Strategic Forward Trading and Technology

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Motivated by the electricity industry's transition towards renewable power, we analyse the impact of production technologies on commodity prices. It is self-evident that technologies directly affect market prices via their production costs: for example wind generators have lower operational costs than conventional gas producers and thereby displace them whenever available. But in this paper we show that this *direct* effect of technology on commodity prices may be complemented, or even counteracted, by another *indirect* effect if two conditions are satisfied: the commodity is traded in both product and financial markets, and competition between producers is imperfect. These conditions are not unusual in commodities and typically characterise electricity trading. Through a model of producers and buyers trading in both spot and forward markets, we show that apart from the direct effect of marginal production costs, the operational characteristics of technology have an indirect first-order effect on market prices through altering the balance of spot and forward trading. This result is driven by the combination of market participants' *hedging* and *strategic* motivations for forward trading: a forward market allows risk sharing over spot uncertainty, but it also affects spot outcomes through the production commitments of suppliers able to influence prices. Thus, both the level of spot prices and the forward premium over spot will be influenced by changes to quantities offered into the forward and spot markets. In the context of the electricity industry, where there is typically a diverse mix of production processes and operational constraints, we analyse flexible (e.g., gas), inflexible (e.g., nuclear), and intermittent (e.g., wind) technologies and show how these constraints influence trading and production decisions, and thereby the market prices. For example, despite its lower marginal cost, more intermittent capacity may not necessarily lower prices due to its effect of reducing forward trading. We discuss policy as well as managerial implications.

Key words: Forward trading, Cournot competition, Electricity markets; Renewable Energy

1. Introduction

How does production technology affect commodity prices? This question is particularly acute for electricity markets, which are rapidly shifting from conventional coal- and gas-fired generation towards low-carbon renewable sources such as wind and solar energy. Due to their lower operating costs, renewable sources undercut conventional power producers, and are generally expected to reduce wholesale power prices. This so-called *merit-order effect* reflects the direct influence of

lower operating costs and has been the widely used analytical focus to model market price movements, changes in power plant utilisations and asset revaluations associated with the transition to renewable power production (Woo et al. 2011, Baldick 2012, Ketterer 2014).

However, we observe that analysing just this direct cost impact of production technologies on market prices may be insufficient if the various technologies have different operating features. In electricity generation, gas plants are reliably available and able to quickly adjust production to demand, but nuclear stations are inflexible and the production of wind farms is weather-dependent. It may be thought that such concerns should not alter the overall merit-order effect, as intermittently available low-cost capacity may simply reduce prices on average. However, focusing on direct cost competition alone neglects two important aspects of power markets, financial contracting and market concentration, which together create a potentially important link between operating factors and market prices.

Specifically, this link results from combining two well-known rationales for the widespread financial contracting documented in power markets.[1] The first of these motivations is the *hedging* of risk exposures by both sides of the market. Electricity retail companies, usually operating with small profit margins and large customer bases, will cover their sales contracts and tariffs to end-users with forward purchases in the wholesale market. Power producers similarly hedge their production against spot price risk, with positions large enough to be regularly reported to the capital markets.[2] Moreover, this hedging context is not fully efficient, but exhibits systematic *forward premia*, i.e., differences in forward and spot prices for the same delivery period (e.g., Redl and Bunn 2013, Weron and Zator 2014). These premia have been sustained over several years, often with forward prices expected to be higher than spot (Longstaff and Wang 2004, Hadsell 2008, Bowden et al. 2009). This systematic manifestation implies the absence and/or inability of sufficient speculators to remove the apparent arbitrage opportunities, and forward markets thus function as risk-sharing mechanisms between producers and retailers, with premia reflecting the balance of these risks (Bessembinder and Lemmon 2002).

The second rationale for forward trading is *strategic*, based on considerations of supplier market power. Supply-side concentration is commonplace in the electricity industry, with typically a few large conventional generating companies with power to influence prices through their production decisions. From an economic gaming perspective, a forward position implies a first-mover advantage in spot trading, and strategic producers hence trade forward to gain market share (Allaz and

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[1] In the UK, for example, over 90% of wholesale electricity is traded via forward contracts for future power delivery (Ofgem 2009).

[2] See for example the year-ahead contracting of the UK power producer Drax at http://www.drax.com/media/66455/trading-update-november-2015.pdf

Vila 1993). Power producers may therefore tend towards forward contracting even though the implied commitment to higher production reduces power prices (Borenstein et al. 2002, Puller 2007, Bushnell et al. 2008).

Production technologies will however impose constraints on forward and spot trading. The increasing replacement of conventional thermal power generation with renewable sources is restricting the amount of forward trading (because of output uncertainty) and increasing the requirements for active intra-day balancing of spot demand and supply. And whilst the inflexibility of nuclear power has for many years precluded spot market engagement and motivated forward sales, with renewable technologies in contrast, the opposite may be happening because of their intermittent production. These impacts may further be amplified by policy instruments such as renewable support schemes that may shield them from risk exposure, for example fixed feed-in tariffs with priority dispatch (Klessmann et al. 2008) or contracts for differences with forward reference prices (DECC 2013). In summary, production technology may alter forward trading in various ways.

We therefore seek to understand how the operational factors of production, such as the intermittency of renewable power, may affect market prices. Our main contribution is showing that beyond the direct merit-order effect of operating costs on power prices, there is a complementary indirect effect of operational constraints, and other fundamentals, on prices. That is, fundamentals change the balance of capacities offered into the forward and spot markets, and these changes as a consequence then move price levels. We first establish these results in a market with a single (conventional) production technology, which is *flexible* and *reliable*: producers can respond to demand, and face no uncertainty over effective supply. This allows us to capture the essential features of many current power markets with limited renewable capacity before introducing multiple technologies with operational constraints.

From the considerations above, we further characterise the market setting as having producers and retailers trading in both spot and forward markets, market power by the producers, and limited arbitrage. These market characteristics are together more realistic than the assumptions used in previous theory, providing the basis for new results. Specifically, our model synthesises the hedging and strategic rationales for forward trading established in largely separate streams of literature. The hedging literature (Bessembinder and Lemmon 2002) derives forward prices and premia from a risk-sharing equilibrium between producers and retailers facing demand uncertainty, but in the absence of market power. The strategic literature studies a game between producers with market power (Allaz and Vila 1993), but presumes arbitrage between the forward and spot markets and does not therefore permit the emergence of forward premia.

Focusing first on the single-technology setting, we combine the hedging and strategic perspectives into a single formulation and derive the spot-forward equilibrium between producers and

retailers. We show how market fundamentals, such as demand and production costs, determine the participants' need for hedging, and hence the volume of forward trading. But this volume determines the implied production commitments of strategic producers, and hence affects the spot price. This is the indirect effect of fundamentals: they move *spot* prices not only directly, but also through forward market risk sharing. The effect yields a rich set of comparative statics on the determinants of power prices and forward premia. The empirical literature on electricity markets is largely inconclusive and sometimes contradictory on how various fundamentals, such as demand uncertainty, affect price levels and forward premia. Our results indicate that this lack of consensus may be partly explained by the novel interaction effects arising from the indirect effect. For example, we show how sign reversals in the forward premia, often reported as questioning one of the Bessembinder and Lemmon (2002) implications, may be a function of demand variance.

Building on these results, we next consider the impact of different production technologies on power prices. To capture the technological specificities of power markets, we include two additional types of production technology with low production costs but constrained operations: *inflexible* ("nuclear") and *intermittent* ("wind") capacity. These technologies displace conventional production through cost competition of the merit-order effect. But we show their operating contraints also have the complementary indirect effect on power prices by adjusting the quantities available in the forward and spot markets. We characterise the impact of technology on prices and forward premia and show, for example, the price impact of a policy of increasing intermittent capacity. Whilst replacing conventional capacity with low-cost renewables will have a direct downward influence on power prices, the additional spot uncertainty from renewables may also cause producers to significantly reduce their forward commitments which induces higher prices through the indirect effect. Surprisingly, sufficient additional renewable capacity may therefore *increase* both forward and spot prices, despite its lower production cost.

Finally, we use the model to study the implications of different renewable financing schemes in a market context. Depending on the design of these schemes, renewables may or may not face market risk exposure and participate in forward trading. We show that through the indirect effect, the impact of increasing intermittent renewable producers on electricity prices may substantially depend on whether they trade in forward markets. The design of policy interventions may therefore have unintended *pricing* consequences. Furthermore, for policies with payments tied to spot or forward prices (such as contracts for difference), the long-term cost of the intervention will depend on this choice as increasing renewable capacity will change the premium between these prices, a novel consideration for policy evaluation. Together, these results indicate that analysing the direct merit-order effect of technology alone may neglect additional dependencies of power prices on the operational factors of production, mediated through financial markets.

2. Related Literature

Prior research on forward contracting has established its hedging and strategic roles, but in largely separate streams of work. In the hedging literature, forward trading is motivated as a risk-sharing mechanism between market participants (e.g., Anderson and Danthine 1980, Hirshleifer and Subrahmanyam 1993). For electricity, in the absence of both storage (and hence standard no-arbitrage cost-of-carry arguments for forward pricing, e.g., MacKinlay and Ramaswamy 1988), and sufficient speculation, persistent forward premia have been documented (Longstaff and Wang 2004, Hadsell 2008, Bowden et al. 2009, Redl and Bunn 2013). Much of this literature has thus sought to understand the determinants of the spot-forward price relationship and premia, using either assumptions on forward price evolution (e.g., Pirrong and Jermakyan 2008) or the equilibrium risk-sharing approach (Bessembinder and Lemmon 2002). In this latter literature, research has studied, for example, the connection between equilibrium hedging and the procurement of ancillary services Siddiqui (2003) and retailer competition Aïd et al. (2011), but in the absence of market power. The literature on the strategic role of forward markets, on the other hand, has focused on market power, but typically from a risk-neutral standpoint precluding forward premia. Suppliers may strategically commit forward to gain spot market share (Allaz and Vila 1993), but this leads to a more competitive market with lower price levels, as empirically documented in the power industry (Borenstein et al. 2002). This strategic role of forward trading has also been studied from the operational perspectives of investment decisions (Murphy and Smeers 2010), different timing of production (Popescu and Seshadri 2013), and asymmetric production costs (Su 2007, Ke 2008). The literature combining the two roles is sparse. Allaz (1992) considers how strategic producers hedge together with speculators, but does not include demand-side market participants or study forward premia; Powell (1993) and Green (2004) study risk-neutral strategic producers trading with retailers under different assumptions. We contribute to this literature by fully combining the strategic and hedging roles, analysing prices and forward premia resulting from risk-sharing between producers and retailers, and also including different production technologies.

The integration of intermittent renewable sources into power generation has been the subject of a growing operations-management literature. This research has studied the optimal operation of renewables via curtailment and storage (Wu and Kapuscinski 2013, Zhou et al. 2014), investments in these technologies (Aflaki and Netessine 2015, Kök et al. 2015, Hu et al. 2015), as well as the optimal adoption of renewable technologies through subsidy schemes (Boomsma et al. 2012, Alizamir et al. 2016). Complementing this literature, we study the impact of technological diversity, including intermittency, on electricity market outcomes. In this vein, Twomey and Neuhoff (2010) show that conventional producers' market power may reduce the profitability of wind generators, while both Al-Gwaiz et al. (2016) and Sunar and Birge (2014) study the impacts of operational factors on

supply function equilibria in a spot electricity market with system-operator balancing. Al-Gwaiz et al. (2016) consider producers with operational characteristics of technologies similar to those in our model, showing that ignoring such factors may overstate the competitiveness of the market, as producers may exploit their competitors' inflexibility in supply-function bidding. Sunar and Birge (2014) study optimal supply-function offers for a single intermittent technology in a (single) day-ahead market setting with the system operator setting production mismatch penalties. Like us, they find that renewable capacity may increase power prices, but through a different mechanism, i.e., the system-operator penalties reducing the quantities sold to the market. Both these papers focus on single-stage competition models. By contrast, we study trading in and production decisions in sequential forward and spot markets. Specifically, we analyse a novel mechanism through which technology affects commodity prices: operating factors alter risk sharing in the forward market, and hence indirectly move also spot prices through strategic forward commitments.

Our analysis also links to the broader literature on commodity trading from different supply-chain perspectives (e.g., Wu and Kleindorfer 2005, Spinler and Huchzermeier 2006, Dong and Liu 2007, Mendelson and Tunca 2007, Pei et al. 2011, Secomandi and Kekre 2014). Research to date has studied how the operational factors of production influence both financial contracting (Gaur and Seshadri 2005, Caldentey and Haugh 2006, Ding et al. 2007, Chod et al. 2010) and product market competition (Babich et al. 2007, Anupindi and Jiang 2008, Deo and Corbett 2009, Tang and Kouvelis 2011), yet in largely separate streams of work. We combine these perspectives in analysing the impact of technology on competition and trading in commodity markets. Specifically, we examine how operational factors such as yield uncertainty change the relation between firms' financial hedging (forward trading) decisions and their product market competition.

3. Model with Conventional Technology

Our goal is to develop a simple and tractable model to capture the following features of present-day electricity markets.

- **Production technologies.** Electricity is a non-storable homogeneous commodity, at present produced mostly with conventional thermal technologies such as gas, coal, and oil plants, which are able to quickly adjust production to demand peaks (ie *flexible*) and consistently available (ie *reliable*). Some markets, however, also include *inflexible* nuclear power and, increasingly, *intermittent* renewable sources such as wind and solar power. To contrast our study with the literature and provide a baseline for analysing the impact of technology, in this section we study a single production technology corresponding to a present-day market setting with only conventional generation, which is both flexible and reliable. We consider multiple technologies in the next section.

- **Supplier market power.** Producer market concentration is commonplace in power markets, with typically a small number of generators selling power via wholesale markets to a larger number of customers, such as retailers. We therefore consider a duopoly of producers selling power to price-taking customers. We capture producer market power as quantity (Cournot) competition, which has been used extensively in both theoretical and empirical studies of electricity trading (e.g., Wolak and Patrick 2001, Bushnell 2003, Puller 2007, Sweeting 2007). In many markets, producers may be able to offer supply curves of price-quantity pairs to the market (e.g., Anderson and Philpott 2002). For bilateral forward trading, via OTC or power exchanges, generators will however offer contracts in terms of fixed volumes, and in practice companies with a single production technology often do not make full use of this option. Given our focus on insights on optimal contracting, we therefore focus on a model with sequential quantity choices, following the literature (e.g., Allaz and Vila 1993, Bushnell 2007).

- **Elastic and inelastic demand components.** Many consumers are on fixed-price contracts with electricity retailers, and hence do not react in the short term to wholesale prices. Other consumers, such as some industrial users, may prefer to respond to real-time prices, either through retailers or by trading directly in the wholesale market. We capture this diversity with respectively inelastic and elastic demand components.

- **Spot and forward markets.** Electricity is actively traded in both forward and spot markets. Forward markets typically do not exhibit efficient speculation, with significant and persistent forward premia in the difference between expected spot and forward prices. We therefore assume there are no outside speculators in the market. Producers may sell their production in the forward market, and the retailers may procure forward, but we assume the fringe real-time customers do not participate in it. This is based on the observation that retailers with customers who are on a fixed retail tariff (eg most residentials) will generally want to hedge their sales contracts with forward purchases in the wholesale market, whereas many commercial and industrial customers who can respond to time-of-day pricing in the wholesale spot market will choose to do so much less often. As an aside, in Appendix E we provide an extension of the model where this elastic demand is also traded forward. This does not qualitatively affect our main insights.

We assume that firms trading in the forward market seek to reduce the risk in their profits. The corporate finance literature provides several justifications for why firms may benefit from hedging and reduced profit volatility due to various frictions, for example to avoid costly external financing (Froot et al. 1993) or costs of financial distress (Smith and Stulz 1985), and informational asymmetry over risks (DeMarzo and Duffie 1995). Power markets, in particular, exhibit significant volatility due to non-storability, and even large producers regularly

announce their forward exposures as part of their financial reporting. Following e.g., Bessembinder and Lemmon (2002), we therefore assume that the trading firms consider both their expected profit and the volatility of these profits, i.e., they have mean-variance utility. In other words, they act as if they are risk averse; the weight placed on profit variance can be alternatively interpreted as the weight of various frictions being proportional to the volatility of their cash flows.

Thus, we consider a homogeneous non-storable product traded in two stages, first on a forward market, and then on a spot market. Demand is uncertain in the forward stage and realized before the spot stage, where all production also occurs. There are three types of market participants in our model: Cournot producers on the supply side, with price-taking inelastic and elastic consumers on the demand side. There are two identical producers $i = 1, 2$ competing in quantities. Let f_i and q_i denote the forward and spot quantities of producer i, and F and Q the total quantities; the forward and spot prices are p_f and p_s. The producers have equal marginal production costs c.[3]

The demand side of the market is price taking, meaning that the participants procure their demand at the market price. We roughly characterise the inelastic and elastic consumer segments as "retail" and "industrial", but these labels are simple euphemisms and do not imply for example that all industrial consumers in reality are elastic and trade only on the spot. There are N_R retail companies who procure electricity from the wholesale market and sell it to consumers for an exogenous fixed price p_R. This demand component is inelastic component as the customers can use as much power as they want at this price. The retailers may procure power in either the spot or the forward market. We let f_{Ri} denote the quantity purchased forward by retailer Ri, and its realized demand by θ_{Ri}; its spot procurement is the difference between these. We assume that $\theta_{Ri} = \alpha_{Ri}\theta$, where α_{Ri} is the retailer's market share, and θ is the total inelastic demand. For simplicity, we let the market shares be equal: $\alpha_{Ri} = \frac{1}{N_R}$.[4] The elastic demand component represents an aggregation of consumers who are responsive to market prices. It is linear with intercept a and slope $1/b$. We further assume that these elastic consumers prefer to respond to real time spot prices and choose not to access to the forward market. Total demand is the sum of these components, and the spot price is determined by the inverse demand function

$$p_s(Q) = ab + b\theta - bQ, \tag{1}$$

where Q is the total quantity produced by the suppliers.[5]

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[3] Appendix F considers an alternative formulation with convex production costs.

[4] This is equivalent to assuming each retailer's demand is perfectly correlated with the total demand, which is reasonable as long as the retailers are similarly diversified.

[5] Technically, spot trading is in the difference between production and previous forward trades: $p_s = ab + b(\theta - f_R) - b(Q - F)$, but given that forward contracts are in zero net supply ($f_R = F$), these cancel out.

Demand is uncertain in the forward stage but realised before the spot stage. For simplicity, we assume there is uncertainty only in the inelastic (retail) demand component θ.[6] The distribution of θ has support $[\underline{\theta}, \overline{\theta}]$, mean μ_θ, variance σ_θ^2, and skewness τ_θ.

We first derive the spot stage equilibrium taking into account contracted forward positions, and then study optimal contracting in the forward stage.

3.1. The spot market equilibrium

In the spot stage, the demand-side participants simply procure their demand at the spot price. The producers select their production quantities to maximise profits

$$\pi_{i,s}(q_i) = p_s(q_i + q_j)[q_i - f_i] - cq_i. \tag{2}$$

Given that producer i has already contracted f_i in the forward market, it is only selling its residual production over this commitment. Here p_s is the spot price given by (1).

We focus on interior solutions where the spot price is set by the elastic demand. A violation of this assumption in the electricity context would be a blackout; avoiding them is one of the main objectives of regulators, and they are hence rare in mature markets. Indeed, regulators are generally keen to incentivise demand-response arrangements to improve resource adequacy. Furthermore, corner solutions in the spot market may lead to problems with forward market equilibrium existence (Murphy and Smeers 2010). We therefore restrict the support of the demand distribution to guarantee an interior solution.[7]

ASSUMPTION 1 (**No blackouts**). *The entire inelastic demand is served in equilibrium:* $Q^* \geq \theta$, $\forall \theta \in [\underline{\theta}, \overline{\theta}]$.

With this assumption, the spot market Cournot equilibrium with forward commitments is given in the following lemma.

LEMMA 1 (**Strategic commitment**). *The spot market equilibrium given forward positions f_i, f_j is*

$$q_i^* = \frac{q_{0,C} + 2bf_i - bf_j}{3b}, \tag{3}$$

$$p_s = \frac{p_{0,C} - bF}{3}, \tag{4}$$

where $q_{0,C} \triangleq ab - c + b\theta$ and $p_{0,C} \triangleq ab + 2c + b\theta$ reflect the (un-normalised) production and price in the absence of forward commitments.

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[6] We assume a single demand uncertainty for tractability. Alternatively, we could assume that both a and θ result from the same uncertainty with a certain market size division; this would not alter our main insights.

[7] In practice, at times of scarcity, the network system operator often makes ad hoc offers to industrial consumers to reduce load. We further assume that it is not profitable for a supplier to deviate to a lower quantity and only serve inelastic demand. This could be achieved for instance through a price cap, which are common in electricity markets.

The lemma shows how forward positions affect (expected) spot outcomes through strategic supplier commitment. Committing to a forward position f_i is lucrative because it increases the firm's spot market share in (3). But selling production forward also makes the spot market more competitive, with a lower expected price in (4). With fully efficient (risk-neutral) speculation, the forward price is equal to the expected spot price, and both markets similarly become more competitive (Allaz and Vila 1993). But in a less efficient hedging context, we need to derive the forward equilibrium from the market participants' hedging needs.

3.2. The forward market equilibrium and the indirect effect

We next use the spot equilibrium to determine both the retailers' and the producers' optimal forward positions. There is uncertainty over spot demand in the forward stage, and we assume that all market participants act as if they are risk averse. Specifically, both producers and retailers maximise the firm's expected profit, but with a penalty for profit variance (e.g., Bessembinder and Lemmon 2002 and Aïd et al. 2011):

$$U_k(\pi) = \mathbb{E}[\pi] - \frac{\lambda_k}{2} V(\pi). \tag{5}$$

The parameters λ_R, λ_P determine the retailers' and producers' demand degree of aversion to profit volatility, respectively. We assume in the following that the firms seek to (strictly) reduce profit volatility through forward trading and hence $\lambda_P > 0$ and $\lambda_R > 0$; we discuss this assumption in Appendix D for the setting with multiple production technologies.

The producers choose forward positions to maximise $U_P(\pi_{i,f})$ with profits

$$\pi_{i,f}(f_i, f_j) = p_f(f_i, f_j)f_i + \pi_{i,s}^*(f_i, f_j). \tag{6}$$

Here p_f is the inverse forward market demand, defined below, and $\pi_{i,s}^*$ denotes the equilibrium spot profit that depends on the forward positions. Consistent with the spot market, the producers have market power, that is, strategically choose forward positions to influence market prices.

The retailers select forward positions to maximise $U_R(\pi_{Ri,f})$ with profits consisting of the difference between sales and procurement costs:

$$\pi_{Ri,f}(f_{Ri}) = p_R\theta_{Ri} - p_s\theta_{Ri} + p_s f_{Ri} - p_f f_{Ri}. \tag{7}$$

The price-taking retailers are not strategic; but they are forward-looking, meaning that their spot expectations are unbiased.

ASSUMPTION 2 (**Forward-looking participants**). *Price-taking market participants hold unbiased expectations of spot prices in the forward stage. They are not strategic: they do not optimise forward trading to influence spot prices.*[8]

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[8] In the Appendix, we also consider the alternative case where participants choose forward positions taking the spot impact into account. We show that the strategic participants' forward positions converge to the non-strategic positions with high N_R. See the proof of Lemma 2.

Based on this assumption, we can derive the retailers' optimal forward positions using the first-order conditions of maximising expression (5) with the profits given in (7).

LEMMA 2 **(Retailer hedging)**. *The retailers' total forward position is given by:*

$$f_R = N_R \underbrace{\frac{\mathbb{E}[p_s] - p_f}{\lambda_R V(p_s)}}_{\text{Bias term}} + \sum_i \underbrace{\frac{-Cov(p_R \theta_{Ri} - p_s \theta_{Ri}, p_s)}{V(p_s)}}_{\text{Hedging term}}. \tag{8}$$

The optimal retailer forward position consists of two terms. The bias term represents speculation dependent on whether forward or spot procurement is cheaper in expectation: if the forward price is low, retailers will procure more forward as the bias favors them as buyers. The hedging term, on the other hand, reflects the retailers' risk over spot procurement, that is, the covariance of their revenues in the absence of forward trading and the spot price. Thus, for instance, the higher the retail price, the less the retailers will hedge, as their risk is lower; and they will conversely hedge more if market fundamentals (e.g., demand) increase their procurement costs. The spot price variance $V(p_s)$ moderates both the bias and the hedging terms: with high variance, it is costly to commit to a forward position.

The forward market clears by matching retailers' and producers' positions at zero net contract supply $F = f_R$. With this condition, we can translate the retailer positions into a linear inverse demand function. Using this demand in the producers' problem in (6), we have the following equilibrium.

PROPOSITION 1. *The single-technology spot-forward equilibrium is as follows.*[9]

$$q_{i,C}^* = \frac{q_{0,C}}{3b} + \frac{\omega_C}{3\nu_C}, \qquad f_{i,C}^* = \frac{\omega_C}{b\nu_C}, \tag{9}$$

$$p_{s,C} = \frac{p_{0,C}}{3} - \frac{2\omega_C}{3\nu_C}, \qquad p_{f,C} = a_{f,C} - \frac{2b_{f,C}\omega_C}{b\nu_C}, \tag{10}$$

where $q_{0,C} = ab - c + b\theta$ and $p_{0,C} = ab + 2c + b\theta$, and

$$\omega_C = N_R \left(\mathbb{E}[q_{0,C}](9 + 4b\lambda_P \sigma_\theta^2) + 2b^2 \lambda_P \tau_\theta \right)$$
$$+ 9b\lambda_R \left((\mathbb{E}[p_{0,C}] + b\mu_\theta - 3p_R)\sigma_\theta^2 + b\tau_\theta \right) \tag{11}$$

$$\nu_C = 54b\lambda_R \sigma_\theta^2 + N_R(45 + 8b\lambda_P \sigma_\theta^2) \tag{12}$$

$$a_{f,C} = \frac{ab + 2c + b\mu_\theta}{3} + \frac{b\lambda_R}{9N_R} \left((ab + 2b\mu_\theta + 2c - 3p_R)\sigma_\theta^2 + b\tau_\theta \right) \tag{13}$$

$$b_{f,C} = \frac{1}{9N_R} \left(3bN_R + 2\lambda_R b^2 \sigma_\theta^2 \right). \tag{14}$$

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[9] Assumption 1 (interior solution) requires that $b\nu_C \theta \leq 2((ab - c)\nu_C + \omega_C)$ for all θ, i.e., the quantity produced to be large enough to cover the inelastic demand. It is easy to see that there is a threshold $\bar{p}_R$ so that the inequality holds for all θ for $p_R \leq \bar{p}_R$; that is, when the retail market is competitive enough. Alternatively, the condition would hold for elastic demand component a large enough compared to maximum inelastic demand.

The equilibrium shows how the existence of a forward market affects the price of the product. In the absence of forward trading, the spot price p_s would be determined *directly* by market fundamentals in the expression $p_{0,C}$. But the higher the forward positions of the strategic producers, the more they will additionally sell on the spot market, and the lower the price. The spot price therefore also depends *indirectly* on any factors influencing forward trading via the ratio ω_C/ν_C.

This indirect effect combines the strategic commitment and hedging motivations for forward trading. We can recover the forward positions arising purely from the strategic motivation by ignoring risk and setting $\lambda_P = \lambda_R = 0$: We then have the result of Allaz and Vila (1993), where forward trading simply makes the market more competitive and moderates the impact of fundamentals on prices. But here the first line and second lines of ω_C also reflect the producers' and retailers' risk hedging incentives, respectively. The term ν_C conversely moderates forward trading, reflecting the risk of committing to a large forward position. If market fundamentals increase these incentives, the size of the forward market also increases. Thus, for example, a higher (mean) demand expands trading on the forward market. Through the producers' strategic commitment to spot production, any such changes will move market prices. We next examine these results in the context of electricity markets.

3.3. Implications for Electricity Prices

Spot price. The literature on the determinants of electricity prices typically studies a set of market fundamentals including production cost and current demand realization. But the indirect effect identified above implies that this set should be extended to include a wider range of variables.

COROLLARY 1. *The impact of market fundamentals on the spot price is summarized in Table 1. The expected spot price is increasing in μ_θ, a, c, and p_R, and decreasing in τ_θ.*

Table 1   The impact of market fundamentals on the spot price.

Effect	a	c	θ	μ_θ	σ_θ^2	τ_θ	p_R
p_s – Direct	$+$	$+$	$+$	N/A	N/A	N/A	N/A
p_s – Indirect	$-$	$+^*$	N/A	$-$	$+/-$	$-$	$+$
p_s – **Total**	$+$	$+$	$+$	$-$	$+/-$	$-$	$+$
$\mathbb{E}[p_s]$ – **Total**	$+$	$+$	N/A	$+$	$+/-$	$-$	$+$

* if $N_R \geq 5$.
$+$ and $-$ indicate partial derivatives ≥ 0 and ≤ 0, respectively

The corollary shows that the direct effect of a higher demand increasing power prices is moderated by an opposite indirect effect: higher demand leads to higher forward commitments and hence a more competitive spot market. But it also suggests novel determinants of wholesale power prices, such as the retail price p_R. Downstream retail prices are typically not seen as affecting upstream

wholesale prices, but here a high retail price reduces retailers' need to hedge, and hence increases the expected spot price. This is because the producers will also hedge less to keep the forward market in balance: they then act less competitively on the spot market, and the price increases. A non-competitive downstream retail market can therefore contribute to a non-competitive upstream wholesale market through this commitment effect. The distribution of demand similarly moves prices indirectly: positive skewness, for example, increases forward trading as participants seek to hedge against spikes, and hence reduces the spot price. Thus, combining the hedging and strategic effects predicts new drivers of electricity spot prices: without the two effects together, neither the retail price level, nor the demand variance and skewness would apparently affect average wholesale spot prices.

Forward premia. The forward premium is defined as the difference between the forward and expected spot prices: $\psi = p_f - \mathbb{E}[p_s]$. Due to the prevalence of forward trading for electricity and the persistence of large and systematic premia, their determinants are scrutinised by both traders and regulators, yet empirical evidence on these factors is conflicting (Redl and Bunn 2013). For example, evidence of the impact of demand variance (and hence market volatility) on premia is ambiguous with respect to its sign and its intuition is not well explained by existing theory (e.g., Bessembinder and Lemmon 2002). The following result suggests a potential reason for this controversy: the impact of factors like demand variance on premia should be examined not only through their direct effects but also their *interactions*.

COROLLARY 2. *Both the forward premium and the impact of demand variance on it are increasing in c, μ_θ, and τ_θ, and decreasing in p_R. These results are summarized in Table 2.*

Table 2   The effect of market fundamentals on the forward premium, and their interaction effects with demand variance on the premium.

|	a	c	μ_θ	σ_θ^2	τ_θ	p_R
$\psi = p_f - \mathbb{E}[p_s]$	+/−	+	+	+/−	+	−
$\dfrac{d\psi}{d\sigma_\theta^2}$	+/−*	+	+	+/−	+	−

*: − if N_R sufficiently high.

The corollary reveals that demand variance tends to *amplify* the forward premium, regardless of its sign. The forward premium reflects the balance of the forward market: a positive (negative) premium is the result of the demand (supply) side being more willing to pay to reduce its risk. Thus, a high marginal cost, a low retail price, and a positively skewed demand distribution all increase retailers' hedging needs relative to those of producers, increasing the forward premium. Demand variance adds to these effects by magnifying the participants' hedging incentives. Furthermore, with

sufficiently high demand and marginal (fuel) costs, the premium will be positive, and producers will benefit from forward sales compared to spot. A high premium may even reverse the Allaz and Vila (1993) result that forward markets reduce suppliers' total profits by making the industry more competitive: while the spot market still becomes more competitive with forward sales, the premium compensates for it.

Figure 1 shows how the impact of demand uncertainty on the forward premium may be reversed depending on whether trading incentives are "short" or "long". In panel (a), the marginal production (fuel) cost is low, and both spot and forward prices decrease with higher variance. Variance increases spot uncertainty, leading to more forward trading and hence lower spot prices. The forward price, however, decreases even more as the suppliers pay to hedge against spot risk, and the premium is hence negative and decreasing in demand variance. But these results are reversed by a change in just the fuel cost. In panel (b), the cost is high: prices are then higher and the premium is positive and increasing in demand variance. With higher costs driving up the spot price, retailers are more willing to hedging spot risk, resulting in a positive, increasing premium. In both cases, a higher variance reduces both spot and forward prices. An even lower marginal cost, however, would reverse this effect with the spot price *increasing* with variance. These results are consistent with evidence of day-night and winter-summer switches in forward premia (Bunn and Chen 2013), and, more broadly, may partly explain the lack of consensus in empirical evidence on the impact of fundamentals on forward premia. Moreover, such questions are increasingly relevant with multiple production technologies with varying operational characteristics, which we analyse next.

Figure 1   Forward and expected spot prices as functions of demand variance.

(a) Low marginal cost.   (b) High marginal cost.
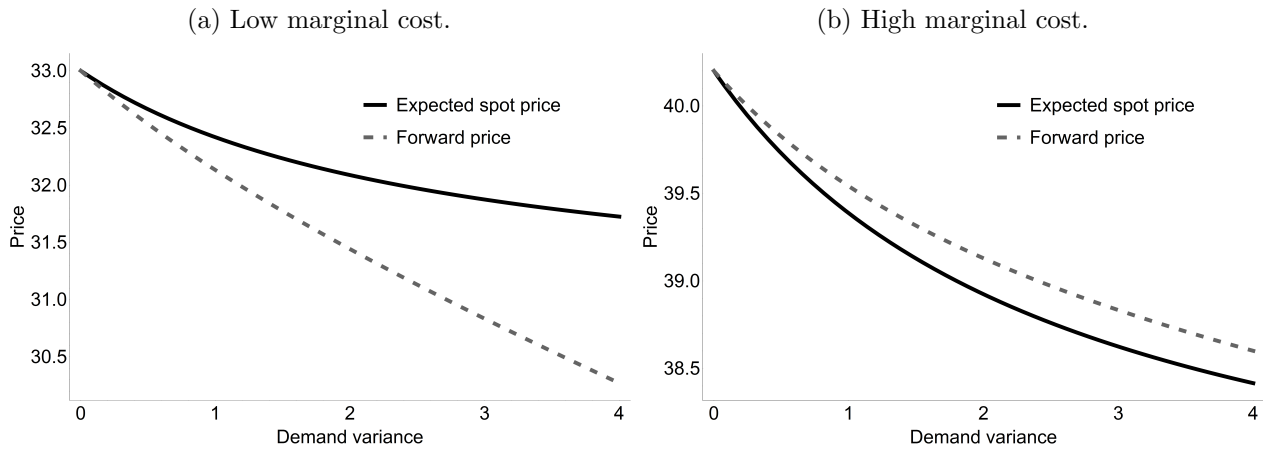
Note. Parameters $N_R = 6, \mu_\theta = 25, \tau_\theta = 0, a = 40, b = 1, p_R = 40, \lambda = 1; c = \{25, 34\}$ in panels {a,b}.

4.   Multiple Production Technologies

In the above present-day market context with a single conventional production technology, we have seen how market participants' hedging and strategic motivations for forward trading together create an indirect effect of market fundamentals on power prices. We next expand this model to examine the impact of different technologies on power prices, and specifically the merit-order effect of increasing renewable production. To capture the stylised features of electricity markets, we now include three technologies in the model:

- **Conventional producers**. As above, these producers are both flexible (they can control production rates to quickly react to changes in demand), and reliable (they can maintain constant production availability).[10] These producers form a majority of the generation capacity in most markets, and have power to influence prices as above.

- **Intermittent producers**. The effective production capacity of these producers is unreliable because of environmental factors: their yield is uncertain at the forward stage. Their marginal production cost, however, is lower than for conventional production. Wind power, for example, typically has a capacity factor of 20-30%, and cannot ramp up production as needed. We assume these producers do not have power to influence prices. While they could potentially reduce their production, small-scale renewables, even if aggregated as virtual entities, are unlikely to act strategically.[11]

- **Inflexible producers**. These producers are reliable, but not able to react to demand, and hence need to operate at a constant production level for sustained periods of time. Their marginal production cost, however, is lower than that of conventional production. Nuclear plants, though reliable, have inflexible short-term operation schedules. Exercising market power through short-run capacity adjustment would be difficult for inflexible producers because of the technical constraints, and we hence assume they too are price taking.

This model simplifies the market structure of current electricity markets in that the ownership of different assets is separated. In many markets, much of the new renewable capacity is small-scale, partly due to subsidy conditions. Alternatively, some of the larger projects such as offshore wind are often set up as separate joint ventures or as off-balance sheet special entities.[12] Moreover, utilities do not view conventional and renewable capacity as complementary assets: the German utility Eon, for example, recently decided to separate these divisions (Vasagar and Clark 2015). We

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[10] We abstract from supply issues like faults or maintenance.

[11] We do not focus on the broader issue of curtailment of renewable capacity in this paper; for a detailed discussion of optimal curtailment, see e.g., Wu and Kapuscinski (2013).

[12] The world's largest offshore wind farm in 2014 was the London Array with 175 turbines, jointly owned by four companies, http://www.londonarray.com/

focus on separate price-taking ownership in order to isolate the impact of technology on market outcomes.

In addition to the two flexible producers, the supply side of the market now includes N_W intermittent "wind" and N_N inflexible "nuclear" producers with total capacities q_W and q_N. For simplicity, we assume that their capacities are equal so that $q_{Wi} = q_W/N_W$ for each intermittent producer and $q_{Ni} = q_N/N_N$ for each inflexible producer. We normalise both marginal costs to zero. The fraction of available intermittent capacity ξ is uncertain. In the forward stage, all market participants know only the distribution of intermittent supply. Like demand, this uncertainty is resolved before the spot market. The fraction ξ is the same for each producer[13] and has the range $[\underline{\xi}, \overline{\xi}] \subseteq [0,1]$, mean μ_ξ, variance σ_ξ^2, and skewness τ_ξ. We assume that the demand θ and the intermittent supply ξ are independent. Both intermittent and inflexible producers are price taking, and hence always produce with their entire (available) capacities. The spot inverse (residual) demand for the flexible producers is therefore

$$p_s(Q) = ab + b\theta - bq_N - b\xi q_W - bQ. \tag{15}$$

The inverse demand shows the direct merit-order effect: additional capacity reduces the spot price, and (in expectation) more so as the reliability of intermittent production increases. This capacity will, however, also change the conventional suppliers' equilibrium production.

As before, we solve the game backwards from the spot stage. We again focus on interior solutions of the spot market game, requiring that the conventional producers always set the price. In the electricity context, this translates to a present-day market setting where renewable production capacity is not dominant and curtailment is rare. Recent research by the (IEA 2014) suggests that renewable capacities of 40% are feasible without significant curtailment. We focus on such medium-term scenarios and leave the analysis of curtailment required by the most ambitious long-term targets (e.g., Germany's 80% target by 2050) for future research. The following assumption also subsumes the assumption on no blackouts by guaranteeing that inelastic demand is always served.

ASSUMPTION 3 (**No curtailment**). *For all values of θ and ξ, the conventional producers set the price in the spot market: $Q^* > 0$. Furthermore, $Q^* + q_N + \xi q_W \geq \theta$.*

In the following, we contrast between two relevant forward market settings. Depending on market design and prevalent financing schemes, intermittent and inflexible producers may or may not participate in forward trading. If these producers are supported through fixed feed-in arrangements or contracts for difference, their revenues do not reflect spot risk, and they may be effectively excluded from the market. On the other hand, a lack of subsidies or the use of other subsidy

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[13] That is, each intermittent producer's output ξ_i is perfectly correlated with the total intermittent production ξ. In Appendix C, we relax this assumption; its impact on the equilibrium is typically small.

formats such as renewable obligations would require the producers to consider spot sales risk and optimal forward market strategies. We first examine the price impact of production technologies when they trade on the spot market only, which allows us to separate the impact of technology from that of forward market participation. We then repeat the analysis with all producers trading forward. Comparing the two scenarios, we then show that achieving the same renewable capacity under different subsidy schemes may result in substantially different electricity spot prices. Finally, based on these differences, we suggest implications for designing support schemes.

4.1. No Forward Market Participation

Let us first consider the situation where intermittent and inflexible producers do not participate in the forward market, and simply sell their entire effective capacity in the spot stage. We can then derive the equilibrium as above, but updating the conventional producers' and retailers' forward trading incentives with respect to the spot market in (15).

The following result establishes that beyond the direct merit-order effect apparent in (15), the operating characteristics of production technologies have a further indirect effect on the spot price through the forward market.

PROPOSITION 2. *In the game with multiple technologies, for any realisation of θ and ξ, the spot price p_s indirectly depends on the entire market production portfolio, in particular the distribution of intermittent supply via $\mu_\xi, \sigma_\xi^2, \tau_\xi$. The equilibrium is as follows.*[14]

$$q_{i,S}^* = \frac{q_{0,S}}{3b} + \frac{\omega_S}{3\nu_S}, \qquad f_{i,S}^* = \frac{\omega_S}{b\nu_S}, \tag{17}$$

$$p_{s,S} = \frac{p_{0,S}}{3} - \frac{2\omega_S}{3\nu_S}, \qquad p_{f,S} = a_{f,S} - \frac{2b_{f,S}\omega_S}{b\nu_S}, \tag{18}$$

where $q_{0,S} = ab - c + b\theta - bq_N - b\xi q_W$, $p_{0,S} = ab + 2c + b\theta - bq_N - b\xi q_W$, and

$$\omega_S = N_R \mathbb{E}[q_{0,S}](9 + 4b\lambda_P(\sigma_\theta^2 + q_W^2\sigma_\xi^2)) + 2b^2\lambda_P N_R(\tau_\theta - q_W^3\tau_\xi)$$

$$+ 9b\lambda_R \left((\mathbb{E}[p_{0,S}] + b\mu_\theta - 3p_R)\sigma_\theta^2 + b\mu_\theta q_W^2\sigma_\xi^2 + b\tau_\theta \right) \tag{19}$$

$$\nu_S = 27b\lambda_R \left(2\sigma_\theta^2 + q_W^2\sigma_\xi^2 \right) + N_R \left(45 + 8b\lambda_P \left(\sigma_\theta^2 + q_W^2\sigma_\xi^2 \right) \right) \tag{20}$$

$$a_{f,S} = \frac{ab + 2c - bq_W\mu_\xi - bq_N + b\mu_\theta}{3}$$

$$+ \frac{b\lambda}{9N_R} \left((ab + 2c + 2b\mu_\theta - bq_W\mu_\xi - bq_N - 3p_R)\sigma_\theta^2 + bq_W^2\mu_\theta\sigma_\xi^2 + b\tau_\theta \right) \tag{21}$$

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[14] Assumption 3 requires that production cover at least inelastic demand. This is true when $\theta \leq 2q_i^* + q_N + \xi q_W$. Let us assume conservatively that $\underline{\xi} = 0$. Then we need

$$b\nu_S\theta \leq 2(\nu_S(ab - c - bq_N) + \omega_S) + 3b\nu q_N = (2ab - 2c + bq_N)\nu_S + 2\omega_S. \tag{16}$$

Inflexible capacity relaxes the constraint, and it holds unless μ_θ and q_W are very large compared to a and q_N. We also assume that $q_i^* \geq 0$ for any values of θ and ξ. This constraint essentially requires inflexible and intermittent capacities low enough so that we never need to curtail them.

$$b_{f,S} = \frac{1}{N_R} \left[\frac{bN_R}{3} + \frac{\lambda b^2}{9} \left(2\sigma_\theta^2 + q_W^2 \sigma_\xi^2 \right) \right]. \tag{22}$$

The proposition shows how the indirect effect of technology combines the hedging and strategic motivations for forward trading. The distribution of available spot production capacity changes producer and retailer hedging incentives in the first and second lines of ω_S, respectively, and these incentives indirectly move the spot price through the producers' strategic commitment to forward positions $f_{i,S}^*$. Considering the hedging motivation alone would result in the spot market outcome determined by the merit-order effect in the current realisation of market uncertainties in $p_{0,S}$. As before, considering the strategic motivation alone ($\lambda_P = \lambda_R = 0$) would result in a modified Allaz-Vila result ignoring hedging incentives and forward premia. But combining the two rationales for forward trading, the spot price for any uncertainty realisation depends on the entire technological portfolio on the market, specifically the *distribution* of intermittent capacity in addition to its current realisation. We next contrast these indirect effects to the direct merit-order effect in electricity markets.

Implications for electricity prices. We focus here on how production technologies affect the spot price, and return to forward premia when comparing the results with forward market participation. The following corollary summarizes the spot price impacts, showing that the indirect effect may reverse the direct merit-order effect of renewable capacity.

COROLLARY 3. *The impact of market fundamentals on the expected spot price is summarized in Table 3. In particular, it decreases with q_N, but may either increase or decrease with q_W.*[15]

Table 3   The impact of market fundamentals on the expected spot price, and the cross-effects of fundamentals on the impact of renewable capacity.

	a	c	μ_θ	σ_θ^2	τ_θ	p_R	q_N	q_W	μ_ξ	σ_ξ^2	τ_ξ
$\mathbb{E}[p_s]$ – Direct effect	+	+	+	N/A	N/A	N/A	−	−	−	N/A	N/A
$\mathbb{E}[p_s]$	+	+	+	+/−	−	+	−	+/−	−	+/−	+
$\dfrac{d\mathbb{E}[p_s]}{dq_W}$	−*	+*	−	+/−	+	−	+*	+/−	+/−	+/−	+

* if $N_R \geq 5$.

Adding either inflexible or intermittent capacity to the market should reduce the expected spot price by replacing more costly conventional production in $p_{0,S}$ in Proposition 2. For inflexible capacity q_N, the indirect effect *weakens* the merit-order effect: as q_N increases, the strategic suppliers also need to hedge less production, reducing forward trading in $f_{i,S}^*$, and indirectly increasing the price. The total effect, however, is still to reduce the price.

[15] Note that these comparative statics, and the examples below, are derived holding the other parameters constant. Thus, they ignore how q_W may change the distribution of wind outcomes. In particular, if new wind resources are not correlated with existing ones, variance will tend to increase less than linearly with q_W. These results therefore best describe a geographically fairly small or uniform market.

Intermittent capacity q_W similarly *weakens* the merit-order effect through its mean availability μ_ξ. But the price impact of q_W also depends on its variability, with an ambiguous net effect. That is, additional renewable capacity both increases the producers' hedging, because of higher profit variability, but also decreases their hedging through, because committing to a forward position becomes in itself riskier. As a result of the latter impact, the direct merit-order effect of intermittent capacity may sometimes be *reversed* by the indirect effect. For instance, if intermittent supply is positively skewed,[16] additional capacity considerably reduces the optimal forward positions of conventional suppliers as committing to a position becomes riskier with a greater chance of high intermittent production. If hedging is reduced, the expected spot price may in fact increase with higher intermittent capacity, reversing the merit-order effect. Introducing renewable capacity may therefore not always significantly reduce electricity prices as strategically acting producers may compensate for this capacity through the forward market, mitigating the direct merit-order effect and even reversing it.

But renewable capacity may also increase producers' hedging, and hence *strengthen* the merit-order effect. For example, with a high expected demand, the producers tend to increase their hedging with more renewable capacity to reduce the risk in their spot sales, and this effect may dominate the additional risk involved in taking these positions. The spot price then decreases more than predicted by the direct merit-order effect. The overall effect of renewables on prices is hence ambiguous, a how other market fundamentals interact with renewable capacity, as detailed in Corollary 3. In general, the expected spot price is more likely to increase with intermittent capacity if the forward market balance "favours" the producers over the retailers, that is, the retailers' hedging incentives are high compared to those of the producers (the second line of ω_S compared to its first line in Proposition 2). With the producers less willing to hedge, intermittency increases the risk of committing forward, reducing their trading. Conversely, with the producers more willing to hedge, trading is more likely to increase, and prices decrease, with renewable capacity.

Figure 2 displays two examples of the impact of increasing intermittent capacity on prices. In panel (a), intermittent capacity reduces spot prices, showing the direct effect of adding more capacity; forward prices first decrease and then increase. In panel (b), the effect is reversed and the spot price *increases* with more low marginal cost capacity in the market. The forward price also considerably increases with intermittent capacity. Compared to panel (a), we have introduced positive skewness into the intermittent supply τ_ξ. The conventional producers then reduce their forward trading to avoid being committed to forward positions if intermittent production turns

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[16] A positive skewness is typical for wind power. For example, daily wind power output in Denmark, a significant adopter of wind capacity, had yearly skewness ranging from 0.6 to 0.9 in 2010-2013 (data available from www.energinet.dk). Similar values are obtained for hourly output.

Figure 2   Forward and expected spot prices as functions of intermittent capacity.

(a) No wind output skewness.   (b) Positive wind output skewness.
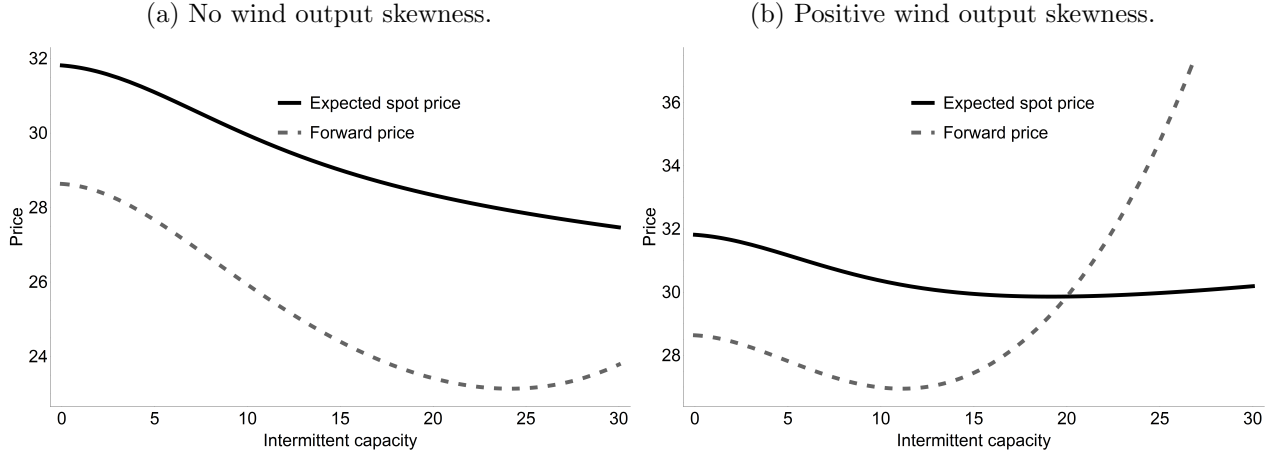
Note. Parameters $N_R = 6, \tau_\theta = 0, b = 1, p_R = 40, \lambda = 1, q_N = 10, \mu_\xi = 0.3, \sigma_\xi^2 = 0.1, a = 50, c = 25, \mu_\theta = 30, \sigma_\theta^2 = 9, \tau_\xi = \{0, 0.1\}$ in panels $\{(a), (b)\}$.

out high. As the producers reduce their forward trading, the spot price first decreases less, and then increases with additional renewable capacity. With the retailers more willing to trade against the spot risk of renewables, the forward price increases. Indeed, as Figure 3 shows, the producers' total expected profits then also increase with more renewable capacity, as the forward market shifts in their favour for a positive premium on their production. We next study how the impact of technology may change when the intermittent and inflexible producers also participate in forward markets; we return to the determinants of the premium under both scenarios in Section 4.3.

Figure 3   Producer profits as a function of intermittent capacity.
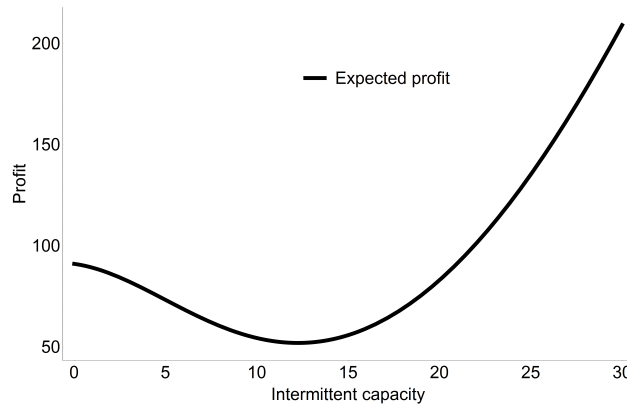
Note. Parameters $N_R = 6, \tau_\theta = 0, b = 1, p_R = 40, \lambda = 1, q_N = 10, \mu_\xi = 0.3, \sigma_\xi^2 = 0.1, a = 50, c = 25, \mu_\theta = 30, \sigma_\theta^2 = 9, \tau_\xi = 0.1$.

4.2. Active Forward Market Participation

Let us consider the alternative market setting where the inflexible and intermittent producers actively participate in the forward market. Given their zero marginal costs, each inflexible and intermittent producer's profits are, respectively,

$$\pi_{Ni} = p_s q_{Ni} - p_s f_{Ni} + p_f f_{Ni} \tag{23}$$

$$\pi_{Wi} = p_s q_{Wi}^e - p_s f_{Wi} + p_f f_{Wi} \tag{24}$$

Since these producers are price taking, we can construct their optimal forward positions from mean-variance utility (5) similarly to those of the retailers. The following lemma reports the forward positions. We assume in this section that all participants place an equal weight λ on profit variance.

LEMMA 3. *The total positions forward positions of inflexible and intermittent producers are*

$$f_N = \frac{N_N (p_f - \mathbb{E}[p_s])}{\lambda V(p_s)} + q_N, \tag{25}$$

$$f_W = \underbrace{\frac{N_W (p_f - \mathbb{E}[p_s])}{\lambda V(p_s)}}_{Bias\ term} + \underbrace{\frac{q_W Cov(\xi p_s, p_s)}{V(p_s)}}_{Hedging\ term}. \tag{26}$$

These positions, like those of the retailers above, consist of bias and hedging terms. Inflexible producers, facing no uncertainty over output, hedge their entire capacity q_N by default, and speculatively adjust this hedging based on the forward premium: a positive bias in the forward price makes forward sales lucrative. Intermittent producers may similarly speculate on the premium, but hedge based on the covariance of their spot profits and the spot price, both of which depend on their availability. We can again use these positions to derive a (residual) inverse forward demand for the conventional producers, and hence the equilibrium. Proposition 3 gives the equilibrium, which we next use to compare the price impact of technology under the two market settings.

PROPOSITION 3. *In the game with residual forward demand from retailers and intermittent and inflexible producers, the equilibrium is as follows.*[17]

$$q_{i,T}^* = \frac{q_{0,T}}{3b} + \frac{\omega_T}{3b\nu_T}, \qquad f_{i,T}^* = \frac{\omega_T}{b\nu_T}, \tag{27}$$

$$p_{s,T} = \frac{p_{0,T}}{3} - \frac{2\omega_T}{3\nu_T}, \qquad p_{f,T} = a_{f,T} - \frac{2b_{f,T}\omega_T}{b\nu_T} \tag{28}$$

where $q_{0,T} = ab - c + b\theta - bq_N - b\xi q_W$, $p_{0,T} = ab + 2c + b\theta - bq_N - b\xi q_W$, $N = N_R + N_W + N_N$ *and*

$$\omega_T = N\mathbb{E}[q_{0,T}](9 + 4b\lambda V_s) + 2Nb^2\lambda(\tau_\theta - q_W^3 \tau_\xi)$$

$$+ 9b\lambda \left((\mathbb{E}[p_{0,T}] + b\mu_\theta - bq_N - b\mu_\xi q_W)V_s - 3p_R\sigma_\theta^2 + b(\tau_\theta - q_W^3 \tau_\xi) \right), \tag{29}$$

$$\nu_T = 45N + b\lambda(8N + 54)V_s, \tag{30}$$

$$V_s = \sigma_\theta^2 + q_W^2 \sigma_\xi^2. \tag{31}$$

[17] Our assumption on an interior solution requires conditions similar to those in Proposition 2.

4.3. The price impact of technology: active vs. inactive producers

Spot price comparison. Let us compare spot prices under the two market settings. The direct merit-order effect, based on lower production costs, is independent of forward markets. This is evident from Propositions 2 and 3, where $p_{0,S} = p_{0,T}$. However, the following result shows that the spot price is *not* independent of whether the intermittent and inflexible producers participate in forward trading, because of the indirect effect.

PROPOSITION 4. *If either $q_W > 0$ or $q_N > 0$, $p_{s,S} \neq p_{s,T}$. Moreover,*

(a) *If q_N is sufficiently high, the spot price is higher with active producers than with inactive producers.*

(b) *There exists a threshold such that if the renewable capacity q_W is sufficiently low, the intermittent producers' hedging incentive $Cov(\xi p_{s,T}, p_{s,T})$ is negative. Furthermore, if q_N, μ_ξ, τ_ξ, and c are sufficiently low and the spot variance V_s is sufficiently high, intermittent producers take negative positions, and the spot price is lower with active producers than with inactive producers.*

Whether the price-taking producers trade forward will, in turn, change how much the conventional producers trade forward in f_i^*, and hence the spot price through their strategic commitment. We would typically expect that both inflexible and intermittent producers would hedge by selling substantial parts of their production on the forward market, and hence crowd out the conventional producers from the forward market. This lower strategic commitment would in turn increase the spot price. The proposition, however, also shows that while this reasoning holds for inflexible capacity, it is not always true for intermittent producers, who may have an incentive to *buy* on the forward market. The intermittent producers' profits are negatively correlated with the spot price: the more they produce, the lower the price. Put another way, the spot price is high whenever intermittent generators produce less, and they hence reduce forward sales not to be caught with large positions they would have to balance at a high spot price. They may therefore take negative positions to both hedge against spot risk and speculate on the forward price. Indeed, when effective price-taking capacity is low (i.e., low q_N and μ_ξ) and spot variance is high, the optimal forward positions are low for inflexible producers and negative for intermittent producers. Conventional producers then conversely trade more forward, reducing the expected spot price. By contrast, with plenty of effective price-taking capacity, the forward trading of inflexible and intermittent producers displaces the conventional generators in the forward market, resulting in higher prices through a weaker strategic commitment effect.

Figure 4 illustrates two possible effects of intermittent producers' hedging, adapting Figure 2(b) with active producers. First, when the intermittent capacity q_W is low, these producers'

hedging is negative. While an unusually strong example of the potentially negative forward positions taken by intermittent producers, the figure highlights the broader point that these producers' hedging incentives are often negative; they may further speculate on the forward premium with the same result. The figure also shows how other market participants compensate for these changes in their hedging. Because of the resulting stronger forward commitment from conventional producers, prices are significantly lower than in Figure 2(b). But second, the opposite effect of increasing prices emerges with higher q_W as intermittent producers' hedging increases: With higher forward positions, renewables' forward trading reduces conventional producers' trading, raising spot prices. In sum, the impact of renewables' forward market participation on power prices depends upon to what extent they crowd out the conventional producers.

Figure 4 **Forward and expected spot prices (a) and forward positions (b) as functions of intermittent capacity.**
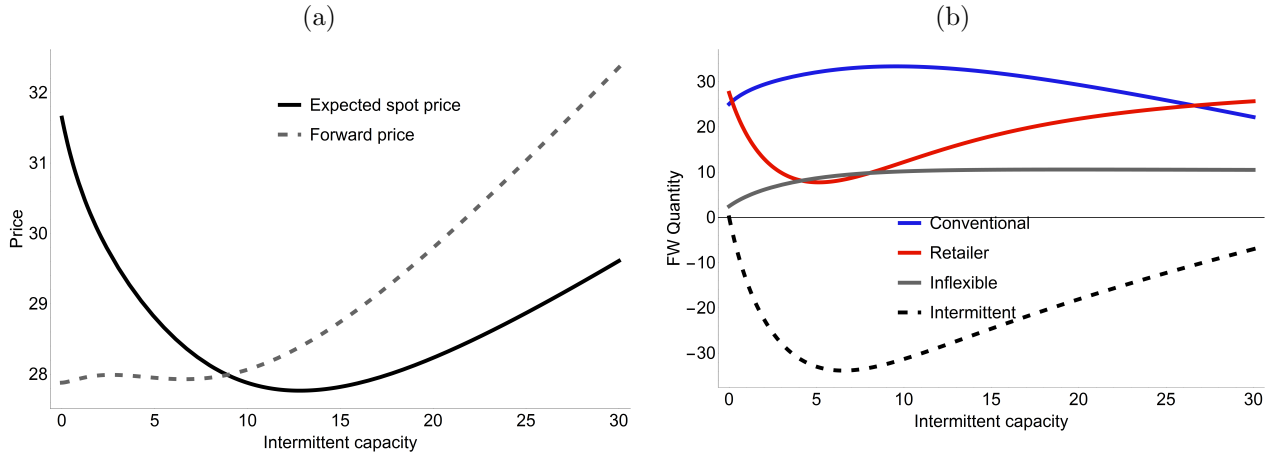
Note. Parameters $N_R = 6, N_N = 2, \tau_\theta = 0, b = 1, p_R = 40, \lambda = 1, q_N = 10, \sigma_\xi^2 = 0.1, \tau_\xi = 0.1, a = 50, c = 25, \mu_\theta = 30, \sigma_\theta^2 = 9, N_W = q_W/0.2$. We fix the size of intermittent producers and increase their number along with the capacity.

Forward premium comparison. In addition to affecting the spot price, whether inflexible or intermittent capacity participates in forward trading may also imply significantly different forward premia. The following corollary shows that additional renewable capacity may have inverse effects on forward premia depending on whether these producers participate in forward markets.

COROLLARY 4. *The impact of market fundamentals on the forward premium is summarised in Table 4. In particular, the premium may be increasing in the inflexible capacity q_N with inactive producers and decreasing in it with active producers.*

Consider first the addition of inflexible capacity q_N. If these producers are inactive, more price-taking capacity in the market reduces conventional producers' spot sales and hence their need

Table 4   The impact of market fundamentals on the forward premium, and the cross-effects of fundamentals on the impact of renewable capacity, under inactive (ψ_S) and active (ψ_T) producers.

	a	c	μ_θ	σ_θ^2	τ_θ	p_R	q_N	q_W	μ_ξ	σ_ξ^2	τ_ξ
ψ_S	$+/-$	$+$	$+$	$+/-$	$+$	$-$	$+/-^*$	$+/-$	$+/-^*$	$+/-$	$+$
$\dfrac{d\psi_S}{dq_W}$	$-$	$-$	$-$	$+/-$	$+$	$-$	$+$	$+/-$	$+$	$+/-$	$+$
ψ_T	$+/-$	$+$	$+$	$+/-$	$+$	$+$	$-$	$+/-$	$-$	$+/-$	$-$
$\dfrac{d\psi_T}{dq_W}$	$-$	$+$	$+$	$+/-$	$-$	$+$	$-$	$+/-$	$-$	$+/-$	$-$

$^*+$ if $b\lambda\sigma_\theta^2 \geq \frac{9N_R}{2(4N_R-9)}$

to trade forward. As retailers become relatively more willing to pay for risk-sharing, the forward premium then increases (under a mild condition). Put another way, reducing producers' volume risk favors them in the forward market and the premium increases, even if they trade less. Active inflexible producers, by contrast, will trade more forward with higher production and the balance of the forward market hence shifts towards the demand side, lowering the forward price compared to the spot price, and moving the premium to the opposite direction.

The impact of increasing intermittent capacity q_W on the premium, on the other hand, is ambiguous and reflects interactions with other market factors. For instance, if the forward market is favorable to retailers (e.g., through a high retail price), intermittent capacity is more likely to reduce the premium, as higher capacity increases supply variance, which moderates the premium. Thus, similarly to demand variance, the effect of intermittent capacity on premia depends on interactions with other fundamentals. However, the corollary shows that many of these cross-effects on the premium have opposite signs with active producers compared to the setting with inactive producers. For example, based on reasoning similar to the impact of q_N above, a higher q_W is more likely to increase the premium with high q_N with active producers but decrease it with inactive producers. Indeed, these producers' forward market participation may reverse the premium and hence the participants' trading profits. Moreover, given these potentially different price impacts, the evaluation of policy interventions for increasing renewable capacity should account not only for the intermittency of this capacity, but also the details of the policy itself (whether or not the capacity participates in forward trading). We discuss these next.

4.4. Policy implications

Subsidy schemes. Based on the above results, designing support schemes without considering market context has welfare implications from two perspectives. The first consideration is the price impact of the supported capacity and whether or not it participates in forward trading. As Proposition 4 shows, this participation influences not just forward but also spot electricity prices. Under green certificates or renewable obligations (ROs) or in the absence of subsidies, producers are subject to price risk and hence likely to participate in forward markets. This trading may result in

higher electricity prices: if the increasing capacity crowds out conventional producers from forward trading, the competition-increasing strategic effect is mitigated, increasing prices. However, as we have seen in Proposition 4, under some conditions prices may decrease.

Second, the payments made from support schemes may depend on the capacity's price impact. Contracts for difference (CfDs) are becoming increasingly widespread as alternatives to fixed feed-in arrangements for renewable generators (Pöyry 2015). They guarantee a pre-specified price level for production (*strike* price), with subsidy payments relative to the market price of electricity (*reference* price). The reference price may be either the spot or forward price (in the UK, for instance, the day-ahead forward price is used for intermittent technologies and the seasonal forward price for inflexible facilities, DECC (2013)). Based on Corollary 4, the design of these schemes should take into account how the premium between these prices changes with capacity. As intermittent production capacity increases over a scheme's lifetime, a forward reference price may result in significantly higher payments compared to a spot reference if the capacity amplifies a negative premium. The payments from the scheme, and hence the revenues of these producers, are subject to a reference-price based risk. Thus, while these results are based on a partial equilibrium analysis of prices, without considering investment decisions under such schemes or their optimal design, they suggest that achieving a renewable capacity target under CfDs may be subject to payment uncertainty through the reference price, whereas ROs may bear a risk of higher price levels.

Replacing nuclear power. Above we have assumed that additional intermittent capacity replaces conventional production capacity. An alternative policy may reduce inflexible capacity instead: Germany, for example, is phasing out nuclear production while increasing renewable capacity (Vasagar and Clark 2015). To illustrate how this changes our results, when increasing q_W we simultaneously decrease q_N to keep the expected effective price-taking capacity constant, letting $q_N = q_{PT} - \mu_\xi q_W$, where q_{PT} is a constant. Phasing out nuclear power should increase prices directly, and increasing renewables should conversely reduce them. This formulation ensures that the merit-order effect on conventional capacity is constant; this is different from the above examples, where the total capacity q_{PT} increases with q_W.

Figure 5 illustrates the resulting prices, adapting Figure 2(b) (with no participation from these technologies). When intermittent production replaces inflexible capacity, its direct merit-order effect is cancelled on average, but spot uncertainty increases. This has two effects. First, as less conventional capacity is replaced, prices are higher. But second, due to the uncertainty, conventional producers' incentives to trade forward also increase. Through the first effect, the expected spot price hence typically decreases less (or increases more) with more intermittent capacity compared to just increasing renewable capacity; through the second one, the forward price conversely increases less

(or decreases more). The second effect, however, also partly mitigates the first one through higher strategic commitment. In sum, phasing out nuclear capacity in parallel with increasing renewables cancels the direct merit-order effect of renewables, leading to higher spot prices, but also lower forward prices and higher forward trading volumes.

Figure 5   Forward and expected spot prices as functions of intermittent capacity replacing inflexible capacity.
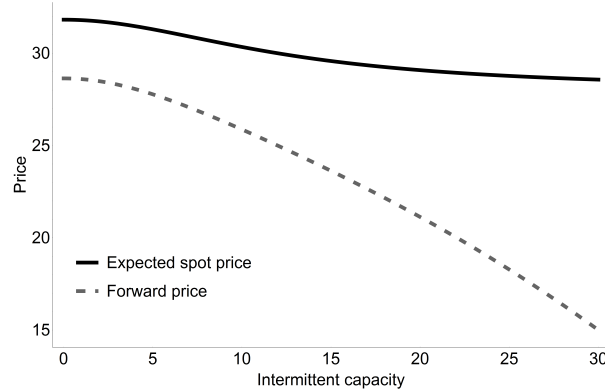
Note. Parameters $N_R = 6, \tau_\theta = 0, b = 1, p_R = 40, \lambda = 1, q_{PT} = 10, \mu_\xi = 0.3, \sigma_\xi^2 = 0.1, \tau_\xi = 0, a = 50;\ c = 25, \mu_\theta = 30, \sigma_\theta^2 = 9.$

5.   Conclusions

We have studied how the operational characteristics of production technologies and other fundamentals may influence commodity trading and thereby affect market prices. Specifically, fundamentals influence the balance of forward and spot trading and this in turn can have an indirect effect on price formation. Whilst forward trading allows risk sharing over spot procurement or sales uncertainty, it also implies a strategic commitment to a higher market share. Any factors affecting risk sharing will therefore also indirectly move prices. This indirect effect of fundamentals on market prices suggests a potential reason for the lack of consensus on the determinants of electricity forward premia: fundamentals move prices not only directly, but also through their interactions. For instance, the impact of market volatility on prices may change depending on fuel prices.

The indirect effect also provides a novel perspective on the impact of renewable power on electricity prices. The direct merit-order effect of this capacity's lower operating costs reducing wholesale power prices has been widely employed to model price movements and asset revaluations associated with the transition to renewable power. But beyond the direct merit-order effect, renewable capacity risk sharing in forward markets, and hence indirectly also the spot price. This effect complements, and may even counteract, the direct merit-order effect, and both spot and forward electricity prices may increase with additional renewable capacity. However, whether this indirect

effect mitigates or strengthens the merit-order effect depends on interactions with other fundamentals, such as demand and the extent of nuclear capacity on the market, suggesting a set of new empirical hypotheses.

The indirect effect further implies that spot prices depend on whether renewables, or other producers, participate in forward trading and hence change risk sharing and strategic commitments. In addition to reversing many insights on the determinants of prices depending on the setting, this suggests several policy implications. Whether market design or renewable support schemes shield these participants from forward market participation has welfare implications through this price impact. Thus, achieving the same capacity with a scheme that precludes forward market participation (e.g., a feed-in-tariff) may result in different prices than through renewable obligations. If these producers trade forward and crowd out conventional generators from the forward market, prices typically increase. This effect then favours schemes shielding renewables from risk. But if subsidy levels are tied to a reference spot or forward price, payments from the scheme will depend on this choice as the forward premium may change significantly with more renewable capacity.

We have studied a simplified market model. In particular, our assumption of no curtailment of intermittent supply will not be realistic in the long run with projected amounts of renewable generation. Modeling curtailment in a strategic market setting would require a complementarity approach (e.g. Bushnell et al. 2008, Shanbhag et al. 2011), with potential challenges in equilibrium existence (Murphy and Smeers 2010). We believe that our main insights—the technology-dependence of spot-forward markets and, more specifically, intermittency driving a reduction in forward trading and leading to less reduced, or even higher, spot prices in electricity markets—would be robust to such extensions. We have also focused on particular operational characteristics and ignored, for example, fuel price uncertainty, which would also reverberate in the market through the indirect effect. Overall, our results suggest that long-term decarbonisation policies may have unintended pricing consequences in imperfectly competitive electricity markets.

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Appendix A: List of Notation

Table 5 summarises frequently used notation.

Appendix B: Proofs

Proof of Lemma 1. Omitted; see Allaz and Vila (1993).   □

Proof of Lemma 2. Assuming non-strategic participants, each retailer maximises mean-variance utility $U_R(\pi_{Ri}) = \mathbb{E}[\pi_{Ri}] + \frac{\lambda_R}{2}V(\pi_{Ri})$, with $\pi_{Ri} = p_R\theta_{Ri} - p_s\theta_{Ri} + p_s f_{Ri} - p_f f_{Ri}$. The variance is $V(\pi_{Ri}) = V(p_R\theta_{Ri} - p_s\theta_{Ri}) + V(p_s f_{Ri}) + 2Cov(p_R\theta_{Ri} - p_s\theta_{Ri}, p_s f_{Ri})$. The f_{Ri}-dependent terms lead to the first-order condition

$$f_{Ri} = \frac{\mathbb{E}[p_s] - p_f}{\lambda_R V(p_s)} - \frac{Cov(p_R\theta_{Ri} - p_s\theta_{Ri}, p_s)}{V(p_s)}. \tag{32}$$

With $p_s = \frac{ab+2c+b\theta-bF}{3}$ and $\theta_{Ri} = \alpha_{Ri}\theta$, the covariance term is equal to $\alpha_{Ri}\eta_R = \frac{\alpha_{Ri}b}{9}\left((ab+2c+2b\mu_\theta - bF - 3p_R)\sigma_\theta^2 + b\tau_\theta\right)$. Summing these terms for each (identical) retailer and gathering terms, we have the forward demand:

$$a_{f,C} = \frac{ab+2c+b\mu_\theta}{3} + \frac{b\lambda_R}{9N_R}\left((ab+2b\mu_\theta+2c-3p_R)\sigma_\theta^2 + b\tau_\theta\right) \tag{33}$$

Table 5   Notation.

N_k	number of price-taking participants of type $k \in \{R, W, N\}$ (retailer, intermittent (wind) producer, inflexible (nuclear) producer)
$a_{m,j}$	inverse (elastic) demand intercept; $m \in \{f, \cdot\}$ denotes forward and spot market; in the forward market, $j \in \{C, S, T\}$ denotes market setting with (c)onventional producers only, (s)pot impact only, all (t)echnologies trading forward.
$b_{m,j}$	inverse demand slope in optional market setting j
$p_{l,j}$	spot price; $l \in \{s, f, R\}$ denotes spot and forward markets and the exogenous retail price; optional $j \in \{C, S, T\}$ denotes market setting.
θ	inelastic demand, with mean μ_θ, variance σ_θ^2, skewness τ_θ, range $[\overline{\theta}, \underline{\theta}]$; for retailer i, market share is $\theta_i = \frac{\theta}{N_R}$.
q_{ki}	spot production (or demand) of price-taking participant i of type k; in the absence of k, conventional producer i's spot production, with total production Q, and optimal quantity q_i^*.
f_{ki}	forward position of price-taking participant i of type k; in the absence of k, conventional producer i's forward position, total position is F, optimal quantity f_i^*.
c	conventional producers' marginal production cost
$\pi_{i,s}$	conventional producer i's spot profit.
π_{ki}	price-taking participant i's ex post profit; e.g., retailer i's profit: $\pi_{Ri} = p_R\theta_{Ri} - p_s\theta_{Ri} + p_sf_{Ri} - p_ff_{Ri}$.
$q_{0,j}$	normalised spot quantity in the absence of forward trading in market setting j.
$p_{0,j}$	normalised spot price in the absence of forward trading in market setting j.
U_k	utility (of participant of type k), $U_k(\pi) = \mathbb{E}[\pi] - \frac{\lambda_k}{2}V(\pi)$, where $\mathbb{E}[\cdot]$ denotes expectation and $V(\cdot)$ variance.
λ_k	risk aversion parameter of participant type k.
η_k	covariance term in f_k.
ω_j	numerator of optimal forward position in market setting j.
ν_j	denominator of optimal forward position in market setting j.
ψ	forward premium $\psi = p_f - \mathbb{E}[p_s]$.
ξ	the fraction of available intermittent capacity, with range $[\underline{\xi}, \overline{\xi}] \in [0, 1]$, mean μ_ξ, variance σ_ξ^2, and skewness τ_ξ.

$$b_{f,C} = \frac{1}{9N_R}\left(3bN_R + 2\lambda_Rb^2\sigma_\theta^2\right). \tag{34}$$

Let us repeat the analysis for strategic forward-trading. Each retailer still maximises $U_R(\pi_{Ri}) = \mathbb{E}[\pi_{Ri}] + \frac{\lambda_R}{2}V(\pi_{Ri})$ with $\pi_{Ri} = p_R\theta_{Ri} - p_s\theta_{Ri} + p_sf_{Ri} - p_ff_{Ri}$, but now takes into account the dependence of p_s on f_{Ri} in the optimisation. That is, we write $F = f_{Ri} + f_{-Ri}$ in p_s, and the retailer optimises $U_R(\pi_{Ri}(f_{Ri}))$. With $\theta_{Ri} = \alpha_{Ri}\theta$, the variance is derived from

$$V(\pi_{Ri}) = V(p_R\theta_{Ri} - p_s\theta_{Ri}) + V(p_sf_{Ri}) + 2Cov(p_R\theta_{Ri} - p_s\theta_{Ri}, p_sf_{Ri}) \tag{35}$$

$$= V(p_R\theta_{Ri}) + V(p_s\theta_{Ri}) - 2Cov(p_R\theta_{Ri}, p_s\theta_{Ri}) + 2Cov(p_R\theta_{Ri} - p_s\theta_{Ri}, p_sf_{Ri}) \tag{36}$$

$$= V(p_R\alpha_{Ri}\theta) + \frac{\alpha_{Ri}^2}{9}V((ab + 2c + b\theta - bF)\theta) - \frac{2p_R\alpha_{Ri}^2}{3}Cov(\theta, (ab + 2c + b\theta - bF)\theta)$$
$$+ \frac{2p_R\alpha_{Ri}}{3}Cov(\theta, (ab + 2c + b\theta - bF)f_{Ri}) - \frac{2\alpha_{Ri}}{9}Cov((ab + 2c + b\theta - bF)\theta, (ab + 2c + b\theta - bF)f_{Ri}) \tag{37}$$

$$= V(p_R\alpha_{Ri}\theta) + \frac{\alpha_{Ri}^2b^2}{9}V(\theta^2) + \frac{\alpha_{Ri}^2(ab + 2c - bF)^2}{9}V(\theta) + \frac{\alpha_{Ri}^2b^2}{9}V(\theta^2) \tag{38}$$

$$+ \frac{\alpha_{Ri}^2(ab+2c-bF)b}{9}Cov(\theta^2,\theta) - \frac{2p_R\alpha_{Ri}^2 b}{3}Cov(\theta^2,\theta) - \frac{2p_R\alpha_{Ri}(ab+2c-bF)}{3}V(\theta)$$

$$+ \frac{2p_R\alpha_{Ri}bf_{Ri}}{3}V(\theta) - \frac{2\alpha_{Ri}b^2 f_{Ri}}{9}Cov(\theta^2,\theta) - \frac{2\alpha_{Ri}(ab+2c-bF)bf_{Ri}}{9}V(\theta).$$

$$\frac{d}{df_{Ri}}[V(\pi_{Ri})] = -\frac{2b\alpha_{Ri}^2(ab+2c-bF)}{9}V(\theta) - \frac{\alpha_{Ri}^2 b^2}{9}Cov(\theta^2,\theta) + \frac{2p_R b\alpha_{Ri}^2}{3}V(\theta) + \frac{2p_R\alpha_{Ri}b}{3}V(\theta)$$

$$- \frac{2\alpha_{Ri}b^2}{9}Cov(\theta^2,\theta) - \frac{2b\alpha_{Ri}(ab+2c-bF)}{9}V(\theta) - \frac{2\alpha_{Ri}b^2 f_{Ri}}{9}V(\theta) \tag{39}$$

$$= -\frac{2}{9}\left(b\alpha_{Ri}(1+\alpha_{Ri})\left((ab+2c-bF-3p_R)V(\theta) + bCov(\theta^2,\theta)\right) - \alpha_{Ri}b^2 f_{Ri}V(\theta)\right) \tag{40}$$

The first order condition is now $\frac{d}{df_{Ri}}\left[\mathbb{E}[\pi_{Ri}] + \frac{\lambda_R}{2}V(\pi_{Ri})\right] = 0$, with $\frac{d}{df_{Ri}}[\mathbb{E}[\pi_{Ri}]] = \frac{\alpha_{Ri}b\mu_\theta}{3} - p_f + \mathbb{E}[p_s] - \frac{bf_{Ri}}{3}$, and $\frac{d}{df_{Ri}}[V(\pi_{Ri})]$ as derived above. Solving these simultaneously for all retailers and letting $\alpha_{Ri} = \frac{1}{N_R}$, we have

$$a_{f,C} = \frac{ab+2c+b\mu_\theta\left(1+\frac{1}{N_R}\right)}{3} + \frac{b\lambda_R\left(1+\frac{1}{N_R}\right)}{9N_R}\left((ab+2b\mu_\theta+2c-3p_R)\sigma_\theta^2+b\tau_\theta\right) \tag{41}$$

$$b_{f,C} = \frac{1+\frac{1}{N_R}}{9N_R}\left(3bN_R+2\lambda_R b^2\sigma_\theta^2\right), \tag{42}$$

which converges to the non-strategic result with high N_R. $\qquad\square$

Proof of Proposition 1. The conventional generators' objective functions are

$$U_P(f_i,\pi_{i,s}) = p_f f_i + \mathbb{E}[\pi_{i,s}] - \frac{\lambda_P}{2}V(\pi_{i,s}), \tag{43}$$

with variance $V(\pi_{i,s}) = V(p_s(q_i-f_i)-cq_i) = V(p_s(q_i-f_i))+V(cq_i)-2Cov(p_s(q_i-f_i),cq_i)$. The second term does not depend on f_i so we can disregard it. With $q_i = \frac{ab+b\theta-c+2bf_i-bf_j}{3b}$, we can develop the expressions further to get

$$V(p_s(q_i-f_i)) = V\left(\frac{ab+2c+b\theta-b\xi q_W-bq_N-bF}{3}\frac{ab+b\theta-c-b\xi q_W-bq_N-bF}{3b}\right), \tag{44}$$

where the terms relevant to us are the ones depending on F: $V(p_s(q_i-f_i)) = V(f_i)+\ldots$, which can be written as $V(f_i) = V\left(\frac{ub\theta}{9b}\right) + 2Cov\left(\frac{ub\theta}{9b},\frac{b^2\theta^2}{9b}\right) = \frac{u^2}{81}V(\theta) + \frac{2ub}{81}Cov(\theta,\theta^2)$, $u = 2ab+c-2b(f_i+f_j)$.

For the covariance term, we have

$$Cov(p_s(q_i-f_i),cq_i) = Cov\left(\frac{ab+2c+b\theta-bF}{3}\frac{ab+b\theta-c-bF}{3b},\frac{cb\theta}{3b}\right) \tag{45}$$

$$Cov(f_i) = \frac{1}{27}Cov(u\theta,cb\theta) = \frac{cub}{27}V(\theta) \tag{46}$$

The derivatives with respect to f_i become

$$\frac{dV(\pi_{i,s})}{df_i} = -\frac{8b(ab-c-bF)}{81}\sigma_\theta^2 - \frac{4b^2}{81}Cov(\theta,\theta^2). \tag{47}$$

We can combine this with $\frac{d}{df_i}p_f f_i = a_f - 2b_f f_i - b_f f_j$ and $\frac{d}{df_i}\mathbb{E}[\pi_{i,s}] = -\frac{1}{9}(2ab+2b\mu_\theta+7c-2b(f_i+f_j))$ to get the first-order condition $\frac{d}{df_i}U(\pi_{i,s}) = 0$. Solving the firms' first-order conditions simultaneously, and using the forward demand function from Lemma 2, the equilibrium outcome follows. $\qquad\square$

Proof of Corollary 1. The first part follows from differentiating the expected spot price. The second part follows from differentiating the forward positions (and cross-derivatives), for example, $\frac{df_{i,C}^*}{d\mu_\theta} = \frac{9N_R+18b\lambda\sigma_\theta^2+4N_R b\lambda\sigma_\theta^2}{45N_R+54b\lambda\sigma_\theta^2+8N_R b\lambda\sigma_\theta^2} \geq 0$, and $\mathbb{E}[p_{s,C}] = \frac{ab+2c+b\mu_\theta}{3} - \frac{2\omega}{3\nu}$. $\qquad\square$

Proof of Corollary 2. The first part of the corollary follows from differentiating the forward premium $\psi = p_f - \mathbb{E}[p_s]$ with respect to the parameters. For the second part, for example, the cross-derivative $\frac{d^2\psi}{d\sigma_\theta^2 dp_R} = -\frac{b\lambda(972b^2\lambda^2\sigma_\theta^4 + N_R^2(45+8b\lambda\sigma_\theta^2)^2 + 36b\lambda N_R\sigma_\theta^2(45+16b\lambda\sigma_\theta^2))}{3N_R(54b\lambda\sigma_\theta^2 + N_R(45+8b\lambda\sigma_\theta^2))^2}$ is constant and negative; letting p_R increase, $\frac{d\psi}{d\sigma_\theta^2}$ will be positive. Assuming the spot price will not be lower than the expected spot price, and hence solving for $p_R = \mathbb{E}[p_s]$, we have

$$p_R^E = \frac{9ab(3N_R + 4b\lambda_R\sigma_\theta^2) + 12c(6b\lambda_R\sigma_\theta^2 + N_R(9+2b\lambda_P\sigma_\theta^2)) + b(9\mu_\theta(3N_R + 2b\lambda_R\sigma_\theta^2) - 2b(9\lambda_R + 2\lambda_P N_R)\tau_\theta)}{3(36b\lambda_R\sigma_\theta^2 + N_R(45 + 8b\lambda_P\sigma_\theta^2))}.$$

(48)

Substituting this into the expected price, setting $\lambda_P = \lambda_R = \lambda$, we have

$$\frac{d^2\psi}{d\sigma_\theta^2 dp_R} = \frac{2b\lambda(-108(N_R-3)(ab-c) - 27b\mu_\theta(3+4N_R) + 4b\lambda(9+2N_R)^2\tau_\theta)}{3(36b\lambda\sigma_\theta^2 + NR(45+8b\lambda\sigma_\theta^2))^2}.$$

(49)

we have that $\frac{d\psi}{d\sigma_\theta^2}$ is negative if μ_θ is high enough compared to τ_θ (and $N_R \geq 3$). $\quad\square$

Proof of Proposition 2. Let us first derive the retailers' optimal forward positions. The total profit for a retailer is again $\pi_{Ri} = p_R\theta_{Ri} - p_s\theta_{Ri} + p_s f_{Ri} - p_f f_{Ri}$ and the optimal forward positions from mean-variance utility are

$$f_{Ri} = \frac{\mathbb{E}[p_s] - p_f}{\lambda V(p_s)} - \frac{Cov(p_R\theta_{Ri} - p_s\theta_{Ri}, p_s)}{V(p_s)} = \frac{\mathbb{E}[p_s] - p_f}{\lambda V(p_s)} - \frac{\eta_R\alpha_{Ri}}{V(p_s)}$$

(50)

$$f_R = \sum_i f_{Ri} = \frac{N_R(\mathbb{E}[p_s] - p_f)}{\lambda V(p_s)} - \frac{\eta_R}{V(p_s)}.$$

(51)

The covariance term η_R above is derived as follows:

$$Cov((p_R - p_s)q_R, p_s) = \frac{\alpha_{Ri}bp_R\sigma_\theta^2}{3} - \frac{b\alpha_{Ri}}{9}\left((ab+2c-bq_W\mu_\xi-bq_N-bF)\sigma_\theta^2 + bq_W^2\mu_\theta\sigma_\xi^2 + bCov(\theta,\theta^2)\right) \quad (52)$$

$$= \frac{b\alpha_{Ri}}{9}\left(-(ab+2c-bq_W\mu_\xi-bq_N-bF-3p_R)\sigma_\theta^2 - bq_W^2\mu_\theta\sigma_\xi^2 - bCov(\theta,\theta^2)\right) \quad (53)$$

$$= \eta_R\alpha_{Ri}. \quad (54)$$

Hence we can write out the inverse forward demand facing the flexible generators as stated in the Proposition:

$$a_{f,S} = \frac{ab + 2c - bq_W\mu_\xi - bq_N + b\mu_\theta}{3}$$

$$+ \frac{b\lambda}{9N_R}\left((ab+2c+2b\mu_\theta - bq_W\mu_\xi - bq_N - 3p_R)\sigma_\theta^2 + bq_W^2\mu_\theta\sigma_\xi^2 + b\tau_\theta\right) \quad (55)$$

$$b_{f,S} = \frac{1}{N_R}\left[\frac{bN_R}{3} + \frac{\lambda b^2}{9}\left(2\sigma_\theta^2 + q_W^2\sigma_\xi^2\right)\right] \quad (56)$$

With two sources of uncertainty in the problem, we also have to adjust the conventional generators' objective functions $U(\pi_{i,f}) = p_f f_i + \mathbb{E}[\pi_{i,s}] - \frac{\lambda}{2}V(\pi_{i,s})$. The variance is $V(\pi_{i,s}) = V(p_s(q_i - f_i) - cq_i) = V(p_s(q_i - f_i)) + V(cq_i) - 2Cov(p_s(q_i - f_i), cq_i)$. The second term does not depend on f_i so we can disregard it. We can develop the expressions further to get

$$V(p_s(q_i - f_i)) = V\left(\frac{ab+2c+b\theta - b\xi q_W - bq_N - bF}{3}\frac{ab+b\theta - c - b\xi q_W - bq_N - bF}{3b}\right), \quad (57)$$

where the terms relevant to us are the ones depending on F, with $V(p_s(q_i - f_i)) = V(F) + V(\ldots)$:

$$V(F) = V\left(\frac{ub\theta}{9b}\right) + V\left(\frac{ub\xi q_W}{9b}\right) + 2Cov\left(\frac{ub\theta}{9b}, \frac{b^2\theta^2 + b^2\xi^2 q_W^2 - 2b^2\theta\xi q_W}{9b}\right)$$

$$- 2Cov\left(\frac{ub\xi q_W}{9b}, \frac{b^2\theta^2 + b^2\xi^2 q_W^2 - 2b^2\theta\xi q_W}{9b}\right) - 2Cov\left(\frac{ub\xi q_W}{9b}, \frac{ub\theta}{9b}\right) \quad (58)$$

$$u = 2ab + c - 2bq_N - 2b(f_i + f_j). \quad (59)$$

The last covariance term is zero as long as the variables are uncorrelated. We thus have

$$V(F) = \frac{u^2}{81}V(\theta) + \frac{u^2 q_W^2}{81}V(\xi) + \frac{2ub}{81}\left(Cov(\theta, \theta^2) - 2q_W\mu_\xi V(\theta)\right) - \frac{2ubq_W}{81}\left(q_W^2 Cov(\xi, \xi^2) - 2q_W\mu_\theta V(\xi)\right). \quad (60)$$

For the covariance term in profit variance, we have (again ignoring terms not depending on F and using the independence assumption)

$$Cov(p_s(q_i - f_i), cq_i) =$$
$$Cov\left(\frac{ab + 2c + b\theta - b\xi q_W - bq_N - bF}{3}\ \frac{ab + b\theta - c - b\xi q_W - bq_N - bF}{3b}, \frac{c(b\theta - b\xi q_W)}{3b}\right) \quad (61)$$

$$Cov(F) = \frac{1}{27}\left(Cov\left(u\theta, cb\theta\right) + Cov\left(u\xi q_W, cb\xi q_W\right)\right) = \frac{cub}{27}\left(V(\theta) + q_W^2 V(\xi)\right) \quad (62)$$

The derivatives with respect to f_i become

$$\frac{dV(p_s(q_i - f_i))}{df_i} = -\frac{4ub}{81}\left(V(\theta) + q_W^2 V(\xi)\right) - \frac{4b^2}{81}\left(Cov(\theta, \theta^2) - 2q_W\mu_\xi V(\theta)\right.$$
$$\left. - \left(q_W^3 Cov(\xi, \xi^2) - 2q_W^2\mu_\theta V(\xi)\right)\right) \quad (63)$$

$$\frac{dCov(p_s(q_i - f_i), cq_i)}{df_i} = -\frac{2bc}{27}\left(V(\theta) + q_W^2 V(\xi)\right) \quad (64)$$

$$\frac{dV(\pi_{i,s})}{df_i} = -\frac{8b(ab - c - bq_N - bF)}{81}\left(\sigma_\theta^2 + q_W^2\sigma_\xi^2\right)$$
$$- \frac{4b^2}{81}\left(Cov(\theta, \theta^2) - 2q_W\mu_\xi\sigma_\theta^2 - q_W^3 Cov(\xi, \xi^2) + 2q_W^2\mu_\theta\sigma_\xi^2\right). \quad (65)$$

Again we can combine this derivative with the other terms $\frac{d}{df_i}p_f f_i = a_f - 2b_f f_i - b_f f_j$ and $\frac{d}{df_i}\mathbb{E}[\pi_{i,s}] = -\frac{1}{9}\left(2ab + 2b\mu_\theta + 7c - 2bq_N - 2b\mu_\xi q_W - 2b(f_i + f_j)\right)$ to get the first-order condition $\frac{d}{df_i}U(\pi_{i,s}) = 0$. Solving the firms' first-order conditions simultaneously, the equilibrium outcome follows. $\square$

Proof of Corollary 3. Follows from derivatives and cross-derivatives with respect to the parameters. $\square$

Proof of Lemma 3. We have already derived the optimal positions for the retailers. Let us also derive these for the other participants. The inflexible generators maximise $U(\pi_{Ni}) = \mathbb{E}[\pi_{Ni}] - \frac{\lambda}{2}V(\pi_{Ni})$, $\pi_{Ni} = p_s q_{Ni} - p_s f_{Ni} + p_f f_{Ni}$. As they are not acting strategically, this results in the first order condition $-\mathbb{E}[p_s] + p_f - \lambda f_{Ni}V(p_s) + \lambda Cov(p_s q_{Ni}, p_s) = 0$ and positions $f_{Ni} = \frac{p_f - \mathbb{E}[p_s]}{\lambda V(p_s)} + \frac{Cov(p_s q_{Ni}, p_s)}{V(p_s)}$, which results in total position

$$f_N = \sum_i f_{Ni} = \frac{N_N(p_f - \mathbb{E}[p_s])}{\lambda V(p_s)} + q_N. \quad (66)$$

Solving similarly the positions for intermittent producers with profits $\pi_{Wi} = p_s q_{Wi}^e - p_s f_{Wi} + p_f f_{Wi}$ we have $f_{Wi} = \frac{p_f - \mathbb{E}[p_s]}{\lambda V(p_s)} + \frac{Cov(p_s q_{Wi}^e, p_s)}{V(p_s)}$ and total position

$$f_W = \sum_i f_{Wi} = \frac{N_W(p_f - \mathbb{E}[p_s])}{\lambda V(p_s)} + \frac{\eta_W}{V(p_s)}q_W. \quad (67)$$

The covariance term η_W is derived as follows:

$$Cov(p_s q_W^e, p_s) = \frac{1}{9}Cov((ab + b\theta + 2c - bq_N - b\xi q_W - bF)\xi q_{Wi}, ab + b\theta + 2c - bq_N - b\xi q_W - bF) \quad (68)$$

$$= \frac{1}{9} \left((ab + 2c - bq_N - bF)q_{Wi}Cov(\xi, b\theta - b\xi q_W) + q_{Wi}Cov(b\theta\xi, b\theta - b\xi q_W) \right.$$
$$\left. - q_W q_{Wi}Cov(b\xi^2, b\theta - b\xi q_W) \right) \tag{69}$$

$$= \frac{bq_{Wi}}{9} \left(-(ab + 2c - bq_N - bF)q_W \sigma_\xi^2 + bCov(\theta\xi, \theta) - bq_W Cov(\theta\xi, \xi) \right.$$
$$\left. - bq_W Cov(\xi^2, \theta) + bq_W^2 Cov(\xi, \xi^2) \right) \tag{70}$$

$$= \frac{bq_{Wi}}{9} \left(-(ab + 2c + b\mu_\theta - bq_N - bF)q_W \sigma_\xi^2 + b\mu_\xi \sigma_\theta^2 + bq_W^2 Cov(\xi, \xi^2) \right) \tag{71}$$

$$= \eta_W q_{Wi}. \tag{72}$$

Combining the forward positions, we have for $F = f_R - f_W - f_N$

$$F = \frac{N_R(\mathbb{E}[p_s] - p_f)}{\lambda V(p_s)} - \frac{\eta_R}{V(p_s)} - \frac{N_W(p_f - \mathbb{E}[p_s])}{\lambda V(p_s)} - \frac{\eta_W}{V(p_s)}q_W - \frac{N_N(p_f - \mathbb{E}[p_s])}{\lambda V(p_s)} - q_N \tag{73}$$

$$p_f = \mathbb{E}[p_s] - \frac{\lambda(\eta_R + \eta_W q_W + q_N V(p_s)) + \lambda V(p_s)F}{N_R + N_W + N_N} \tag{74}$$

Using this expression, we can write out the inverse forward demand facing the flexible generators as

$$p_f = a_{f,T} - b_{f,T}F \tag{75}$$

$$a_{f,T} = \frac{ab + 2c - bq_W\mu_\xi - bq_N + b\mu_\theta}{3} + \frac{b\lambda}{9N} \left((ab + 2c - bq_W\mu_\xi - bq_N - 3p_R)\sigma_\theta^2 + bq_W^2\mu_\theta\sigma_\xi^2 + bCov(\theta, \theta^2) \right)$$
$$+ \frac{b\lambda q_W}{9N} \left((ab + 2c + b\mu_\theta - bq_N)q_W\sigma_\xi^2 - b\mu_\xi\sigma_\theta^2 - bq_W^2 Cov(\xi, \xi^2) \right) - \frac{b^2\lambda q_N}{9N} \left(\sigma_\theta^2 + q_W^2\sigma_\xi^2 \right) \tag{76}$$

$$= \frac{ab + 2c - bq_W\mu_\xi - bq_N + b\mu_\theta}{3} + \frac{b\lambda}{9N} \left((ab + 2c - 2bq_N)(\sigma_\theta^2 + q_W^2\sigma_\xi^2) + 2\mu_\theta bq_W^2\sigma_\xi^2 - 2\mu_\xi q_W b\sigma_\theta^2 - 3p_R\sigma_\theta^2 \right.$$
$$\left. + bCov(\theta, \theta^2) - bq_W^3 Cov(\xi, \xi^2) \right) \tag{77}$$

$$= \frac{ab + 2c - bq_W\mu_\xi - bq_N + b\mu_\theta}{3} + \frac{b\lambda}{9N} \left((ab + 2c + 2b\mu_\theta - 2b\mu_\xi q_W - 2bq_N)(\sigma_\theta^2 + q_W^2\sigma_\xi^2) - 3p_R\sigma_\theta^2 + b\tau_\theta - bq_W^3\tau_\xi \right) \tag{78}$$

$$b_{f,T} = \frac{1}{N} \left[\frac{bN}{3} + \frac{2\lambda b^2}{9} \left(\sigma_\theta^2 + q_W^2\sigma_\xi^2 \right) \right] \tag{79}$$

In the last equality for $a_{f,T}$, we have used $Cov(x, x^2) = \tau_x + 2\mu_x\sigma_x^2$, where τ_x is the third central moment. $\square$

Proof of Proposition 3. Similar to that of Proposition 2, but applying Lemma 3. $\square$

Proof of Proposition 4. The first part follows from comparing derivatives. The first statement of the second part follows from Lemma 3.

To see that conventional producer forward positions become higher when all technologies trade forward, we shall compare $f_{i,T}^*$ and $f_{i,S}^*$. Comparing these positions is complicated by the different numbers of price-taking market participants in the two cases. To compare the number of price-taking trading firms in the two situations, let us assume that with active participants, their total number is a multiple of N_R, i.e., we write $N_T = N_R + N_W + N_N = \kappa N_R = \kappa N_T$, where $\kappa \geq 1$. Then the difference $\Delta f = f_{i,T}^* - f_{i,S}^* = \frac{b\omega_T}{\nu_T} - \frac{b\omega_S}{\nu_S}$, with

$$\omega_S = N_R\mathbb{E}[q_0](9 + 4b\lambda V_s) + N_R\tau_P + 9b\lambda \left((\mathbb{E}[p_0] + b\mu_\theta - 3p_R)\sigma_\theta^2 + b\mu_\theta q_W^2\sigma_\xi^2 + b\tau_\theta \right) \tag{80}$$

$$\nu_S = 27b\lambda \left(2\sigma_\theta^2 + q_W^2\sigma_\xi^2 \right) + N_R \left(45 + 8b\lambda \left(\sigma_\theta^2 + q_W^2\sigma_\xi^2 \right) \right) \tag{81}$$

$$\omega_T = \kappa N_R\mathbb{E}[q_0](9 + 4b\lambda V_s) + \kappa N_R\tau_P + 9b\lambda \left((\mathbb{E}[p_0] + b\mu_\theta - bq_N - b\mu_\xi q_W)V_s - 3p_R\sigma_\theta^2 + b(\tau_\theta - q_W^3\tau_\xi) \right) \tag{82}$$

$$\nu_T = 45\kappa N_R + b\lambda(8\kappa N_R + 54)V_s \tag{83}$$

with $V_s = \sigma_\theta^2 + q_W^2 \sigma_\xi^2$ and $\tau_P = 2b^2 \lambda (\tau_\theta - q_W^3 \tau_\xi)$. Differentiating, we see that the sign of

$$\frac{d\Delta f}{d\kappa} = \frac{(N_R \mathbb{E}[q_0](9 + 4b\lambda V_s) + N_R \tau_P)\nu_T - N_R(45 + 8b\lambda V_s)\omega_T}{\nu_T^2} \tag{84}$$

$$= \frac{N_R}{\nu_T^2}(54b\lambda V_s(\mathbb{E}[q_0](9 + 4b\lambda V_s) + \tau_P) \tag{85}$$

$$- (45 + 8b\lambda V_s)9b\lambda\left((\mathbb{E}[p_0] + b\mu_\theta - bq_N - b\mu_\xi q_W)V_s - 3p_R\sigma_\theta^2 + b(\tau_\theta - q_W^3\tau_\xi))\right) \tag{86}$$

does not depend on κ. Letting $\tau_\theta = 0$, the derivative is positive as long as $b\lambda V_s \geq \frac{9}{2}$ and $c, \tau_\xi, \mu_\xi, q_N$ are sufficiently small. Then, if $\Delta f > 0$ at $\kappa = 1$, it will be true for any $\kappa \geq 1$. At $\kappa = 1$, Δf is decreasing in $c, \tau_\xi, \mu_\xi, q_N$. Setting these to zero, we have $\Delta f > 0$, and this is true for sufficiently low values of $c, \tau_\xi, \mu_\xi, q_N$. Higher positions imply that $\mathbb{E}[p_{s,T}] \leq \mathbb{E}[p_{s,S}]$. $\square$

Proof of Corollary 4. Most of the statements follow from derivatives and cross-derivatives. For instance the derivative of the forward premium ψ_S on μ_ξ, we have

$$\frac{d\psi}{d\mu_\xi} = \frac{b^2\lambda(-9b\lambda\sigma_\theta^2(2\sigma_\theta^2 + q_W^2\sigma_\xi^2) + N_R(8b\lambda\sigma_\theta^4 + 2q_W^2\sigma_\xi^2(9 + 4b\lambda q_W^2\sigma_\xi^2) + \sigma_\theta^2(-9 + 16b\lambda q_W^2\sigma_\xi^2)))}{9N_R(27b\lambda(2\sigma_\theta^2 + q_W^2\sigma_\xi^2) + N_R(45 + 8b\lambda(\sigma_\theta^2 + q_W^2\sigma_\xi^2)))} \tag{87}$$

which is positive if $b\lambda\sigma_\theta^2 \geq \frac{9N_R}{2(4N_R - 9)}$.

The other statements similarly follow from derivatives. $\square$

Appendix C: Imperfect Correlation of Intermittent Production

When trading forward, each intermittent producer needs to take into account the distribution of its own production ξ_i. We assume that $\mu_{\xi_i} = \mu_\xi$ for all producers. We also need to consider the correlation of each producer with the total wind output, which is in general imperfect (Apt 2007). For simplicity, we assume that this correlation is equal for all producers. We can then derive the positions:

$$f_W = \frac{N_W(p_f - \mathbb{E}[p_s])}{\lambda V(p_s)} + \frac{\eta_W q_W}{V(p_s)}, \tag{88}$$

$$\eta_W = \frac{b}{9}\left(-(ab + 2c + b\mu_\theta - b\mu_\xi q_W - bq_N - bF)q_W\rho_W\sigma_\xi^2 + b\mu_\xi(\sigma_\theta^2 + q_W^2\rho_W\sigma_\xi^2) + bq_W^2\rho_W\tau_\xi\right). \tag{89}$$

With $\rho_W = 1$, the expression coincides with the result in the text. Higher correlation with total wind output intuitively tends to reduce hedging incentives, as own output is more likely to coincide with a low price.

Combining the forward demands of the price-taking participants, we can again derive a linear (residual) inverse forward demand for the conventional producers.

LEMMA 4. *The total forward demand with intermittent and inflexible capacity and imperfect wind correlation is*

$$p_{f,T} = a_{f,T} - b_{f,T}F \tag{90}$$

$$a_{f,T} = \frac{ab + 2c - bq_W\mu_\xi - bq_N + b\mu_\theta}{3} + \frac{b\lambda}{9N}\left((ab + 2c + 2b\mu_\theta - 2b\mu_\xi q_W - 2bq_N)(\sigma_\theta^2 + q_W^2\rho\sigma_\xi^2)\right. \tag{91}$$

$$\left. + (1 - \rho_W)(b\mu_\theta - bq_N)q_W^2\sigma_\xi^2 - 3p_R\sigma_\theta^2 + b\tau_\theta - bq_W^3\rho\tau_\xi\right) \tag{92}$$

$$b_{f,T} = \frac{1}{N}\left[\frac{bN}{3} + \frac{\lambda b^2}{9}\left(2\sigma_\theta^2 + (1 + \rho_W)q_W^2\sigma_\xi^2\right)\right]. \tag{93}$$

Proof. The positions for intermittent producers are again

$$f_W = \sum_i f_{Wi} = \frac{N_W (p_f - \mathbb{E}[p_s])}{\lambda V(p_s)} + \frac{\eta_W}{V(p_s)} q_W. \tag{94}$$

Let us derive the covariance term η_W:

$$Cov(p_s q_W^e, p_s) = \frac{1}{9} Cov((ab + b\theta + 2c - bq_N - b\xi q_W - bF)\xi_i q_{Wi}, ab + b\theta + 2c - bq_N - b\xi q_W - bF) \tag{95}$$

$$= \frac{1}{9} ((ab + 2c - bq_N - bF)q_{Wi} Cov(\xi_i, b\theta - b\xi q_W) + q_{Wi} Cov(b\theta\xi_i, b\theta - b\xi q_W)$$

$$- q_W q_{Wi} Cov(b\xi\xi_i, b\theta - b\xi q_W)) \tag{96}$$

$$= \frac{bq_{Wi}}{9} \left(-(ab + 2c - bq_N - bF)q_W \rho_W \sigma_\xi^2 + b Cov(\theta\xi, \theta) - bq_W \rho_W Cov(\theta\xi, \xi) \right.$$

$$\left. - bq_W Cov(\xi^2, \theta) + bq_W^2 \rho_W Cov(\xi, \xi^2) \right) \tag{97}$$

$$= \frac{bq_{Wi}}{9} \left(-(ab + 2c + b\mu_\theta - bq_N - bF)q_W \rho_W \sigma_\xi^2 + b\mu_\xi \sigma_\theta^2 + bq_W^2 \rho_W Cov(\xi, \xi^2) \right) \tag{98}$$

$$= \eta_W q_{Wi}. \tag{99}$$

We can then write out the inverse forward demand facing the flexible generators as

$$p_f = a_{f,T} - b_{f,T} F \tag{100}$$

$$a_{f,T} = \frac{ab + 2c - bq_W \mu_\xi - bq_N + b\mu_\theta}{3} + \frac{b\lambda}{9N} \left((ab + 2c + 2b\mu_\theta - 2b\mu_\xi q_W - 2bq_N)(\sigma_\theta^2 + q_W^2 \rho \sigma_\xi^2) \right. \tag{101}$$

$$\left. + (1 - \rho_W)(b\mu_\theta - bq_N)q_W^2 \sigma_\xi^2 - 3p_R \sigma_\theta^2 + b\tau_\theta - bq_W^3 \rho \tau_\xi \right) \tag{102}$$

$$b_{f,T} = \frac{1}{N} \left[\frac{bN}{3} + \frac{\lambda b^2}{9} \left(2\sigma_\theta^2 + (1 + \rho_W)q_W^2 \sigma_\xi^2 \right) \right]. \tag{103}$$

$\square$

The expressions match the perfect correlation result when $\rho_W = 1$. Higher correlation reduces intermittent producers' forward trading, as high own production is more likely to coincide with low prices. Using the inverse forward demand, we can again derive the equilibrium.

PROPOSITION 5. *In the game with residual forward demand from retailers and intermittent and inflexible producers, and imperfect correlation of intermittent production, the equilibrium is as follows.*[18]

$$q_{i,T}^* = \frac{q_{0,T}}{3b} + \frac{\omega_T}{3b\nu_T}, \qquad f_{i,T}^* = \frac{\omega_T}{b\nu_T}, \tag{104}$$

$$p_{s,T} = \frac{p_{0,T}}{3} - \frac{2\omega_T}{3\nu_T}, \qquad p_{f,T} = a_{f,T} - \frac{2b_{f,T}\omega_T}{b\nu_T} \tag{105}$$

where $q_{0,T} = ab - c + b\theta - bq_N - b\xi q_W$, $p_{0,T} = ab + 2c + b\theta - bq_N - b\xi q_W$, $N = N_R + N_W + N_N$ and

$$\omega_T = N\mathbb{E}[q_{0,T}](9 + 4b\lambda V_s) + 2Nb^2\lambda(\tau_\theta - q_W^3 \tau_\xi)$$

$$+ 9b\lambda \left((\mathbb{E}[p_{0,T}] - 2b\mu_\xi q_W)(\sigma_\theta^2 + q_W^2 \rho_W \sigma_\xi^2) + (b\mu_\theta - bq_N)V_s - 3p_R \sigma_\theta^2 + b(\tau_\theta - \rho_W q_W^3 \tau_\xi) \right) \tag{106}$$

$$\nu_T = 45N + b\lambda(8N + 54)V_s \tag{107}$$

$$V_s = \sigma_\theta^2 + q_W^2 \sigma_\xi^2. \tag{108}$$

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[18] Our assumption on an interior solution again requires conditions similar to those in Proposition 2.

With sufficiently high ρ_W, all the comparative statics obtained in the main text still hold. But when the correlation decreases, some of them are reversed. The intermittent producers trade more forward, and the equilibrium is in between the results with or without forward trading. Hypothetically, with $\rho_W = 0$, the producers only hedge their production against demand risk, and further speculate on the forward premium through the bias term.

Let us reproduce the illustration in Figure 4 with imperfect correlation. In comparison, the forward price is reduced and spot price increased in Figure 6. But even with correlation as low as $\rho_W = 0.3$, the differences are fairly small compared to the difference to the case where producers do not trade forward.

Figure 6 **Forward and expected spot prices (a) and forward positions (b) as functions of intermittent capacity.**
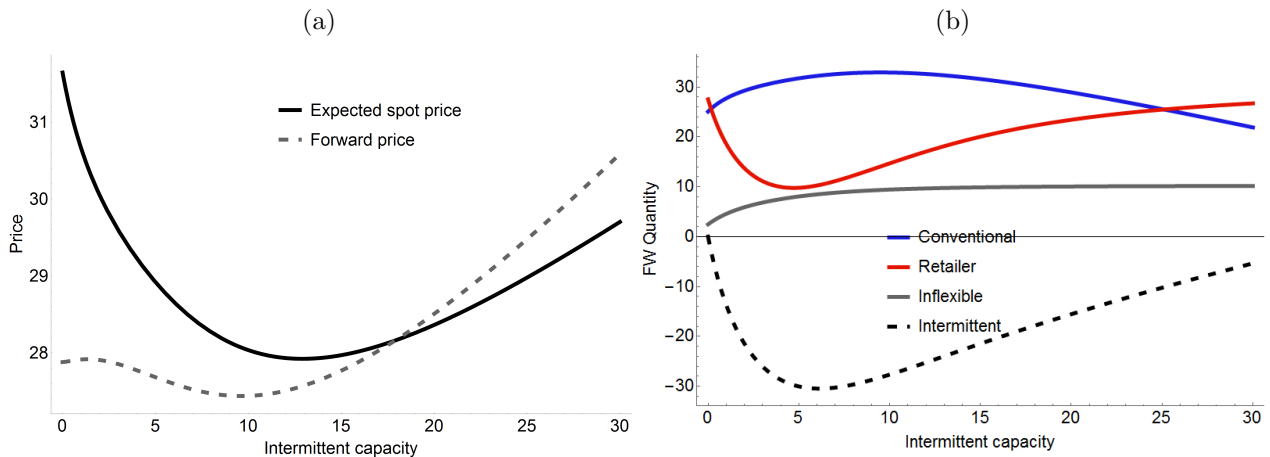
Note. Parameters $N_R = 6, N_N = 2, \tau_\theta = 0, b = 1, p_R = 40, \lambda = 1, q_N = 10, \sigma_\xi^2 = 0.1, \tau_\xi = 0.1, a = 50, c = 25, \mu_\theta = 30, \sigma_\theta^2 = 9, N_W = q_W/0.2, \rho_W = 0.4$.

Appendix D: Different Risk Aversions

In this section, we analyse the impact of different risk aversions of the market participants in the setting with inactive intermittent and inactive producers. That is, the conventional producers' and the retailers' risk aversion parameters are λ_P and λ_R, respectively. Electricity retailers, with commitments to serve inelastic demand, would likely be more risk averse than producers, with $\lambda_P \leq \lambda_R$. Let us first consider this situation, and then the alternative with more risk averse producers.

The equilibrium in Proposition 2 shows the impacts of the parties' risk aversions on trading and prices. In the extreme, if the producers are risk neutral, forward trading is driven by their strategic motivation combined with retailers' hedging. This typically reduces equilibrium forward trading, and hence increases the spot price. However, while most comparative statics are similar to the risk-averse case, price comparison of the impact of intermittent production is ambiguous. Based on our numerical experiments, with risk neutral producers, the spot price is more likely to decrease and the forward price more likely to increase with renewable capacity. The forward premium hence tends to increase. This is because the risk-neutral producers take advantage of willingness of the retailers to hedge their spot profits. Retailers pay to reduce risk, and the premium is hence positive. Moreover, the producers sell more forward as a result of increasing uncertainty,

strengthening the strategic effect on the spot price. This is shown in Figure 7, which adapts Figure 2(b). Prices are higher compared to the situation where producers also hedge their spot risk, and the premium increases with intermittent capacity. However, it is still possible to identify cases in which more intermittent capacity leads to a higher spot price. Specifically, this is more likely to happen when demand uncertainty is low, as the retailers then mainly speculate on intermittency, and both they and the producers contract their forward trading with more uncertainty.

Figure 7   Forward and expected spot prices when producers are risk neutral.
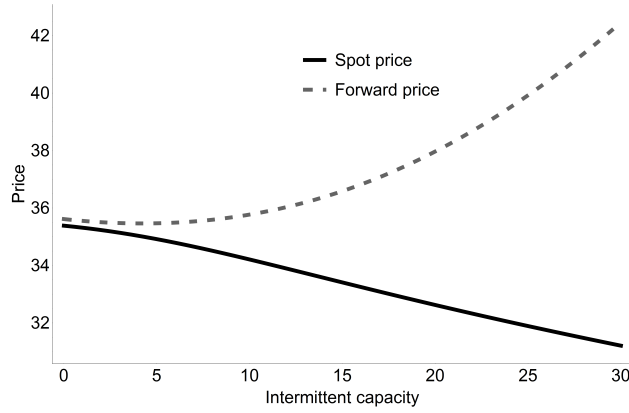
Note. Parameters $N_R = 6, \tau_\theta = 0, b = 1, p_R = 40, \lambda_P = 0, \lambda_R = 1, q_N = 10, \sigma_\xi^2 = 0.1, a = 50, c = 25, \mu_\theta = 30, \sigma_\theta^2 = 9, \tau_\xi = 0.1$.

In the opposite case, with retailers less risk averse than producers, the retailers become increasingly like risk-neutral speculators as we reduce λ_R. As a result, the market moves towards a setting where risk-averse producers trade with risk-neutral speculators. In the extreme, if $\lambda_R = 0$, we have no forward premium with $\mathbb{E}[p_s] = p_f$. The existence of forward premia thus requires sufficiently constrained hedging from the perspective of the retailers.

Finally, let us note the equilibrium outcome with only the strategic rationale on forward tarding, i.e., if the firms do not seek to reduce profit volatility. This is given in the following result, which shows that focusing solely on the strategic rationale mitigates the direct merit-order impact on prices.

PROPOSITION 6. *In the game with multiple technologies and risk-neutral participants, the strategic ratio-nale reduces the impact of q_W and q_N on the power price:* $\frac{d\mathbb{E}[p_{0,S}]}{dq_W} \leq \frac{d\mathbb{E}[p_{s,S}]}{dq_W}$. *The equilibrium is as follows.*

$$q_{i,S}^* = \frac{q_{0,S}}{3b} + \frac{f_{i,S}^*}{3b}, \qquad f_{i,S}^* = \frac{\mathbb{E}[q_{0,S}]}{5b}, \tag{109}$$

$$p_{s,S} = \frac{\mathbb{E}[p_{0,S}]}{3} - \frac{2bf_{i,S}^*}{3}, \qquad p_{f,S} = \mathbb{E}[p_{s,S}] = \frac{ab + 4c + b\mu_\theta - bq_N - b\mu_\xi q_W}{5}, \tag{110}$$

where $q_{0,S} = ab - c + b\theta - bq_N - b\xi q_W$, $p_{0,S} = ab + 2c + b\theta - bq_N - b\xi q_W$.

Appendix E: Elastic Demand Traded Forward

In this section we extend the model in Section 4.1 to consider the situation where both inelastic and elastic demand may be traded forward. To capture this situation in a parsimonious way, suppose both types of consumers contract with the retailers for their power demand. That is, the retailers now sell the product to both the customers with inelastic (as before) and those with elastic demand. The price set for customers with elastic demand is the spot price marked up by a factor δ. Denote the inelastic demand served by retailer i by q_{Ii}, and let the retail market shares be equal.

Let us derive a retailer's optimal forward position. Its profit is the difference between sales and procurement costs:

$$\pi_{Ri,f}(f_{Ri}) = p_R \theta_{Ri} - p_s \theta_{Ri} + (1+\delta)p_s q_{Ii} - p_s q_{Ii} + p_s f_{Ri} - p_f f_{Ri}. \tag{111}$$

The optimal retailer forward position is given in the following result.

LEMMA 5. *Each retailer's optimal forward position is given by*

$$f_{Ri} = \frac{\mathbb{E}[p_s] - p_f}{\lambda V(p_s)} - \frac{Cov(p_R \theta_{Ri} - p_s \theta_{Ri} + \delta p_s q_{Ii}, p_s)}{V(p_s)}. \tag{112}$$

We can immediately see that if the markup $\delta = 0$, the retailer does not hedge the elastic demand component at all. The model is then exactly the same as before, and the elastic demand has no impact on the forward market. This is because in the absence of a markup, the retailer simply passes the procurement cost through to its consumers with real-time pricing. Evidently, if the markup is small, this trading does not affect the insights from the model. A similar result would obtain if these consumers purchased power directly from the market and the value of consumption closely corresponded to the price paid for the product.

We omit the derivation of the full equilibrium: it is similar to the one Section 4.1, but substituting the forward demand from the retailers, defined in the proof of Lemma 5. However, we note here that the higher the markup $\delta \geq 0$, the less the retailers will hedge, as the markup increases their spot profits. Its impact is therefore similar to that of the retail price for inelastic consumers p_R: it reduces forward trading, and hence leads to a higher spot price. Furthermore, again similarly to p_R, by restricting retailers' trading, it also tends to make the impact of intermittent capacity on the spot price more negative.

Proof of Lemma 5. The proof follows similar steps as Lemma 2 in deriving the optimal position from $U_R(\pi_{Ri,f})$, except using the profits under technology, and including the final covariance term. Assuming equally sized retailers, $q_{Ii} = Q/N_R$. The covariance is then

$$Cov(\delta p_s q_{Ii}, p_s) = \frac{2\delta}{27bN_R} Cov\left((ab + 2c + b\theta - bq_N - b\xi q_W - bF)(ab - c + b\theta - bq_N - b\xi q_W + bF/2), b\theta - b\xi q_W\right) \tag{113}$$

$$= \frac{2\delta}{27N_R} \Big[Cov(b^2\theta^2, \theta) + Cov(b\theta(2ab + c - 2bq_N - bF/2), \theta) - Cov(b^2\xi^2 q_W^2, q_W\xi) $$
$$+ Cov(b\xi q_W(2ab + c - 2bq_N - bF/2), \xi q_W) - 2Cov(b^2\xi\theta q_W, \theta - q_W\xi) \Big] \tag{114}$$

$$= \frac{2b\delta}{27N_R} \Big[bCov(\theta^2, \theta) + bq_W^3 Cov(\xi^2, \xi) + (2ab + c - 2bq_N - bF/2)(\sigma_\theta^2 + q_W\sigma_\xi^2) - 2Cov(b\xi\theta q_W, \theta - q_W\xi) \Big] \tag{115}$$

$$= \frac{2b\delta}{27N_R} \left[(2ab + c + 2b\mu_\theta - 2bq_W\mu_\xi - 2bq_N - bF/2)(\sigma_\theta^2 + q_W^2\sigma_\xi^2) + b\tau_\theta + bq_W^3\tau_\xi \right] \tag{116}$$

We can combine this with the other terms and translate the result into the forward demand:

$$a_{f,S} = \frac{ab + 2c + b\mu_\theta - bq_N - b\mu_\xi q_W}{3} + \frac{b\lambda_R}{9N_R} \left((ab + 2c + 2b\mu_\theta - bq_N - b\mu_\xi q_W - 3p_R)\sigma_\theta^2 + b\mu_\theta q_W^2\sigma_\xi^2 + b\tau_\theta \right)$$

$$- \frac{2b\lambda_R}{27N_R} \left((2ab + c + 2b\mu_\theta - 2bq_N - 2b\mu_\xi q_W)(\sigma_\theta^2 + q_W^2\sigma_\xi^2) + b\tau_\theta + bq_W^3\tau_\xi \right) \tag{117}$$

$$b_{f,S} = \frac{1}{27N_R} \left(9bN_R + \lambda b^2((5+\delta)\sigma_\theta^2 + (3+\delta)q_W^2\sigma_\xi^2) \right). \tag{118}$$

□

Appendix F: Increasing Marginal Cost

We have assumed that the conventional producers have constant marginal costs. In this section, we derive the equilibrium under an increasing marginal cost, i.e., convex total production cost. Specifically, let $C(q_i) = cq_i^2$. The resulting spot equilibrium is given in the following lemma.

LEMMA 6. *The spot market equilibrium given forward positions f_i, f_j is*

$$q_i^* = \frac{q_{0,S} + b^2(2f_i - f_j) + 2bcf_i}{(3b + 2c)(b + 2c)}, \tag{119}$$

$$p_s = \frac{p_{0,S} - b^2F}{3b + 2c}, \tag{120}$$

where $q_{0,S} = p_{0,S} = b(b+2c)(a + \theta - q_N - \xi q_W)$ reflect the (un-normalised) production quantity and price in the absence of forward commitments.

The equilibrium again shows the strategic motivation to trade forward: more a producer sells forward, the more it will produce in the spot stage. However, this will also result in lower prices. The forward stage equilibrium is given in the results below.

LEMMA 7. *With quadratic production costs, the forward demand from retailers is as follows.*

$$a_{f,S} = \frac{b(b+2c)}{3b+2c}(a + \mu_\theta - q_N - q_W\mu_\xi) \tag{121}$$

$$+ \frac{\lambda_R b(b+2c)}{N_R(3b+2c)^2} \left(\sigma_\theta^2(b(b+2c)(a + 2\mu_\theta - q_N - q_W\mu_\xi) - (3b+2c)p_R) + b(b+2c)(\mu_\theta q_W^2\sigma_\xi^2 + \tau_\theta) \right) \tag{122}$$

$$b_{f,S} = \frac{b^2}{3b+2c} + \frac{\lambda_R b^2(b+2c)}{N_R(3b+2c)^2} \left(2(b+c)\sigma_\theta^2 + (b+2c)q_W^2\sigma_\xi^2 \right). \tag{123}$$

PROPOSITION 7. *In the spot-forward game with multiple technologies and quadratic production costs, the equilibrium is as follows.*[19]

$$q_{i,S}^* = \frac{q_{0,S}}{(3b+2c)(b+2c)} + \frac{b\omega_S}{(3b+2c)\nu_S}, \qquad f_{i,S}^* = \frac{\omega_S}{\nu_S}, \tag{125}$$

---

[19] Assumption 3 requires that production cover at least inelastic demand. This is true when $\theta \le 2q_i^* + q_N + \xi q_W$. Let us assume conservatively that $\underline{\xi} = 0$. Then we need

$$(b+2c)\theta \le 2ab + (b+2c)q_N + 2b\omega_S/\nu_S. \tag{124}$$

Inflexible capacity relaxes the constraint, and it holds unless μ_θ and q_W are very large compared to a and q_N. We also assume that $q_i^* \ge 0$ for any values of θ and ξ, i.e., q_W, q_N low enough to avoid curtailment.

$$p_{s,S} = \frac{p_{0,S}}{3b+2c} - \frac{2b^2\omega_S}{(3b+2c)\nu_S}, \qquad p_{f,S} = a_{f,S} - \frac{2b_{f,S}\omega_S}{\nu_S}, \tag{126}$$

where $q_{0,S} = p_{0,S} = b(b+2c)(a+\theta-q_N-\xi q_W)$. *Furthermore, letting* $b = c = 1$,

$$\omega_S = N_R((a+\mu_\theta-q_N-q_W\mu_\xi)(25+216\lambda_P(\sigma_\theta^2+q_W^2\sigma_\xi^2))-180\lambda_P(\sigma_\theta^2+q_W^2\sigma_\xi^2))+108\lambda_P N_R(\tau_\theta-q_W^3\tau_\xi)$$

$$+ 225\lambda_R\left((3(a+2\mu_\theta-q_N-q_W\mu_\xi)-5p_R)\sigma_\theta^2+3\mu_\theta q_W^2\sigma_\xi^2+3\tau_\theta\right) \tag{127}$$

$$\nu_S = 675\lambda_R\left(4\sigma_\theta^2+3q_W^2\sigma_\xi^2\right)+N_R\left(475+432\lambda_P\left(\sigma_\theta^2+q_W^2\sigma_\xi^2\right)\right) \tag{128}$$

The proposition reports the equilibrium under the simplifying assumptions $b = c = 1$. We can similarly solve the problem for general b and c, but the expressions for ω_S and ν_S become cumbersome. Comparative statics are similarly difficult to obtain. Figure 8, however, demonstrates that with convex production costs, the spot price may still increase with renewable capacity. That is, the mechanism behind this result is robust to the cost function: the producers reduce their forward trading in order not to be caught with substantial positions that they would need to balancec in spot in the event of high output from the intermittent producers.

Figure 8   Forward and expected spot prices when producers are risk neutral.
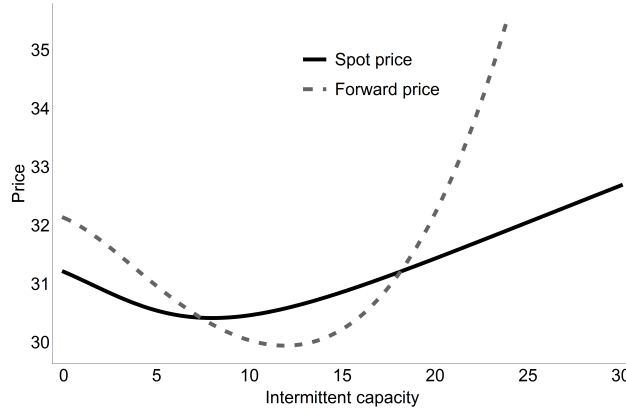
Note. Parameters $N_R = 10, \tau_\theta = 0, b = 1, p_R = 40, \lambda_P = \lambda_R = 0.5, q_N = 10, \sigma_\xi^2 = 0.1, a = 50, c = 1, \mu_\theta = 30, \sigma_\theta^2 = 9, \tau_\xi = 0.3$.

Proof of Lemma 6. Follows from simultaneously solving the first-order conditions of the producers' spot profits, but under quadratic costs.   □

Proof of Lemma 7. Let us derive the retailers' optimal forward positions. A retailer's forward profit is the difference between sales and procurement costs:

$$\pi_{Ri,f}(f_{Ri}) = p_R\theta_{Ri} - p_s\theta_{Ri} + p_s f_{Ri} - p_f f_{Ri}. \tag{129}$$

The optimal forward position is given by

$$f_{Ri} = \frac{\mathbb{E}[p_s] - p_f}{\lambda V(p_s)} - \frac{Cov(p_R\theta_{Ri} - p_s\theta_{Ri}, p_s)}{V(p_s)}. \tag{130}$$

The variance is now

$$V(p_s) = \frac{b^2(b+2c)^2}{(3b+2c)^2}\left(V(\theta) + q_W^2 V(\xi)\right).$$ (131)

The covariance term can be written as

$$Cov(p_R\theta_{Ri} - p_s\theta_{Ri}, p_s) = \frac{1}{N_R}Cov(\theta(p_R - p_s), p_s)$$ (132)

$$= \frac{b(b+2c)}{N_R(3b+2c)}Cov(\theta(p_R - p_s), \theta - q_W\xi)$$ (133)

$$= \frac{z}{N_R}Cov(\theta(p_R - p_s), \theta - q_W\xi)$$ (134)

$$= \frac{z}{N_R}\left(p_R Cov(\theta, \theta) - Cov(\theta(z(\theta - q_W\xi) + (z(a - q_N) - \frac{b^2 F}{3b+2c}), \theta - q_W\xi)\right)$$ (135)

$$= \frac{z}{N_R}\left(\sigma_\theta^2(p_R - 2z\mu_\theta + zq_W\mu_\xi - z(a - q_N) - \frac{b^2 F}{3b+2c}) - z(\tau_\theta - q_W^2\sigma_\xi^2\mu_\theta)\right)$$ (136)

$$= \frac{b(b+2c)}{N_R(3b+2c)^2}\left(\sigma_\theta^2((3b+2c)p_R - b(b+2c)(2\mu_\theta + q_W\mu_\xi - a + q_N) - b^2 F)\right.$$
$$\left. - b(b+2c)(\tau_\theta - q_W^2\sigma_\xi^2\mu_\theta)\right).$$ (137)

Summing up the individual retailer forward positions, the inverse forward demand can be written as

$$p_f = a_{f,S} - b_{f,S}F,$$ (138)

$$a_{f,S} = \frac{b(b+2c)}{3b+2c}(a + \mu_\theta - q_N - q_W\mu_\xi)$$ (139)

$$+ \frac{\lambda_R b(b+2c)}{N_R(3b+2c)^2}\left(\sigma_\theta^2(b(b+2c)(a + 2\mu_\theta - q_N - q_W\mu_\xi) - (3b+2c)p_R) + b(b+2c)(\mu_\theta q_W^2\sigma_\xi^2 + \tau_\theta)\right)$$ (140)

$$b_{f,S} = \frac{b^2}{3b+2c} + \frac{\lambda_R b^2(b+2c)}{N_R(3b+2c)^2}\left(2(b+c)\sigma_\theta^2 + (b+2c)q_W^2\sigma_\xi^2\right).$$ (141)

□

Proof of Proposition 7. The conventional producers select forward positions to maximize their utility

$$U(\pi_i^f) = p_f f_i + \mathbb{E}[\pi_{i,s}] - \frac{\lambda}{2}V(\pi_{i,s}).$$ (142)

The FOC is

$$\frac{d}{df_i}U(\pi_i^f) = 0 \iff p_f + \frac{dp_f}{df_i}f_i + \frac{d}{df_i}\mathbb{E}[\pi_{i,s}] - \frac{\lambda}{2}\frac{d}{df_i}V(\pi_{i,s}) = 0.$$ (143)

Using the two lemmas, we have:

$$\frac{dp_f}{df_i} = -b_{f,S}$$ (144)

$$\mathbb{E}[\pi_{i,s}] = \mathbb{E}[p_s(q_i - f_i) - cq_i]$$ (145)

$$= \mathbb{E}[\frac{p_{0,S} - b^2 F}{3b+2c}\frac{q_{0,S} - f_i(b^2 + 6bc + 4c^2) - b^2 f_j}{(3b+2c)(b+2c)}] - \mathbb{E}[c\frac{q_{0,S} + b^2(2f_i - f_j) + 2bcf_i}{(3b+2c)(b+2c)}]$$ (146)

$$\frac{d}{df_i}\mathbb{E}[\pi_{i,s}] = \frac{-b^2(\mathbb{E}[q_{0,S}] - b^2 f_j + 2b(b+c)f_i) - 2b(b+c)(\mathbb{E}[p_{0,S}] - b^2 F)}{(3b+2c)^2(b+2c)} - \frac{2bc(b+c)}{(3b+2c)(b+2c)}$$ (147)

The variance is $V(\pi_{i,s}) = V(p_s(q_i - f_i) - cq_i) = V(p_s(q_i - f_i)) + V(cq_i) - 2Cov(p_s(q_i - f_i), cq_i)$. Here

$$V(cq_i) = c^2 V(q_i) = c^2 V\left(\frac{q_{0,S}}{(3b+2c)(b+2c)}\right)$$ (148)

is independent of f_i. The other terms can be written as

$$V(p_s(q_i - f_i)) = V\left(\frac{p_{0,S} - b^2 F}{3b + 2c}\frac{q_{0,S} - f_i(b^2 + 6bc + 4c^2) - b^2 f_j}{(3b + 2c)(b + 2c)}\right) \tag{149}$$

$$= \frac{1}{(3b + 2c)^4(b + 2c)^2}\left[V\left(p_{0,S}^2\right) + [2f_i(b + c)(b + 2c) + 2b^2 f_j]^2 V\left(p_{0,S}\right)\right.$$
$$\left. - 2[2f_i(b + c)(b + 2c) + 2b^2 f_j]Cov(p_{0,S}^2, p_{0,S})\right] \tag{150}$$

$$\frac{d}{df_i}V(p_s(q_i - f_i)) = \frac{4(b + c)(b + 2c)}{(3b + 2c)^4(b + 2c)^2}\left[[f_i(b + c)(b + 2c) + b^2 f_j]V(p_{0,S}) - Cov(p_{0,S}^2, p_{0,S})\right] \tag{151}$$

$$Cov(p_s(q_i - f_i), cq_i) = Cov\left(\frac{p_{0,S}[p_{0,S} - b^2(f_i + f_j)] - f_i(b^2 + 6bc + 4c^2) - b^2 f_j]}{(3b + 2c)^2(b + 2c)}, \frac{cp_{0,S}}{(3b + 2c)(b + 2c)}\right) \tag{152}$$

$$= \frac{c}{(3b + 2c)^3(b + 2c)^2}\left[Cov\left(p_{0,S}^2, p_{0,S}\right) - 2[f_i(b + 2c)(b + c) + b^2 f_j]V\left(p_{0,S}\right)\right] \tag{153}$$

$$\frac{d}{df_i}Cov(p_s(q_i - f_i), cq_i) = \frac{-2b^2 c(b + c)(b + 2c)}{(3b + 2c)^3}\left(\sigma_\theta^2 + q_W^2 \sigma_\xi^2\right) \tag{154}$$

The variance and covariance terms are

$$V(p_{0,S}) = b^2(b + 2c)^2 V(a + \theta - q_N - \xi q_W) = b^2(b + 2c)^2(\sigma_\theta^2 + q_W^2 \sigma_\xi^2) \tag{155}$$

$$Cov(p_{0,S}^2, p_{0,S}) = Cov(b^2(b + 2c)^2(a + \theta - q_N - \xi q_W)^2, b(b + 2c)(a + \theta - q_N - \xi q_W)) \tag{156}$$

$$= b^3(b + 2c)^3 Cov(\theta^2 + q_W^2 \xi^2 - 2q_W \theta\xi + 2\theta(a - q_N) - 2q_W \xi(a - q_N), \theta - q_W \xi) \tag{157}$$

$$= b^3(b + 2c)^3\left[2\sigma_\theta^2 \mu_\theta + \tau_\theta - q_W^3(2\sigma_\xi^2 \mu_\xi + \tau_\xi) - 2q_W \sigma_\theta^2 \mu_\xi + 2q_W^2 \sigma_\xi^2 \mu_\theta\right.$$
$$\left. + 2(a - q_N)(\sigma_\theta^2 + q_W^2 \sigma_\xi^2)\right]. \tag{158}$$

Hence we can write the derivative as

$$\frac{d}{df_i}V(p_s(q_i - f_i)) = \frac{4b^2(b + c)(b + 2c)}{(3b + 2c)^4}\left[[-2b(b + 2c)(a - q_N) + f_i(b + c)(b + 2c) + b^2 f_j](\sigma_\theta^2 + q_W^2 \sigma_\xi^2)\right.$$
$$\left. - b(b + 2c)\left[2\sigma_\theta^2 \mu_\theta + \tau_\theta - q_W^3(2\sigma_\xi^2 \mu_\xi + \tau_\xi) - 2q_W \sigma_\theta^2 \mu_\xi + 2q_W^2 \sigma_\xi^2 \mu_\theta\right]\right]. \tag{159}$$

Combining the terms, the entire derivative is therefore

$$\frac{d}{df_i}V(\pi_{i,s}) = -\frac{4b^2(b + c)(b + 2c)}{(3b + 2c)^4}\left[[2b(b + 2c)(a - q_N) - c(3b + 2c) - f_i(b + c)(b + 2c) - b^2 f_j](\sigma_\theta^2 + q_W^2 \sigma_\xi^2)\right.$$
$$\left. + b(b + 2c)[2\sigma_\theta^2 \mu_\theta + \tau_\theta - q_W^3(2\sigma_\xi^2 \mu_\xi + \tau_\xi) - 2q_W \sigma_\theta^2 \mu_\xi + 2q_W^2 \sigma_\xi^2 \mu_\theta]\right]. \tag{160}$$

Substituting these into the first-order condition and solving simultaneously, we can derive the equilibrium. It is easy to check the second-order condition to guarantee the equilibrium. $\square$