Horizontal Subcontracting and Intermittent Power Generation

Jan Bouckaert[1] and Geert Van Moer[2]

September 2014

Abstract

Intermittent power sources bring opportunities for firms to reduce their costs by horizontally subcontracting generation. We analyze a state-contingent option contract, used by firms to implement monopoly profits or to sustain collusion. Since each Bertrand-competing firm boost its subcontracting revenues by charging the highest price, we find that Cournot competition can result in higher consumer welfare. Conventional plants serve as strategic back-up, even when not used, since the opportunity to dispatch them credibly limits the price paid for subcontracting. Plant profitability therefore underestimates firms' incentives to install back-up capacity, and hence, to secure supply.

Keywords: subcontracting, intermittency, back-up, security of supply.

JEL-code: D430, L130, L140

For insightful feedback and discussion, we thank Stef Proost, Luc Lauwers and Yossi Spiegel. Also, we thank seminar participants at the Düsseldorf Institute for Competition Economics and UAntwerp .

[1] Department of Economics, University of Antwerp and College of Europe. jan.bouckaert@uantwerpen.be

[2] Department of Economics, University of Antwerp. geert.vanmoer@uantwerpen.be

1. Introduction

A typical property of important renewable energy sources, like wind or solar, is their intermittent character. 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 power 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, reliable back-up capacity 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 zero to low marginal generation costs and often enjoy priority of dispatch. As a consequence, they have *reduced* the capacity factor of the conventional, dispatchable power plants. That is, residual load profiles of conventional power plants have decreased considerably and therefore diminished profitability at the plant level. 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).

These numbers *suggest* that the industry lacks incentives to secure supply by installing reliable, flexible capacity. Accordingly, the industry has called for appropriate public intervention, like capacity payments, to re-organize the market and guarantee the secure supply of electric power.

Our setting shows that firms have sufficient strategic incentives to be equipped with reliable, flexible capacity. In our model, horizontally competing firms gain from subcontracting. The 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 can rely on its flexible unit, but cannot generate power from its intermittent source, its willingness to pay for outsourcing equals at most its opportunity cost. That is, the ability to dispatch conventional coal or gas-fired plants credibly puts an upper bound on the subcontracting price.

As a result, conventional capacity, even if *never* used for power generation, serves as credible protection against a hold-up and reduces subcontracting costs. An exclusive measure of plant

profitability, such as the capacity factor, is therefore misleading to assess a firm's returns from adequate capacity.

The subcontracting terms alter firms' equilibrium behavior. We analyze a state-contingent option contract that can serve as device to increase industry profits or, in a dynamic setting, to sustain collusion.

If subcontracting payments are low, competition is fierce and consumers are well-off. Firms typically set a low price (Bertrand) or a high quantity (Cournot) when they experience low costs. In contrast, firms are reluctant to compete fiercely if subcontracting payments are substantial. The intuition stems from two distinct effects. First, low price-cost margins may not cover the subcontracting payments in the event the firm has no wind power available. This causes firms to set a higher price or lower quantity. Second, firms may reduce subcontracting revenues by applying competitive margins. 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 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, since the subcontracting terms shape a firm's incentives to serve the market, we show that it can be used to increase 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 conventional plants 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. Such an agreement is clearly detrimental to consumer welfare. In contrast, suppose conventional plants are expensive to use. Consequently, the contractor is willing to make large subcontracting payments in return for low-cost power. As a result, there is scope to increase industry output in order to maximize industry profits by setting the subcontracting terms below the contractor's opportunity cost. This 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 offer firms scope to maximize the 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. At the same time, however, a deviating firm also makes good profits from the next period onwards. Consequently, subcontracting need not result in low discount

factors, to the contrary. Interestingly, it is impossible for a third party to distinguish collusive from competitive behavior on the basis of the subcontracting terms.

Related literature — Our paper relates to the literature on horizontal subcontracting. A number of papers explain 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. Reversely, if the loser determines the terms of the subcontract, firms set higher prices and make positive profits.

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, written 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.

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).

Second, we add an analysis of collusion to the subcontracting literature. 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.[3] Contrasting Spiegel's results, subcontracts signed between quantity competing firms *always* enhance both consumer and producer welfare.[4] To increase consumer welfare when firms compete in prices or supply schedules, the subcontracting terms should favor the outsourcing firm sufficiently.

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 discourage the rival's incentive to trigger a price war. Our analysis reveals a different motivation for firms to maintain unused back-up capacity. Namely, it provides firms an alternative to the subcontract, and hence, it credibly limits the outsourcing price paid to the rival.

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 technologies. Our paper complements theirs by showing that strategically interdependent firms are willing to be equipped with both a reliable and intermittent technology.

Other applications — Our set-up applies well to 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

[3] This finding relates to 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.

[4] Interestingly, Marion (forthcoming) takes an empirical approach to study subcontracting. Our result that subcontracting increases consumer welfare is consistent with his finding that the efficiency effect of subcontracting outweighs its reducing effect on competition.

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.

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, or by borrowing at high cost from the Central Bank. 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. We consider collusion in section 5 and offer a welfare analysis in section 6. Our robustness and discussion can be found in section 7, after which we conclude in section 8.

2. The model

Two symmetric, profit-maximizing power generating firms i, with $i=1,2$, offer a homogeneous good. 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 production technology characterized by zero marginal cost. For example, each firm may rely on its wind mill park to generate power. This zero marginal cost technology is, however, only intermittently available, depending on the state of nature. 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 production technology that serves as a reliable back-up. The reasoning is that each power plant must deliver its output q_i independent of the state of nature. If the intermittent energy source is unavailable, each firm can use its reliable back-up technology, e.g. a gas-fired power plant, that is characterized by the convex cost function

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

with $0\leq\beta$. Our production cost function could easily be modified without changing the qualitative insights. Upward sloping marginal costs are important, though. Marginal costs are upward sloping. So, firms generate power with the lowest marginal generation cost first. If more generation is required, they must turn to more expensive power facilities.[5] We will

[5] In the context of power generation, our cost function captures the "merit order" or "dispatch curve" (Joskow, 2011).

assume, for simplicity, that both technologies have no capacity constraints.[6] As a result, if available, one firm's wind park or gas-fired plant can meet total industry demand.

The back-up technology is perfectly reliable. It is available in all states of nature. In contrast, the availability of each firm's zero-cost technology is random and takes a Bernoulli distribution. Let w and $\bar{w}$ refer to wind availability and wind unavailability, respectively. The four states of nature are then denoted by (w,w), $(w,\bar{w})$, $(\bar{w},w)$ and $(\bar{w},\bar{w})$, where the first and second element refer to firm i's and firm j's generation conditions, respectively. We define $0 \leq \rho \leq 1$ as the probability that both firms experience identical conditions to generate power. If weather conditions are perfectly negatively correlated ($\rho = 0$), states (w,w) and $(\bar{w},\bar{w})$ occur with zero probability. At the other extreme, perfect positive correlation ($\rho = 1$) rules out states $(w,\bar{w})$ and $(\bar{w},w)$. 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.

In addition, 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 zero-cost technology. The introduction of both parameters (ρ and α) requires that $0.5(1-\rho) \leq \alpha \leq 0.5(1+\rho)$, which is always satisfied if each firm is maximally intermittent ($\alpha = 0.5$). To summarize, figure 1 depicts the four states of nature and their probabilities.

		firm j: w	firm j: $\bar{w}$
firm i	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.

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 quantity Q results. In the event of a tie, the firm serving the

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

whole market is chosen by the toss of a fair coin.[7] 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.[8]

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 their 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 back-up technology is characterized by upward sloping marginal costs. Equal sharing of generation between two portfolios of back-up facilities, 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 back-up or, alternatively, contract power generation to the rival firm. If both firms are wind-abundant, there are no gains from subcontracting because marginal costs are zero.

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

We model electricity as a homogeneous good.[9] Because the effect of subcontracts on competition and consumers is distinct for price and quantity competition, we provide both analyses.

---

[7] 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 write subcontracts. Without subcontracts, however, the alternative settlement rule would create additional equilibria in pure strategies.

[8] 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).

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

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 reliable back-up 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

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

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 reliable back-up technology β.

4. Subcontracting

This section studies what happens if firms can write subcontracts. Since we look for the subgame perfect Nash equilibrium, we start our analysis in the subcontracting stage (stage

two). Firms use subcontracts to trade power. We first study the potential gains from subcontracting in each possible state. Second, we discuss how these gains are shared.

In state (w,w), there are no gains from subcontracting because both firms have access to their zero-cost technology. In state $(\overline{w},w)$, however, firms experience asymmetric generation conditions. Without trade, the windless firm i must use its costly back-up 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, therefore, equal the reduction in industry production costs resulting from the subcontract, or, equivalently firm i's opportunity cost $TC(q_i)=0.5\beta q_i^2$. Analogously, in state $(w,\overline{w})$, windless firm j buys from firm i so that gains from subcontracting equal $TC(q_j)=0.5\beta q_j^2$. 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 therefore efficient that firm i sells power up to the point where both firms produce $0.5(q_i+q_j)$. Potential gains from subcontracting then equal the difference in industry production costs

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

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, with $0\leq\boldsymbol{\sigma}\leq 1$.[10]

We distinguish two types of subcontracts. *Ex post subcontracts* are written 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 $\boldsymbol{\sigma}=\sigma_{\mathrm{p}}$.[11] In contrast, an *ex ante subcontract* is written 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 be paid

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

[11] 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 $\boldsymbol{\sigma}=0.5$.

by the contractor to exercise the option. The exercise price depends on the state and each firm's sales.[12]

Our efficient ex ante subcontract should satisfy the following properties. First, both firms should agree to the contract that maximizes each firm's 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.[13] The option to buy from the subcontractor will never be exercised in stage two, however, if $\sigma_a > 1$. In-house production would then outperform the option contract. To meet subgame perfectness, we therefore impose $\sigma_a \leq 1$ 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

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

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 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.

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

[13] Notice that the intermittent production 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.

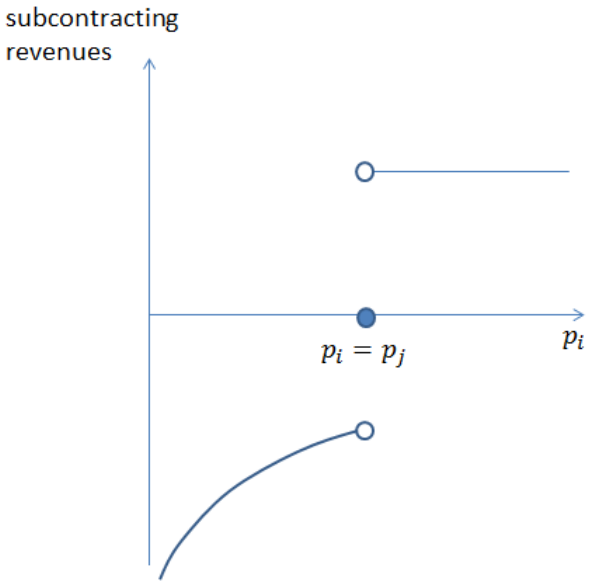


Figure 2: subcontracting revenues when firms compete à la Bertrand.

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 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. Formally,

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

It can be checked that, at price $p^* \equiv \frac{\beta\left(1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\right)}{8+\beta\left(1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\right)}$, firms cannot profitably deviate.[14] 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.

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

Interestingly, firms maximally gain from subcontracting when their intermittent technology is perfectly negatively correlated ($\rho = 0$ and $\alpha = 0.5$). 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. 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 set the subcontracting terms. Under the constraint that $\sigma_{\mathrm{a}} \leq 1$, each firm independently maximizes its profits with respect to σ_{a} so that firms set

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

We find that if the back-up technology is sufficiently expensive, the subcontracting terms can be set to let firms choose monopoly output levels in the first stage and obtain monopoly rents. Reversely, if back-up 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, the optimal ex ante subcontract is fixed at $\sigma_{\mathrm{a}}^{*} = 1$. By doing so, the 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 subcontracting to a wind-abundant firm. It follows that industry generation costs are always zero in equilibrium. If the back-up 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 back-up is 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 $\sigma_a^* = 0.5$. 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 ($\sigma_a = 0$) is not profit-neutral.[15]

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

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

The first term offers firm i's revenues from serving its customers, whereas the second term represents its costs without subcontracting. The third term represents firm i's expected gains from subcontracting in the events that firms encounter asymmetric generation conditions. 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. 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 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 that this equilibrium is locally stable, so that firms' profits can be written as

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

[15] 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)).

When firms engage in ex post subcontracting, the terms of trade $\boldsymbol{\sigma} = \sigma_{\mathrm{p}}$ is exogenous and firms' profits are as stated above. However, if firms rely on ex ante subcontracts, symmetric firms set $\boldsymbol{\sigma} = \sigma_{\mathrm{a}}$ 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.

To conclude this section, we state the following propositions.

Proposition 1: Even if the back-up technology remains idle in equilibrium ($\rho = 0$), more expensive back-up lowers industry output.

Proof: Suppose $\rho = 0$ (and hence $\alpha = 0.5$). Now let firms compete à la Bertrand and, so that industry output equals

$$1 - p^{*} = 1 - \frac{4\beta\boldsymbol{\sigma}}{8 + 4\beta\boldsymbol{\sigma}}$$

and is decreasing in β. Suppose instead that firms compete à la Cournot. Industry output then equals

$$q_i^{*} + q_j^{*} = \frac{2}{3 + 0.5\beta\boldsymbol{\sigma}}$$

and is also decreasing in β.■

Proposition 1 clearly illustrates the strategic role of back-up capacity. If firms sign subcontracts, back-up capacity need not be dispatched in equilibrium. However, since back-up determines the subcontracting terms, it affects industry output and profits.

Interestingly, by jointly raising their back-up costs, firms are better able to design the subcontract in order to implement monopoly profits. Unilaterally, however, firms like to limit the transfer paid to the rival by installing cheap back-up facilities.

Proposition 2: If firms sign ex post subcontracts, industry profits are concave with respect to the back-up cost parameter β and reach the monopoly level for $\beta = \dfrac{8}{\sigma_{\mathrm{p}}(6 - 2\rho - 4\alpha) + 2\alpha - \rho - 1}$ (Bertrand) or $\beta = \dfrac{2}{\sigma_{\mathrm{p}}(1-\rho)}$ (Cournot). When ex ante

subcontracts are written, sufficiently expensive back-up ($\beta \geq \frac{8}{5-2\alpha-3\rho}$ Bertrand or $\beta \geq \frac{2}{1-\rho}$ Cournot) enables firms to implement monopoly profits.

The proof easily follows from the previous analysis.

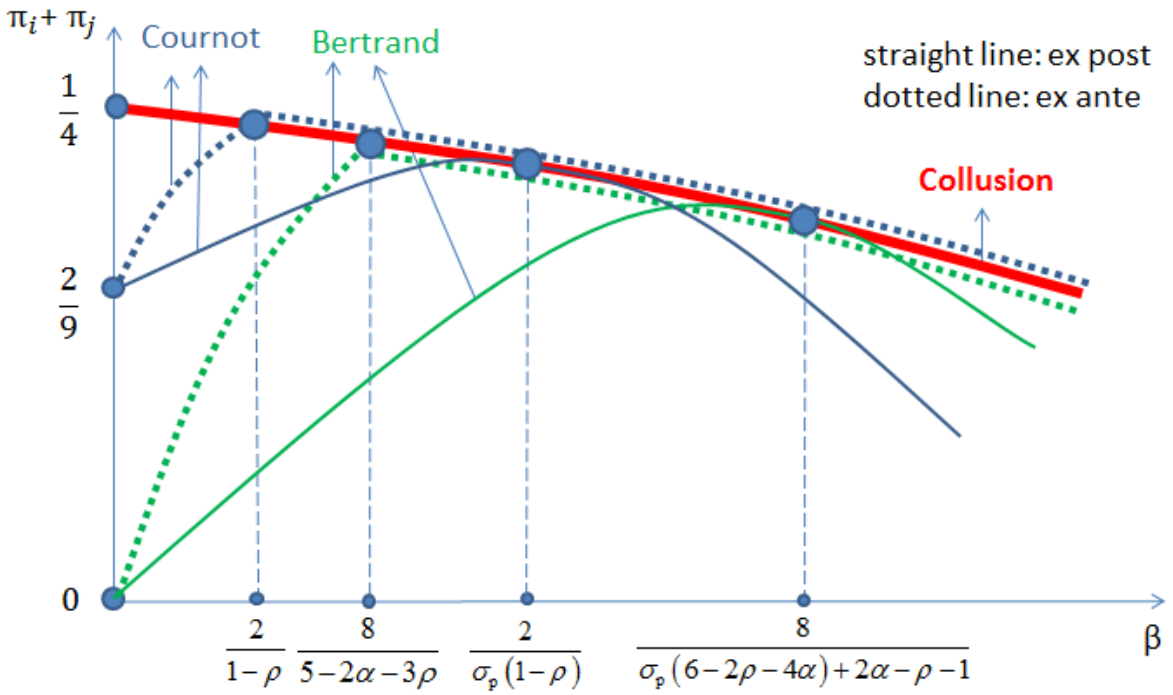


Figure 3: industry profits when firms sign subcontracts.

Figure 3 illustrates industry profits when firms sign subcontracts. For expositional clarity we let $\frac{8}{5-2\alpha-3\rho} < \frac{2}{\sigma_p(1-\rho)}$.[16] If conventional capacity is costless to use, price-competing firms earn zero profits. In contrast, firms make positive profits when they compete à la Cournot. To further increase profits, firms need to collude. As conventional capacity becomes more expensive, subcontracting payments effectively reduce industry output. Also, collusive profits go down since firms incur generation costs in state $(\bar{w}, \bar{w})$. If the cost parameter β is relatively small, subcontracting is too cheap to maximize industry profits. Hence, ex ante subcontracts raise subcontracting costs up to the contractor's opportunity cost. If β is large, ex post subcontracting costs are too high from a profit maximization perspective. As a result, firms can reach monopoly profits by fixing the subcontracting payments ex ante. In general, firms earn higher profits if they sign ex ante contracts.

[16] Or equivalently, we suppose $\sigma_p < \frac{5-2\alpha-3\rho}{1-\rho}$. This condition ensures the order of all intersections illustrated in figure 2.

5. Tacit collusion

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

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 the windless firm i's opportunity cost $TC(q_i)$. 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 $\boldsymbol{\sigma}$ 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

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

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 immediately receives collusive subcontracting payments $\sigma_{\mathrm{p}}^{\mathrm{c}} TC\left(q_i\right)$ 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 $\sigma_{\mathrm{p}} TC\left(q_i\right)$ to wind-abundant firm j, after which both firms compete forever.

Proposition 3: 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 then 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 study 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 the Bertrand case delivers the same insights.

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

$$\left(q_i + q_j\right)(1 - q_i - q_j) - 0.5\beta q_i^{\,2} - 0.5\beta q_j^{\,2}.$$

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 back-up technology is more expensive.

Subcontracting — Since expensive back-up remains idle in equilibrium ($\rho = 0$), the industry generation cost equals zero. 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 write ex post subcontracts, if deviation occurs during stage one, the subcontracting terms are determined by the exogenous share σ_{p}. If firms sign ex ante subcontracts, a deviating firm can contractually enforce $\sigma_{\mathrm{a}}^{\mathrm{c}}$ to be the seller's share of gains from subcontracting.

Proposition 4: The optimal deviation quantity equals $\frac{3}{2(4+\sigma_{\mathrm{p}}\beta)}$ (ex post) or $\frac{3}{2(4+\sigma_{\mathrm{a}}^{\mathrm{c}}\beta)}$ (ex ante). It is larger than the collusive quantity if subcontracting payments are low ($\sigma_{\mathrm{p}}\beta < 2$ ex post or $\sigma_{\mathrm{a}}^{\mathrm{c}}\beta < 2$ ex ante). If subcontracting payments are substantial ($\sigma_{\mathrm{p}}\beta > 2$ ex post or $\sigma_{\mathrm{a}}^{\mathrm{c}}\beta > 2$ ex ante), firms deviate by setting a lower quantity.

The optimal deviation quantity is the best response to the competitor's collusive quantity 0.25. If back-up is sufficiently cheap, the "revenue effect" from selling more outweighs the expected additional subcontracting cost. In contrast, if back-up is sufficiently expensive, 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 $\sigma_{\mathrm{p}}\beta = 2$ (ex post) or $\sigma_{\mathrm{a}}^{\mathrm{c}}\beta = 2$ (ex ante), both effects cancel out: collusive quantities coincide with competitive quantities.

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

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

The critical discount factor, for $\sigma_p\beta \neq 2$, then equals

$$\frac{(\sigma_p\beta+6)^2}{(\sigma_p\beta)^2+20\sigma_p\beta+68}.$$

If ex ante subcontracts are allowed, colluding firms can set σ_a^c such that the critical discount factor is minimized. If a firm deviates in stage one, it can contractually enforce to let σ_a^c share the gains from subcontracting. From the next period onwards, firms behave competitively and set σ_a accordingly. The incentive constraint to sustain collusion becomes

$$\begin{cases} \underbrace{\frac{1}{1-\delta}\frac{1}{8}}_{\text{collusive profits}} \geq \underbrace{\frac{9}{16(4+\sigma_a^c\beta)}+\frac{\sigma_a^c\beta}{64}}_{\text{deviation profits}}+\frac{\delta}{1-\delta}\underbrace{\frac{2(2+\beta)}{(6+\beta)^2}}_{\text{competition profits}} & \text{for } \beta<2 \\ \underbrace{\frac{1}{1-\delta}\frac{1}{8}}_{\text{collusive profits}} \geq \underbrace{\frac{9}{16(4+\sigma_a^c\beta)}+\frac{\sigma_a^c\beta}{64}}_{\text{deviation profits}}+\frac{\delta}{1-\delta}\underbrace{\frac{1}{8}}_{\text{competition profits}} & \text{for } \beta\geq 2. \end{cases}$$

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

Suppose firms set $\sigma_a^c = 2/\beta$. Then deviation profits coincide with collusive profits. Collusion is maximally sustainable because firms cannot gain from deviating. However, if $\sigma_a^c > 1$, in-house production outperforms the option contract. Therefore, if $\beta \leq 2$, colluding firms raise 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

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

The subcontracting terms can be set such that the deviating firm has little to win. It must be noted, however, that subcontracting need result in low critical discount factors. The reason is that, due to subcontracts, deviation may result in fairly good competition profits from the next period onwards.

Proposition 5: The ex ante subcontracting terms if firms behave competitively also maximize the sustainability of collusion. It is therefore impossible for a third party to distinguish collusive from competitive behavior on the basis of the 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.

6. 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 6: If the subcontractor appropriates a larger share of the subcontracting rents ($\boldsymbol{\sigma}$ goes up), industry output decreases so that consumers are better 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 high 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 7: When firms compete à la Bertrand, subcontracts enhance consumer surplus if and only if the subcontracting terms favor the buyer/contractor ($\boldsymbol{\sigma} \le 0.5$). When firms compete à la Cournot, subcontracts always make consumers better off. Subcontracts always increase industry profits.

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

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

Or equivalently,

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

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

Producers competing in prices are also better off using subcontracts since

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

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

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

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

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

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

It can be checked that this condition always holds.■

We distinguish two opposing effects of subcontracts on consumers. First, if firms can reduce 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 a higher price, so that they are less willing to compete fiercely when $\boldsymbol{\sigma}$ is large.

Intuitively, firms gain from subcontracting since it reduces the industry generation cost.

Proposition 8: If ex post subcontracting payments are significant ($\beta > \frac{4}{4\boldsymbol{\sigma}(1-\alpha)-\rho+2\alpha-1} > 0$), quantity competition outperforms price competition with regard to consumer surplus.

Proof: 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

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

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. 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 quantity choice does not affect firm j's output. 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.

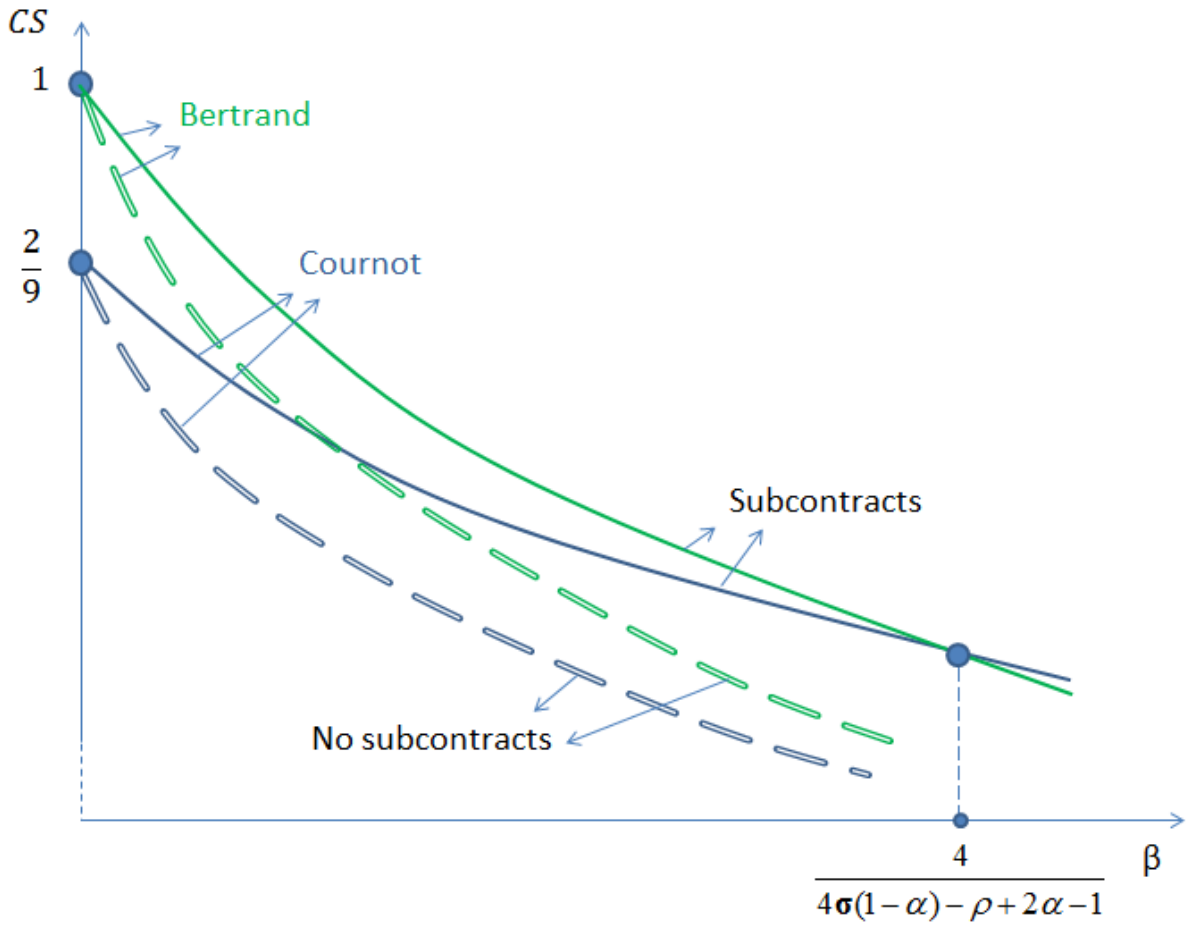


Figure 4: the effect of subcontracts on consumer welfare.

Figure 4 illustrates the effect of subcontracts on consumer welfare when $4\sigma(1-\alpha)-\rho+2\alpha-1>0$. If conventional capacity is inexpensive, subcontracting costs are low so that firms compete fiercely. Price competition leaves consumers best off. As conventional capacity becomes more expensive to use, industry output rapidly decreases if firms do not sign subcontracts. Instead, if firms use subcontracts to reduce costs, consumers benefit. For significant subcontracting payments, quantity competition outperforms price competition with regard to consumer surplus.

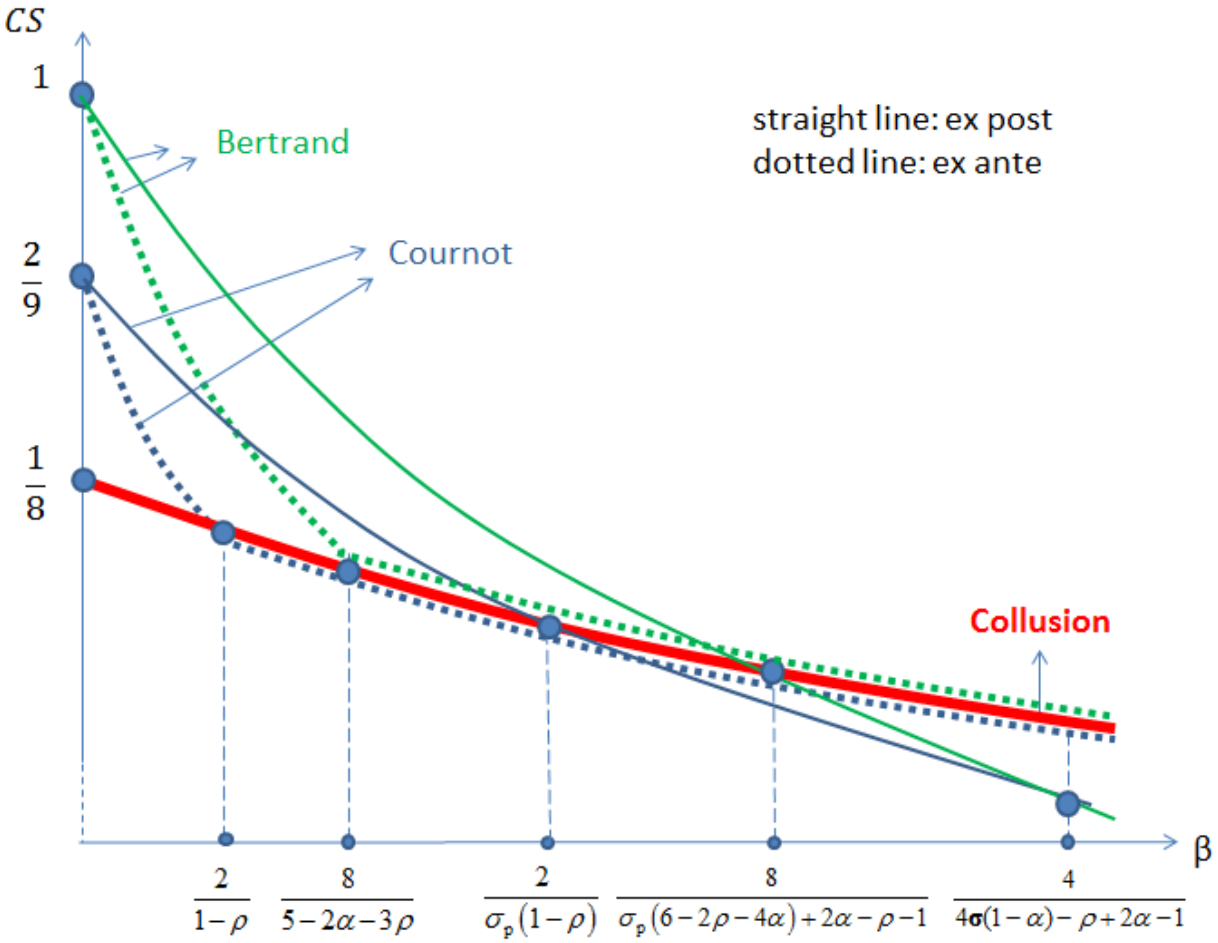


Figure 5: the effect of ex post and ex ante subcontracts on consumer surplus

Figure 5 illustrates the effect of ex post and ex ante subcontracts on consumer surplus. For expositional clarity we let $\frac{8}{5-2\alpha-3\rho} < \frac{2}{\sigma_p(1-\rho)}$ and $\frac{4}{4\sigma(1-\alpha)-\rho+2\alpha-1} > \frac{8}{\sigma_p(6-2\rho-4\alpha)+2\alpha-\rho-1}$.[17] If firms sign ex post subcontracts, subcontracting payments strictly increase as conventional plants become more expensive. As a result, for sufficiently expensive back-up, industry output can drop well below the collusive output. Firms can then leave consumers better off by signing ex ante subcontracts to raise industry output up to the collusive level. In contrast, if conventional plants are cheap, the ex post 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.

[17] Ex post subcontracting Bertrand and Cournot profits intersect since $\frac{4}{4\sigma(1-\alpha)-\rho+2\alpha-1} > 0$. Both inequalities ensure the order of all intersections illustrated in figure 5.

7. 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.[18] 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.[19] 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 $\frac{\partial^2 D(p,\varepsilon)}{\partial p \partial \varepsilon}=0$, so that ε increases demand while preserving the slope of demand with respect to p. After competing in stage one, firms can write subcontracts in stage two. For simplicity, we assume that subcontracting always occurs ($\rho=0$ and $\alpha=0.5$).

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 $p\left(D(p,\varepsilon)-q_j(p)\right)-0.5TC\left(D(p,\varepsilon)-q_j(p)\right)+0.5\boldsymbol{\sigma}\underbrace{TC\left(q_j(p)\right)}_{\substack{\text{gains from}\\ \text{subcontracting}\\ \text{in state } (w,\bar{w})}}+0.5(1-\boldsymbol{\sigma})\underbrace{TC\left(D(p,\varepsilon)-q_j(p)\right)}_{\substack{\text{gains from subcontracting}\\ \text{in state } (\bar{w},w)}}$. If $D(p,\varepsilon)$ and $TC(q)$ are continuously differentiable, any equilibrium outcome should satisfy the first-order condition

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

for all possible realizations of demand. Interestingly, contrasting to our Cournot setup, firm i's strategy affects firm j's quantity. If firm i submits a more competitive supply schedule,

[18] 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.

[19] 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.

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 $(w,\bar{w})$). 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 $(w,\bar{w})$ 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

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

Since back-up is never used for power generation ($\rho=0$), marginal costs consist 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 $0.5\boldsymbol{\sigma}TC\left(q_j(p)\right)$, 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 asking high prices.

To analytically investigate welfare in a supply function framework, we proceed with our quadratic back-up cost function $TC=0.5\beta q^2$. 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 $L_i(q_i)\equiv\dfrac{p-0.5\boldsymbol{\sigma}\beta q_i}{p}$. 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

$$q_i = b_i p$$

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.[20] After applying symmetry, we find that the optimal b_i equals

$$b_i^* = \frac{\sqrt{1+\frac{16}{\boldsymbol{\sigma}\beta}}-1}{4}$$

such that firm i's equilibrium supply schedule becomes[21]

$$q_i^* = \underbrace{\frac{\sqrt{1+\frac{16}{\boldsymbol{\sigma}\beta}}-1}{4}}_{b_i^*} p \ .$$

The interpretations coincide with our Bertrand and Cournot framework. 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 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

$$q_i^* = \underbrace{\frac{\sqrt{1+\frac{8}{\beta}}-1}{2}}_{b_i^*} p \ .$$

Subcontracting raises consumer welfare whenever

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

[21] 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.

$$\frac{\sqrt{1+\frac{16}{\boldsymbol{\sigma}\beta}}-1}{4} > \frac{\sqrt{1+\frac{8}{\beta}}-1}{2}.$$

Or equivalently, if and only if

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

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 7 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.

Consistent with our previous findings, competition by submitting supply functions can outperform Bertrand competition with regard to consumer surplus. 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

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' conventional plants. 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, which reach a maximum when $\bar{q} = q_i + q_j$.

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 conventional production parks. The gains from subcontracting equal

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

Again, this term is generally 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 the wind-abundant firms to serve windless firms can become sharp. In that event, the sellers' gain from subcontracting drops to zero and equilibrium output expands. Of course, in contrast to our two-firm setting, a wind-abundant firm may fall short of capacity to subcontract all windless firms. If a wind-abundant firm cannot serve all windless firms, scarcity of wind power results. Our main insights, then, remain as long as wind-abundant firms, with some positive probability, obtain subcontracting rents during stage two. Consequently, subcontracting payments happen between windless firms and wind-abundant firms, with similar results like our setting has studied.

Price competition and the settlement in the event of a tie — In our Bertrand framework, a tie is settled by the toss of a fair coin. The outcome off 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 ($p_i = p_j$). Formally, i's profits equal

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

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 $(3) \geq (2)$, which can be rewritten as the condition

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

Clearly, at price $p=1$, firms sell zero and therefore profitably deviate by setting a substantially lower price. In contrast, firm do not profitably deviate from price $p^* \equiv \frac{\beta\left(1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\right)}{8+\beta\left(1-2\alpha\left(2\boldsymbol{\sigma}+1\right)-\rho\left(2\boldsymbol{\sigma}-1\right)+6\boldsymbol{\sigma}\right)}$, which makes it the unique symmetric equilibrium price. Notice that p^* equals the equilibrium price we analyzed using the toss of a fair coin. In other words, the symmetric price equilibrium we analyze in this paper is valid and unique, irrespective of the choice between both settlement rules in case of a tie.

Linear tariffs — In our framework, firms take advantage of all potential 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, interestingly, 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 $\alpha = 0$, so that we think of a world where the availability of intermittent energy sources is negatively correlated.

The day-ahead market, stage one, is characterized by price competition and proceeds as before. The low-price firm i serves market demand $1-p_i$ and earns $\left(1-p_i\right)p_i$ 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 balancing 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 balancing market, it is willing to pay the marginal generation cost of using its back-up technology. Since $1-p_i-q$ is the number of units firm i produces in-house, where $0 \leq q \leq 1-p_i$, that marginal cost equals $\beta\left(1-p_i-q\right)$. Consequently, firm i's inverse demand equals $\tau = \beta\left(1-p_i-q\right)$, where τ denotes the uniform linear tariff on the balancing market.

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

$$\beta(1-p_i-q)q\,.$$

The first-order condition is

$$q^* = \frac{1-p_i}{1+\varphi},$$

which we generalize by defining $0 \le \varphi \le 1$ as the exogenous ratio of actual market power over maximally attainable market power (monopoly).[22] As a result, firm i's subcontracting costs amount to

$$\beta\varphi\left(\frac{1-p_i}{1+\varphi}\right)^2$$

and are increasing in β, which confirms the strategic role of back-up. Windless firm i produces $(1-p_i)\frac{\varphi}{1+\varphi}$ in-house by using its expensive back-up technology. Notice that linear tariffs do not guarantee an efficient outcome. Namely, firm i uses expensive back-up, 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

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

It can be checked that the unique symmetric equilibrium price is $p^* = \frac{\beta\varphi(\varphi+4)}{\beta\varphi(\varphi+4)+4(\varphi+1)^2}$, and is increasing in φ. As before, consumers are best off if subcontracting payments are low, that is, if selling firms exert little market power on intraday or balancing markets.

Arbitrage — Organized balancing 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, credible back-up lowers a firm's willingness to pay on the spot market. If it thereby reduces the price paid in stage two, back-up takes 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.

---

[22] 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 $0 \le \varphi \le 1.$

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 emission.

We first discuss the case where 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 back-up plant. Let firms shift generation from conventional plants 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.

Reliable and intermittent production technology — Our set-up assumed that both firms each have two technologies to generate their power with.

Let us first discuss why each firm i has access to a reliable technology. Suppose otherwise, namely that firm i is only equipped with an intermittent technology. It then risks not being able to deliver the promised quantity. In that event, it must contract power, regardless of the subcontracting payment. The lack of reliable alternative leaves firm i in a vulnerable position. Therefore, to limit the price paid for subcontracting, firm i has a profitable incentive to be equipped with the reliable technology.[23]

Second, we motivate why each firm also adopts the zero-marginal cost, intermittent technology. To be precise, we show that each firm benefits from the intermittent technology, irrespective of whether the opponent adopts.[24]

Let us start with Bertrand competition. We first check whether it is optimal to adopt, given that the opponent does not adopt. If no firm has access to the intermittent technology, the equilibrium price is such that each firm i is indifferent between serving the market and subcontracting only, or

$$(1-p)\,p - 0.5\beta(1-p)^2 + (1-\boldsymbol{\sigma})0.25\beta(1-p)^2 = 0.25\boldsymbol{\sigma}\beta(1-p)^2 .$$

[23] In fact, without a reliable technology, a firm can choose not to sell anything during stage one, earning subcontracting revenues only. Also in this case, it can be shown that firms benefit from being equipped with a reliable technology.

[24] Or equivalently, provided that fixed costs are zero, it is a dominant strategy to be equipped with the intermittent technology.

The first term on the left hand side reflects its revenues from charging p. The second term refers to its generation costs without subcontracting. The third term reflects the gains from subcontracting with the other firm. The right hand side captures the gains from subcontracting appropriated to the firm that does not serve the market. Therefore, each firm charges a price

$$\frac{\beta(1+2\boldsymbol{\sigma})}{4+\beta(1+2\boldsymbol{\sigma})}$$

and earns

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

Now suppose only firm i adopts the intermittent technology, so that it enjoys a cost advantage. We provide the analysis when the intermittent technology is a non-drastic process innovation.[25] Firm j, without intermittent technology, is indifferent between serving the market and earning

$$(1-p)p-0.5\beta(1-p)^2+0.5(1-\boldsymbol{\sigma})\underbrace{0.25\beta(1-p)^2}_{\substack{\text{gains from}\\ \text{subcontracting in } (\bar{w},\bullet)}}+0.5(1-\boldsymbol{\sigma})\underbrace{0.5\beta(1-p)^2}_{\substack{\text{gains from}\\ \text{subcontracting in } (w,\bullet)}}$$

or subcontracting only and receiving $0.5\boldsymbol{\sigma}0.25\beta(1-p)^2$.

Firm j is indifferent between these profits and charges

$$\frac{\beta(1+4\boldsymbol{\sigma})}{8+\beta(1+4\boldsymbol{\sigma})}.$$

Since the intermittent technology is a non-drastic innovation, firm i slightly undercuts firm j's price so that its profits amount to

$$\frac{24\beta\boldsymbol{\sigma}}{\left(8+\beta(1+4\boldsymbol{\sigma})\right)^2}.$$

Firm i is willing to adopt the intermittent technology given firm j has not, since it can be checked that

$$\frac{24\beta\boldsymbol{\sigma}}{\left(8+\beta(1+4\boldsymbol{\sigma})\right)^2}\geq\frac{4\beta\boldsymbol{\sigma}}{\left(4+\beta(1+2\boldsymbol{\sigma})\right)^2}.$$

We now verify whether firm j has an incentive to adopt, given firm i's decision to adopt. If firm j does not adopt, its profits are

[25] If the intermittent technology is a drastic innovation, the incentives to unilaterally introduce the technology are stronger.

$$\frac{8\beta\boldsymbol{\sigma}}{\left(8+\beta(1+4\boldsymbol{\sigma})\right)^2}.$$

However, if both firms adopt, firm j earns

$$\frac{8\boldsymbol{\sigma}\beta\left(2-\rho\right)}{\left(8+\beta\left(4\boldsymbol{\sigma}-\rho\left(2\boldsymbol{\sigma}-1\right)\right)\right)^2},$$

exceeding profits from non-adoption. Interestingly, and in contrast with the standard Bertrand result, both firms can have a dominant strategy to symmetrically decrease their marginal costs by incurring a fixed expenditure. The intuition is that, since subcontracts soften competition in a price-setting framework, industry profits are positive and decreasing in industry generation costs.

We now proceed with Cournot competition and follow the same logic to check whether it is profitable to adopt. If no firm has access to the intermittent technology, firm i's profits are

$$(1-q_i-q_j)q_i-0.5\beta{q_i}^2+\begin{cases}\underbrace{\boldsymbol{\sigma}0.5\beta(q_i^2+q_j^2-0.5(q_i+q_j)^2)}_{i\text{'s gains from subcontracting}} & \text{if } q_i\le q_j\\ \underbrace{(1-\boldsymbol{\sigma})0.5\beta(q_i^2+q_j^2-0.5(q_i+q_j)^2)}_{i\text{'s gains from subcontracting}} & \text{if } q_i\ge q_j.\end{cases}$$

The symmetric equilibrium is characterized by profit-maximizing quantities $q_i^*=1/(3+\beta)$, so that profits are

$$\frac{2+\beta}{2(3+\beta)^2}.$$

Alternatively, suppose firm i has access to the intermittent zero-marginal cost technology, given that firm j does not. Firm i then maximizes its profits

$$(1-q_i-q_j)q_i-0.25\beta{q_i}^2+0.5\boldsymbol{\sigma}\frac{\beta}{2}\left(q_j^2\right)+\begin{cases}\underbrace{0.5\boldsymbol{\sigma}\frac{\beta}{2}(q_i^2+q_j^2-0.5(q_i+q_j)^2)}_{i\text{'s gains from subcontracting if }(\bar{w},\,\bullet)} & \text{if } q_i\le q_j\\ \underbrace{0.5(1-\boldsymbol{\sigma})\frac{\beta}{2}(q_i^2+q_j^2-0.5(q_i+q_j)^2)}_{i\text{'s gains from subcontracting if }(\bar{w},\,\bullet)} & \text{if } q_i\ge q_j.\end{cases}$$

Given i's cost advantage, we find that it optimally sets a higher quantity $q_i\ge q_j$. Equilibrium quantities equal

$$q_i^*=\frac{2\left(\beta\left(2\sigma+1\right)+4\right)}{\beta^2\left(\sigma^2+\sigma+1\right)+2\beta\left(4\sigma+5\right)+24}\ge q_j^*=\frac{2\left(\beta+4\right)}{\beta^2\left(\sigma^2+\sigma+1\right)+2\beta\left(4\sigma+5\right)+24}.$$

Using these optimal quantities, it can be checked that i's profits exceed $\frac{2+\beta}{2(3+\beta)^2}$, meaning that it is willing to be equipped with the intermittent technology given that firm j is not.

By non-adopting, firm j earns

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

By inserting the equilibrium quantities, it can be shown that firm j can do better by adopting as well and earning

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

8. 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 reliable capacity. On the other hand, they have decreased the use of conventional plants. According to the industry, its introduction is clearly at the expense of conventional gas-fired plants. Utilities complain about low plant profitability and consider mothballing their underused units, unless the government comes with appropriate public policies, like capacity payments, to secure supply.

Our framework provides the policy insight that firms have strategic incentives to install costly but reliable capacity. 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 power from its intermittent units, reliable back-up credibly exerts a disciplining effect on the subcontracting price. Even if the gas-fired plant is never used for power generation, access to it offers utilities that lack low-cost power from their intermittent sources a credible alternative that reduces the price paid for subcontracting. Profitability at the conventional plant level does not capture that maintaining back-up is strategically advantageous. Interestingly, the unilateral incentive to install cheap gas-fired plants conflicts with firms' joint incentive to raise back-up costs in order to implement monopoly profits. Further research should consider the long run, where capacity decisions are endogenized.

We introduce a state-contingent option contract, where the terms of trade maximize each firm's expected profits non-cooperatively. If conventional plants are cheap to use, firms want to raise subcontracting payments to reduce competition, at the expense of consumers. In contrast, if conventional plants are expensive, firms optimally lower the price paid for subcontracting. Such an option contract makes producers *and* consumers better off.

In addition, we analyze collusion and find that subcontracts need not result in lower critical discount factors. Although firms can set the subcontracting terms to minimize deviation profits, the prospect of competing forever does not imply a large drop in profits. Interestingly, in our setting, the subcontracting terms alone do not enable an antitrust authority to distinguish collusive from competitive behavior.

Finally, to study welfare, our framework distinguishes between price and quantity competition. By charging the highest price, a firm earns considerable subcontracting revenues in the event its competitor is windless. Consequently, price-competing firms have less incentives to compete fiercely. This effect is also present with supply function competition, where firms apply markups which exceed the inverse price elasticity of residual demand. Cournot competing firms, in contrast, suffer less from a reduction in subcontracting revenues by serving more consumers. As a result, we find that consumers can be better off when firms compete in quantities rather than prices or supply functions. In the same spirit, we show that subcontracts between price-competing firms should favor the outsourcing firm sufficiently in order to increase consumer surplus. There is no such requirement for horizontal subcontracts signed between quantity-competing firms, which always enhance consumer surplus.

Appendix

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: Local stability is guaranteed if the spectral radius of the Jacobian of the best-reply map $\left|\frac{\partial q_i\left(q_j\right)}{\partial q_j}\right|\left|\frac{\partial q_j\left(q_i\right)}{\partial q_i}\right| \leq 1$. Since both players are symmetric, without loss of generality, let $q_i \geq q_j$. Then the equilibrium is stable if

$$\frac{-4-\beta\boldsymbol{\sigma}\left(1+\rho-2\alpha\right)}{8+\beta\left(2+\rho(2-3\boldsymbol{\sigma})+\boldsymbol{\sigma}-2\alpha(2-\boldsymbol{\sigma})\right)}\frac{-4-\beta\left(1-\boldsymbol{\sigma}\right)\left(1+\rho-2\alpha\right)}{8+\beta\left(1+\rho(1-\boldsymbol{\sigma})+3\boldsymbol{\sigma}-2\alpha(1+\boldsymbol{\sigma})\right)} \leq 1 .$$

Rearranging gives the condition

$$\beta^2\left(8\alpha^2+2\rho^2(1-\boldsymbol{\sigma})(1-2\boldsymbol{\sigma})+4\rho(1-2\boldsymbol{\sigma}^2)+2\left(\boldsymbol{\sigma}^2+3\boldsymbol{\sigma}+1\right)+4\alpha\left(\rho(3\boldsymbol{\sigma}-2)-3\boldsymbol{\sigma}-2\right)\right)+\beta\left(-40\alpha+4(\rho\left(5-8\boldsymbol{\sigma}\right)+8\boldsymbol{\sigma}+5\right)+48 \geq 0 .$$

We prove that the expression on the left hand side is non-negative in three steps. (i) The expression evaluated at $\boldsymbol{\sigma}=0$, $\beta^2\left(8\alpha^2+2\rho^2+4\rho+2-8\alpha\left(1+\rho\right)\right)+\beta\left(-40\alpha+20(\rho+1)+48\right.$, is positive. (ii) The derivative of the expression with respect to $\boldsymbol{\sigma}$ evaluated at $\boldsymbol{\sigma}=0$, $2\beta^2\left(-6\alpha(1-\rho)-3\rho^2+3\right)+32\beta\left(1-\rho\right)$, is non-negative. (iii) The derivative of the expression with respect to $\boldsymbol{\sigma}$, $2\beta^2\left(-6\alpha(1-\rho)+\rho^2(4\boldsymbol{\sigma}-3)-8\rho\boldsymbol{\sigma}+4\boldsymbol{\sigma}+3\right)+32\beta\left(1-\rho\right)$, does not decrease in $\boldsymbol{\sigma}$. That is, the second derivative, $8\beta^2\left(1-\rho\right)^2$, is non-negative. This shows that the equilibrium is locally stable. ■

No subcontracting Bertrand competition — 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 $\frac{0.5}{2(2+\beta)}$. However, firms can also optimally deviate by setting a price equal to $\frac{1+\beta}{2+\beta}-\varepsilon$, where ε is arbitrarily small and positive, such that deviation profits become $\frac{1}{2(2+\beta)}$.

Sustained collusion must then satisfy the following condition

$$\frac{1}{1-\delta}\underbrace{\frac{0.5}{2(2+\beta)}}_{\text{collusive profits}} \geq \underbrace{\frac{1}{2(2+\beta)}}_{\text{deviation profits}}+\frac{\delta}{1-\delta}\underbrace{0}_{\substack{\text{competition}\\ \text{profits}}},$$

resulting in a critical discount factor of 0.5.

Subcontracting Bertrand competition — Since expensive back-up 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 A2: If a deviating price-competing firm expects low subcontracting payments ($\sigma_{\mathrm{p}}\beta < 2$ ex post or $\sigma_{\mathrm{a}}^{\mathrm{c}}\beta < 2$ ex ante), it sets $p_i = 0.5 - \varepsilon$ and serves the entire market. In contrast, suppose subcontracting payments are substantial ($\sigma_{\mathrm{p}}\beta > 2$ ex post or $\sigma_{\mathrm{a}}^{\mathrm{c}}\beta > 2$ ex ante). A deviating firm then chooses not to serve the market by increasing its price, thereby earning subcontracting revenues only.

Proof: We provide the proof for ex post subcontracts. The proof for ex ante subcontracts simply replaces σ_{p} by $\sigma_{\mathrm{a}}^{\mathrm{c}}$. 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 $(1 - p_i)\, p_i - 0.25\sigma_{\mathrm{p}}\beta(1 - p_i)^2$. To maximize revenues and minimize subcontracting costs, a deviating firm that serves the market sets $p_i = 0.5 - \varepsilon$, earning $0.25 - \sigma_{\mathrm{p}}\beta/16$. 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 $\sigma_{\mathrm{p}}\beta/16$. Choosing to serve the market is optimal whenever $0.25 > \sigma_{\mathrm{p}}\beta/8$. That is, the "revenue effect" (left hand side), should dominate the "subcontracting effect" (right hand side). Notice that, if $\sigma_{\mathrm{p}}\beta = 2$, both effects cancel out: collusive profits coincide with competition profits.

Sustained collusion should satisfy

$$\begin{cases} \dfrac{1}{1-\delta}\underbrace{\dfrac{1}{8}}_{\substack{\text{collusive}\\ \text{profits}}} \geq \underbrace{\dfrac{1}{4} - \sigma_{\mathrm{p}}\dfrac{\beta}{16}}_{\text{deviation profits}} + \dfrac{\delta}{1-\delta}\underbrace{\dfrac{\sigma_{\mathrm{p}}\beta}{\left(2+\sigma_{\mathrm{p}}\beta\right)^2}}_{\text{competition profits}} & \text{if } \sigma_{\mathrm{p}}\beta < 2 \\ \dfrac{1}{1-\delta}\underbrace{\dfrac{1}{8}}_{\substack{\text{collusive}\\ \text{profits}}} \geq \underbrace{\sigma_{\mathrm{p}}\dfrac{\beta}{16}}_{\text{deviation profits}} + \dfrac{\delta}{1-\delta}\underbrace{\dfrac{\sigma_{\mathrm{p}}\beta}{\left(2+\sigma_{\mathrm{p}}\beta\right)^2}}_{\text{competition profits}} & \text{if } \sigma_{\mathrm{p}}\beta > 2. \end{cases}$$

This results in the following critical discount factors

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

The incentive constraint to sustain collusion becomes

$$\begin{cases} \dfrac{1}{1-\delta}\underbrace{\dfrac{1}{8}}_{\substack{\text{collusive}\\ \text{profits}}} \geq \underbrace{\dfrac{1}{4}-\sigma_{\mathrm{a}}^{\mathrm{c}}\dfrac{\beta}{16}}_{\text{deviation profits}}+\dfrac{\delta}{1-\delta}\underbrace{\dfrac{\sigma_{\mathrm{a}}\beta}{\left(2+\sigma\beta\right)^2}}_{\text{competition profits}} & \text{if } \sigma_{\mathrm{a}}^{\mathrm{c}}\beta<2 \\ \dfrac{1}{1-\delta}\underbrace{\dfrac{1}{8}}_{\substack{\text{collusive}\\ \text{profits}}} \geq \underbrace{\sigma_{\mathrm{a}}^{\mathrm{c}}\dfrac{\beta}{16}}_{\text{deviation profits}}+\dfrac{\delta}{1-\delta}\underbrace{\dfrac{\sigma_{\mathrm{a}}\beta}{\left(2+\sigma\beta\right)^2}}_{\text{competition profits}} & \text{if } \sigma_{\mathrm{a}}^{\mathrm{c}}\beta>2. \end{cases}$$

If ex ante contracts are allowed, colluding price-competing firms optimally set

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

References

Ambec, S., & Crampes, C. (2012). Electricity provision with intermittent sources of energy. *Resource and Energy Economics*, *34*(3), 319-336.

Armstrong, M. (1998). Network interconnection in telecommunications. *The Economic Journal*, *108*(448), 545-564.

Dixit, A. (1979). A model of duopoly suggesting a theory of entry barriers. *Bell Journal of Economics*, *10*(1), 20-32.

Energinet. (2014). *2013 was a record-setting year for Danish wind power.* Retrieved from http://www.energinet.dk/EN/El/Nyheder/Sider/2013-var-et-rekordaar-for-dansk-vindkraft.aspx (checked August, 17, 2014).

Fauli-Oller, R., & Sandonis, J. (2002). Welfare reducing licensing. *Games and Economic Behavior*, *41*(2), 192-205.

Freixas, X., & Parigi, B. (1998). Contagion and efficiency in gross and net interbank payment systems. *Journal of Financial Intermediation*, *7*(1), 3-31.

Green, R. J., & Newbery, D. M. (1992). Competition in the British electricity spot market. *Journal of Political Economy*, 100(5), 929-953.

Green, R. (1996). Increasing competition in the British electricity spot market. *The Journal of Industrial Economics*, 44(2), 205-216.

Joskow, P. L. (2011). Comparing the costs of intermittent and dispatchable electricity generating technologies. *The American Economic Review*, 100(3), 238-241.

Kamien, M. I., Li, L., & Samet, D. (1989). Bertrand competition with subcontracting. *The RAND Journal of Economics*, 20(4), 553-567.

Klemperer, P. D., & Meyer, M. A. (1989). Supply function equilibria in oligopoly under uncertainty, *Econometrica*, 57(6), 1243-1277.

Laffont, J. J., Rey, P., & Tirole, J. (1998). Network competition: I. Overview and nondiscriminatory pricing. *The RAND Journal of Economics*, 29(1), 1-37.

Marion, J. (forthcoming). Sourcing from the enemy: horizontal subcontracting in highway procurement, *Journal of Industrial Economics*.

Maskin, E., & Tirole, J. (1988). A theory of dynamic oligopoly, II: Price competition, kinked demand curves, and Edgeworth cycles. *Econometrica: Journal of the Econometric Society*, 571-599.

NYISO—New York Independent System Operator. (2010). *Growing wind - final report of the NYISO 2010 wind generation study.* Retrieved from http://www.nyiso.com/public/webdocs/media_room/press_releases/2010/Child_New_York_Grid_Ready_for_More_Wind_093010/GROWING_WIND_-_Final_Report_of_the_NYISO_2010_Wind_Generation_Study.pdf (checked August, 17, 2014).

Omie. (2014). *Market results.* Retrieved from http://www.omie.es/files/flash/ResultadosMercado.swf (checked September 25, 2014).

Red Eléctrica de España. (2014). *Statistical series.* Retrieved from www.ree.es (latest update August, 13, 2014).

Spiegel, Y. (1993). Horizontal subcontracting. *The RAND Journal of Economics*, 24(4), 570-590.