporting conditions and customers' specific needs vary intermittently. As a result, it is often difficult to meet precise contractual obligations in space and time. One alternative is to foresee costly reserve capacity that is always available for all possible contingencies. At the same time, other competing cargo companies may, for some reason, have idle capacity at the right time and the right location. Horizontal subcontracting between rivals may then enable firms to obtain better load factors.

installation cost, but do not consider market power. For more work on capacity payment mechanisms, see also e.g. Cramton and Stoft (2006) and Joskow (2006, 2008).

In the financial sector, banks undertake contractual commitments to supply liquidity towards customers. Depositors, however, intermittently request liquidity, so that banks may suffer from unexpected withdrawals. This calls for efficient ways for banks to manage liquidity shocks by holding more cash than needed. Alternatively, competing banks can gain from setting up interbank payment systems (see Freixas and Parigi, 1998).

Section 2 describes the model. As a benchmark, section 3 presents the analysis when firms sign no subcontracts. Section 4 studies subcontracts, after which we analyze investment in idle dispatchable units in section 5. We consider collusion in section 6 and offer a welfare analysis in section 7. Our robustness and discussion can be found in section 8. Section 9 concludes.

2. The model

Two symmetric, profit-maximizing power generating firms i, with $i = 1, 2$, offer a homogeneous good on the wholesale market. Demand originates from non-strategic final consumers or competitive retail suppliers. The inverse market demand is linear and equal to

$$P = 1 - Q$$

where P denotes the market price and q_i firm i's output such that $Q = q_i + q_j$ with $i \neq j$. Each firm has access to a generating technology characterized by zero marginal cost, e.g. a wind park. This technology is, however, only intermittently available, depending on the state of nature. Hence, we refer to this technology as the *intermittent technology*. Since the use of each firm's wind mills depends on wind availability, the stochastic nature of wind availability requires each firm to have access to a second technology that serves as reliable back-up, the *dispatchable technology*. The reasoning is that each firm must deliver its output q_i independent of the state of nature. If the intermittent energy source is unavailable, each firm can use its dispatchable technology, e.g. a portfolio of gas-fired power plants, that is characterized by the convex variable cost function

$$C(q) = 0.5\beta q^2$$

with $0 \leq \beta$.[6] Our production cost function could easily be modified without changing the qualitative insights. Our model captures that marginal costs are upward sloping. Firms generate power with the lowest marginal generation cost first. If more generation is required, they must turn to more expensive generation units.[7]

We can interpret a change in β in two ways. First, a decrease in β may reflect that the existing dispatchable units become more efficient. For instance, by equipping gas-fired plants with state-of-the-art technologies, firms can generate the same amount of power using less fuel.

Second, we may interpret a firm's marginal cost function βq as a horizontal summation of plant-level marginal cost functions. Firms can then reduce β by installing additional dispatchable units, thereby rotating their marginal cost function to the right.

Note that the dispatchable units need not be *owned* by the firms. It is equally possible that firms buy the access and usage of dispatchable units from a competitive fringe, for instance in return for a fixed and variable fee.

We will assume, for simplicity, that both technologies have no capacity constraints. As a result, if available, one firm's wind park can meet total industry demand.[8] A firm can also use its dispatchable technology to generate sufficient power. Of course, generating large amounts is then costly because costs are convex.

The dispatchable technology is perfectly reliable. It is available in all states of nature. In contrast, the availability of each firm's intermittent technology is random and takes a Bernoulli distribution. Let w

[6] We discuss the role of fixed costs in Section 5.

[7] The insights of our analysis also stand when firms' costs are linear. In the context of power generation, though, our cost function captures the "merit order" or "dispatch curve" (Joskow, 2011).

[8] We discuss this assumption in the robustness section.

and $\overline{w}$ refer to wind availability and wind unavailability, respectively. The four states of nature are then denoted by (w,w), $(w,\overline{w})$, $(\overline{w},w)$ and $(\overline{w},\overline{w})$, where the first and second element refer to firm i's and firm j's generation conditions, respectively.

Let each firm be wind-abundant with probability α and windless with the remaining probability. Each firm's wind variability $\alpha(1-\alpha)$ then measures the *firm intermittency* of the intermittent technology. To avoid that our results follow from asymmetries, we characterize each firm's wind park by the same availability factor.

Interestingly, in general, this approach need not imply that both firms' wind availability coincides at all times. To the contrary, the location and wind-abundance of firms' wind parks can differ. We introduce and define $0 \leq \rho \leq 1$ as the *probability* that both firms experience identical conditions to generate power.[9] If weather conditions are perfectly negatively correlated ($\rho = 0$), states (w,w) and $(\overline{w},\overline{w})$ occur with zero probability. At the other extreme, perfect positive correlation ($\rho = 1$) rules out states $(w,\overline{w})$ and $(\overline{w},w)$. We interpret ρ as a measure of *system intermittency*. System intermittency is absent when there is always exactly one wind-abundant firm ($\rho = 0$). As ρ goes up, wind-availability in the system becomes more variable.[10] To summarize, figure 1 depicts the four states of nature and their corresponding probabilities.

The staging of the game is as follows. In stage one, both firms compete to serve the market, uncertain about the state of nature. If firms compete *à la Bertrand*, they simultaneously announce their price. The low-price firm i serves market demand $Q = 1 - p_i$, with p_i firm i's price, and the market clearing

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[9] Probability ρ relates to, but does *not* equal, the correlation coefficient between both firms' wind-availability. An alternative approach describes the probabilities corresponding to the four states of nature by using the correlation coefficient (see appendix). It yields longer expressions without adding new insights.

[10] The introduction of both parameters (ρ and α) involves the parameter restriction that $0.5(1-\rho) \leq \alpha \leq 0.5(1+\rho)$. To see why, if both firms are always wind-abundant ($\alpha = 1$) or windless ($\alpha = 0$), they necessarily experience the same generation conditions at all times ($\rho = 1$). In contrast, any ρ satisfies if each firm is maximally intermittent ($\alpha = 0.5$). The remainder of our paper considers intermittent power generation, so that $\alpha \neq 1$ and $\alpha \neq 0$.

quantity Q results. In the event of a tie, the firm serving the whole market is chosen by the toss of a fair coin.[11] In contrast, when firms compete *à la Cournot,* each firm simultaneously announces its output q_i and the market clearing price P results. In stage two, firms are completely informed about stage one outcomes. The state of nature is revealed and each firm must serve its consumers. Since consumers do not respond to prices in real time, each firm's sales are fixed. Firms can, however, outsource generation to one another using subcontracts.

Our two-stage setting fits the power generation industry well. Stage one can be interpreted as a futures market where firms sell power to be delivered the next month or year. Stage two, then, can be regarded as the spot market close to delivery, where firms exchange power as a response to more precise weather forecasts. Spot power exchange can take place on a bilateral basis or, alternatively, on organized day-ahead, intraday or balancing markets.[12]

We analyze what the strategic effects are when firms can subcontract power generation to one another. Subcontracting of power generation enables firms to reallocate generation in order to reduce costs. The gains from trade (henceforth gains from subcontracting) equal the reduction in industry generation costs made possible by subcontracting. If both firms are windless, state $(\overline{w},\overline{w})$, gains from subcontracting can arise because the dispatchable technology is characterized by upward sloping marginal costs. Equal sharing of generation between two portfolios of dispatchable units, rather than, for instance, serving all market demand using only one firm's generation, economizes on costs. If exactly one firm is windless, in state $(w,\overline{w})$ or $(\overline{w},w)$, that firm can either call on its own expensive dispatchable units or, alternatively, contract power generation to the rival firm. If both firms are wind-abundant, there are no gains from subcontracting because variable costs are zero.

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[11] Alternatively, each firm could serve half of market demand in the event they set equal prices. We show in the robustness section that this settlement rule leads to the same symmetric equilibrium price when firms sign subcontracts. Without subcontracts, however, the alternative settlement rule would create additional equilibria in pure strategies.

[12] In 2013, power exchange on the Spanish day-ahead and intraday markets amounted to €12 billion. These markets traded 71% of total power supply (Omie, 2014 & Red Eléctrica de España, 2014).

As a benchmark, we start with the assumption that firms cannot sign subcontracts. Since both firms can benefit from trade, we then analyze two forms of subcontracting. Firms can sign ex post subcontracts in stage two, after the state of nature is known. In contrast, firms sign ex ante subcontracts before they compete in stage one.

We model power as a homogeneous good.[13] Because the effects of subcontracts on competition and consumers are distinct for price and quantity competition, we provide both analyses.

3. No subcontracting

Bertrand competition – Firm i 's profit function can be written as

$$\begin{cases} p_i(1-p_i)-(1-\alpha)0.5\beta(1-p_i)^2 & \text{if } i \text{ wins} \\ 0 & \text{if } j \text{ wins.} \end{cases}$$

Firm i wins if $p_i < p_j$. The first term reflects its revenues since it sells at price p_i and serves market demand $Q=1-p_i$. Since firm i uses its dispatchable technology only with probability $1-\alpha$, its expected costs are $(1-\alpha)0.5\beta(1-p_i)^2$. In the event of a tie ($p_i = p_j$), a winner is randomly chosen by the toss of a fair coin. If firm j wins, firm i 's profits are zero as it does not serve any consumer at all.

Firms optimally set a price such that they are indifferent between winning and losing. As a result, their expected profits must be zero. We find that the equilibrium price, where it is impossible for firms to profitably deviate, equals

[13] Alternatively, consumers could have a preference for renewable energy. Our paper, however, focuses on intermittency, not on renewability.

$$p_i^* = p_j^* = \frac{(1-\alpha)\beta}{2+(1-\alpha)\beta}.$$

Cournot competition – Firm i 's profit function can be written as

$$(1-q_i-q_j)q_i-(1-\alpha)0.5\beta q_i^2,$$

where the first term reflects firm i 's revenues from selling q_i units and the second part equals expected production costs. The necessary and sufficient first-order conditions for profit maximization look like

$$q_i(q_j) = \frac{1-q_j}{2+(1-\alpha)\beta},$$

resulting in equilibrium quantities

$$q_i^* = q_j^* = \frac{1}{3+(1-\alpha)\beta}.$$

Equilibrium quantities are decreasing in the cost parameter of the dispatchable technology β.

4. Subcontracting

This section studies what happens if firms sign subcontracts. Since we look for the subgame perfect Nash equilibrium, we start our analysis in the subcontracting stage (stage two). Firms use subcontracts to outsource power generation. We first study the potential gains from subcontracting in each possible state. Second, we model how these gains are shared.

In state (w,w), there are no gains from subcontracting because both firms have access to zero-cost generation from their intermittent technology. In state $(\overline{w},w)$, however, firms experience asymmetric generation conditions. Without trade, the windless firm i must use its costly dispatchable technology to deliver its announced stage-one output q_i. In contrast, an efficient subcontract allows it to buy q_i from the wind-abundant firm, which produces at zero marginal cost. Total gains from subcontracting equal the reduction in industry production costs resulting from the subcontract, or, equivalently firm i 's opportunity cost $C(q_i)=0.5\beta q_i^2$. Analogously, in state $(w,\overline{w})$, windless firm j buys from firm i so that gains from subcontracting equal $C(q_j)=0.5\beta q_j^2$. Finally, in state $(\overline{w},\overline{w})$, both firms are windless. The efficient subcontract then allocates production equally between both firms. For instance, if $q_i<q_j$, firm i has a lower marginal production cost as compared to firm j. It is then efficient that firm i sells power up to the point where both firms produce $0.5(q_i+q_j)$. Potential gains from subcontracting equal the reduction in industry production costs

$$C(q_i)+C(q_j)-2C\left(0.5(q_i+q_j)\right)=0.5\beta(q_i^2+q_j^2-0.5(q_i+q_j)^2).$$

We assume efficient subcontracting, meaning that firms take advantage of all potential gains from trade. Subcontracts are, in our setting, ex post Pareto-efficient and therefore renegotiation-proof. Let $\boldsymbol{\sigma}$ be the share of realized gains from subcontracting appropriated by the selling firm (subcontractor), with $0\le\boldsymbol{\sigma}\le 1$.[14]

We distinguish two types of subcontracts. *Ex post subcontracts* are signed in stage two, after the state of nature is revealed. Then, the terms of trade at which the contractor buys power from the subcontractor is determined *exogenously* by $\boldsymbol{\sigma}=\sigma_{\mathrm{p}}$.[15] In contrast, an *ex ante subcontract* is signed before firms compete in stage one. It is an option contract that, if exercised, allocates generation efficiently. The efficient amount of outsourcing between both firms depends on the state of nature and each firm's sales. The ex ante subcontract also specifies how firms *share* the gains from subcontracting. Formally, firms contractually set $\boldsymbol{\sigma}=\sigma_{\mathrm{a}}$ *endogenously* before the state of nature reveals. Share σ_{a} results in a price to

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[14] We assume $\boldsymbol{\sigma}$ is player and state invariant.

[15] Share σ_{p} captures a wide range of exogenous factors or institutions that determine the seller's bargaining or market power. Kamien et al. (1989) interpret the seller as a Stackelberg leader if $\boldsymbol{\sigma}=1$. The symmetric Nash-bargaining solution corresponds to $\boldsymbol{\sigma}=0.5$.

be paid by the contractor to exercise the option. The exercise price depends on the state and each firm's sales.[16] The remainder of our paper refers to ex ante subcontracts and option contracts interchangeably.

Our efficient ex ante subcontract should satisfy the following properties. First, both firms should agree to the contract that maximizes their expected profits non-cooperatively. To be precise, we look for a subgame perfect symmetric equilibrium where firms share a preference for the same σ_{a}.[17] The option to buy from the subcontractor will never be exercised in stage two, however, if $\sigma_{\mathrm{a}} > 1$. In-house production would then outperform exercising the option contract. To meet subgame perfectness, we therefore impose $\sigma_{\mathrm{a}} \leq 1$ as a second requirement.

We now turn to stage one, where firms compete to serve the market. We study Bertrand and Cournot competition, respectively.

Bertrand competition — Firm i 's profit function can be written as

$$\begin{cases} (1-p_i)\,p_i - (1-\alpha)0.5\beta(1-p_i)^2 + (1-\boldsymbol{\sigma})\underbrace{\left(\frac{1\text{-}\rho}{2}0.5\beta(1-p_i)^2 + \frac{1-2\alpha+\rho}{2}0.25\beta(1-p_i)^2\right)}_{\text{expected gains from subcontracting}} & \text{if } i \text{ wins} \\ \boldsymbol{\sigma}\underbrace{\left(\frac{1\text{-}\rho}{2}0.5\beta(1-p_j)^2 + \frac{1-2\alpha+\rho}{2}0.25\beta(1-p_j)^2\right)}_{\text{expected gains from subcontracting}} & \text{if } j \text{ wins.} \end{cases}$$

If firm i wins (by charging the lowest price or, in the event of a tie, by winning the toss of a fair coin) and serves the market, its customer revenues are captured by the first term. The second term reflects its expected costs without subcontracting. The last term represents its expected gains from efficient subcontracting. That is, the winning firm i buys power from firm j in states $(\overline{w}, w)$ and $(\overline{w}, \overline{w})$. Therefore, in addition to its customer revenues, firm i appropriates share $(1-\boldsymbol{\sigma})$ of the expected gains

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[16] Implementing the efficient ex ante subcontract can prove challenging when firms are asymmetrically informed. This interesting issue is not the focus of our paper.

[17] Notice that the intermittent technology enables us to explain subcontracts between (ex ante) *symmetric* firms. With asymmetric firms, it becomes less clear how σ_{a} is determined. For instance, Spiegel (1993) then assumes firms maximize joint profits.

from subcontracting. If firm i loses (by charging the highest price or, in the event of a tie, by losing the toss of a fair coin) and does not serve the market, it still makes positive profits since it can extract a share $\boldsymbol{\sigma}$ of the expected gains from efficient subcontracting.

Figure 2 depicts firm i's expected subcontracting revenues as a function of its price p_i. Notice the discontinuity at price $p_i = p_j$, where firm i can boost its subcontracting revenues by raising its price ($p_i > p_j$). In a symmetric equilibrium, a firm's incentive to increase its price — and earn subcontracting revenues only — should be offset by sufficient consumer revenues during stage one. A symmetric equilibrium price should necessarily satisfy that a firm is indifferent between serving and not serving the market.[18] We obtain that firms cannot profitably deviate when they charge

$$p^* \equiv \frac{\beta\left(1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\right)}{8+\beta\left(1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\right)}.$$

As a result, the unique symmetric equilibrium price equals $p_i^* = p_j^* = p^*$, increasing in share $\boldsymbol{\sigma}$ and decreasing in probability α, where profits are positive and equal

$$\frac{8\boldsymbol{\sigma}\beta\left(3-\rho-2\alpha\right)}{\left(8+\beta\left(1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\right)\right)^2}.$$

When $\boldsymbol{\sigma}$ is low, firms earn little subcontracting revenues during stage two, so that they are willing to compete fiercely during stage one. When $\boldsymbol{\sigma}$ is high, in contrast, competition for consumers is reduced because firms also benefit significantly from charging the highest price.

Interestingly, firms maximally gain from subcontracting when they never experience identical generation conditions ($\rho = 0$). The windless firm always buys cheap power from the wind-abundant firm. As the system becomes more intermittent (ρ goes up), we find two opposing effects on the equilibrium price.

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[18] Obviously, firms can profitably deviate from $p = 1$ by lowering their price and serving consumers.

On the one hand, generation costs increase, which tends to increase the price. On the other hand, firms compete more fiercely by charging a lower price because the high-price firm earns less expected subcontracting revenues. It can be checked that the second effect dominates if and only if the subcontractor receives sufficient stage-two revenues ($\boldsymbol{\sigma} > 0.5$).

If firms sign ex post subcontracts, share $\boldsymbol{\sigma} = \sigma_{\mathrm{p}}$ is exogenous and profits are as stated above. However, if firms sign ex ante subcontracts, we should further analyze how firms will choose the subcontracting terms endogenously. Under the constraint that $\sigma_{\mathrm{a}} \leq 1$, each firm independently maximizes its profits with respect to σ_{a} so that firms set

$$\begin{cases} \sigma_{\mathrm{a}}^{*} = \dfrac{8+\beta\left(1+\rho-2\alpha\right)}{2\beta(3-\rho-2\alpha)} & \text{for } \beta \geq \dfrac{8}{5-2\alpha-3\rho} \\ \sigma_{\mathrm{a}}^{*} = 1 & \text{for } \beta < \dfrac{8}{5-2\alpha-3\rho}. \end{cases}$$

We find that if the dispatchable technology is sufficiently expensive, the subcontracting terms can be set to let firms choose monopoly price levels in the first stage and obtain monopoly rents. Conversely, if dispatchable generation costs are low, firms would like to implement subcontracting costs that outweigh the opportunity costs in order to maximize industry profits. However, since the contractor then prefers the “make”-option to the “buy”-option, firms optimally determine the subcontracting terms by setting $\sigma_{\mathrm{a}}^{*} = 1$. By doing so, the optimal ex ante contract raises the subcontracting payments to the level of the contractor’s opportunity costs.

We illustrate the intuition behind ex ante subcontracting by using a numerical example. Let $\rho = 0$ and $\alpha = 0.5$ such that either $(\bar{w}, w)$ or $(w, \bar{w})$ occurs. Put differently, there is exactly one windless firm that contracts power from the wind-abundant firm. It follows that industry generation costs are always zero in equilibrium. If the dispatchable technology is cheap, e.g. $\beta = 1$, firms set $p^{*} = \dfrac{1}{1+2/\sigma_{\mathrm{a}}}$. Firms’ equilibrium prices are increasing in subcontracting costs. Ideally, firms would like to raise subcontracting costs such that they each charge monopoly price $p^{m} = 1/2$. This, however, would require $\sigma_{\mathrm{a}} = 2$ and the subcontracting cost would exceed the cost of dispatching the expensive back-up plant. Therefore, firms can do no better than setting $\sigma_{\mathrm{a}}^{*}=1$, earning expected profits of $1/9$, equivalent to Cournot profits with zero costs. Now suppose dispatchable units are expensive, e.g. $\beta=4$, wherefrom firms set a higher price $p^{*}=\dfrac{1}{1+1/(2\sigma_{\mathrm{a}})}$. Firms can now obtain monopoly profits by pinning down $\sigma_{\mathrm{a}}^{*}=0.5$. That is, the gains from subcontracting are shared according to the symmetric Nash bargaining solution.

Remark that the price paid for subcontracting matters since it alters firms' marginal cost, and therefore prices, even when expected subcontracting payments cancel out in equilibrium. A "bill-and-keep" system where payments are zero ($\sigma_{\mathrm{a}}=0$) is not profit-neutral.[19]

Cournot competition — Firm i's profit function can be written as

$$(1-q_i-q_j)q_i-(1-\alpha)0.5\beta q_i^2+\frac{1-\rho}{2}\frac{\beta}{2}\left(\boldsymbol{\sigma}q_j^2+(1-\boldsymbol{\sigma})q_i^2\right)+\begin{cases}\dfrac{(1-2\alpha+\rho)}{2}\underbrace{\boldsymbol{\sigma}\dfrac{\beta}{2}(q_i^2+q_j^2-0.5(q_i+q_j)^2)}_{i\text{'s gains from subcontracting in }(\bar{w},\bar{w})} & \text{if } q_i\leq q_j\\ \dfrac{(1-2\alpha+\rho)}{2}\underbrace{(1-\boldsymbol{\sigma})\dfrac{\beta}{2}(q_i^2+q_j^2-0.5(q_i+q_j)^2)}_{i\text{'s gains from subcontracting in }(\bar{w},\bar{w})} & \text{if } q_i\geq q_j.\end{cases}$$

The first term displays firm i's revenues from serving its customers, whereas the second term represents its costs without subcontracting. The third term denotes firm i's expected gains from subcontracting in the events that firms encounter asymmetric generation conditions (states $(\bar{w},w)$ and $(w,\bar{w})$). If firm i happens to have favorable wind conditions, it receives its share $\boldsymbol{\sigma}$ of the gains from subcontracting. Otherwise, it appropriates a fraction $1-\boldsymbol{\sigma}$ of the gains from subcontracting. The last term captures the gains from subcontracting if both firms have unfavorable wind conditions (state $(\bar{w},\bar{w})$). The profit function depends here on firm i's quantity as compared to firm j's. If $q_i<q_j$, firm i sells power and

[19] The intuition also relates to two-way access competition in industries with a bottleneck like in telecommunications (see Armstrong (1998) and Laffont, Rey, and Tirole (1998)).

obtains the seller's share $\boldsymbol{\sigma}$ of available surplus. If $q_i > q_j$, it acts as a buyer and gets share $1-\boldsymbol{\sigma}$ of available surplus. Both expressions coincide if $q_i = q_j$ or $\boldsymbol{\sigma} = 0.5$.

We maximize firm i 's profits with respect to q_i. Using the necessary and sufficient first-order conditions, we find that equilibrium quantities equal

$$q_i^* = q_j^* = \frac{1}{3 + 0.5\beta\left(\boldsymbol{\sigma} + (1-\boldsymbol{\sigma})\rho\right) + \beta\left(0.5 - \alpha\right)}.$$

They are increasing in α and decreasing in $\boldsymbol{\sigma}$ and ρ. We show in the Appendix (proposition A1) that this equilibrium is locally stable, so that firms' profits can be written as

$$\frac{4 + \beta\left(\rho\left(1-2\boldsymbol{\sigma}\right) + 2\boldsymbol{\sigma} + 1 - 2\alpha\right)}{\left(6 + \beta\left(\rho\left(1-\boldsymbol{\sigma}\right) + \boldsymbol{\sigma} + 1 - 2\alpha\right)\right)^2}.$$

When firms engage in ex post subcontracting, the share $\boldsymbol{\sigma} = \sigma_{\mathrm{p}}$ is exogenous and firms' profits are as stated above. However, if firms rely on ex ante subcontracts, symmetric firms choose $\boldsymbol{\sigma} = \sigma_{\mathrm{a}}$ endogenously such that each firm's profits are maximized. Subject to $\sigma_{\mathrm{a}} \leq 1$, firms set

$$\begin{cases} \sigma_{\mathrm{a}}^* = \dfrac{2}{\beta(1-\rho)} & \text{for } \beta \geq \dfrac{2}{1-\rho} \\ \sigma_{\mathrm{a}}^* = 1 & \text{for } \beta < \dfrac{2}{1-\rho}, \end{cases}$$

where the interpretation is analogous to our Bertrand case.

The role of the cost parameter β is twofold. First, it directly determines firms' generation costs when firms are obliged to use their dispatchable technology (state $(\overline{w}, \overline{w})$). Intuitively, high costs imply low industry output and low profits.

Second, interestingly, the cost parameter β also determines the gains from subcontracting, and hence, the subcontracting terms. As such, β also has an indirect effect on industry output and profits. The following section is concerned with this indirect effect and studies to what extent installing dispatchable units can be strategically advantageous.

5. Investment in idle dispatchable units

This section investigates whether firms have *strategic* motivations to install or maintain dispatchable units, and hence, to provide back-up power supply. Simple measures of plant profitability are then inappropriate to evaluate how dispatchable units contribute to a firm's profits. Otherwise stated, profit maximization by firms need not imply that each of its plants generates sufficient revenues to cover its costs.

To simplify the analysis, we consider a setting where the capacity factor of the dispatchable technology is zero. Formally, dispatchable units never generate power (are idle) when $\rho = 0$, and hence $\alpha = 0.5$ due to symmetry. In this setting, dispatchable units only affect each firm's profits by their strategic role. We also assume that firms sign ex ante subcontracts. The interpretation is that firms take advantage of the possibility to increase their profits. Finally, note that investment in dispatchable units is interpreted as a *decrease* in β (see section 2). Conversely, cost parameter β *increases* when firms divest their dispatchable units.

We successively state and interpret our three central propositions. Proposition 1 shows that, whenever dispatchable power generation is sufficiently expensive, firms implement monopoly profits by charging subcontracting payments below the contractor's opportunity cost of in-house generation. Alternatively, subcontracting costs are raised up to the opportunity cost of in-house generation. In that event, firms can increase profits by *jointly* divesting idle dispatchable units (proposition 2). *Unilaterally*, in contrast, firms have an incentive to install additional idle dispatchable units (proposition 3). Proposition 1 follows directly from our analysis in section 4. The appendix provides the proofs of proposition 2 and 3.

Proposition 1: Firms reach monopoly profits whenever idle dispatchable power generation is sufficiently expensive.

When dispatchable units are expensive to use ($\beta \geq 2$), in-house generation is costly so that firms have a high willingness to pay for outsourcing. Accordingly, firms implement monopoly profits by signing the ex ante subcontract that determines the optimal subcontracting payments.

Proposition 2: When subcontracting payments amount to the contractor's opportunity cost of in-house generation, firms increase profits by jointly divesting idle dispatchable units.

The intuition behind proposition 2 goes as follows. For $\beta < 2$, firms use ex ante subcontracts to make outsourcing as expensive as in-house generation. When firms jointly divest dispatchable units, it is more costly for the contractor to generate its power in-house. Consequently, it has a higher willingness to pay for the subcontract. Firms can then design more expensive subcontracting payments, less consumers are served and profits increase.

Proposition 3: When subcontracting payments amount to the contractor's opportunity cost of in-house generation, unilaterally, a firm is willing to incur a fixed cost in order to build additional *idle* dispatchable units.

For $\beta < 2$, a firm's subcontracting costs equal its opportunity cost of in-house generation in the event it is windless. Being equipped with additional idle dispatchable units is then profitable because it reduces the opportunity cost of generating in-house, and hence, the subcontracting payments made to the rival.

In summary, investment in dispatchable units displays features of a prisoner's dilemma. Unilaterally, firms are willing to incur a fixed investment cost to install dispatchable units. By doing so, they reduce the subcontracting payments made to the rival. In contrast, firms can make in-house power generation expensive by jointly divesting dispatchable units. Such a joint action raises profits because it enables firms to determine higher subcontracting payments that reduce industry output.

As such, overcapacity in power markets can be explained by firms protecting themselves against hold-up by the rival. Alternatively, instances of numerous mothballed peaking plants in some countries could be the result of a joint action to raise prices.

Interestingly, when the dispatchable technology remains idle, one might think that each firm is better off being equipped with the intermittent technology only. Then, if that firm makes sales and turns windless, it must outsource generation to the rival, irrespective of the subcontracting payment. Clearly, the lack of reliable alternative results in prohibitive subcontracting costs. Therefore, without a dispatchable technology, the firm optimally chooses to wait and not to serve any consumers during stage one. However, provided that the rival serves consumers, the firm *does* earn subcontracting revenues in the event the rival is windless.[20]

The appendix shows that each firm strictly profits from its idle dispatchable units (proposition A2). A firm equipped with the dispatchable technology, characterized by zero plant profitability, earns strictly higher profits. It is willing to incur a fixed (maintenance) cost to be equipped with the dispatchable technology.

6. Tacit collusion

In this section we study the possibilities for firms to sustain tacit collusion. For simplicity, we focus on state $(w, \overline{w})$ and $(\overline{w}, w)$ by setting $\rho = 0$ and $\alpha = 0.5$. There is exactly one windless firm, which contracts its output from the wind-abundant firm.

[20] Of course, the rival is then a monopolist during stage one. If firms compete à la Bertrand, a higher price is charged, and fewer consumers are served accordingly. This results in low subcontracting revenues. In contrast, if both firms compete in stage one, the equilibrium consists of a lower price and higher sales. More consumers are served, and the firm, with its idle dispatchable units, earns higher subcontracting revenues (or it profits equivalently when it serves the market).

We study collusive agreements where colluding firms maximize industry profits, which they share equally in expectation. As a result, in stage one, colluding firms set prices or quantities such that industry profits are maximized. If there is a subcontracting stage (stage two), we allow the collusive agreement to include a collusive subcontracting transfer from the windless firm i to the wind-abundant firm j. It is based on windless firm i's opportunity cost $C(q_i)$. Let $\sigma_{\mathrm{p}}^{\mathrm{c}}$ be the share of surplus from the ex post subcontract appropriated to the seller under collusion. Likewise, if firms collude, share $\sigma_{\mathrm{a}}^{\mathrm{c}}$ allocates the gains from an ex ante contract. These transfers do not affect firms' expected profits from collusion. They may, though, affect both firms' incentives to deviate.

Colluding firms employ grim-trigger strategies, such that any deviation from the collusive agreement results in competing forever. Since we assume firms are completely informed about the outcome of stage one, firms detect any deviation immediately. Sustainable collusion then requires two incentive constraints. First, firms should prefer not to deviate in stage one. Second, firms should neither prefer to deviate in stage two.

For convenience, we start with the analysis of the second incentive constraint. Once colluding firms attain stage two, they should not have an incentive to revert to market-based subcontracting terms, where the seller receives share $\boldsymbol{\sigma} = \sigma_{\mathrm{p}}$ or $\boldsymbol{\sigma} = \sigma_{\mathrm{a}}$ of the subcontracting rents.

Clearly, this incentive constraint is only relevant if subcontracting is allowed. Otherwise, there is no stage two.

We start with ex post subcontracting. Let Π^{coll} and Π^{comp} be a firm's expected profits under collusion and competition, respectively, where $\Pi^{\mathrm{coll}} \geq \Pi^{\mathrm{comp}}$. Denote the common discount factor by $0 \leq \delta < 1$. The second incentive constraint can then be written as

$$\begin{cases} \sigma_{\mathrm{p}}^{\mathrm{c}} C(q_i) + \dfrac{\delta}{1-\delta}\Pi^{\mathrm{coll}} \geq \sigma_{\mathrm{p}} C(q_i) + \dfrac{\delta}{1-\delta}\Pi^{\mathrm{comp}} & \text{firm } j \\ -\sigma_{\mathrm{p}}^{\mathrm{c}} C(q_i) + \dfrac{\delta}{1-\delta}\Pi^{\mathrm{coll}} \geq -\sigma_{\mathrm{p}} C(q_i) + \dfrac{\delta}{1-\delta}\Pi^{\mathrm{comp}} & \text{firm } i. \end{cases}$$

It consists of two components. The upper component reflects the condition that wind-abundant firm j should not prefer deviating. Likewise, the lower component states the condition under which windless firm i is unwilling to deviate. Sustainable collusion requires both conditions to be satisfied.

The left hand side denotes, for both firms, profits from complying with the collusive subcontracting transfer. In that event, wind-abundant firm j receives collusive subcontracting payments $\sigma_{\mathrm{p}}^{\mathrm{c}} C\left(q_i\right)$ from windless firm i, after which both firms collude forever. Deviation profits are shown at the right hand sides of the inequalities. Then, firms share the gains from subcontracting at the prevailing ex post subcontracting terms. Windless firm i pays an amount of $\sigma_{\mathrm{p}} C\left(q_i\right)$ to wind-abundant firm j, after which both firms compete forever.

Proposition 4: If colluding firms apply the prevailing ex post subcontracting terms ($\sigma_{\mathrm{p}}^{\mathrm{c}} = \sigma_{\mathrm{p}}$), firms never profitably deviate in stage two.

Proof: If $\sigma_{\mathrm{p}}^{\mathrm{c}} = \sigma_{\mathrm{p}}$, firms cannot alter ex post subcontracting payments by deviating. The second incentive constraint reduces to

$$\begin{cases} \dfrac{\delta}{1-\delta}\Pi^{\mathrm{coll}} \geq \dfrac{\delta}{1-\delta}\Pi^{\mathrm{comp}} & \text{firm } j \\ \dfrac{\delta}{1-\delta}\Pi^{\mathrm{coll}} \geq \dfrac{\delta}{1-\delta}\Pi^{\mathrm{comp}} & \text{firm } i, \end{cases}$$

which is always satisfied since $\Pi^{\mathrm{coll}} \geq \Pi^{\mathrm{comp}}$. ■

We now assess the second incentive constraint if ex ante subcontracts are allowed. Then, firms are contractually committed to share the gains from subcontracting as agreed ex ante. Since it is impossible to do better for both firms, the ex ante subcontract is renegotiation-proof. Firms cannot deviate from an enforceable contract and, as a result, the second incentive constraint is always satisfied.

We proceed the analysis with the first incentive constraint. To sustain collusion, each firm should profitably set the collusive price (Bertrand) or quantity (Cournot) in stage one. As a benchmark, we start with no subcontracts. We then study subcontracts. In each case, our analysis requires three components: collusive profits, deviation profits and competition (or non-cooperative) profits. We can make use of the competition profits obtained from sections 3 and 4.

We provide the analysis for Cournot competitors. The appendix checks that Bertrand competition yields the same insights.

No subcontracting — The industry profits under collusion result from maximizing the joint profit function

$$\left(q_i+q_j\right)(1-q_i-q_j)-0.25\beta q_i^{2}-0.25\beta q_j^{2}.$$

with respect to q_i and q_j, where symmetry requires $q_i=q_j$.

It can be checked that the condition for sustained collusion should satisfy

$$\frac{1}{1-\delta}\underbrace{\frac{1}{8+\beta}}_{\text{collusive profits}}\geq\underbrace{\frac{(6+\beta)^2}{(4+\beta)(8+\beta)^2}}_{\text{deviation profits}}+\frac{\delta}{1-\delta}\underbrace{\frac{4+\beta}{(6+\beta)^2}}_{\text{competition profits}}.$$

As a result, the critical discount factor equals

$$\frac{(6+\beta)^2}{2(34+12\beta+\beta^2)}.$$

Remark that $\partial\delta/\partial\beta<0$ so that tacit collusion is more difficult to sustain when the dispatchable technology is more expensive.

Subcontracting — Since the dispatchable technology remains idle in equilibrium ($\rho=0$), the industry generation cost always equals zero. Symmetric colluding firms each set $q_i=q_j=0.25$ such that industry profits are maximized at $1/8$ per firm.

The following proposition discusses how firms optimally deviate. A deviating firm takes into account potential subcontracting payments during stage two. When firms sign ex post subcontracts, if deviation occurs during stage one, the subcontracting terms are determined by the exogenous share $\boldsymbol{\sigma} = \sigma_{\mathrm{p}}$. If firms sign ex ante subcontracts, a deviating firm can contractually enforce $\boldsymbol{\sigma} = \sigma_{\mathrm{a}}^{\mathrm{c}}$ to be the seller's share of gains from subcontracting.

Proposition 5 : Firms deviate from the collusive quantity by selling less if and only if subcontracting payments are substantial.

A deviating firm optimally sells $\dfrac{3}{2(4+\boldsymbol{\sigma}\beta)}$, the best response to the competitor's collusive quantity 0.25. If subcontracting is sufficiently cheap ($\boldsymbol{\sigma}\beta < 2$), the "revenue effect" from selling more outweighs the expected additional subcontracting cost. A firm then deviates by choosing a higher quantity. In contrast, if subcontracting payments are substantial ($\boldsymbol{\sigma}\beta > 2$), the deviating firm optimally sets a *lower* quantity. The reasoning is that a lower quantity has a "subcontracting effect." That is, it decreases the subcontracting cost in the event the firm is windless. A firm's optimal deviation quantity trades off the revenue effect versus the subcontracting effect. Notice that, if $\boldsymbol{\sigma}\beta = 2$, both effects cancel out: collusive quantities coincide with competitive quantities.[21]

If firms sign ex post subcontracts, any deviation in stage one can immediately be detected in stage two. The subcontracting terms are then determined by the exogenous share σ_{p}. It follows that sustained collusion should satisfy

$$\frac{1}{1-\delta}\underbrace{\frac{1}{8}}_{\substack{\text{collusive}\\\text{profits}}} \geq \underbrace{\frac{9}{16(4+\sigma_{\mathrm{p}}\beta)}+\frac{\sigma_{\mathrm{p}}\beta}{64}}_{\text{deviation profits}}+\frac{\delta}{1-\delta}\underbrace{\frac{2(2+\sigma_{\mathrm{p}}\beta)}{(6+\sigma_{\mathrm{p}}\beta)^2}}_{\text{competition profits}}.$$

The critical discount factor, for $\sigma_{\mathrm{p}}\beta \neq 2$, then equals $\dfrac{(\sigma_{\mathrm{p}}\beta+6)^2}{(\sigma_{\mathrm{p}}\beta)^2+20\sigma_{\mathrm{p}}\beta+68}$.

[21] In that event, any discount factor sustains collusion because firms cannot profitably deviate.

When ex ante subcontracts are signed, if a firm deviates in stage one, it can contractually enforce to let $\sigma_{\mathrm{a}}^{\mathrm{c}}$ share the gains from subcontracting. From the next period onwards, firms behave competitively and set σ_a^* accordingly, as analyzed in section 4. The incentive constraint to sustain collusion becomes

$$\frac{1}{1-\delta}\underbrace{\frac{1}{8}}_{\substack{\text{collusive}\\ \text{profits}}} \geq \underbrace{\frac{9}{16(4+\sigma_{\mathrm{a}}^{\mathrm{c}}\beta)}+\frac{\sigma_{\mathrm{a}}^{\mathrm{c}}\beta}{64}}_{\text{deviation profits}}+\frac{\delta}{1-\delta}\underbrace{\frac{2(2+\sigma_a^*\beta)}{(6+\sigma_a^*\beta)^2}}_{\text{competition profits}}.$$

Notice that expected collusive profits, as well as competition profits are invariant to the choice of $\sigma_{\mathrm{a}}^{\mathrm{c}}$. As a consequence, to maximize the sustainability of collusion, firms simply set $\sigma_{\mathrm{a}}^{\mathrm{c}}$ such that deviation is least attractive.

Suppose firms set $\sigma_{\mathrm{a}}^{\mathrm{c}} = 2/\beta$. Then deviation profits coincide with collusive profits. Collusion is maximally sustainable because firms cannot gain from deviating. However, if $\sigma_{\mathrm{a}}^{\mathrm{c}} > 1$, in-house production outperforms exercising the option contract. Therefore, if $\beta \leq 2$, colluding firms minimize deviation profits by raising subcontracting costs as high as possible, up to the level of the opportunity cost. To conclude, if ex ante contracts are allowed, colluding firms optimally set

$$\begin{cases} \sigma_{\mathrm{a}}^{\mathrm{c}*} = \dfrac{2}{\beta} & \text{for } \beta \geq 2 \\ \sigma_{\mathrm{a}}^{\mathrm{c}*} = 1 & \text{for } \beta < 2. \end{cases}$$

For $\beta \geq 2$, firms implement monopoly profits, irrespective of their discount factor. They do not need to collude in order to maximize their profits. For $\beta < 2$, firms have an interest in deviating from the collusive agreement. Even when firms make deviation least attractive by setting $\sigma_{\mathrm{a}}^{\mathrm{c}*} = 1$, collusion remains difficult to sustain with subcontracts. The reason is that a deviating firm has the prospect of earning nice competition profits from the next period onwards.[22]

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[22] It can be shown that the critical discount factor for $\beta < 2$ is higher with subcontracts than without subcontracts. Whether subcontracts increase consumer welfare is discussed in the next section.

Proposition 6: The ex ante subcontracting terms if firms behave competitively also maximize the sustainability of collusion. It is therefore impossible for a third party, i.e. a regulator or antitrust authority, to distinguish collusive from competitive behavior on the basis of the ex ante subcontracting terms.

This result arises because the objectives of competing and colluding firms are related. Competing firms use the subcontracting terms to maximize competition profits. Otherwise stated, they minimize the difference between collusive and competition profits. Quite similarly, colluding firms minimize the gain from deviation, defined as the difference between collusive and deviation profits.

7. Welfare

This section presents and discusses the welfare implications that follow from our analysis. Producer welfare is measured by industry profits. Consumer welfare is measured by consumer surplus $CS = 0.5Q^{*2}$, which is a function of the equilibrium industry output Q^*.

Proposition 7: If the subcontractor appropriates a larger share $\boldsymbol{\sigma}$ of the subcontracting rents, industry output decreases so that consumers are worse off.

Proof: If firms compete à la Bertrand, industry output equals

$$1-p^* = 1-\frac{\beta\left(1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\right)}{8+\beta\left(1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\right)}$$

and is decreasing in $\boldsymbol{\sigma}$. When firms compete à la Cournot, industry output equals

$$q_i^* + q_j^* = \frac{2}{3+0.5\beta\left(\boldsymbol{\sigma}+(1-\boldsymbol{\sigma})\rho\right)+\beta\left(0.5-\alpha\right)}$$

and is also decreasing in $\boldsymbol{\sigma}$.■

If firms compete à la Bertrand, there is fierce competition to serve the market when subcontracting is cheap. Firms have a strong incentive to undercut. However, if subcontracting payments are significant, firms also profit from setting the highest price. The losing firm can extract a large share $\boldsymbol{\sigma}$ of subcontracting rents, paid for by the winning firm. As a consequence, there is less incentive to undercut the rival and serve the market. Firms set higher equilibrium prices and, as a result, fewer consumers are served.

If competition is characterized by quantity-setting, low subcontracting payments invite firms to increase output. That is, firms are willing to incur extra subcontracting costs in return for more consumer revenues. In contrast, if subcontracting payments are substantial, firms are reluctant to compete fiercely.

Proposition 8: Subcontracts that sufficiently favor the contractor increase consumer surplus. Subcontracts always increase industry profits.

The appendix provides the proof.

When firms compete à la Bertrand, subcontracts enhance consumer surplus for every $\boldsymbol{\sigma} \leq 0.5$. When firms compete à la Cournot, subcontracts make consumers better off if $\boldsymbol{\sigma} \leq 1$.

We distinguish two opposing effects of subcontracts on consumers. First, if firms can reduce generation costs by outsourcing generation to the rival firm, they have a stronger incentive to serve many consumers. Second, price competing firms boost their subcontracting revenues by charging the highest price, so that they are less willing to compete fiercely when $\boldsymbol{\sigma}$ is large.

To state the following proposition, we define the threshold value $\hat{\beta} \equiv \dfrac{4}{4\boldsymbol{\sigma}(1-\alpha)-\rho+2\alpha-1}$. Notice that $\hat{\beta}$ can be positive or negative.

Proposition 9: If the dispatchable technology is sufficiently expensive ($\beta > \hat{\beta} > 0$), quantity competition outperforms price competition with regard to consumer surplus.

The appendix provides the proof.

A firm has less incentives to serve consumers if it thereby reduces its subcontracting revenues. This effect, which makes consumers worse off, is stronger for price competition than for quantity competition. If firms compete à la Bertrand, the low-price firm serves the whole market. Consequently, it never earns subcontracting revenues since the high-price firm sells zero output. The high-price firm, in contrast, *does* benefit from subcontracting payments in the event the low-price firm is windless (see figure 2). As a result, firms are less inclined to compete for the market. This effect is far less apparent if firms compete à la Cournot, where firm i 's subcontracting revenues are continuous in its output q_i . To be precise, by serving more consumers, firm i does not alter its subcontracting revenues if it sells wind power to firm j . Quantity-competing firms, therefore, suffer less from a reduction in subcontracting revenues by competing fiercely for customers.

Figure 3 illustrates the effect of subcontracts on consumer surplus when $\hat{\beta} > 0$ and $\boldsymbol{\sigma} > 0.5$. If dispatchable units are inexpensive to use ($\beta < \hat{\beta}$), costs are low so that firms compete fiercely. Bertrand competition then leaves consumers best off. Since the subcontractor benefits significantly from the subcontract ($\boldsymbol{\sigma} > 0.5$), subcontracts *reduce* consumer surplus if firms compete à la Bertrand. In contrast, if Cournot-competing firms use subcontracts to reduce costs, consumers benefit. For subcontracting with a sufficiently expensive dispatchable technology ($\beta > \hat{\beta}$), quantity competition outperforms price competition with regard to consumer surplus.

Figure 4 illustrates the effect of ex post and ex ante subcontracts on consumer surplus.[23] Subcontracting costs increase as dispatchable units become more expensive. If conventional plants are cheap, the ex post

[23] Figure 4 illustrates the general case where $0 < \sigma_{\mathrm{p}} < 1$. It is illustrated that, for β sufficiently large, the ex ante subcontract outperforms the ex post subcontract in terms of consumer surplus, or $\sigma_{\mathrm{p}} > \sigma_a^*$ (from proposition 7). When firms compete à la Cournot, $\lim_{\beta \to \infty} \sigma_a^* = 0$, so that any $0 < \sigma_{\mathrm{p}} < 1$ can indeed exceed the profit-maximization σ_a^* for large β . When firms compete à la Bertrand, however, our figure only applies if $\sigma_{\mathrm{p}} > \lim_{\beta \to \infty} \sigma_a^* = \dfrac{1+\rho-2\alpha}{2(3-\rho-2\alpha)}$ from l'Hôpital's rule.

subcontract is characterized by low payments. An ex ante subcontract would then be used by firms to raise the price, at the expense of consumer surplus.

In contrast, for sufficiently expensive dispatchable units, if firms sign ex post subcontracts, industry output can drop well below the collusive output. Firms can then leave consumers better off by signing ex ante subcontracts that reduce subcontracting costs and raise industry output up to the collusive level. Counterintuitively, ex ante subcontracts can outperform ex post subcontracts with regard to consumer surplus.

8. Discussion and robustness

Supply function competition — Our set-up assumed Bertrand or Cournot competition in stage one. We now consider the possibility that firms compete by submitting supply functions.[24] That is, every firm submits a continuously differentiable non-decreasing schedule $q_i(p)$, which specifies, for each price, the quantity it is willing to offer.

The supply function approach contributes to our paper because it enables us to tractably introduce demand uncertainty.[25] Moreover, the analysis of relative markups nicely integrates our insights on price and quantity competition. Finally, since the linear supply function equilibrium can be described analytically, we can study to what extent our welfare conclusions depend on the mode of competition.

As in Klemperer and Meyer (1989), demand $D(p,\varepsilon)$ depends on random shock ε, unknown to firms when they each submit their supply function in stage one. Let $\frac{\partial D(p,\varepsilon)}{\partial p}<0$, $\frac{\partial D(p,\varepsilon)}{\partial \varepsilon}>0$ and

[24] Supply function equilibria under uncertainty were first studied by Klemperer and Meyer (1989). Green and Newbery (1992) applied supply function analysis to model electricity spot markets.

[25] In fact, demand uncertainty is useful since it restricts the set of supply function equilibria. The intuition is that, if demand is stochastic, a firm's supply function should be optimal against a *range* of realizations of residual demand.

$\frac{\partial^2 D(p,\varepsilon)}{\partial p \partial \varepsilon} = 0$, so that ε increases demand while preserving the slope of demand with respect to p.

For simplicity, we assume that subcontracting always occurs ($\rho = 0$ and $\alpha = 0.5$). After competing in stage one, the windless firm outsources generation to the wind-abundant firm.

Since the market-clearing condition requires that $q_i(p) = D(p,\varepsilon) - q_j(p)$, firm i 's profits can generally be written as

$$p\left(D(p,\varepsilon) - q_j(p)\right) - 0.5C\left(D(p,\varepsilon) - q_j(p)\right) + 0.5\boldsymbol{\sigma}\underbrace{C\left(q_j(p)\right)}_{\substack{\text{gains from} \\ \text{subcontracting} \\ \text{in state } (w,\overline{w})}} + 0.5\left(1 - \boldsymbol{\sigma}\right)\underbrace{C\left(D(p,\varepsilon) - q_j(p)\right)}_{\substack{\text{gains from subcontracting} \\ \text{in state } (\overline{w},w)}}.$$

If $D(p,\varepsilon)$ and $C(q)$ are continuously differentiable with respect to price p, any equilibrium outcome should satisfy the first-order condition

$$q_i = \left[p - 0.5\boldsymbol{\sigma}C'\left(q_i\right)\right]\left(-D'(p) + q_j{}'(p)\right) - 0.5\underbrace{\boldsymbol{\sigma}C'\left(q_j\right)q_j{}'(p)}_{\substack{\text{marginal subcontracting} \\ \text{revenues in state } (w,\overline{w})}}$$

for all possible realizations of demand. Interestingly, contrasting to our Cournot setup, firm i 's strategy affects firm j 's quantity $q_j(p)$. If firm i submits a more competitive supply schedule, the price falls, causing firm j to sell less. Firm i will then earn less subcontracting revenues in the event that firm j is windless (state $(w,\overline{w})$). As a result, firm i optimally sells less because it foregoes subcontracting revenues by setting a competitive schedule. Firm i 's marginal subcontracting revenues in state $(w,\overline{w})$ therefore appear in its first-order condition. Notice that the term drops out when firms compete à la Cournot. In that case, firm j offers fixed quantity q_j, so that $q_j{}'(p) = 0$.

We now explore the role of subcontracting revenues in explaining markups. For ease of exposition, let γ_i^{res} represent the (positive) price-elasticity of i 's residual demand $D(p) - q_j(p)$. The first-order condition can then be rearranged to obtain the relative markup with regard to expected marginal cost

$$\frac{p-0.5\boldsymbol{\sigma}C'(q_i)}{p}=\frac{1}{\gamma_i^{\text{res}}}\left(1+\frac{0.5\boldsymbol{\sigma}C'(q_j)\dfrac{\partial q_j}{\partial p/p}}{pq_i}\right).$$

Dispatchable units are never used for power generation ($\rho=0$), and hence, marginal costs consist only of subcontracting costs. The left hand side reveals that, since firms apply markups based on their marginal costs, the subcontracting terms alter firms' equilibrium behavior. That relative markup consists of two components (right hand side). First, not surprisingly, firms set higher prices if they thereby give up little customers in stage one. The second term, interestingly, exceeds 1 because of the subcontracting stage. Firm i applies a high markup if, by increasing the stage one price as a percentage $\partial p/p$, it substantially enhances its subcontracting revenues $0.5\boldsymbol{\sigma}C(q_j(p))$, relative to its customer revenues pq_i. The intuition is that firms balance stage one earnings versus earnings from subcontracting. A firm is less eager to win customers by setting a competitive schedule, if it might as well benefit from subcontracting revenues by charging high prices.

To analytically investigate welfare in a supply function framework, we proceed with our quadratic back-up cost function $C=0.5\beta q^2$. Furthermore, demand is linear and equals $D(p)=\varepsilon-p$, where $\varepsilon>0$. Let $L_i(q_i)$ be the relative markup with regard to expected marginal cost, such that $L_i(q_i)\equiv\frac{p-0.5\boldsymbol{\sigma}\beta q_i}{p}$. Rearranging gives us

$$p=0.5\frac{\boldsymbol{\sigma}\beta}{1-L_i(q_i)}q_i.$$

As in Green (1996), to arrive at analytical solutions, we focus on the equilibrium where each firm applies a constant relative markup $L_i=L_i(q_i)$. We can then write firm i's supply schedule as $q_i=b_ip$ with slope $b_i\equiv\frac{2(1-L_i)}{\boldsymbol{\sigma}\beta}$. We insert the demand function, total cost function and each firm's supply schedule

$q_i = b_i p$ into the first-order condition.[26] After applying symmetry, we find that the optimal b_i equals $0.25\left(\sqrt{1+\frac{16}{\boldsymbol{\sigma}\beta}}-1\right)$ so that firm i 's equilibrium supply schedule becomes

$$q_i = 0.25\left(\sqrt{1+\frac{16}{\boldsymbol{\sigma}\beta}}-1\right)p.$$

The interpretations coincide with our Bertrand and Cournot framework.[27] That is, for any given price, a firm is willing to offer a lower quantity if subcontracting payments are substantial. As a result, firms can shape the subcontracting terms to increase industry profits.

It can be checked that this framework also provides nice analytical solutions for the equilibrium quantities and profits. As before, we find that consumer welfare is decreasing in $\boldsymbol{\sigma}$.

As in the Bertrand framework, subcontracting can soften competition to the extent that consumers are better off without subcontracts. The no subcontracting benchmark is retrieved from Klemperer and Meyer (1989, p. 1261). Each firm's supply function equals

$$q_i = 0.5\left(\sqrt{1+\frac{8}{\beta}}-1\right)p.$$

Subcontracting raises consumer welfare whenever $0.25\left(\sqrt{1+\frac{16}{\boldsymbol{\sigma}\beta}}-1\right) > 0.5\left(\sqrt{1+\frac{8}{\beta}}-1\right)$, or equivalently, if and only if

$$\boldsymbol{\sigma} < \bar{\boldsymbol{\sigma}} \equiv \frac{8+\beta\sqrt{\frac{\beta+8}{\beta}}+\beta}{2(8+\beta)}.$$

[26] Our demand and back-up cost specification guarantee that the profit function is strictly concave with regard to the price.

[27] Remark that if subcontracting payments converge to zero, the perfect competitive outcome results. To be precise, by using l'Hôpital's rule, it can be shown that the price converges to zero.

Interestingly, the threshold value of sigma, $\bar{\boldsymbol{\sigma}}$, is bounded by $\lim_{\beta\to 0}\bar{\boldsymbol{\sigma}} = 0.5$ and $\lim_{\beta\to\infty}\bar{\boldsymbol{\sigma}} = 1$. Notice from proposition 8 that threshold value $\bar{\boldsymbol{\sigma}}$ converges to the Bertrand result when β goes to 0 and the Cournot result when β goes to infinity.

Also, consistent with our previous findings, competition by submitting supply functions can outperform Bertrand competition with regard to consumer surplus.[28]

Limited wind — Our analysis assumed so far that if a firm has wind available, it can serve total market demand. Though this is a strong assumption, our general insights remain valid even when firms do not have sufficient wind to provide the market. Assume firm j is windless and firm i can only generate $\bar{q}$ wind power. With subcontracting, the remaining power production is efficiently shared across firms' dispatchable units. Suppose first that firm i has sufficient wind power capacity to serve its own customers, but not to serve the entire market, so that $q_i \le \bar{q} \le q_i + q_j$. Gains from subcontracting then equal

$$0.5\beta q_j^2 - 2\left(0.5\beta\left(\frac{q_i + q_j - \bar{q}}{2}\right)^2\right).$$

Clearly, subcontracting will result in gains from trade. The gains reach a maximum when wind power is most abundant, or $\bar{q} = q_i + q_j$.

Second, suppose firm i has insufficient wind power capacity to serve its own customers ($0 \le \bar{q} \le q_i$). Still, subcontracting pays off since it enables firms to efficiently share production over both firms' dispatchable technologies. The gains from subcontracting equal

[28] We provide a simple numerical example. For easy comparison, let the demand shock equal $\varepsilon = 1$ so that demand is $D(p) = 1 - p$. Suppose the subcontractor enjoys all bargaining power ($\boldsymbol{\sigma} = 1$) and $\beta = 16/3$. Each firm then offers $q(p) = p/4$, so that the equilibrium price equals $2/3$. In contrast, if firms compete à la Bertrand, they each set a higher price of $8/11$. Consumers are best off paying price $11/17$, which results when firms compete in quantities.

$$0.5\beta\left(q_i-\bar{q}\right)^2+0.5\beta q_j^2-2\left(0.5\beta\left(\frac{q_i+q_j-\bar{q}}{2}\right)^2\right).$$

Again, this term is positive. Our insights remain valid even when firm i has limited wind capacity.

Oligopoly — Our analysis has only considered two firms for analytical reasons. When the number of competing firms is $n \geq 3$, the number of states of nature where more than one firm enjoys favorable wind conditions increases rapidly. If so, competition between wind-abundant firms to serve windless firms can become fierce. The price paid for wind power drops and equilibrium output expands. Of course, in contrast to our two-firm setting, a wind-abundant firm may fall short of capacity to provide wind power to the entire market. In that event, scarcity may result. Subcontracting payments happen from windless firms to wind-abundant firms, with similar results like our setting has studied.

Price competition and tie-breaking rules — In our Bertrand framework, a tie is settled by the toss of a fair coin. The outcome of the toss determines which firm serves the whole market. Alternatively, in case of equal prices, we can assume that both firms each receive half of market demand.

Each firm i 's profit function then consists of three components. As before, profits are stated if i serves the entire market ($p_i < p_j$) and if it does not ($p_i > p_j$). Additionally, profits are specified in the event of a tie ($p_i = p_j$).

First consider the case where firms do *not* sign subcontracts. Firm i 's profits are

$$\begin{cases} \left(1-p_i\right)p_i-\left(1-\alpha\right)0.5\beta\left(1-p_i\right)^2 & \text{if } p_i < p_j \\ 0 & \text{if } p_i > p_j \\ 0.5\left(1-p_i\right)p_i-\left(1-\alpha\right)0.5\beta\left(0.5\left(1-p_i\right)\right)^2 & \text{if } p_i = p_j. \end{cases}$$

Since costs are convex, it is expensive for one firm to generate all power. Costs are reduced, however, if production is shared equally. Suppose firms set prices

$$p_i = p_j = \frac{\left(1-\alpha\right)\beta}{2+\left(1-\alpha\right)\beta},$$

i.e. the equilibrium prices we obtained in section 3. By the new sharing rule where both firms serve half of market demand, firms incur less costs, and hence, make positive profits. If firm i deviates from the equilibrium by setting a higher price $p_i > p_j$, it makes zero profits. From section 3, we know that slightly undercutting the rival by setting $p_i = p_j - \varepsilon$ also leads to zero profits. Therefore, the equilibrium we analyzed in section 3 remains valid when we apply the alternative sharing rule.

Lower price equilibria where firms earn positive profits are also possible. To see why, charging a higher price would surely not be profitable because it leads to zero sales and profits. Alternatively, a firm makes losses by undercutting the rival, because it is too costly for one firm to serve all consumers.

There are implications for proposition 8, which compares subcontracts to no subcontracts. Because lower price equilibria are also possible, the consumer surplus we stated when firms do not sign subcontracts represents a lower bound. As a result, for subcontracts to enhance consumer surplus with price-competing firms, the condition that the subcontracting terms should favor the contractor sufficiently could be more restrictive ($\boldsymbol{\sigma}$ sufficiently below 0.5).

To be complete, our result that producer surplus is always increased by ex ante subcontracts remains valid. This need not hold, however, when firms sign ex post subcontracts. To see why, if the subcontractor appropriates no gains ($\sigma_{\mathrm{p}} = 0$), firms make zero profits.

Second, let firms sign subcontracts. Firm i's profits equal

$$\begin{cases} (1) \equiv (1-p_i)\,p_i - (1-\alpha)0.5\beta(1-p_i)^2 + (1-\boldsymbol{\sigma})\underbrace{\left(\frac{1\text{-}\rho}{2}0.5\beta(1-p_i)^2 + \frac{1-2\alpha+\rho}{2}0.25\beta(1-p_i)^2\right)}_{\text{expected gains from subcontracting}} & \text{if } p_i < p_j \\ (2) \equiv \boldsymbol{\sigma}\underbrace{\left(\frac{1\text{-}\rho}{2}0.5\beta(1-p_j)^2 + \frac{1-2\alpha+\rho}{2}0.25\beta(1-p_j)^2\right)}_{\text{expected gains from subcontracting}} & \text{if } p_i > p_j \\ (3) \equiv 0.5(1-p_i)\,p_i - (1-\alpha)0.5\beta\big(0.5(1-p_i)\big)^2 + \frac{1\text{-}\rho}{2}\big(\boldsymbol{\sigma} + (1-\boldsymbol{\sigma})\big)0.5\beta\big(0.5(1-p_i)\big)^2 & \text{if } p_i = p_j. \end{cases}$$

When firms set equal prices $p_i = p_j$, they do not gain from subcontracting if they experience symmetric generation conditions (states (w,w) and $(\overline{w},\overline{w})$). In contrast, if firms enter state $(w,\overline{w})$ or $(\overline{w},w)$, the wind-abundant firm subcontracts power to the windless firm and appropriates share $\boldsymbol{\sigma}$ of the subcontracting rents.

We look for a symmetric equilibrium in pure strategies. An equilibrium price at which both firms share the market satisfies that no firm has an incentive (i) to set a price significantly lower than its rival's price, (ii) to slightly undercut its rival, or (iii) to set a higher price, thereby gaining from subcontracting revenues. Formally, these last two requirements are satisfied if and only if the price is such that $(3) \geq (1)$ and $(3) \geq (2)$. Clearly, at price $p=1$, firms sell zero and therefore profitably deviate by setting a substantially lower price. The price that satisfies all three requirements is unique and equals

$$p^* \equiv \frac{\beta\left(1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\right)}{8+\beta\left(1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\right)}.$$

Notice that p^* equals the equilibrium price we analyzed using the toss of a fair coin. In other words, the symmetric price equilibrium we use when firms sign subcontracts is valid and unique, irrespective of the choice between both settlement rules in case of a tie.

Linear tariffs — In our framework, both firms take advantage of all gains from trade during the subcontracting stage. This is a reasonable assumption when firms directly engage in bilateral trade, outside the context of a power exchange. Nowadays, it is increasingly common that firms take buying or selling positions on organized day ahead, intraday or balancing markets. These markets take place close to delivery, and thereby facilitate horizontal subcontracting.

Consider an organized balancing market in stage two, characterized by a uniform clearing price. For simplicity, we set $\rho=0$ and $\alpha=0.5$, so that we think of a world where the availability of intermittent energy sources is negatively correlated.

The futures market, stage one, is characterized by price competition and proceeds as before. The low-price firm i serves market demand $q_i\left(p_i\right) \equiv 1-p_i$ and earns $q_i\left(p_i\right)p_i$ customer revenues.

With probability 0.5 we arrive in state $(w,\bar{w})$, where low-price firm i is wind-abundant. In that event, there is no trade on the spot market.

Otherwise, also with probability 0.5, low-price firm i is windless (state $(\bar{w},w)$). Then, for each additional unit q it buys on the spot market, it is willing to pay the marginal generation cost of using its back-up technology. Since $q_i(p_i)-q$ is the number of units firm i produces in-house, where $0 \le q \le q_i(p_i)$, that marginal cost equals $\beta\left(q_i(p_i)-q\right)$. Consequently, firm i's inverse demand equals $\tau = \beta\left(q_i(p_i)-q\right)$, where τ denotes the uniform linear tariff on the spot market.

Wind-abundant firm j is the only seller on the spot market. Provided that it sets quantity q, its stage two earnings are

$$\beta\left(q_i(p_i)-q\right)q.$$

The first-order condition is $q^* = \frac{q_i(p_i)}{1+\varphi}$, which we generalize by defining $0 \le \varphi \le 1$ as the exogenous ratio of actual market power over maximally attainable market power (monopoly).[29] As a result, windless firm i's subcontracting costs amount to $\beta\varphi\left(\frac{q_i(p_i)}{1+\varphi}\right)^2$ and are increasing in β, which confirms the strategic role of dispatchable units. Windless firm i produces $q_i(p_i)\frac{\varphi}{1+\varphi}$ in-house by using its dispatchable technology. Notice that linear tariffs do not guarantee an efficient outcome. Namely, firm i uses expensive dispatchable units to generate power, while at the same time firm j has cheap wind power available. In equilibrium, firms are indifferent between serving the market or earning subcontracting revenues. Formally, the equilibrium price should satisfy

[29] Our monopolist need not take into account the full effect of its strategic variable q on price τ. Given that firm j's stage two profits equal $\tau(q)q$, it sets quantity q that satisfies $\tau + \varphi\frac{\partial \tau}{\partial q}q = 0$, where $0 \le \varphi \le 1$.

$$\left(1-p\right)p-0.5\beta\varphi\left(\frac{1-p}{1+\varphi}\right)^2-0.25\beta\left(\left(1-p\right)\frac{\varphi}{1+\varphi}\right)^2=0.5\beta\varphi\left(\frac{1-p}{1+\varphi}\right)^2.$$

It can be checked that the unique symmetric equilibrium price equals $\frac{\beta\varphi\left(\varphi+4\right)}{\beta\varphi\left(\varphi+4\right)+4\left(\varphi+1\right)^2}$ and increases in φ. As before, consumers are best off if subcontracting payments are low, that is, if selling firms exert little market power on the spot market.

Arbitrage — Organized spot markets can provide opportunities for arbitrageurs to take advantage of price differences between the futures and the spot market. Even in a world where arbitrage is possible, the availability of dispatchable units lowers a firm's willingness to pay on the spot market. If it thereby reduces the price paid in stage two, dispatchable units take the strategic role as we discussed in our paper. To evaluate the precise equilibrium dynamics, however, a different model is required that explicitly introduces arbitrage.

Subsidies and taxes — In many countries, the power industry is characterized by a variety of subsidies or taxes. For instance, the introduction of wind and solar energy tends to be supported by governments. Alternatively, firms are often taxed for greenhouse gas emissions.

We first discuss the case where the intermittent technology is subsidized per unit of output. Consider a subcontract that shifts generation from an expensive gas-fired plant to the intermittent technology. As before, gains from subcontracting consist of the reduction in generation costs. Furthermore, by increasing the output of the intermittent energy source, the subcontract enables firms to obtain additional subsidies. The subsidy expands the gains from subcontracting, so that our insights remain valid.

Second, consider a per unit tax with regard to the conventional dispatchable technology. Let firms shift generation from dispatchable units to the intermittent technology. The subcontract, besides reducing generation costs, also avoids taxes. Again, the gains from subcontracting are increased, so that our analysis also applies with the tax.

9. Conclusions

The shift towards carbon-neutral, intermittent sources for power generation, like wind and solar, continues to be a priority in many economies. On the one hand, intermittent power units have increased the need for dispatchable units to back-up power supply. On the other hand, intermittent units often run whenever available, thereby reducing the revenues generated by conventional dispatchable plants. Utilities complain about low dispatchable plant profitability and consider mothballing their underused units, unless the government introduces appropriate public policies, like capacity payment mechanisms, to secure supply.

Our framework provides the policy insight that firms have strategic unilateral incentives to install dispatchable units such as gas-fired plants. Horizontally competing firms gain from subcontracting by outsourcing generation from their expensive conventional plants and buying low-cost power from a competitor's intermittent units. Then, if a firm experiences unfavorable conditions to generate wind power, being equipped with gas-fired plants credibly exerts a disciplining effect on the subcontracting price. Profitability at the plant level does not capture that maintaining dispatchable units is strategically advantageous. This effect mitigates the public good problem of securing supply. It should accordingly be taken into account when countries choose whether and how to implement e.g. capacity payment mechanisms.

From a welfare point of view, any subcontract that sufficiently favors the outsourcing firm increases consumer surplus. Firms can further increase profits by signing option contracts that determine the subcontracting terms before generation conditions reveal. We show that, if dispatchable units are cheap to use, such a profit-maximizing option contract raises subcontracting costs. Clearly, this reduces competition at the expense of consumers. In contrast, if dispatchable generation is expensive, firms profitably lower the price paid for subcontracting. Such an option contract makes producers *and* consumers better off.

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Appendix

The appendix describes how to model the correlation coefficient between both firm's wind availability and proves that the Cournot equilibrium is locally stable (proposition A1). It then provides the proofs for propositions 2, 3 and A2, after which we analyze collusion when firms compete à la Bertrand (no subcontracting, subcontracting and proposition A3). The appendix ends with the proofs of proposition 8 and 9.

Modelling the correlation coefficient. Each firm i 's wind availability is Bernoulli distributed with support $X_i \in \{0,1\}$, where 1 and 0 represent wind-abundant and windless, respectively. Let r denote the correlation coefficient $r = \frac{\operatorname{cov}(X_i, X_j)}{\sqrt{\operatorname{var}(X_i)}\sqrt{\operatorname{var}(X_j)}}$, which can be rewritten as

$$\frac{\Pr\left(X_i = X_j = 1\right)(1-\alpha)^2 + \Pr\left(X_i = 1, X_j = 0\right)(1-\alpha)(-\alpha) + \Pr\left(X_i = 0, X_j = 1\right)(1-\alpha)(-\alpha) + \Pr\left(X_i = X_j = 0\right)\alpha^2}{\alpha(1-\alpha)}$$

By using the definition of α and the fact that all probabilities sum to 1, the probabilities of each state of nature become

$$\begin{aligned}
&\Pr\left(X_i = X_j = 1\right) = \alpha\left(r + \alpha(1-r)\right)\\
&\Pr\left(X_i = 1, X_j = 0\right) = \alpha(1-\alpha)(1-r)\\
&\Pr\left(X_i = 0, X_j = 1\right) = \alpha(1-\alpha)(1-r)\\
&\Pr\left(X_i = X_j = 0\right) = (1-\alpha)\left(1-\alpha(1-r)\right).
\end{aligned}$$

Proposition A1. The Cournot equilibrium

$$q_i^* = q_j^* = \frac{1}{3 + 0.5\beta\left(\boldsymbol{\sigma} + (1-\boldsymbol{\sigma})\rho\right) + \beta\left(0.5-\alpha\right)}$$

is locally stable.

Proof of proposition A1. Local stability is guaranteed if $\frac{\partial^2\pi_i}{\partial q_i^{\,2}}\frac{\partial^2\pi_j}{\partial q_j^{\,2}} > \frac{\partial^2\pi_i}{\partial q_i \partial q_j}\frac{\partial^2\pi_j}{\partial q_j \partial q_i}$, where π_i and π_j denote i 's and j 's profits, respectively. Equivalently, $\frac{\partial^2\pi_i}{\partial q_i^{\,2}}\frac{\partial^2\pi_j}{\partial q_j^{\,2}} - \frac{\partial^2\pi_i}{\partial q_i \partial q_j}\frac{\partial^2\pi_j}{\partial q_j \partial q_i} > 0$. Tedious algebra gives us the condition

$$\left[\beta\left(2\alpha-\rho(1-\sigma)-1-\sigma\right)-6\right]\left[\beta\left(2\alpha-\rho(1-2\sigma)-1-2\sigma\right)-4\right]>0,$$

which is always satisfied. ■

Proof of proposition 2

Let $\beta<2$, so that firms make subcontracting as expensive as possibly by setting $\boldsymbol{\sigma}=1$ in an ex ante subcontract.

If firms compete à la Bertrand, each firm earns

$$\frac{\beta}{\left(\beta+2\right)^2}.$$

Profits increase with $0\le\beta<2$, that is, profits increase when firms jointly divest their dispatchable units.

If firms compete à la Cournot, each firm earns

$$\frac{4+2\beta}{\left(6+\beta\right)^2},$$

which also increases in cost parameter $0\le\beta<2$.■

Proof of proposition 3.

We model the possibility that both firms are asymmetrically equipped with back-up facilities. Formally, we let firm i and j be characterized by cost parameter β_i and β_j, respectively.

The argument proceeds in two steps. The first step, step (i), shows that, keeping $\boldsymbol{\sigma}$ constant, a firm increases its profits when it installs additional dispatchable units. The second step, step (ii), starts from the result that two symmetric firms prefer $\boldsymbol{\sigma}=1$ when $\beta \leq 2$ (see section 4), and shows that both firms still prefer $\boldsymbol{\sigma}=1$ after one of them installs additional dispatchable units. To be precise, whenever $\beta_i + \varepsilon = \beta_j \leq 2$ with ε arbitrarily small, both firms want to design the ex ante subcontract in order to make subcontracting as expensive as possible ($\boldsymbol{\sigma}=1$).

Suppose first that firms compete à la Cournot. Firm i 's profit function can then be written as

$$(1-q_i-q_j)q_i - 0.25\beta_i q_i^{\,2} + 0.5(1-\boldsymbol{\sigma})0.5\beta_i q_i^{\,2} + 0.5\boldsymbol{\sigma}0.5\beta_j q_j^{\,2},$$

which leads to i 's equilibrium quantity

$$\frac{2\left(2+\beta_j\boldsymbol{\sigma}\right)}{12+4\boldsymbol{\sigma}\left(\beta_i+\beta_j\right)+\boldsymbol{\sigma}^2\beta_i\beta_j}$$

and profits

$$\frac{\left(4+\beta_i\boldsymbol{\sigma}\right)\left(4+\boldsymbol{\sigma}^2\beta_j^2\right)+\beta_j\boldsymbol{\sigma}\left(20+\boldsymbol{\sigma}^2\beta_i^2+8\boldsymbol{\sigma}\beta_i\right)}{\left(12+4\boldsymbol{\sigma}\left(\beta_i+\beta_j\right)+\boldsymbol{\sigma}^2\beta_i\beta_j\right)^2}.$$

To learn about i 's unilateral incentive to install additional dispatchable units, we investigate the derivative of i 's profits with respect to its cost parameter β_i. By keeping $\boldsymbol{\sigma}$ constant, we find that a reduction in β_i results in a strictly positive change of

$$\frac{\boldsymbol{\sigma}\left(\beta_j\boldsymbol{\sigma}+2\right)\left(\beta_j^2\boldsymbol{\sigma}^2\left(\beta_i\boldsymbol{\sigma}+4\right)+2\beta_j\boldsymbol{\sigma}\left(\beta_i\boldsymbol{\sigma}+10\right)+8\left(\beta_i\boldsymbol{\sigma}+5\right)\right)}{\left(12+4\boldsymbol{\sigma}\left(\beta_i+\beta_j\right)+\boldsymbol{\sigma}^2\beta_i\beta_j\right)^3}$$

of firm i 's profits. This completes step (i) for Cournot competition.

Step (ii) requires that profits are increasing in $\boldsymbol{\sigma}$ whenever $\beta_i + \varepsilon = \beta_j \leq 2$. Then, when firms sign an ex ante contract to maximize profits with respect to $\boldsymbol{\sigma}$, the inequality constraint that in-house production should not outperform exercising the option contract, $\boldsymbol{\sigma} \leq 1$, is binding.

Formally, the derivative of i's profits with respect to $\boldsymbol{\sigma}$ should be positive, or

$$-\frac{\beta_j^3\beta_i\boldsymbol{\sigma}^3\left(\beta_i\boldsymbol{\sigma}+4\right)+\beta_j^2\boldsymbol{\sigma}\left(\beta_i^3\boldsymbol{\sigma}^3+8\beta_i^2\boldsymbol{\sigma}^2+24\beta_i\boldsymbol{\sigma}-16\right)-4\beta_j\left(\beta_i^3\boldsymbol{\sigma}^3+6\beta_i^2\boldsymbol{\sigma}^2+8\beta_i\boldsymbol{\sigma}+28\right)+16\beta_i\left(\beta_i\boldsymbol{\sigma}+5\right)}{\left(12+4\boldsymbol{\sigma}\left(\beta_i+\beta_j\right)+\boldsymbol{\sigma}^2\beta_i\beta_j\right)^3} \geq 0,$$

for $\beta_i + \varepsilon = \beta_j \leq 2$. See that the denominator is always positive, so that the condition reduces to

$$\beta_j^3\beta_i\boldsymbol{\sigma}^3\left(\beta_i\boldsymbol{\sigma}+4\right)+\beta_j^2\boldsymbol{\sigma}\left(\beta_i^3\boldsymbol{\sigma}^3+8\beta_i^2\boldsymbol{\sigma}^2+24\beta_i\boldsymbol{\sigma}-16\right)-4\beta_j\left(\beta_i^3\boldsymbol{\sigma}^3+6\beta_i^2\boldsymbol{\sigma}^2+8\beta_i\boldsymbol{\sigma}+28\right)+16\beta_i\left(\beta_i\boldsymbol{\sigma}+5\right)\leq 0.$$

Now insert $\beta_i = \beta_j - \varepsilon$ and take the limit of the expression on the left hand side ($\varepsilon \to 0$). The condition becomes

$$2\beta_j\left(\beta_j^4\boldsymbol{\sigma}+4\beta_j^3\boldsymbol{\sigma}^3-16\beta_j\boldsymbol{\sigma}-16\right)\leq 0,$$

which is always satisfied for $\beta_j \leq 2$.

Second, suppose that firms compete à la Bertrand, so that firm i's profit function can be written as

$$\begin{cases}\left(1-p_i\right)p_i-0.25\beta_i\left(1-p_i\right)^2+0.5\left(1-\boldsymbol{\sigma}\right)0.5\beta_i\left(1-p_i\right)^2 & \text{if } i \text{ wins}\\ 0.5\boldsymbol{\sigma}0.5\beta_j\left(1-p_j\right)^2 & \text{if } j \text{ wins.}\end{cases}$$

Again, we are interested in a firm's change in profits due to investment in additional dispatchable units. We distinguish three cases. The firm under consideration can be the low-cost firm, the high-cost firm, or both firms are symmetric.

Let firm i be the low-cost firm, or formally, let $\beta_i < \beta_j$. Consequently, firm i serves the whole market in equilibrium. Suppose firm i's cost advantage is sufficiently small — or non-drastic — so that firm j

would be willing to serve the market at firm i 's monopoly price. Then, in equilibrium, firm i charges a price such that firm j is just unwilling to undercut. Formally, the price satisfies

$$(1-p)p-0.25\beta_j(1-p)^2+0.5(1-\boldsymbol{\sigma})0.5\beta_j(1-p)^2=0.5\boldsymbol{\sigma}0.5\beta_i(1-p)^2$$

and thus equals

$$\frac{\boldsymbol{\sigma}\left(\beta_i+\beta_j\right)}{\boldsymbol{\sigma}\left(\beta_i+\beta_j\right)+4}.$$

Step (i) checks that firm i earns

$$\frac{4\beta_j\boldsymbol{\sigma}}{\left(\boldsymbol{\sigma}\left(\beta_i+\beta_j\right)+4\right)^2},$$

which decreases in β_i when keeping $\boldsymbol{\sigma}$ constant. The intuition is that installing dispatchable units lowers i 's cost parameter β_i, thereby reducing its subcontracting costs. Using that $\beta_i \leq 2$ and $\beta_j \leq 2$, it can be checked that firm i 's profits are maximized at $\boldsymbol{\sigma}=1$, so that step (ii) is also satisfied.

High-price firm j earns subcontracting revenues only. Its profits equal

$$\frac{4\beta_i\boldsymbol{\sigma}}{\left(\boldsymbol{\sigma}\left(\beta_i+\beta_j\right)+4\right)^2}$$

and decrease in β_j when keeping $\boldsymbol{\sigma}$ constant. By lowering its cost parameter, high-price firm j lowers the equilibrium price at which i serves the market. Consequently, firm i serves more consumers, and hence, i outsources more generation in the event it turns windless. As a result, high-price firm j profits from higher subcontracting revenues. This completes step (i) for the high-price firm. Step (ii) is also satisfied because the high-price firm prefers $\boldsymbol{\sigma}=1$ for any $\beta_i \leq 2$ and $\beta_j \leq 2$.

Finally, if we start from two symmetric firms ($\beta_i=\beta_j=\beta$), each firm earns

$$\frac{\boldsymbol{\sigma}\beta_j}{\left(\boldsymbol{\sigma}\beta_j + 2\right)^2}.$$

Now let firm i install additional dispatchable units so that $\beta_i < \beta_j$. Step (i) checks that firm i, by reducing its cost parameter and keeping $\boldsymbol{\sigma}$ constant, earns larger profits of

$$\frac{4\beta_j\boldsymbol{\sigma}}{\left(\boldsymbol{\sigma}\left(\beta_i + \beta_j\right) + 4\right)^2} = \frac{\boldsymbol{\sigma}\beta_j}{\left(0.5\boldsymbol{\sigma}\left(\beta_i + \beta_j\right) + 2\right)^2} > \frac{\boldsymbol{\sigma}\beta_j}{\left(\boldsymbol{\sigma}\beta_j + 2\right)^2}.$$

From our above analysis, we use that the low-price firm and the high price firm both prefer $\boldsymbol{\sigma} = 1$, so that step (ii) is also satisfied. ■

Proposition A2: A firm equipped with the dispatchable technology, characterized by zero plant profitability, earns strictly higher profits.

Proof: The proof compares i's profits if it is equipped with the intermittent technology only, to its profits if equipped with both technologies. We find that, when equipped with both technologies, it strictly enhances its profits.

Suppose first that firm i only has access to an intermittent technology, while rival firm j is equipped with both an intermittent and dispatchable technology. Then, firm i optimally chooses not to serve any consumers during stage one. However, provided that j serves consumers, firm i can benefit from subcontracting revenues in state $\left(w, \overline{w}\right)$.

Rival firm j is monopolist during stage one. Consequently, the maximization problem can equivalently be written in terms of quantity q_j or price p_j. Profits equal

$$\left(1 - q_j\right)q_j - 0.25\beta\left(q_j\right)^2 + 0.5\left(1 - \boldsymbol{\sigma}\right)0.5\beta\left(q_j\right)^2$$

and are maximized at $q_j = \dfrac{1}{2 + 0.5\beta\boldsymbol{\sigma}}$. As a result, without a dispatchable technology, firm i earns

$$0.5\boldsymbol{\sigma}0.5\beta\left(\frac{1}{2+0.5\boldsymbol{\sigma}\beta}\right)^2,$$

which is irrespective of the mode of competition during stage one.

Because firms are asymmetric, firms may have different preferences with regard to $\boldsymbol{\sigma}$. Consequently, it is unclear how firms determine $\boldsymbol{\sigma}$ in an ex ante contract. We can, however, state that i 's profits reach a maximum for $\boldsymbol{\sigma}=\min(1,4/\beta)$. As a result, firm i 's profits are no larger than

$$\begin{cases} 0.25\beta\left(\dfrac{1}{2+0.5\beta}\right)^2 & \text{if } \beta<4 \\ 1/16 & \text{if } \beta\geq 4. \end{cases}$$

Second, we suppose that both firms are symmetrically equipped with both technologies and show that this setting results in higher profits for firm i .

For $\beta\geq 2$, firms use ex ante subcontracts to attain monopoly profits of $1/8$ per firm. Then, firm i always benefits from having access to the dispatchable technology because

$$\underbrace{\frac{1}{8}}_{\substack{\text{profits with}\\ \text{dispatchable units}}} > \underbrace{\frac{1}{16}}_{\substack{\text{maximal profits}\\ \text{without dispatchable units}}} \geq 0.25\beta\left(\frac{1}{2+0.5\beta}\right)^2.$$

The interpretation is that firms are willing to incur a fixed cost of at least $\frac{1}{8}-\frac{1}{16}=\frac{1}{16}$ to be equipped with the dispatchable technology.

If $\beta<2$, firms set $\boldsymbol{\sigma}=1$. If firms compete à la Bertrand, maintaining dispatchable units is profitable for firm i because it can be checked that it earns

$$\underbrace{\frac{\beta}{(2+\beta)^2}}_{\substack{\text{profits with}\\ \text{dispatchable units}}} > \underbrace{0.25\beta\left(\frac{1}{2+0.5\beta}\right)^2}_{\substack{\text{maximal profits without}\\ \text{dispatchable units and } \beta<2}}.$$

Also, each quantity-competing firm always benefits from its dispatchable units because it earns

$$\underbrace{\frac{4+2\beta}{(6+\beta)^2}}_{\substack{\text{profits with}\\ \text{dispatchable units}}} > \underbrace{0.25\beta\left(\frac{1}{2+0.5\beta}\right)^2}_{\substack{\text{maximal profits without}\\ \text{dispatchable units } \beta<2}} . \blacksquare$$

Collusion Bertrand competition.

No subcontracting — The industry profits under collusion result from maximizing the joint profit function $p(1-p)-0.5\beta(1-p)^2$ with respect to p. A firm's expected collusive profits then are $\frac{1}{8+2\beta}$. However, firms can also optimally deviate by setting a price equal to $\frac{2+\beta}{4+\beta}-\varepsilon$, where ε is arbitrarily small and positive, such that deviation profits become $\frac{1}{4+\beta}$.

Sustained collusion must then satisfy the following condition

$$\frac{1}{1-\delta}\underbrace{\frac{1}{8+2\beta}}_{\text{collusive profits}} \geq \underbrace{\frac{1}{4+\beta}}_{\text{deviation profits}} + \frac{\delta}{1-\delta}\underbrace{0}_{\substack{\text{competition}\\ \text{profits}}},$$

resulting in a critical discount factor of 0.5.

Subcontracting — Since the dispatchable technology remains idle in equilibrium ($\rho=0$ and $\alpha=0.5$), the industry generation cost equals zero. If firms compete à la Bertrand, collusion then implies that each firm sets $p_i=0.5$, earning $1/8$ revenues in expectation.

The following proposition discusses how firms optimally deviate.

Proposition A3: If subcontracting payments are substantial ($\boldsymbol{\sigma}\beta>2$), a deviating firm chooses not to serve the market by increasing its price, thereby earning subcontracting revenues only.

Proof: Suppose the deviating firm i wants to serve the market with probability one. It must then set $p_i<p_j=0.5$, such that it then earns $(1-p_i)p_i-0.25\beta(1-p_i)^2+0.25(1-\boldsymbol{\sigma})\beta(1-p_i)^2$. To

maximize revenues and minimize subcontracting costs, a deviating firm that serves the market sets $p_i = 0.5 - \varepsilon$, earning $0.25 - \boldsymbol{\sigma}\beta/16$. However, the deviating firm may also find it optimal not to serve the market. It then sets $p_i > p_j = 0.5$. In that event, it earns subcontracting revenues $\boldsymbol{\sigma}\beta/16$. Choosing to serve the market is optimal whenever $0.25 - \boldsymbol{\sigma}\beta/16 > \boldsymbol{\sigma}\beta/16$, or $0.25 > \boldsymbol{\sigma}\beta/8$. That is, the "revenue effect" (left hand side), should dominate the "subcontracting effect" (right hand side). As for Cournot-competing firms, if $\boldsymbol{\sigma}\beta = 2$, both effects cancel out: collusive profits coincide with competition profits.

If firms sign ex post subcontracts, sustained collusion should satisfy

$$\frac{1}{1-\delta}\underbrace{\frac{1}{8}}_{\substack{\text{collusive}\\ \text{profits}}} \geq \underbrace{\max\left\{\frac{1}{4} - \sigma_{\mathrm{p}}\frac{\beta}{16}, \sigma_{\mathrm{p}}\frac{\beta}{16}\right\}}_{\text{deviation profits}} + \frac{\delta}{1-\delta}\underbrace{\frac{\sigma_{\mathrm{p}}\beta}{\left(2+\sigma_{\mathrm{p}}\beta\right)^2}}_{\text{competition profits}}.$$

This results in the following critical discount factors

$$\begin{cases} \dfrac{\left(\sigma_{\mathrm{p}}\beta + 2\right)^2}{\left(\sigma_{\mathrm{p}}\beta + 2\right)^2 + 2\sigma_{\mathrm{p}}\beta - 4} < 1 \text{ if } \sigma_{\mathrm{p}}\beta > 2 \\ \dfrac{\left(\sigma_{\mathrm{p}}\beta + 2\right)^2}{\left(\sigma_{\mathrm{p}}\beta + 2\right)^2 - 2\sigma_{\mathrm{p}}\beta + 4} < 1 \text{ if } \sigma_{\mathrm{p}}\beta < 2. \end{cases}$$

If firms sign ex ante subcontracts, the incentive constraint to sustain collusion becomes

$$\frac{1}{1-\delta}\underbrace{\frac{1}{8}}_{\substack{\text{collusive}\\ \text{profits}}} \geq \underbrace{\max\left\{\frac{1}{4} - \sigma_{\mathrm{a}}^{\mathrm{c}}\frac{\beta}{16}, \sigma_{\mathrm{a}}^{\mathrm{c}}\frac{\beta}{16}\right\}}_{\text{deviation profits}} + \frac{\delta}{1-\delta}\underbrace{\frac{\sigma_{\mathrm{a}}\beta}{\left(2+\sigma_{\mathrm{a}}\beta\right)^2}}_{\text{competition profits}}$$

Colluding price-competing firms then optimally set

$$\begin{cases} \sigma_{\mathrm{a}}^{\mathrm{c}*} = \dfrac{2}{\beta} & \text{for } \beta \geq 2 \\ \sigma_{\mathrm{a}}^{\mathrm{c}*} = 1 & \text{for } \beta < 2. \end{cases}$$

Proof of proposition 8

When firms compete à la Bertrand, consumers are better off if firms sign subcontracts if and only if

$$\underbrace{0.5\left(1-\frac{\beta\left(1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\right)}{8+\beta\left(1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\right)}\right)^2}_{CS\ \text{subcontracting}} \geq \underbrace{0.5\left(1-\frac{4(1-\alpha)\beta}{8+4(1-\alpha)\beta}\right)^2}_{CS\ \text{no subcontracting}}.$$

Or equivalently,

$$1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\leq 4(1-\alpha), \text{ or}$$

$$\boldsymbol{\sigma}\leq 0.5.$$

Producers competing in prices are better off using subcontracts since

$$\underbrace{2\frac{8\boldsymbol{\sigma}\beta\left(3-\rho-2\alpha\right)}{\left(8+\beta\left(1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\right)\right)^2}}_{\text{industry profits subcontracing}} \geq \underbrace{0}_{\substack{\text{industry profits}\\ \text{no subcontracing}}}.$$

Suppose firms compete à la Cournot. Then, consumers are better off if subcontracts are signed if and only if

$$\underbrace{0.5\left(\frac{2}{3+0.5\beta\left(\boldsymbol{\sigma}+(1-\boldsymbol{\sigma})\rho\right)+\beta\left(0.5-\alpha\right)}\right)^2}_{CS\ \text{subcontracting}} \geq \underbrace{0.5\left(\frac{2}{3+\left(1-\alpha\right)\beta}\right)^2}_{CS\ \text{no subcontracting}}.$$

The inequality is always satisfied since

$$3+0.5\beta\left(\boldsymbol{\sigma}+(1-\boldsymbol{\sigma})\rho\right)+\beta\left(0.5-\alpha\right)\leq 3+\left(1-\alpha\right)\beta.$$

Notice that consumers are equally well off with subcontracts if and only if $\boldsymbol{\sigma}=1$ or $\rho=1$.

Also, producers competing in quantities prefer subcontracts if and only if

$$\underbrace{2\frac{4+\beta\left(\rho\left(1-2\boldsymbol{\sigma}\right)+2\boldsymbol{\sigma}+1-2\alpha\right)}{\left(6+\beta\left(\rho\left(1-\boldsymbol{\sigma}\right)+\boldsymbol{\sigma}+1-2\alpha\right)\right)^2}}_{\text{industry profits subcontracing}} \geq \underbrace{2\frac{2+\beta\left(1-\alpha\right)}{2\left(3+\beta(1-\alpha)\right)^2}}_{\substack{\text{industry profits}\\ \text{no subcontracing}}},$$

Or

$$\underbrace{\frac{4+\beta\left(\rho\left(1-2\boldsymbol{\sigma}\right)+2\boldsymbol{\sigma}+1-2\alpha\right)}{\left(6+\beta\left(\rho\left(1-\boldsymbol{\sigma}\right)+\boldsymbol{\sigma}+1-2\alpha\right)\right)^2}}_{\text{industry profits subcontracing}} \geq \underbrace{\frac{4+2\beta\left(1-\alpha\right)}{\left(6+2\beta(1-\alpha)\right)^2}}_{\substack{\text{industry profits} \\ \text{no subcontracing}}},$$

which always holds since

$$\rho\left(1-2\boldsymbol{\sigma}\right)+2\boldsymbol{\sigma}+1-2\alpha \leq 2\left(1-\alpha\right). \blacksquare$$

Proof of proposition 9

Consumers are better off if both firms compete in quantities instead of prices if and only if

$$0.5\left(2q_i^*\right)^2 > 0.5\left(1-p^*\right)^2$$

or, by rearranging and using results obtained in section 4,

$$2q_i^*-1+p^* = \frac{2}{3+0.5\beta\left(\boldsymbol{\sigma}+(1-\boldsymbol{\sigma})\rho\right)+\beta\left(0.5-\alpha\right)} - 1 + \frac{\beta\left(1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\right)}{8+\beta\left(1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\right)} > 0.$$

Multiply both sides by the positive term

$$\left(8+\beta\left(1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\right)\right)\left(3+0.5\beta\left(\boldsymbol{\sigma}+(1-\boldsymbol{\sigma})\rho\right)+\beta\left(0.5-\alpha\right)\right)$$

and rearrange the inequality to get the condition

$$\beta > \hat{\beta} > 0 \text{ where } \hat{\beta} \equiv \frac{4}{4\boldsymbol{\sigma}(1-\alpha)-\rho+2\alpha-1}. \blacksquare$$

firm j

firm i		w	$\bar{w}$
	w	$0.5(-1+2\alpha+\rho)$	$0.5(1-\rho)$
	$\bar{w}$	$0.5(1-\rho)$	$0.5(1-2\alpha+\rho)$

Figure 1: four states of nature and their probabilities.

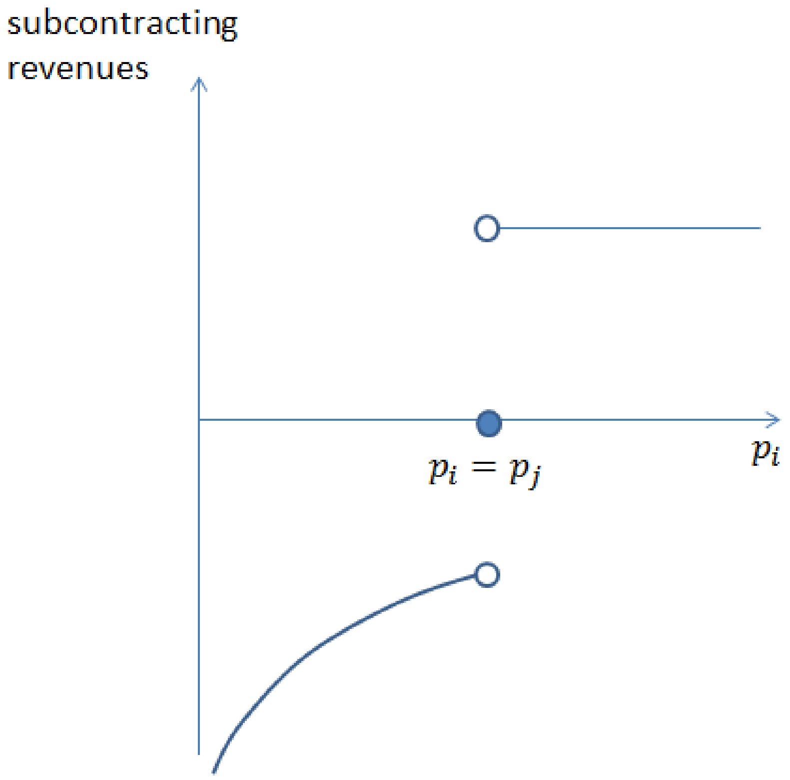

Figure 2: subcontracting revenues when firms compete à la Bertrand.

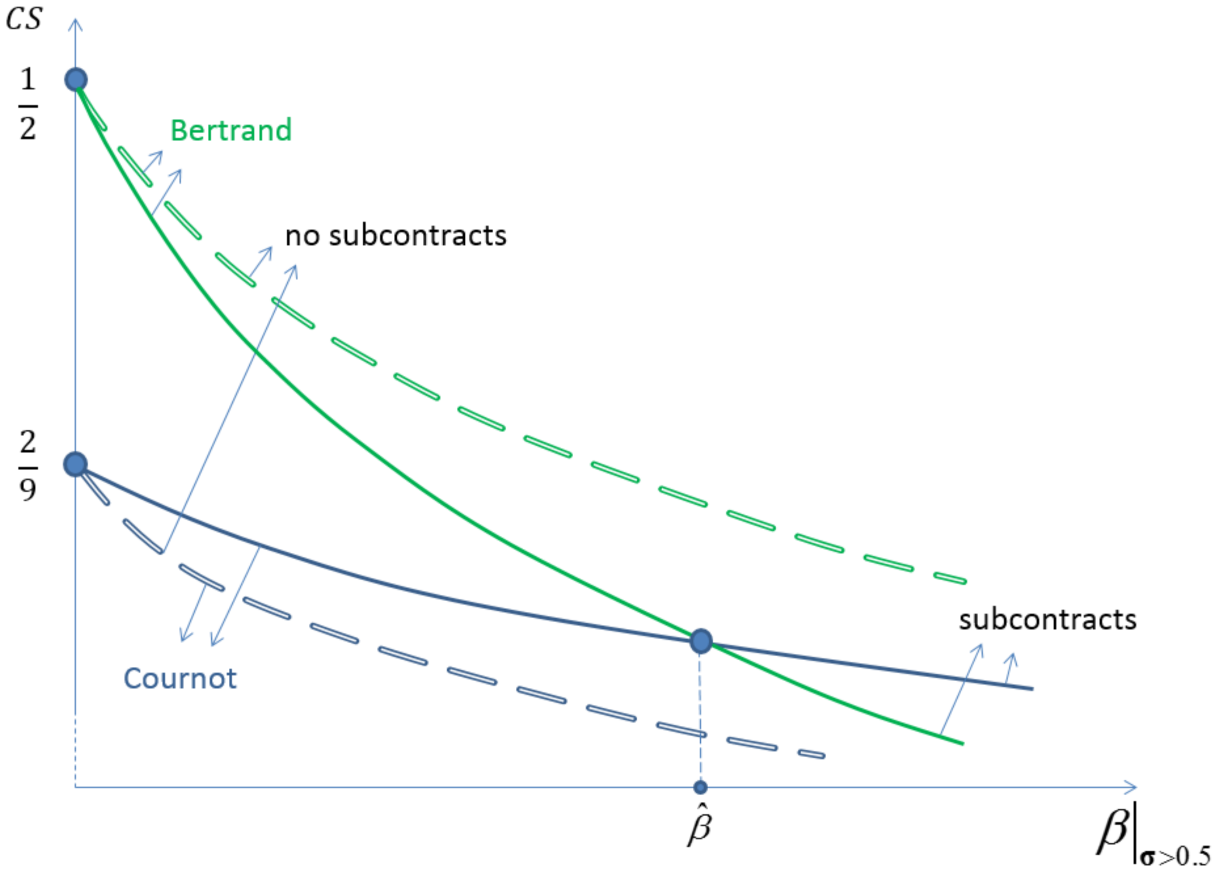

Figure 3: the effect of subcontracts on consumer surplus.

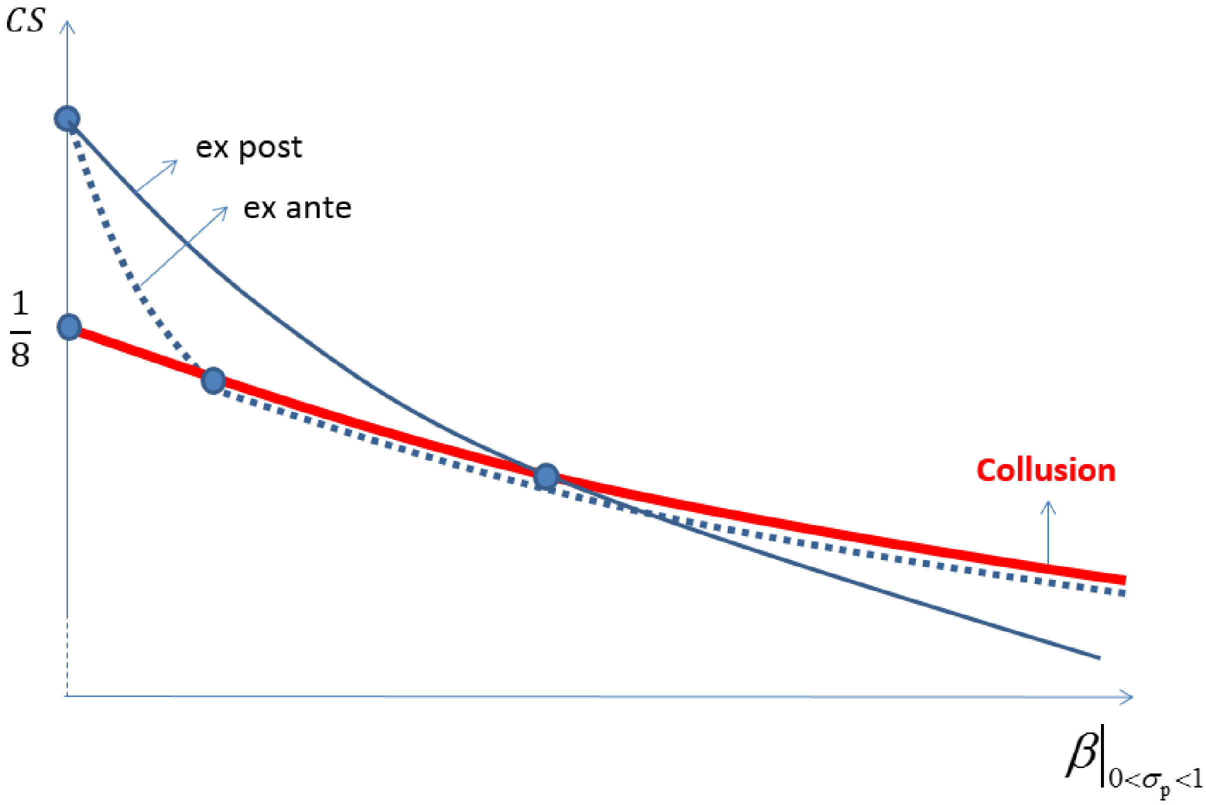

Figure 4: the effect of ex post and ex ante subcontracts on consumer surplus.