Renewable Power and Electricity Prices: The Impact of Forward Markets

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Increasing variable renewable power generation (e.g., wind) is expected to reduce wholesale electricity prices by virtue of its low marginal production cost. This *merit-order effect* of renewables displacing incumbent conventional (e.g., gas) generation forms the theoretical underpinning for investment decisions and policy in the power industry. This paper uses a game-theoretic market model to investigate how intermittently available wind generation affects electricity prices in the presence of forward markets, which are widely used by power companies to hedge against revenue variability ahead of near-real-time spot trading. We find that in addition to the established merit-order effect, renewable generation also affects power prices through forward-market hedging. This "forward" effect reinforces the merit-order effect in reducing prices for moderate amounts of wind generation capacity, but mitigates or even reverses it for higher capacities. For moderate wind capacity, uncertainty over its output increases hedging, and these higher forward sales lead to lower prices. For higher capacities, however, wind variability conversely causes power producers to behave less aggressively in forward trading for fear of unfavorable spot-market positions. The lower sales counteract the merit-order effect, and prices may then paradoxically *increase* with wind capacity despite its lower production cost. We confirm the potential for such reversals in a numerical study, suggesting new empirical questions while providing potential explanations for previously contradictory observed effects of market fundamentals. We conclude that considering the conventional merit-order effect alone is insufficient for evaluating the price impacts of variable renewable generation in the presence of forward markets.

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

1. Introduction

The use of renewable energy sources is growing as different countries seek to reduce their dependence on fossil fuels. The European Union aims to source at least 32% of its energy from renewables by 2030, China is planning for renewables to account for 35% of its power consumption by 2030, and over 30 US states have set comparable policies.[1] The most profound impact of these policies has been on the electricity industry, where wind and

[1] See European Commission (2018), Bloomberg (2018), and National Conference of State Legislatures (2018).

solar power are displacing incumbent conventional coal- and gas-fired combustion turbines. In Germany, for example, wind and solar now account for more than 20% of the power market, with a target of 50% renewable electricity by 2030.

Increasing renewable generation is expected to benefit power consumers by reducing wholesale electricity prices. Power generators sell their output in near-real-time *spot markets*, where renewable (e.g., wind) producers' low short-run production costs allow them to undercut conventional (e.g., gas) producers in the dispatch order of generation offers. The potential benefits from this *merit-order effect* are particularly pronounced in power markets, as generation capacity is often concentrated to large conventional generators (e.g., Borenstein et al. 2002): Smaller renewable producers should limit incumbents' price-setting power, emphasizing their effect in reducing prices. The merit-order effect has thus been the conventional, widely-used analytical focus to model market price movements, changes in power-plant utilizations, and asset revaluations associated with the transition to renewable power (Woo et al. 2011, Baldick 2012).

This purely cost-based view of renewables' price impacts, however, overlooks their other implication for electricity trading, namely higher variability. Due to relatively inelastic demand and a lack of economic storage options, spot electricity prices are already highly volatile, and renewable sources further add to this variability. Unlike consistently available gas turbines, wind power has an average capacity availability of 30% with daily standard deviations of up to 25% (e.g., Sinden 2007), causing the volatility of spot power prices to further increase with renewable penetration (e.g., Ketterer 2014).

It may be thought that irregular wind production would simply result in a more volatile merit-order effect, reducing spot prices according to output. However, while price debates have focused on this spot-market competition, most electricity is traded via financial *forward contracts* ahead of spot. Power producers and retailers use forwards to hedge against spot-revenue volatility, with risk exposures significant enough for companies to regularly report their trading to investors.[2] In the UK, for example, over 90% of electricity is traded as forward contracts specifying a quantity to be delivered in subsequent spot markets (Ofgem 2009). Moreover, the pricing of forward contracts differs from spot-market cost competition. Besides the underlying generation costs, forward electricity prices are determined by the market participants' hedging of risk exposures (Bessembinder and Lemmon

[2] See, e.g., Drax in the UK: http://www.drax.com/media/66455/trading-update-november-2015.pdf.

2002), reflected in sustained *forward premia*, i.e., differences in forward and spot prices for the same delivery period (Longstaff and Wang 2004, Redl and Bunn 2013, Weron and Zator 2014). Increasing variable wind generation is changing not only cost competition but also forward risk exposures, causing companies to adjust their trading between forward and spot markets and hence altering the relationship between the prices. In Germany, for example, there is evidence that trading has shifted from forward contracting towards real time (Aïd et al. 2016) while the merit-order effect has slowed (Ketterer 2014).

In this paper, we revisit the merit-order effect of renewable power on electricity prices, accounting for its variable output and the prevalence of forward contracting in power markets. How will renewable generation, specifically wind power, change trading strategies and prices as it is projected to rapidly increase in the medium term? In particular, we seek to understand the impact of renewables in the presence of forward markets, which—besides pivotal to power companies' risk management—have been central to policy debate in the industry. Regulators have long encouraged forward trading as a means to curtail market power and reduce prices (e.g., Borenstein 2001), and more recently promoted virtual bidding (Jha and Wolak 2013) to introduce efficient forward-market arbitrage, removing price premia between forward and spot markets. How do forward trading, and premia arising from hedging, influence the price impacts of increasing renewable capacity?

We investigate the merit-order effect using a game-theoretic market model that captures the essential factors to manifest the effects of renewable power, but with sufficient stylization to permit analytical results. We study power producers and retailers trading in sequential forward and spot markets: Conventional producers represent an incumbent reliable (gas) technology, while new entrant (wind) producers have lower production costs but variable available capacity. In the forward market, power demand and wind supply are uncertain, and the companies are concerned with both the mean and the variance of their profits. They hedge against revenue variability by trading forward contracts, i.e., financial commitments to produce/buy a corresponding amount of power in the spot stage, with the forward price determined by matching the firms' demands for contracts. In the real-time spot market, conventional producers engage in quantity (Cournot) competition, while wind producers sell their realized production competitively.

When power is traded in spot markets alone, we confirm that higher wind generation reduces prices through the merit-order effect. But accounting for forward trading, we identify an additional effect of wind power on the spot price. This effect results from our model including both forward-market risk-hedging (Bessembinder and Lemmon 2002) and price-setting power by incumbent producers. More specifically, variable wind output changes spot-revenue risks, and hence the volume of forward contracts traded to hedge. For incumbents with market power, however, higher forward sales imply a commitment to generate more power in the spot market (Allaz and Vila 1993). Thus, the more risk-hedging occurs, the more power is generated, and hence the lower the price. Variable wind generation therefore affects the spot price of electricity not only through direct merit-order competition but also indirectly through altering hedging volumes in the forward market.

This additional forward effect may either reinforce or mitigate, and even reverse, the conventional merit-order effect, depending on the amount of wind capacity on the market. When capacity is moderate, its variable output leads power producers to increase their forward trading to hedge against the associated revenue risk. The higher commitments to produce power then reduce prices more than predicted by the conventional merit-order effect. However, with higher wind penetration, producers conversely reduce their forward commitments for fear of an unfavorable position in the spot market in case of high wind output. The lower commitments to produce power may then cause prices to *increase* with wind capacity if its output variability is high enough. Paradoxically, combining low-cost capacity and forward trading, both widely viewed by regulators as pro-competitive, may thus lead spot prices to increase when we take into account the variability of the renewable resource, with the forward price following similar patterns.

We confirm these findings in a numerical study using data from Denmark and the UK. Additional wind capacity reduces prices more than by the conventional merit-order effect at moderate capacities, but with higher capacity the impact becomes neutral or prices even increase. Whether the forward effect counteracts or reinforces the conventional merit-order effect is sensitive to the distribution of wind output and market fundamentals such as fuel prices and demand, suggesting varying effects between onshore and offshore capacity and seasonal trends. Finally, our model provides insights into wholesale electricity pricing beyond the merit-order effect. Specifically, besides supply-side variability, we propose new fundamental demand-side price drivers similarly affecting forward-market hedging, and provide justifications for contradictory observations in the empirical literature on power prices, such as reversals in the sign of forward premia resulting from interaction effects between market demand and fuel prices. We also investigate the price impact of introducing efficient forward-market arbitrage and find that it may increase prices in particular when renewable capacity is low, implying potentially ambiguous welfare effects from policies such as virtual bidding. Together, our findings suggest that accounting for forward-market hedging is integral to understanding the price impacts of variable renewable capacity and market fundamentals, and call for further empirical investigation into these impacts.

The rest of the paper is organized as follows. After reviewing related literature in §2, we develop a model of spot and forward electricity trading in §3 and derive its equilibrium in §4. In §5, we use the equilibrium to derive insights into wholesale electricity pricing, in particular revisiting the conventional expectation that the replacement of fossil fuel generation by renewables will simply reduce wholesale prices through the merit-order effect. We discuss these insights calibrated to real-world data in the numerical study in §6, and conclude in §7. The derivations of all results are included in the Electronic Companion.

2. Related Literature

The integration of variable renewable sources into electricity generation poses significant economic and operational challenges to energy producers, consumers and policy-makers (Carrasco et al. 2006, DeCarolis and Keith 2006, Drake and Spinler 2013). A growing operations-management literature has sought to address questions in this domain ranging from the optimal operation of renewables via curtailment and storage (Wu and Kapuscinski 2013, Zhou et al. 2019) to optimal investments in these technologies and their implications for peak pricing and utilities (Hu et al. 2015, Peura and Bunn 2015, Kök et al. 2016, Aflaki and Netessine 2017, Sunar and Swaminathan 2018) and encouraging their adoption with subsidy schemes (Boomsma et al. 2012, Alizamir et al. 2016).

The focus of this paper, the impact of renewables on electricity market outcomes, is widely considered through the merit-order effect of low-cost renewable capacity displacing conventional generation (Woo et al. 2011, Baldick 2012). A string of recent papers has added nuances to this view by including considerations of output variability. Al-Gwaiz et al. (2016) show that ignoring such operational factors may overstate the competitiveness of a spot market, as producers may exploit their competitors' operational constraints in their bidding strategies, and Sunar and Birge (2019) find that renewables may even increase power prices if the system-operator imposes penalties that reduce quantities of power sold to the market in the face of intermittent output. Relatedly, Twomey and Neuhoff

(2010) show that incumbent conventional producers' bidding in spot and forward markets overstates the price peaks and troughs caused by intermittency and their market power may hence reduce the profitability of wind generators. Complementing this literature, we show how the variability of renewable output changes the merit-order effect through forward-market hedging, potentially causing prices to increase with renewable capacity.

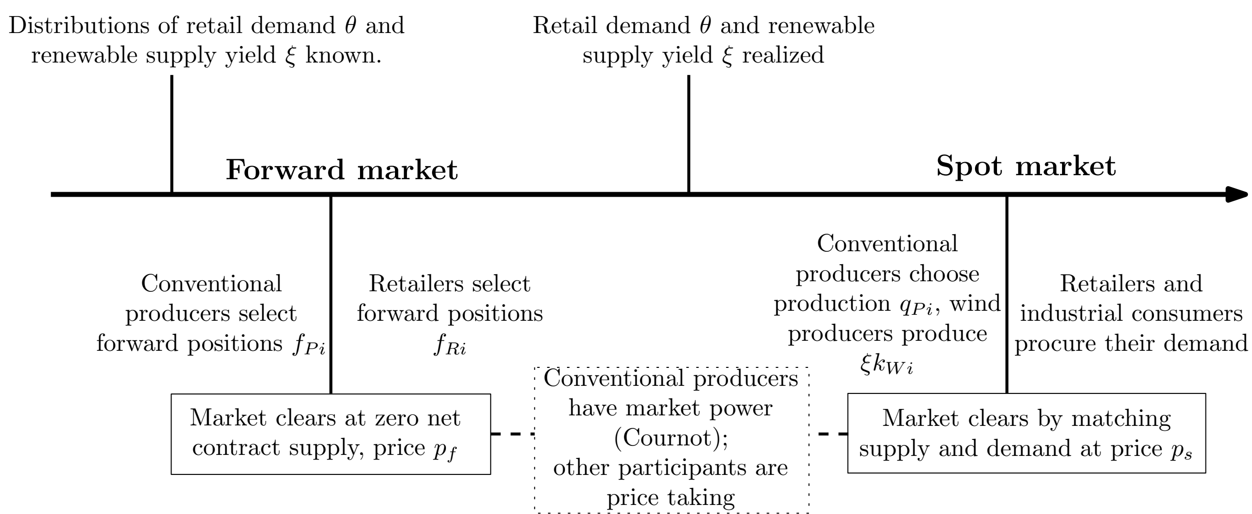
The mechanism behind these findings results from our model combining hedging in the forward market and producer market power. More specifically, including both these features brings together two main rationales for electricity forward trading—hedging and strategic commitment—previously identified in largely separate streams of literature. The hedging literature is motivated by evidence for forward premia in power markets (Longstaff and Wang 2004, Hadsell 2008, Bowden et al. 2009, Redl and Bunn 2013), viewing forward trading as a risk-sharing mechanism between risk-averse market participants (Bessembinder and Lemmon 2002, Siddiqui 2003, Aïd et al. 2011). By contrast, the other main body of work follows Allaz and Vila (1993) from an economic gaming perspective (Su 2007, Ke 2008, Murphy and Smeers 2010), showing how producers with market power may strategically tend towards forward contracting to gain spot market share even though it reduces prices in a form of prisoner's dilemma, as empirically documented in the power industry (Borenstein et al. 2002). However, this theme presumes arbitrage between the forward and spot markets and does not therefore permit the emergence of forward premia. Literature combining the two views 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. Our work is innovative in synthesizing the strategic and hedging perspectives to provide insights into the price impact of increasing variable renewable power generation.

Finally, our work 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). This research 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 analyzing 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

We investigate the impact of renewable generation capacity on power prices with a model of power suppliers and buyers trading electricity, a homogeneous, non-storable commodity. There is a single production period, but the product can be traded in two stages: first in a forward market and then in a real-time spot market. Both demand and effective supply capacity are uncertain in the forward market, but known in the spot market. Figure 1 depicts the model timeline and Table 5 in the Appendix summarizes common notation.

Figure 1 **Timeline.**



3.1. Supply and demand

Demand. We divide electricity demand into two classes, inelastic and elastic, which we label retailers and industrial consumers. We make this distinction to capture the increasing heterogeneity in power consumers: While most small (e.g., residential) consumers traditionally purchase electricity from retailers at a fixed unit price, an increasing number of consumers, such as some industrial users, have the capacity to respond to real-time prices either through retailers or by trading directly in the wholesale market. There are N_R (r)etailers who procure power from the wholesale market and sell it to final consumers for a fixed price p_R.[3] This demand is inelastic: Facing the price p_R, the consumers do not react to wholesale prices in the short term. The realized demand for retailer i is θ_{Ri} and the sum of these demands is θ. There is also an elastic demand component representing an aggregation of consumers who are able to respond to real-time prices; the (i)ndustrial demand is $D_I = a - p_s$, where p_s is the spot price. These retail (inelastic) and industrial (elastic) components aim to capture the diversity of power demand; we note that these labels are simple euphemisms and do not imply that all industrial consumers in reality are elastic, nor that all retail customers are inelastic as smart meters are adopted.

Supply. There are two generation technologies in the market, corresponding to conventional thermal (gas) producers and renewable (wind) producers. The conventional producers have market power, which we capture through duopoly Cournot competition. Each of the two conventional (p)roducers i has a linear production cost function $C(q_{Pi}) = cq_{Pi}$.[4] The conventional technology is operationally *reliable*, in that there is no uncertainty over its supply. There are N_W equally sized (w)ind producers with total generation capacity k_W in the market, with $k_{Wi} = \frac{k_W}{N_W}$. These producers are price taking: While they could potentially reduce their production to try to influence prices, small-scale renewables, even if aggregated as virtual entities, are unlikely to act strategically. The technology has a negligible production cost: $C_W(q_{Wi}) = 0$ for any $q_{Wi} \leq k_{Wi}$. Its effective available generation capacity is variable; typical average wind power availability is 20-40% (see the numerical study calibration in §6 for more details).

This model simplifies the structure of current electricity markets in that the ownership of the new renewable assets is distinct from the conventional portfolio generators. In many markets, much of the new renewable capacity is small-scale, partly due to subsidy incentives for market entry; alternatively, some large e.g., offshore wind projects are often set up as separate joint ventures or as off-balance sheet special entities. Both sets of circumstances would tend to lead the operators to behave as price-takers. We focus on separate price-taking ownership in order to isolate the impact of operational factors on market outcomes.

The Cournot model has been used extensively in both theoretical and empirical studies of electricity trading (e.g., Wolak and Patrick 2001, Bushnell 2003, Puller 2007, Sweeting

[3] The retail market is competitive and we thus assume the number of retailers is larger than that of conventional producers; specifically we require $N_R > 6$ for some technical results.

[4] An alternative specification with increasing marginal cost does not alter our main insights. We assume that the marginal cost does not exceed the retail price and demand, $c \leq \min\{p_R, a\}$, to guarantee some technical results.

2007). It simplifies the market setting in the sense that in many markets, producers may offer multiple price-quantity pairs to the market (e.g., Anderson and Philpott 2002, Sunar and Birge 2019). Given our focus on insights on contracting, we focus on sequential quantity choices, following the literature (e.g., Allaz and Vila 1993, Bushnell 2007).

3.2. Uncertainty, risk reduction, and the forward market

Both demand and renewable supply are known in the spot market but uncertain in the forward market. We consider aggregate demand and supply uncertainties to avoid the complications of modelling firm-level distributions. The total available renewable capacity in the spot market is ξk_W, where the yield ξ is uncertain in the forward period, but resolved before spot trading. The yield ξ is the same for each producer[5] and is distributed according to $H(\xi)$ with range $[\underline{\xi}, \overline{\xi}] \subseteq [0,1]$, mean μ_ξ, variance σ_ξ^2, and third moment (unnormalized skewness) τ_ξ. Similarly, the total retail demand θ is known in the spot market, but only up to a distribution $G(\theta)$ in the forward market; the retailers have equal market shares with $\theta_{Ri} = \frac{\theta}{N_R}$. The demand θ has support $[\underline{\theta}, \overline{\theta}]$, mean μ_θ, variance σ_θ^2, and third moment (unnormalized skewness) τ_θ. There is no separate uncertainty in the industrial demand component a; further, θ and ξ are independent.[6] These simplifications regarding the distributions allow us to develop a parsimonious model to capture the salient features of power markets.

The producers and retailers use the forward market to hedge the uncertainty in their spot revenues. They consider both expected profits and profit volatility when choosing forward contract positions, acting as though they are risk averse; we specify their objective functions later. The corporate-finance literature has identified several reasons for which firms may act risk averse, including avoiding costly external financing (Froot et al. 1993) or expected costs of financial distress (Smith and Stulz 1985), or reducing informational asymmetry over risks (DeMarzo and Duffie 1995). In power markets, even large companies are exposed to significant risk from price volatility (Bessembinder and Lemmon 2002), and risk-averse trading behavior is evidenced by the sustained and persistent forward premia

[5] In other words, each producer's output ξ_i is perfectly correlated with the total production ξ; the impact of imperfect correlations on our insights is typically small.

[6] We could alternatively consider both the industrial demand a and the retail demand θ resulting from a single demand realization according to some market-size rule; this would not alter our main insights. The independence assumption is reasonable for wind power, but less appropriate for solar power, the output of which is typically positively correlated with daily demand peaks.

observed in many markets (Longstaff and Wang 2004, Redl and Bunn 2013, Weron and Zator 2014), implying the absence of full risk-neutral speculation by either power companies or third parties. We hence follow the literature (e.g., Bessembinder and Lemmon 2002) in modelling the forward market as a closed system between risk-averse suppliers and buyers with no outside speculators. We contrast our results with risk-neutral trading in §5.2.

The conventional producers and retailers participate in the forward market, but renewable producers and industrial consumers do not. The demand from industrial consumers represents an aggregation of relatively small consumers who do not trade forward.[7] Renewable producers do not face the same incentive to commit forward as conventional producers. With zero marginal costs, they can expect to run and achieve substantial inframarginal rent, whilst trading forward is expensive for small players. Moreover, if they are financed through e.g., fixed feed-in arrangements, their revenues do not reflect spot risk, and they may be explicitly or implicitly excluded from the forward market. To isolate the impact of technology from that of forward market participation, we consider the price impact of the technology when they trade on the spot market only.[8]

4. Equilibrium Analysis

We derive the equilibrium using backward induction, beginning from the spot market in §4.1, followed by the forward equilibrium in §4.2.

The supply side of the market consists of conventional and renewable (wind) producers. Let f_{Pi} and q_{Pi} denote the forward sales and production quantity of conventional producer i. The forward contract quantities f_{Pi} are observable and enforceable and call for the delivery of the corresponding amount of the commodity in the spot period; $f_{Pi} > 0$ denotes producer i *selling* forwards (taking a short position). The renewable producers do not trade forward and hence $f_{Wi} = 0$. In the spot market, the conventional producers decide the production quantities q_{Pi}; the quantity sold in the spot market is the difference $q_{Pi} - f_{Pi}$, which may be negative. The renewable producers are price taking and sell their entire realized zero-cost production ξk_{Wi} to the market. The producers' ex post profits are

$$\pi_{Pi} = p_s(q_P, k_W)[q_{Pi} - f_{Pi}] + p_f f_{Pi} - C(q_{Pi}), \tag{1}$$

[7] Power retailers' inelastic consumption necessitates hedging in the forward markets, whilst industrials may prefer to avoid the trading cost of hedging (e.g., collateral calls), especially when they have some flexibility to adjust consumption in the spot markets. Allowing industrial consumers to trade forward does not alter our main insights.

[8] The alternative specification where renewable producers trade forward, acting similarly to the retailers in the forward market, does not alter our main findings.

$$\pi_{Wi} = p_s(q_P, k_W)\xi k_{Wi}, \tag{2}$$

where p_f and p_s are the forward and spot prices.

The demand side of the market consists of industrial consumers and retailers. The industrial consumers' aggregate elastic demand is $D_I = a - p_s$ which is procured in total in the spot market. The N_R retailers may procure power in either the spot or the forward market. They sell power to their customers at fixed price p_R immediately following spot procurement. We let f_{Ri} denote the quantity purchased forward by retailer i, where $f_{Ri} > 0$ implies the retailer *buying* forwards (taking a long position). The sum of these positions is f_R. In the spot market, the retailers procure the difference between their realized demand and their forward purchase, $\theta_{Ri} - f_{Ri}$. The retailers' ex post profits are the difference between sales revenues and procurement costs:

$$\pi_{Ri} = p_R\theta_{Ri} - p_s(\theta_{Ri} - f_{Ri}) - p_f f_{Ri}. \tag{3}$$

4.1. Spot market

The conventional producers choose their production quantities q_{Pi} to maximize their profits. The total spot-market sales quantity is

$$Q_s = q_P - f_P + \xi k_W. \tag{4}$$

The demand-side participants are price taking and procure at the realized market price. Total spot demand consists of both the industrial and retail demand components:

$$D_s = \max\{a - p_s + \theta - f_R, 0\}. \tag{5}$$

The spot market clears at the price that equates supply (4) and demand (5) with $D_s = Q_s$. Since forward contracts must be in zero net supply ($f_P = f_R$), the inverse (residual) spot demand facing the conventional producers is:

$$p_s = \max\{a + \theta - \xi k_W - q_P, 0\}. \tag{6}$$

We focus on interior equilibria of the spot Cournot game where the reliable capacity sets the price. A violation of this assumption in the electricity context would mean either a demand blackout or curtailment of the renewable capacity. Avoiding blackouts is one of the main objectives of regulators and policy-makers and they are hence rare in mature markets.[9] The assumption of no curtailment fits a present-day market setting where renewable production capacity is not dominant and curtailment is rare; research by the IEA (2014) suggests that renewable capacities of up to 40% are feasible without significant curtailment. Assumption 1 formalizes this discussion.

Assumption 1 **(No blackouts or curtailment)**. *The conventional producers set the price in the spot market:* $q_P > 0$ *and* $q_P + \xi k_W \geq \theta$.

With this assumption, the spot price is strictly positive and the equilibrium is given by the conventional producers maximizing profits in (1) under the inverse demand defined in (6). The following lemma shows the spot-market equilibrium given the conventional producers' committed forward positions.

Lemma 1 **(Spot equilibrium)**. *The spot-market equilibrium given forward positions* f_{Pi} *is:*

$$q_{Pi}^* = \frac{q_0 + 2f_{Pi} - f_{Pj}}{3}, \tag{7}$$

$$p_s = \frac{p_0 - (f_{Pi} + f_{Pj})}{3}, \tag{8}$$

and $q_{Wi}^* = \xi k_{Wi}$. *Here* $q_0 := a - c + \theta - \xi k_W$ *and* $p_0 := a + 2c + \theta - \xi k_W$ *reflect the production quantity and price in the absence of forward contracts.*

The equilibrium demonstrates the conventional merit-order effect: In the absence of forward trading ($f_{Pi} = f_{Pj} = 0$), for any realization of wind output ξ (and demand θ), a higher wind capacity k_W reduces conventional producers' production quantities and the spot price, as evident in p_0. However, the lemma also shows that the producers' forward commitments affect spot-market outcomes. The more producer i has sold forward (f_{Pi}), the more it will produce (q_{Pi}^*); its competitor's forward sales conversely reduce its production. Selling forward thus increases a producer's market share, giving it a strategic "first-mover advantage" in the spot market. However, because of this increased production, forward sales also reduce the spot price p_s, making the market more competitive (Allaz and Vila 1993).

[9] 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.

4.2. Forward market

In the forward market, the retailers and producers hedge to reduce the volatility in their spot revenues. They choose forward positions to maximize their expected utility, which is a linear combination of expected profit and a penalty for profit variance (following e.g., Bessembinder and Lemmon 2002):

$$U(\pi) = \mathbb{E}[\pi] - \frac{\lambda}{2} V(\pi). \tag{9}$$

The parameter determines the participants' degree of aversion to profit volatility. We focus on the case $\lambda > 0$ in the main analysis and discuss the risk-neutral case $\lambda = 0$ in §5.2. The firms simultaneously choose forward positions anticipating their equilibrium profits given by Lemma 1 and (1) and (3), respectively. In line with the spot market, the producers have market power, that is, they choose forward quantities taking into account the potential effect on (spot and forward) market prices. The price-taking retailers hold unbiased expectations on spot outcomes, but do not choose positions to influence prices.

Let us first develop intuition into hedging through the retailers' forward trading. They select positions by maximizing the expected utility in (9) with profits given in (3). The following result shows that their forward positions consist of hedging and speculative components.

Lemma 2 **(Retailer hedging)**. *The retailers' total forward position is:*

$$f_R = N_R \underbrace{\frac{\mathbb{E}[p_s] - p_f}{\lambda V(p_s)}}_{\text{Basis term}} + \sum_{i=1}^{N_R} \underbrace{\frac{-Cov(p_R\theta_{Ri} - p_s\theta_{Ri}, p_s)}{V(p_s)}}_{\text{Hedging term}}. \tag{10}$$

The *basis* term in the forward positions represents the retailers' incentive to speculate on the forward market: If the forward price is lower than the expected spot price, the retailers will procure more forward to benefit from this basis. The lower the weight λ they place on reducing spot revenue variance, the larger the risk they are willing to take on spot-forward price differences. The *hedging* term, on the other hand, reflects the retailers' spot procurement risk, that is, the covariance of the spot price and revenues in the absence of forward trading. The spot price variance $V(p_s)$ moderates both the basis and hedging terms: A highly variable price increases the risk of committing to a large forward position.

The producers similarly maximize their expected utility, and the forward market clears at zero net contract supply $f_P = f_R$. The following theorem characterizes the equilibrium.

Theorem 1 **(Forward-spot equilibrium)**. *The equilibrium is as follows:*[10]

$$q^*_{Pi} = \frac{q_0}{3} + \frac{\omega}{3\nu}, \qquad f^*_{Pi} = \frac{\omega}{\nu}, \tag{11}$$

$$p_s = \frac{p_0}{3} - \frac{2\omega}{3\nu}, \qquad p_f = a_f - \frac{2b_f\omega}{\nu}, \tag{12}$$

where $q_0 = a - c + \theta - \xi k_W$, $p_0 = a + 2c + \theta - \xi k_W$, *and*

$$\begin{aligned}\omega =& 9\mathbb{E}[q_0] + 2\lambda\left(2\mathbb{E}[q_0](\sigma_\theta^2 + k_W^2\sigma_\xi^2) + (\tau_\theta - k_W^3\tau_\xi)\right) \quad \textbf{\textit{[Producer incentives]}} \\ &+ \frac{9\lambda}{N_R}\left((\mathbb{E}[p_0] + \mu_\theta - 3p_R)\sigma_\theta^2 + \mu_\theta k_W^2\sigma_\xi^2 + \tau_\theta\right) \quad \textbf{\textit{[Retailer incentives]}} \end{aligned} \tag{13}$$

$$\nu = 45 + 8\lambda\left(\sigma_\theta^2 + k_W^2\sigma_\xi^2\right) + \frac{27\lambda}{N_R}\left(2\sigma_\theta^2 + k_W^2\sigma_\xi^2\right) \tag{14}$$

$$a_f = \frac{\mathbb{E}[p_0]}{3} + \frac{\lambda}{9N_R}\left((\mathbb{E}[p_0] + \mu_\theta - 3p_R)\sigma_\theta^2 + \mu_\theta k_W^2\sigma_\xi^2 + \tau_\theta\right) \tag{15}$$

$$b_f = \frac{1}{3} + \frac{\lambda}{9N_R}\left(2\sigma_\theta^2 + k_W^2\sigma_\xi^2\right). \tag{16}$$

The equilibrium refines our understanding of how renewable capacity k_W affects the spot power price p_s. The current realization of available renewable capacity reduces the spot price in the term p_0 by ξk_W, displacing gas production through the conventional merit-order effect. But the spot price now also depends on k_W through the producers' forward positions f^*_{Pi}. The reason is our model including both risk hedging in the forward market and producer market power, or more specifically combining the hedging (Bessembinder and Lemmon 2002) and strategic (Allaz and Vila 1993) rationales for forward trading. By the hedging rationale, uncertainty over spot renewable output (its variance and skewness) changes hedging quantities in the forward market. By the strategic rationale, the more producers trade forward, the higher their implied spot production commitments in Lemma 1, and the lower the spot price. Uncertainty over renewable output thus feeds back to the spot price through hedging and strategic forward commitments. More specifically, the expression ω in f^*_{Pi} captures how both producers' and retailers' hedging incentives (the latter in Lemma 2) influence the spot price through this mechanism. The expression ν conversely moderates forward trading, reflecting the risk of committing to a forward position, or effectively the elasticities of the participants' hedging incentives. Besides the

[10] Assumption 1 requires that production covers at least the inelastic demand. This holds when $\theta \leq 2q^*_{Pi} + \xi k_W$. Let us assume conservatively that $\underline{\xi} = 0$. Then we need $\nu\theta \leq 2(\nu(a-c)+\omega) = 2(a-c)\nu + 2\omega$. This constraint holds unless $\overline{\theta}$ and μ_θ and k_W are very large compared to a. We also assume that $q^*_{Pi} \geq 0$ for any values of θ and ξ. This constraint essentially requires renewable capacity to be low enough so that it never needs to be curtailed.

conventional merit-order effect based on current renewable output ξ, the spot price hence depends on the *distribution of renewable output* when power is traded forward.

The forward price p_f is determined by hedging incentives through the positions f^*_{Pi} and the effective forward demand from the retailers, characterized by the terms a_f and b_f. Reflecting the relative hedging needs of the parties, the forward price is generally different from the expected spot price, giving rise to a *forward premium*. We next investigate the price implications in more detail.

5. Implications for Power Markets

In this section, we use the equilibrium to derive insights into wholesale electricity pricing. We first revisit the conventional expectation that replacing fossil fuel generation by renewables will simply reduce wholesale prices through the merit-order effect (§5.1). Besides renewable generation, we study the price impact of risk-neutral hedging (§5.2), identify novel demand-side drivers of power prices (§5.3), and investigate reasons behind empirical contradictions over the influence of market fundamentals on forward premia (§5.4).

5.1. How does renewable capacity affect electricity prices?

The conventional merit-order effect of increasing renewable capacity k_W is to reduce the expected spot price $\mathbb{E}[p_s]$ by displacing conventional generation. Theorem 1 shows that besides this effect, renewables also affect the spot price through forward trading. We now investigate whether and how this *forward* effect changes power prices. We will develop intuition by first studying this effect separately before considering renewables' total price impact. The next result shows that the forward effect from additional renewable capacity may be either positive or negative, that is, it may correspondingly either mitigate or reinforce the conventional merit-order effect.

Proposition 1 **(Forward effect on the spot price)**. *Denote by $h_f := -\frac{\partial}{\partial k_W}\frac{2\omega}{3\nu}$ the forward effect of additional renewable capacity k_W on the expected spot price $\mathbb{E}[p_s]$. There exist thresholds $\overline{k}_W \geq \underline{k}_W \geq 0$ such that $h_f \geq 0$ when $k_W \leq \underline{k}_W$ or $k_W \geq \overline{k}_W$. Moreover, if the demand distribution is not too positively skewed, $\tau_\theta \leq \overline{\tau}_\theta$ (where $\overline{\tau}_\theta > 0$), then there exists a threshold $\underline{\mu}_\xi > 0$ such that $h_f < 0$ for $\underline{k}_W < k_W < \overline{k}_W$ for mean renewable output $\mu_\xi \leq \underline{\mu}_\xi$.*

We first discuss the intuition behind these results and then elaborate on their technical details. The proposition reflects how renewable capacity affects forward trading in three ways. First, forward trading mitigates the merit-order effect: As renewables displace conventional producers in spot trading, the producers accordingly reduce their forward positions in anticipation, and these lower commitments lead to higher prices. When renewable capacity is low ($k_W \leq \underline{k}_W$), this impact dominates and the forward effect from additional renewable capacity mitigates the merit-order effect. Second, as renewable capacity increases, its variable output plays a larger role in its price impact. The resulting higher spot-market volatility first increases hedging on the forward market. In particular, if the mean renewable availability μ_ξ is not too high relative to this uncertainty, forward volumes increase for moderate values of renewable capacity ($\underline{k}_W < k_W < \overline{k}_W$), reinforcing the price reductions from the conventional merit-order effect. However, the uncertainty over renewable output also increases the risk of committing to a forward position and being caught with an unfavorably high commitment in spot trading. When renewable capacity is high ($k_W \geq \overline{k}_W$), its variability hence conversely reduces forward trading, resulting in a positive price impact and counteracting the conventional merit-order effect.

Proposition 1 thus refines our understanding of the merit-order effect: It establishes the existence of thresholds ($\underline{k}_W, \overline{k}_W$) such that the taking into account forward trading mitigates the conventional effect for high enough and low enough values of renewable capacity, as well as a sufficient condition for the effect to be reinforced between the thresholds when the mean renewable output μ_ξ is not too high. The condition requires that the distribution of demand is not highly positively skewed, which is generally true in power markets since the distribution of demand is symmetric (see §6.1 for more discussion). While we cannot obtain closed-form values for the thresholds, we provide closed-form approximations for $\underline{k}_W, \overline{k}_W$ based on model parameters in the proof of the proposition in the Electronic Companion. We quantify and discuss the thresholds, as well as those derived in the next results, in the numerical study in §6.

Renewables' total price impact combines the conventional merit-order effect from higher expected generation and the forward effect from the hedging of its output variability. The next result shows that taking into account this hedging may overturn the conventional expectation that additional renewable capacity always reduces power prices.

Proposition 2 **(Renewables' price impact)**. *Denote by $CV_\xi = \frac{\sigma_\xi}{\mu_\xi}$ and $\tau_\xi^N = \frac{\tau_\xi}{\sigma_\xi^3}$ the coefficient of variation and (normalized) skewness of renewable output distribution. There exists a threshold $\zeta > 0$ such that if $CV_\xi \tau_\xi^N \geq \zeta$, then there exists a threshold $\overline{k}_W^s$ such that*

$\mathbb{E}[p_s]$ is decreasing in k_W for $k_W < \overline{k}_W^s$ and increasing for $k_W \geq \overline{k}_W^s$; moreover there exists a threshold $\overline{k}_W^f$ such that p_f is increasing in k_W for $k_W \geq \overline{k}_W^f$.

We first note that if renewable output were certain, prices would always decrease with more capacity: The forward effect would simply mitigate the conventional merit-order effect through reduced forward trading, as with low capacity in Proposition 1.[11] When output is variable, the impact on the expected spot price also reflects the forward effect. Initially, up to moderate amounts of renewables, this effect mitigates and then reinforces the conventional merit-order effect, and prices hence decrease with additional capacity. With higher renewable capacity, however, prices may conversely increase. Specifically, if the distribution of renewable output is positively skewed and has a high coefficient of variation, then the forward effect eventually reverses the merit-order effect. This is because higher skewness and coefficient of variation increase conventional producers' risk of being caught with an unfavorably high forward position in the spot market. As per Proposition 1, they then sharply reduce their forward trading and the lower commitments reduce power generation and increase the spot price. For the same reason, the forward price also increases with high enough renewable capacity.

That prices may increase with renewable capacity is particularly intriguing because it results from the interplay of two well-known pro-competitive forces: low-cost capacity and forward trading. Renewables are expected to reduce prices through the merit-order effect, while forward trading has been commonly encouraged by regulators for its potential in reducing prices (as per Allaz and Vila 1993).[12] However, when we take into account how renewables' variability affects hedging, forward trading may instead lead prices to increase with sufficient additional capacity.

Besides output variability, renewables' price impact depends on interactions with other market factors such as demand and fuel cost. The next result shows these interactions.

Proposition 3 **(Market fundamentals and renewables' spot price impact)**. *Table 1 displays the interactions of renewables' spot price impact with market factors.*

The proposition suggests that increasing renewable capacity may have market-specific price effects that evolve over time. Consider the expected retail power demand μ_θ. The

[11] This scenario corresponds to increasing reliable low-cost power generation, for example nuclear power.

[12] Allaz and Vila (1993) show that risk-neutral producers forward contract in equilibrium in a form of prisoner's dilemma, with the forward commitments leading to lower prices and hence profits.

Table 1 The impact of model parameters on the renewable capacity's effect on the expected spot price.

	a	c	μ_θ	σ_θ^2	τ_θ	p_R
$\dfrac{\partial \mathbb{E}[p_s]}{\partial k_W}$	$-$	$+$	$-$	$+/-$	$+$	$-$

$+$, $-$, and $+/-$ indicate partial derivatives greater than zero, less than zero, and indeterminate in sign, respectively.

higher the demand, the more the producers will tend to increase their hedging with renewable capacity so as to reduce the risk in their spot sales. When demand is high, the spot price may then decrease more with renewable capacity than when demand is low. As expected demand may vary seasonally and exhibit time trends, this result therefore suggests that prices would decrease more with renewables in high-demand seasons. The opposite result holds for the marginal production cost, where prices would decrease more under low fuel costs.

In summary, how renewable capacity affects prices is more nuanced than we would expect based on the conventional merit-order effect alone when we account for forward trading, and depends on the distribution of its output and other fundamentals. As a result, when the amount of renewable capacity is already high, prices decrease less and may even increase with additional capacity. This occurs in particular when the output distribution is positively skewed: We note that positive skewness is typical for wind power output, which fits a Weibull distribution (e.g., Stevens and Smulders 1979, Yeh and Wang 2008). We quantify and discuss these price impacts for plausible ranges of parameter values in the numerical study in §6.

5.2. Efficient arbitrage and prices

We have so far considered a market with "inefficient" arbitrage, that is, allowing a non-zero premium between the forward and expected spot prices. While forward premia are a common feature of present-day power markets, regulators are increasingly encouraging trading activity through measures aimed to increase the efficiency of forward-market arbitrage, such as virtual bidding. We now study the impact of efficient arbitrage on prices, comparing the expected spot prices under risk neutrality (removing arbitrage opportunities between the forward and spot markets) and our base model.[13] The following result

[13] An alternative formulation could introduce additional purely speculative players acting as counter-parties to the risk-averse producers' and retailers' trades. The insights from this alternative model are similar to our main results.

shows that in the no-arbitrage equilibrium, prices always decrease with additional renewable capacity, but removing arbitrage opportunities has an ambiguous price impact under increasing renewable capacity.

PROPOSITION 4 **(Price impact of efficient arbitrage)**. *Denote by* $\mathbb{E}[p_{s,NA}]$ *and* $\mathbb{E}[p_{s,NF}]$ *the expected spot price in the no-arbitrage equilibrium and in the equilibrium with no forward market, respectively. Then* $0 \geq \frac{\partial}{\partial k_W}\mathbb{E}[p_{s,NA}] \geq \frac{\partial}{\partial k_W}\mathbb{E}[p_{s,NF}]$.

Moreover, there exists a threshold $\overline{k}_W^{NA} > 0$ *such that* $\frac{\partial}{\partial k_W}(\mathbb{E}[p_{s,NA}] - \mathbb{E}[p_s]) \leq 0$ *for renewable capacity* $k_W \geq \overline{k}_W^{NA}$. *If demand variability is low* ($\sigma_\theta^2 \leq \overline{\sigma}_\theta^2$, $\tau_\theta = 0$)*, then* $\frac{\partial}{\partial k_W}(\mathbb{E}[p_{s,NA}] - \mathbb{E}[p_s]) > 0$ *for* $k_W < \overline{k}_W^{NA}$.

The first part of the proposition shows that forward trading mitigates the conventional merit-order effect under efficient arbitrage: The producers' anticipated lower average spot sales reduce their forward quantities, weakening the forward effect on the spot price. Thus, while prices decrease with renewable capacity, the reduction is mitigated compared to market with no forward trading. The second part of the proposition compares renewables' price impact under the no-arbitrage equilibrium to those in our main model (Theorem 1). When renewable capacity is high, the price impact of additional capacity is more negative in the no-arbitrage equilibrium. This is because in the main model, as per Propositions 1 and 2, producers' forward-market hedging is reduced with sufficient additional capacity, causing prices to decrease less or even increase. For moderate capacities, by contrast, Proposition 1 implies that the price impact tends to be more negative in the main model, as renewables' variable output increases hedging. The final part of Proposition 4 establishes a condition for this effect to be monotone below the threshold $\overline{k}_W^{NA}$: When demand variability is low, prices first decrease less and then more in the no-arbitrage equilibrium than in the main model. Together, these results suggest that a market with risk-neutral trading may tend to have higher prices for low amounts of renewable capacity (as hedging over demand uncertainty is removed too), and conversely lower prices for high amounts of renewables. We discuss these price implications calibrated to market data in the numerical study (§6.4).

5.3. Demand-side determinants and other price implications

Besides supply-side price impacts from the distribution of renewable capacity, our analysis predicts new effects among fundamental factors influencing power prices. The empirical literature on the determinants of electricity prices has focused on immediate market fundamentals such as production cost and realized demand and supply. Based on the equilibrium in Theorem 1, this set of price drivers should be extended to include new factors. The following result summarizes these findings: In particular, our analysis predicts a new direction of causality in the supply-chain determinants of power prices.

PROPOSITION 5 **(Market fundamentals' price impact)**. *The impact of market fundamentals on the spot price is summarized in Table 2.*

Table 2 The impact of market fundamentals on the spot price.

Effect	a	c	θ	μ_θ	σ_θ^2	τ_θ	p_R
p_s – Spot effect (through p_0)	+	+	+	N/A	N/A	N/A	N/A
p_s – Forward effect (through ω/ν)	−	+	N/A	−	+/−	−	+
$\mathbb{E}[p_s]$ – Total effect	+	+	N/A	+	+/−	−	+

+, −, and +/− indicate partial derivatives greater than zero, less than zero, and indeterminate in sign, respectively.

The proposition shows that the *upstream* wholesale spot price increases with the *downstream* retail price p_R. We would normally expect wholesale prices to feed forward into retail prices, but here retail prices feed back to spot prices.[14] A high retail price reduces retailers' need to hedge and hence reduces trading volumes. With lower forward sales, producers act less competitively on the spot market and the spot price increases. A (non-)competitive retail market therefore contributes to a (non-)competitive wholesale market. The distribution of demand similarly moves prices through forward commitments: Positive (un-normalized) skewness, for example, increases forward trading as participants seek to hedge against spikes, and hence reduces the spot price. Thus, taking into account forward-market hedging predicts new demand-side drivers of electricity spot prices: Without both motivations, neither the retail price level nor variance and skewness of demand would affect the wholesale spot price through the forward market.

5.4. Demand variability and forward premia

Given the prevalence of forward trading, electricity traders and regulators closely scrutinize the determinants of forward premia, defined as the difference between forward and expected spot prices: $\psi := p_f - \mathbb{E}[p_s]$. While forward premia are persistent and systematic, empirical evidence on their determinants is conflicting (e.g., Redl and Bunn 2013). Of particular interest is demand variability as the source of forward premia in markets with limited

[14] We consider the retail price as exogenous; the former effect would naturally also occur if we endogenized it.

supply variability. Sign reversals in premia are commonly observed as day-night and winter-summer switches (Bunn and Chen 2013), but the intuition for such reversals is not well explained by existing theory (e.g., Bessembinder and Lemmon 2002). The equilibrium in Theorem 1 suggests a potential reason for this controversy: The impact of determinants such as demand variance on premia should be examined not only through their direct effects but also through interactions with other factors.

PROPOSITION 6 **(Demand variance and the forward premium)**. *The forward premium ψ and the impact of demand variance on it are increasing in c. Comparative statics on the premium are summarized in Table 3.*

Table 3 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	k_W	μ_ξ	σ_ξ^2	τ_ξ
ψ	$+/-$	$+$	$+$	$+/-$	$+$	$-$	$+/-$	$+/-$	$+/-$	$+$
$\frac{\partial\psi}{\partial\sigma_\theta^2}$	$+/-$	$+$	$+$	$+/-$	$-$	$-$	$+/-$	$+/-$	$+/-$	$+$

The proposition suggests 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 c increases retailers' hedging needs relative to those of producers, increasing the forward premium. Demand variance adds to this effect by magnifying the participants' hedging incentives: The sign of the main effect is the same as that of the cross-effect. These results are consistent with evidence of day-night and winter-summer switches in forward premia (Bunn and Chen 2013), and, more broadly, such interactions may partly explain the lack of consensus in empirical evidence on the impact of fundamentals on forward premia. Our numerical study suggests that similar also occur with variable renewable capacity k_W.

6. Numerical Study

In this section, we quantify the impact of increasing wind capacity on power prices using data from Denmark and the UK. After describing parameter calibration (§6.1), we discuss the price impact of increasing capacity (§6.2), its dependence on the nature of the wind resource (§6.3), and its interaction with market fundamentals (§6.4).

6.1. Parameter calibration

We used data from Denmark and the UK to calibrate the model to a representative market setting capturing plausible parameter ranges. We estimated the distribution of wind power output using data from Denmark for 2016-2018 (from Energinet). We calculated the mean, standard deviation, and third moment (unnormalized skewness) of daily wind power output, normalized by monthly capacity, which gives baseline values of $\mu_\xi = 0.296, \sigma_\xi = 0.197, \tau_\xi = 0.0049$. We discuss different scenarios for wind output variability below.

We divide power demand into industrial and residential components based on data from the UK Department for Business, Energy and Industrial Strategy (BEIS) categorizing power demand into industrial, commercial, and domestic consumption, which are roughly equal in size (see Chart 5.5 in UK BEIS Energy Trends: Electricity, March 2019). We assume that most domestic consumption is inelastic and industrial and commercial demand mostly elastic, and therefore set μ_θ equal to one half of a. We set the baseline demand considering a market with 400TWh yearly electricity consumption, corresponding to an average of about 46GW. We let $a = 60, \mu_\theta = 30$, so that the average total conventional production with zero renewable capacity in our model is close to $q_P = 46$.

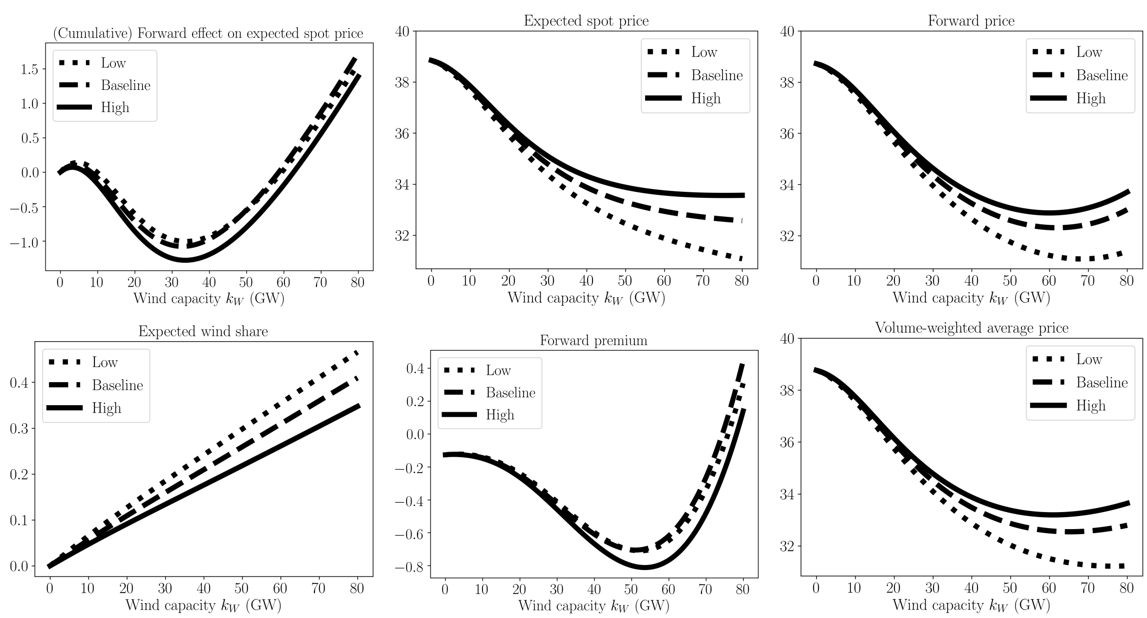
The variability in power demand is typically symmetric around the mean when adjusted for seasonality, and commonly modelled using the Normal distribution (e.g., Paatero and Lund 2006). Given this symmetry, we set $\tau_\theta = 0$. We estimated the coefficient of variation of daily weekday power demand from Great Britain market data (Elexon) for 2016-2018. Quarterly values for the coefficient of variation of demand ranged between $[0.02, 0.06]$ with an average of 0.04. In our model, demand uncertainty is focused on the retail demand; here we normalize the uncertainty over the entire demand and let $\sigma_\theta = 3$. For fuel costs, the UK BEIS estimates the cost of generating CCGT gas power at around $c = 30$ (£/MWh, UK BEIS Electricity Generation Costs, 2016). In line with the literature (Bessembinder and Lemmon 2002), we set the baseline value of risk aversion $\lambda = 0.2$ and the number of retailers $N_R = 20$ to capture a competitive market. To ensure the retail price will remain realistic as we change the capacity mix, we let the retailers set a constant markup of 5% over the (expected) wholesale power price, with the retail price p_R varying with the amount of wind capacity in the market.[15]

[15] Whether the retail price is constant or varies with capacity has little effect on the main numerical results.

6.2. Wind power variability and price impact

We first consider the impact of increasing renewable capacity on power prices. In Proposition 2 we saw that wind power initially reduces prices, but may eventually increase them depending on the coefficient of variation and skewness of its output distribution. To assess the potential scope of this variability, we estimated quarterly values for the distribution parameters in the data, which ranged from mean $\mu_\xi \in [0.22, 0.38]$, standard deviation $\sigma_\xi \in [0.15, 0.25]$ and third moment $\tau_\xi \in [0.0013, 0.0084]$. To investigate the price impact of wind capacity, we generated three scenarios of increasing coefficient of variation and skewness, the factors identified in Proposition 2. In order to show the impact of these factors, we vary μ_ξ and τ_ξ of renewable output to change the coefficient of variation and skewness, respectively, while keeping its variance constant at its baseline value.

Figure 2 Equilibrium outcomes as function of wind capacity.



Note: Low: $\mu_\xi = 0.35, \sigma_\xi = 0.2, \tau_\xi = 0.0$; Baseline: $\mu_\xi = 0.3, \sigma_\xi = 0.2, \tau_\xi = 0.005$; High: $\mu_\xi = 0.25, \sigma_\xi = 0.2, \tau_\xi = 0.008$.

The results in Figure 2 broadly confirm the insights in Propositions 1 and 2 under the three scenarios.[16] The top left panel shows how increasing renewable capacity affects the expected spot price through forward trading; the corresponding average wind power share of total generation depicted in the bottom left figure. The figure shows that the price impact of accounting for forward trading is economically significant. Moreover, it illustrates

[16] We have calibrated the capacity increase such that Assumption 1 is not violated, based on estimated supply and demand ranges $\underline{\xi} = 0, \overline{\xi} = 0.7$ and $\underline{\theta} = \mu_\theta - 3\sigma_\theta^2, \overline{\theta} = \mu_\theta + 3\sigma_\theta^2$.

the insights from Proposition 1: The (marginal) forward effect from additional renewable capacity—the change in the curves—is similar in all scenarios. As per the proposition, the forward effect is first positive (the curves increase), counteracting the conventional merit-order effect. For moderate capacities, the merit-order effect is conversely amplified as hedging volumes increase, before being finally mitigated again as commitment to high forward volumes becomes riskier. The thresholds from Proposition 1 corresponding to the maxima and minima in the figure, $\underline{k}_W \in [2.7, 3.8]$ and $\overline{k}_W \in [34.2, 35.2]$, are very similar across the scenarios. The robustness of the proposition's insights is further demonstrated by the threshold $\underline{\mu}_\xi \in [0.6, 0.7]$ for the forward effect to be negative for midrange values of k_W, covering any plausible wind output variation.

Moving clockwise in the panels, the expected spot price initially decreases with more wind capacity in all scenarios, but flattens with higher capacities due to the positive forward effect. As predicted by Proposition 2, the conventional merit-order effect is reversed in the high-variability scenario for capacities above a threshold ($k_W \geq \overline{k}_W^s \approx 76$). We note that the condition for the expected spot price to first decrease and then increase with renewable capacity in Proposition 2 ($CV_\xi^N \tau_\xi^N \geq \zeta \approx 0.34$) is satisfied for the high-variability and baseline scenarios (where prices flatten; they would increase above $\overline{k}_W^s \approx 126$), but not the low-variability scenario. Also per Proposition 2, the top right panel shows that the forward price increases for sufficiently high capacities ($k_W \geq \overline{k}_W^f \in [60, 70]$) in all scenarios. As a result, the average price over the two markets in the bottom right panel also first decreases and then increases with wind capacity. The results further reveal that the forward price is more likely to increase with high renewable capacity: Even though the producers seek to reduce their positions as they are displaced from the spot market, the retailers are still willing to pay to hedge their spot revenues against wind variability, hence increasing the forward premium in the bottom middle panel. Thus, spot-market variability caused by higher wind capacity may lead to sign reversals in the premium, similarly to demand variability in §5.4.

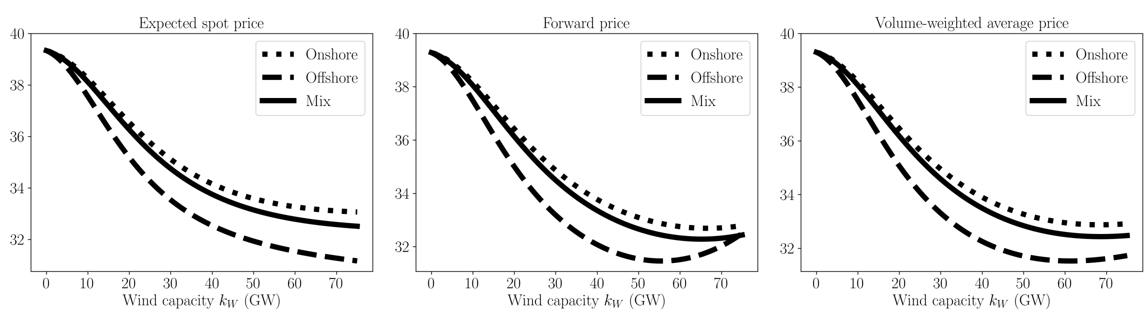
6.3. Wind resource types

We next examine whether and how the price impact of wind power depends on the resource being located onshore or offshore. The resource type influences the variability of wind output: Table 4 shows that the Danish wind output from offshore sources is on average higher and less uncertain (lower coefficient of variation) compared to onshore. Figure 3 shows the price impact of wind power under onshore and offshore output scenarios. The merit-order effect generally leads to lower prices when wind power is generated offshore due to its higher average output. As in the previous scenarios, the hedging of wind variability first reinforces and then reduces or even reverses the price impact, with forward prices in particular increasing as retailers seek to hedge against the higher spot volatility while conventional producers' sales are reduced. Notably, the latter effect is strongest under offshore generation, where higher renewable capacity magnifies this mechanism, resulting in a larger forward premium. These results thus support the preceding findings: When we account for forward trading, renewables initially reduce power prices more than we would expect based on the conventional merit-order effect alone, but less with higher penetration, with forward prices in particular increasing as hedging is reduced. We note that we would observe similar trends for seasonal wind output: Danish wind output is higher in winter compared to summer, resulting in a pattern similar to offshore and onshore.

Table 4 The distribution of daily wind power output for different resource types, Denmark 2016-18.

	μ_ξ	σ_ξ	τ_ξ
Total	0.296	0.197	0.0048
Onshore	0.256	0.187	0.0056
Offshore	0.423	0.247	0.0037

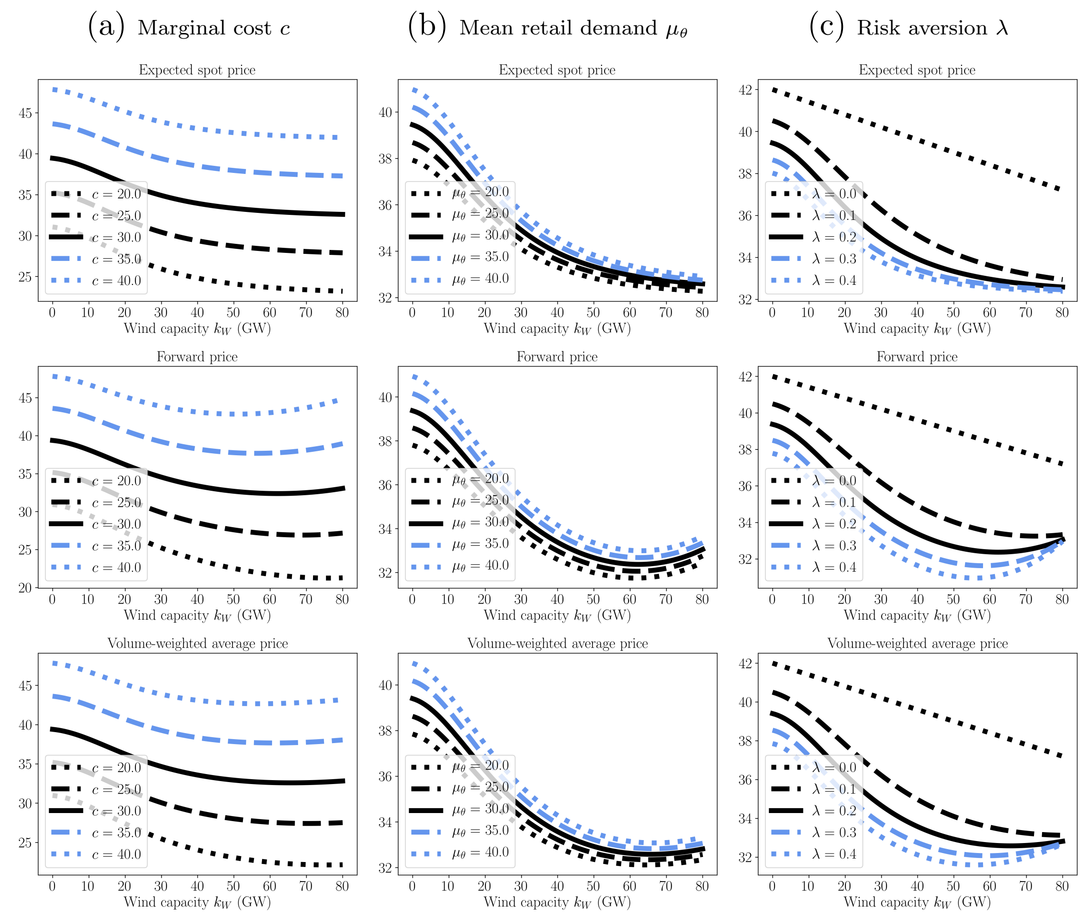
Figure 3 Wind price impact for different resource types.



6.4. Interactions with market fundamentals

We next investigate how market fundamentals interact with renewable capacity. To illustrate the findings in Proposition 3, we vary a single parameter while keeping others at their baseline levels. The first column (a) of Figure 4 shows the impact of varying marginal cost c on prices: As per Proposition 3, the higher the cost, the more positive the effect of renewable capacity on prices, causing prices to diverge with higher capacity in column (a). The impact of retail demand is the opposite: In column (b), higher demand leads to higher prices, but renewable capacity mitigates this impact. Finally, column (c) shows the impact of risk aversion on prices. The figure suggests that a market with no-arbitrage trading ($\lambda = 0$) may have higher prices. With no renewables, risk aversion leads the parties to hedge more, and the increased forward sales reduce prices. As renewable capacity increases, hedging first increases and then decreases, bringing prices closer to the no-arbitrage benchmark, as per Proposition 4. However, even with high renewable capacity, prices are still below the no-arbitrage level, and efficient arbitrage by the participants would lead to higher prices.

Figure 4 **Wind price impact and market fundamentals.**



7. Conclusions

Renewable power generation is expected to reduce wholesale power prices through the merit-order effect of displacing conventional capacity. However, we have seen that renewables also alter pricing through the hedging of their variability in the forward market. With moderate renewable capacity, additional hedging reinforces the merit-order effect, reducing prices further. With higher capacity—and when output variability is high—hedging is instead reduced, and prices decrease less or may even increase with additional capacity. We thus demonstrate an apparent paradox in power pricing: Combining two pro-competitive forces, forward trading and low-cost competition from wind power, may cause prices to increase when we take into account the variability of the wind resource.

The merit-order effect forms the underpinning for medium-term price forecasting and investment and policy analysis in the power industry, where power-plant investment decisions typically rely on 15-20 year price forecasts based on the conventional effect. Our results show that such basis for investment valuations may be flawed, and the underlying pricing models should be updated to include forward trading and the variability of renewable power, calibrated to specific markets. For policy-makers and regulators, it is equally important to update pricing models for setting long-term subsidies and monitoring the effects of market concentration. For example, the design of subsidy policies that may be tied to either spot or forward prices (e.g., contract-for-difference reference prices) should consider the potential divergence of these prices as renewable capacity grows.

Our findings help reconcile contradicting observed pricing phenomena while suggesting new empirical research questions. We provide a justification for observed reversals in forward premia based on interaction effects between market fundamentals. Our results predict that the price impact from wind power may outpace the conventional merit-order effect for moderate capacity but fall behind it when capacity grows. Markets relying on offshore wind compared to onshore are likely to experience stronger variations of these effects, which may vary seasonally too. Finally, we provide predictions on how renewables' price impact depends on varying market characteristics such as fuel costs and demand.

Our results suggest several directions for future work. First, our model can be extended to multiple forward-trading periods in order to contrast against Allaz and Vila's (1993) influential results showing that increasing the number of trading periods causes both spot and forward prices to converge to marginal costs when players are risk neutral. Given the nuance our findings offer to the impact of forward trading in a single trading period, further work is needed to understand the limits of pro-competitive forward trading. Another relevant extension would be allowing curtailment of renewable power to investigate pricing under long-run projections of renewable generation. Modelling curtailment in an imperfect market would require a complementarity approach (e.g. Hobbs 2001, Bushnell et al. 2008, Shanbhag et al. 2011). We believe that our main insights—the forward adjustment of the merit-order effect and, more specifically, variability leading to higher (or less reduced) prices—would be robust to such extensions. We have, moreover, focused solely on intermittency and ignored, for example, so-called “ramping” constraints, which would also affect hedging decisions. Finally, our model could be extended to consider the potential effects of strategic forward trading on congestion in power networks with locational pricing, as applied in many US markets. Under locational pricing, participants may make forward bids to affect congestion in the spot market, which may mitigate the pro-competitive impacts of forward trading (Kamat and Oren 2004), as may renewable uncertainty in our model. Overall, our results suggest that the price implications of long-term decarbonization policies should be evaluated accounting for technological factors and forward markets.

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Appendix A: Notation

Table 5 summarizes frequently used notation.

Table 5 Notation.

a_m	inverse (elastic) demand intercept; $m \in \{f, \cdot\}$ denotes forward and spot market.
b_f	inverse forward demand slope
c	conventional producers' marginal production cost
f_{yi}	forward position of participant i of type y; total position of type y is f_y.
k_{yi}	production capacity of producer i of type y.
N_R	number of retailers on the market.
p_o	spot price; $o \in \{s, f, R\}$ denotes spot and forward markets and the exogenous retail price.
p_0	un-normalized spot price in the absence of forward trading.
q_{yi}	spot production of participant i of type y, with total production q_y, and optimal quantity q^*_{yi}.
q_0	un-normalized spot quantity in the absence of forward trading.
U	utility, $U(\pi_y) = \mathbb{E}[\pi_y] - \frac{\lambda}{2}V(\pi_y)$, where $\mathbb{E}[\cdot]$ denotes expectation and $V(\cdot)$ variance.
η_y	covariance term in f_y.
θ	inelastic demand, with mean μ_θ, variance σ^2_θ, (un-normalized) third moment τ_θ, range $[\overline{\theta}, \underline{\theta}]$; for retailer i, market share is $\theta_i = \frac{\theta}{N_R}$.
λ	risk aversion parameter of participant type y.
ν	denominator of conventional producer equilibrium forward position.
ξ	the fraction of available renewable capacity, with range $[\underline{\xi}, \overline{\xi}] \in [0,1]$, mean μ_ξ, variance σ^2_ξ, and (un-normalized) skewness τ_ξ.
$\pi_{i,s}$	conventional producer i's spot profit.
π_{yi}	participant i's ex post profit; e.g., retailer i's profit: $\pi_{Ri} = p_R\theta_{Ri} - p_s\theta_{Ri} + p_s f_{Ri} - p_f f_{Ri}$.
ψ	forward premium $\psi = p_f - \mathbb{E}[p_s]$.
ω	numerator of conventional producer equilibrium forward position.

Appendix B: Proofs

B.1. Proofs for Section 4

Proof of Lemma 1. The spot-market first-order condition of conventional producer i is

$$\frac{dp_s}{dq_{Pi}}(q_{Pi} - f_{Pi}) + p_s - \frac{dC(q_{Pi})}{dq_{Pi}} = 0$$
$$\iff q_{Pi} = \frac{a + \theta - \xi k_W - c + f_{Pi} - q_{Pj}}{2}. \tag{17}$$

The second derivative is negative, and the problem is hence concave. The equilibrium follows from simultaneously solving the expressions for producers i and j for the quantities q_{Pi}, q_{Pj}. □

Proof of Lemma 2. Each retailer is price taking, and maximizes mean-variance utility $U_R(\pi_{Ri}) = \mathbb{E}[\pi_{Ri}] + \frac{\lambda}{2}V(\pi_{Ri})$, with $\pi_{Ri} = p_R\theta_{Ri} - p_s\theta_{Ri} + p_s f_{Ri} - p_f f_{Ri}$, without considering the price impact of its decision. The profit 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 problem is concave, and from the first-order condition, the optimal forward positions are

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

The total position is the sum of these:

$$f_R = \sum_i f_{Ri} = \frac{N_R(\mathbb{E}[p_s] - p_f)}{\lambda V(p_s)} - \frac{Cov(p_R\theta_R - p_s\theta_R, p_s)}{V(p_s)}. \tag{18}$$

□

Proof of Theorem 1. We first derive the the conventional producers' optimal positions and then combine them with the forward demand from retailers to find the equilibrium.

Conventional producers. The producers' objective functions are $U_P(\pi_{Pi}) = \mathbb{E}[\pi_{Pi}] - \frac{\lambda}{2}V(\pi_{Pi})$, with first-order conditions

$$\frac{d\mathbb{E}[\pi_{Pi}]}{df_{Pi}} - \frac{\lambda}{2}\frac{dV(\pi_{Pi,s})}{df_{Pi}} = 0,$$

where the uncertainty is over the spot profit $\pi_{Pi,s} = p_s(q_{Pi} - f_{Pi}) - cq_{Pi}$. We solve these simultaneously for the two firms. To do so, let us develop the expectation and variance expressions in turn.

Expectation. The derivative of the expected profit is:

$$\frac{d\mathbb{E}[\pi_{Pi}]}{df_{Pi}} = \frac{dp_f}{df_{Pi}}f_{Pi} + p_f + \frac{d\mathbb{E}[\pi_{Pi,s}]}{df_{Pi}}.$$

We assume that as in the spot market the producers engage in Cournot competition in the forward market, choosing positions assuming they have an impact on a linear forward price: $p_f = a_f - b_f f_P$. We will later verify that the forward positions of the retailers can be presented in this form. After some manipulation of the expected profits, the derivative is:

$$\frac{d\mathbb{E}[\pi_{Pi}]}{df_{Pi}} = a_f - 2b_f f_{Pi} - b_f f_{Pj} - \frac{1}{9}\left(2a + 2\mu_\theta + 7c - 2\mu_\xi k_W - 2(f_{Pi} + f_{Pj})\right).$$

Variance. The variance expression is:

$$\begin{aligned} V(\pi_{Pi}) =& V(p_s(q_{Pi} - f_{Pi}) - cq_{Pi}) \\ =& V(p_s(q_{Pi} - f_{Pi})) + V(cq_{Pi}) - 2Cov(p_s(q_{Pi} - f_{Pi}), cq_{Pi}). \end{aligned}$$

We will develop the terms separately and then combine them. Only the parts of the expression depending on forward positions are relevant. Since the spot production is $q_{Pi} = \frac{a+\theta+\xi k_W - c + 2f_{Pi} - f_{Pj}}{3}$, the second term $V(cq_{Pi})$ does not depend on f_{Pi}, so we can disregard it. The first term is:

$$V(p_s(q_i - f_{Pi})) = V\left(\frac{a + 2c + \theta - \xi k_W - f_P}{3}\frac{a + \theta - c - \xi k_W - f_P}{3}\right).$$

Letting V_F denote the terms of this expression that depend on the forward positions f, we have:

$$\begin{aligned} V_F =& V\left(\frac{u\theta}{9}\right) + V\left(\frac{u\xi k_W}{9}\right) + 2Cov\left(\frac{u\theta}{9}, \frac{\theta^2 + \xi^2 k_W^2 - 2\theta\xi k_W}{9}\right) \\ &- 2Cov\left(\frac{u\xi k_W}{9}, \frac{\theta^2 + \xi^2 k_W^2 - 2\theta\xi k_W}{9}\right) - 2Cov\left(\frac{u\xi k_W}{9}, \frac{u\theta}{9}\right), \\ u :=& 2a + c - 2(f_{Pi} + f_{Pj}). \end{aligned}$$

The last covariance term is zero since θ and ξ are uncorrelated. Hence:

$$\begin{aligned} V_F =& \frac{u^2}{81}\sigma_\theta^2 + \frac{u^2 k_W^2}{81}\sigma_\xi^2 + \frac{2u}{81}\left((2\mu_\theta\sigma_\theta^2 + \tau_\theta) - 2k_W\mu_\xi\sigma_\theta^2\right) \\ &- \frac{2uk_W}{81}\left(k_W^2(2\mu_\xi\sigma_\xi^2 + \tau_\xi) - 2k_W\mu_\theta\sigma_\xi^2\right), \end{aligned}$$

where we have used $Cov(x,x^2)=2\mu_x\sigma_x^2+\tau_x$, where τ_x is the (un-normalized) third moment (skewness) of the distribution. For the third term in $V(\pi_{Pi})$, we similarly denote by Cov_F the terms that depend on f_P:

$$Cov(p_s(q_{Pi}-f_{Pi}),cq_{Pi}) = Cov\left(\frac{a+2c+\theta-\xi k_W-f_P}{3}\frac{a+\theta-c-\xi k_W-f_P}{3},\frac{c(\theta-\xi k_W)}{3}\right)$$

$$Cov_F = \frac{1}{27}\left(Cov\left(u\theta,c\theta\right)+Cov\left(u\xi k_W,c\xi k_W\right)\right)=\frac{cu}{27}\left(\sigma_\theta^2+k_W^2\sigma_\xi^2\right).$$

We can now differentiate the variance with respect to f_{Pi}:

$$\begin{aligned}
\frac{dV(p_s(q_{Pi}-f_{Pi}))}{df_{Pi}} &= -\frac{4u}{81}\left(\sigma_\theta^2+k_W^2\sigma_\xi^2\right)-\frac{4}{81}\left((2\mu_\theta\sigma_\theta^2+\tau_\theta)-2k_W\mu_\xi\sigma_\theta^2\right.\\
&\quad\left.-\left(k_W^3(2\mu_\xi\sigma_\xi^2+\tau_\xi)-2k_W^2\mu_\theta\sigma_\xi^2\right)\right),\\
\frac{dCov(p_s(q_{Pi}-f_{Pi}),cq_{Pi})}{df_{Pi}} &= -\frac{2c}{27}\left(\sigma_\theta^2+k_W^2\sigma_\xi^2\right),\\
-\frac{\lambda}{2}\frac{dV(\pi_{i,s})}{df_{Pi}} &= \frac{4\lambda(a-c-f_P)}{81}\left(\sigma_\theta^2+k_W^2\sigma_\xi^2\right)\\
&\quad+\frac{2\lambda}{81}\left(2\mu_\theta\sigma_\theta^2+\tau_\theta-2k_W\mu_\xi\sigma_\theta^2-k_W^3(2\mu_\xi\sigma_\xi^2+\tau_\xi)+2k_W^2\mu_\theta\sigma_\xi^2\right)\\
&=: Z_{P,a}-Z_{P,b}f_P.
\end{aligned}$$

First-order conditions. Substituting the derivatives into the first-order condition for producer i, we have

$$a_f-2b_ff_{Pi}-b_ff_{Pj}-\frac{1}{9}\left(2a+2\mu_\theta+7c-2\mu_\xi k_W-2(f_{Pi}+f_{Pj})\right)+Z_{P,a}-Z_{P,b}(f_{Pi}+f_{Pj})=0,$$

which gives the reaction function

$$f_{Pi}=\frac{a_f-\frac{1}{9}\left(2a+2\mu_\theta+7c-2\mu_\xi k_W\right)+Z_{P,a}-(b_f+Z_{P,b}-\frac{2}{9}b)f_{Pj})}{2b_f+Z_{P,b}-\frac{2}{9}}$$

Next let us derive the forward demand.

Demand. We can write the retailer positions from Lemma 2 as

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

where $p_s=\frac{a+2c+\theta-\xi k_W-f_P}{3}$ and $\theta_{Ri}=\alpha_{Ri}\theta$, so the covariance term above is:

$$\begin{aligned}
Cov((p_R-p_s)\theta_{Ri},p_s) &= \frac{\alpha_{Ri}p_R\sigma_\theta^2}{3}-\frac{\alpha_{Ri}}{9}\left((a+2c-k_W\mu_\xi-f_P)\sigma_\theta^2+k_W^2\mu_\theta\sigma_\xi^2+Cov(\theta,\theta^2)\right)\\
&= \frac{\alpha_{Ri}}{9}\left(-(a+2c-k_W\mu_\xi-f_P-3p_R)\sigma_\theta^2-k_W^2\mu_\theta\sigma_\xi^2-Cov(\theta,\theta^2)\right)\\
&= \eta_R\alpha_{Ri}.
\end{aligned}$$

Summing the positions, we can then write out the inverse forward demand as $p_f=a_f-b_ff_P$, where:

$$a_f = \frac{a+2c-k_W\mu_\xi+\mu_\theta}{3}+\frac{\lambda}{9N_R}\left((a+2c+2\mu_\theta-k_W\mu_\xi-3p_R)\sigma_\theta^2+k_W^2\mu_\theta\sigma_\xi^2+\tau_\theta\right) \tag{19}$$

$$b_f = \frac{1}{N_R}\left[\frac{N_R}{3}+\frac{\lambda}{9}\left(2\sigma_\theta^2+k_W^2\sigma_\xi^2\right)\right]. \tag{20}$$

The equilibrium outcome follows from solving the reaction functions of the producers for f_{Pi} and f_{Pj} and substituting a_f and b_f. We omit the lengthy manipulations leading to the equilibrium expressions. □

B.2. Proofs for Section 5

Proof of Proposition 1. The sign of the forward effect $h_f = -\frac{2}{3}\frac{\partial f^*_{Pi}}{\partial k_W}$ is the opposite of the effect of renewable capacity on the forward positions, $\frac{\partial f^*_{Pi}}{\partial k_W}$. Differentiating this, we have:

$$\frac{\partial f^*_{Pi}}{\partial k_W} = \frac{\omega'\nu - \nu'\omega}{\nu^2}; \qquad \nu' = \left(\frac{27\lambda}{N_R} + 8\lambda\right) k_W \sigma_\xi^2,$$
$$\omega' = -9\mu_\xi + 2\lambda\left(4(a+\mu_\theta - c)k_W\sigma_\xi^2 - 2\mu_\xi(\sigma_\theta^2 + 3k_W^2\sigma_\xi^2) - 3k_W^2\tau_\xi\right) + \frac{9\lambda}{N_R}(2\mu_\theta k_W \sigma_\xi^2 - \mu_\xi).$$

The denominator of $\frac{\partial f^*_{Pi}}{\partial k_W}$ is positive, so the sign is given by the numerator, which expands to a fourth-order polynomial:

$$\begin{aligned}
s_f(k_W) :=& \omega'\nu - \nu'\omega = \alpha_0 + \alpha_1 k_W + \alpha_2 k_W^2 + \alpha_3 k_W^3 + \alpha_4 k_W^4,\\
\alpha_0 =& -\mu_\xi(486\lambda^2\sigma_\theta^4 + 9\lambda N_R\sigma_\theta^2(99 + 32\lambda\sigma_\theta^2) + N_R^2(405 + 252\lambda\sigma_\theta^2 + 32\lambda^2\sigma_\theta^4)),\\
\alpha_1 =& 2\lambda\sigma_\xi^2(162\mu_\theta N_R + 108\mu_\theta N_R^2 + 36\lambda\mu_\theta N_R\sigma_\theta^2 + 729\lambda p_R\sigma_\theta^2 + 216\lambda N_R p_R \sigma_\theta^2\\
&- 9c(12N_R^2 - 27N_R + 54\lambda\sigma_\theta^2 + 28\lambda N_R\sigma_\theta^2) + 9a(12N_R^2 - 27N_R - 27\lambda\sigma_\theta^2 + 4\lambda N_R\sigma_\theta^2))\\
&- \lambda\tau_\theta(243 + 126N_R + 16N_R^2)),\\
\alpha_2 =& -\lambda(\mu_\xi(-243\lambda\sigma_\theta^2 + 9N_R(52\lambda\sigma_\theta^2 - 27) + N_R^2(468 + 64\lambda\sigma_\theta^2))\sigma_\xi^2\\
&+ 6N_R(54\lambda\sigma_\theta^2 + N_R(45 + 8\lambda\sigma_\theta^2))\tau_\xi),\\
\alpha_3 =& 0,\\
\alpha_4 =& -2\lambda^2 N_R(27 + 8N_R)\sigma_\xi^2(2\mu_\xi\sigma_\xi^2 + \tau_\xi).
\end{aligned}$$

We first note that for our standard assumptions $N_R > 6$ and $c \le \min\{a, p_R\}$, $\alpha_0, \alpha_2, \alpha_4$ are all negative, and $\alpha_1 > 0$ if $\tau_\theta < \overline{\tau}_\theta$, where $\overline{\tau}_\theta > 0$ solves $\alpha_1(\tau_\theta) = 0$. To see that there exists a threshold $\underline{k}_W$ such that $s_f(k_W)$ is negative (the forward effect is positive) for $k_W \le \underline{k}_W$, we note that $s_f(0) \le 0$, with the inequality strict for $\mu_\xi > 0$. By continuity, this holds $k_W \le \underline{k}_W$, where $\underline{k}_W$ which is the smallest positive root of $s_f(k_W)$, if one exists. Since α_4 and α_2 are negative, $s_f(k_W)$ is first increasing and then decreasing in k_W and has either no positive roots or two of them. The existence of a threshold $\overline{k}_W$ such that the sign is negative for $k_W \ge \overline{k}_W$ follows from α_4 being strictly negative for $\sigma_\xi > 0$. The threshold is given by the higher positive root of the polynomial, if it exists. We can find lower and upper bounds for the roots by ignoring the fourth-order term in $s_f(k_W)$ and finding the roots of the resulting quadratic function: $k_W^\pm := \frac{-\alpha_1 \pm \sqrt{\alpha_1^2 - 4\alpha_0\alpha_2}}{2\alpha_2} \ge 0$. Thus we have $0 \le k_W^- \le \underline{k}_W \le \overline{k}_W \le k_W^+$.

If $s_f(k_W)$ has two positive roots ($\overline{k}_W > \underline{k}_W$), the forward effect is negative for $\underline{k}_W < k_W < \overline{k}_W$; otherwise the effect is always positive. We next show that there exists a threshold $\underline{\mu}_\xi$ such that if the mean renewable output $\mu_\xi \le \underline{\mu}_\xi$, then $\overline{k}_W > \underline{k}_W$. To see this, let us compare the forward position $f^*_{Pi}(k_W)$ to the position with zero renewable capacity $f^*_{Pi}(0)$. Denote their difference by $\Delta f^*_{P0}(k_W) := f^*_{Pi}(k_W) - f^*_{Pi}(0)$. The sign of $\Delta f^*_{P0}(k_W)$ is then determined by a quadratic function of k_W with a negative second-order term, attaining its maximum at

$$\check{k}_W = \frac{\alpha_1}{8\lambda N_R(54\lambda\sigma_\theta^2 + N_R(45 + 8\lambda\sigma_\theta^2))(2\mu_\xi\sigma_\xi^2 + \tau_\xi)}.$$

When $\mu_\xi = 0$, with $\alpha_1 > 0$ (such that $\tau_\theta < \overline{\tau}_\theta$ at $\mu_\xi = 0$), we can check that $\Delta f^*_{P0}(\check{k}_W) > 0$, $\check{k}_W > 0$, and further $\underline{k}_W = 0$. We therefore have $\overline{k}_W > \check{k}_W > \underline{k}_W$. By continuity, there exists a $\underline{\mu}_\xi$ such that $\overline{k}_W > \underline{k}_W$ for $\mu_\xi \leq \underline{\mu}_\xi$. Finally, we note that $s_f(k_W)$ is decreasing in μ_ξ and first increasing and then decreasing in k_W. Hence, letting $\hat{k}_W(\mu_\xi) = \arg\max_{k_W} s_f(k_W, \mu_\xi)$, which is the unique positive root of the third-order polynomial $\frac{\partial s_f}{\partial k_W}$, the threshold is implicitly given by $s_f(\hat{k}_W(\underline{\mu}_\xi)) = 0$. $\square$

Proof of Proposition 2. We first note that $\frac{\partial \mathbb{E}[p_s]}{\partial k_W} = \frac{1}{3}\left(\frac{2\omega\nu' - 2\omega'\nu - \mu_\xi \nu^2}{\nu^2}\right) =: \frac{s_{p_s}(k_W)}{3\nu^2}$. The denominator is positive and the numerator expands to a fourth-order polynomial, similarly to the expression in the proof of Proposition 1, with the sign given by:

$$
\begin{aligned}
s_{p_s}(k_W) =& \alpha_0 + \alpha_1 k_W + \alpha_2 k_W^2 + \alpha_3 k_W^3 + \alpha_4 k_W^4,\\
&\alpha_0 = -27\mu_\xi(216\lambda^2(\sigma_\theta^2)^2 + 3N_R^2(45 + 8\lambda\sigma_\theta^2) + 2\lambda N_R\sigma_\theta^2(171 + 16\lambda\sigma_\theta^2)),\\
&\alpha_1 = -12\lambda\sigma_\xi^2(162\mu_\theta N_R + 108\mu_\theta N_R^2 + 36\lambda\mu_\theta N_R\sigma_\theta^2 + 729\lambda p_R\sigma_\theta^2 + 216\lambda N_R p_R\sigma_\theta^2\\
&\qquad - 9c(12N_R^2 - 27N_R + 54\lambda\sigma_\theta^2 + 28\lambda N_R\sigma_\theta^2) + 9a(12N_R^2 - 27N_R - 27\lambda\sigma_\theta^2 + 4\lambda N_R\sigma_\theta^2))\\
&\qquad - \lambda\tau_\theta(243 + 126N_R + 16N_R^2)),\\
&\alpha_2 = 18\lambda(18\mu_\xi N_R(2N_R - 27)\sigma_\xi^2 - 3\lambda\mu_\xi(189 + 20N_R)\sigma_\theta^2\sigma_\xi^2 + 90N_R^2\tau_\xi + 4\lambda N_R(27 + 4N_R)\sigma_\theta^2\tau_\xi),\\
&\alpha_3 = 0,\\
&\alpha_4 = 3\lambda^2(27 + 8N_R)\sigma_\xi^2(4N_R\tau_\xi - 27\mu_\xi\sigma_\xi^2).
\end{aligned}
$$

We note that with no uncertainty ($\sigma_\xi = \tau_\xi = 0$), only α_0 is nonzero (negative) and hence $s_{p_s}(k_W) \leq 0$. More generally, to see when $s_{p_s}(k_W)$ is positive above a threshold $k_W \geq \overline{k}^s_W$, we note that $\alpha_4 > 0$ if $\tau_\xi^N CV_\xi > \zeta := \frac{27}{4N_R}$, which also implies $\alpha_2 > 0$. Then since $\alpha_0 \leq 0$, $s_{p_s}(k_W)$ must be first negative and then positive as k_W increases; $\mathbb{E}[p_s]$ is correspondingly first decreasing and then increasing in k_W. The threshold is implicitly given as the root of $s_{p_s}(k_W)$: $s_{p_s}(\overline{k}^s_W) = 0$. An upper bound is given by $\overline{k}^s_W \leq \frac{-\alpha_1 + \sqrt{\alpha_1^2 - 4\alpha_0\alpha_2}}{2\alpha_0}$. For the forward price p_f, the argument is similar so we omit the detailed expressions. We have $\frac{\partial p_f}{\partial k_W} = \frac{a_f'\nu^2 + 2b_f\omega\nu' - 2\nu(b_f\omega' + b_f'\omega)}{\nu^2} =: \frac{s_{p_f}(k_W)}{\nu^2}$, where we can check that the highest-order term of $s_{p_f}(k_W)$ is strictly positive for $\sigma_\xi > 0$ (which is implied by the condition on s_{p_s}). By an argument similar to the one above, there exists a threshold $\overline{k}^f_W$ such that the forward price p_f is increasing in k_W for $k_W \geq \overline{k}^f_W$ where $\overline{k}^f_W$ is implicitly given by the (highest) positive root of $s_{p_f}(k_W)$. $\square$

Proof of Proposition 3. Consider the impact of τ_θ on renewable capacity's impact on the expected spot price $\mathbb{E}[p_s]$:

$$
\frac{\partial}{\partial \tau_\theta}\frac{\partial \mathbb{E}[p_s]}{\partial k_W} = \frac{4(9\lambda + 2\lambda N_R)(27\lambda + 8\lambda N_R)k_W\sigma_\xi^2}{3(27\lambda(2\sigma_\theta^2 + k_W^2\sigma_\xi^2) + N_R(45 + 8\lambda(\sigma_\theta^2 + k_W^2\sigma_\xi^2)))^2} \geq 0. \tag{21}
$$

The other results similarly follow from cross-derivatives with respect to the parameters; the results for c require $N_R > 6$. We omit the rest of the detailed expressions for brevity. $\square$

Proof of Proposition 4. The no-arbitrage equilibrium follows from setting $\lambda = 0$ in Theorem 1:

$$
q^*_{Pi,NA} = \frac{q_0}{3} + \frac{\omega_{NA}}{3\nu_{NA}}, \qquad f^*_{Pi,NA} = \frac{\omega_{NA}}{\nu_{NA}} = \frac{\mathbb{E}[q_0]}{5}, \qquad p_{s,NA} = \frac{p_0}{3} - \frac{2\omega_{NA}}{3\nu_{NA}}, \qquad p_{f,NA} = \mathbb{E}[p_{s,NA}],
$$

where $q_0 = a - c + \theta - \xi k_W$ and $p_0 = a + 2c + \theta - \xi k_W$; the subscript NA denotes (n)o (a)arbitrage. The first part of the proposition follows directly from differentiating the price expressions and comparing to the corresponding impact on the price in Lemma 1 with $f_{Pi} = f_{Pj} = 0$. To compare the spot-price impact of renewables under no arbitrage and the base model, let us define $\Delta f_{Pi}(k_W) := f^*_{Pi} - f^*_{Pi,NA}$. The denominator of this expression is positive and the numerator is a third-order polynomial in k_W:

$$\begin{aligned}
\Delta f_{Pi}(k_W) =& \frac{\alpha_0 + \alpha_1 k_W + \alpha_2 k_W^2 + \alpha_3 k_W^3}{5(27\lambda(2\sigma_\theta^2 + k_W^2\sigma_\xi^2) + N_R(45 + 8\lambda(\sigma_\theta^2 + k_W^2\sigma_\xi^2)))},\\
\alpha_0 =& 3\lambda(12\mu_\theta - 4c(N_R - 12) + 4\mu_\theta N_R + a(4N_R - 3) - 45p_R)\sigma_\theta^2 + 45\tau_\theta + 10N_R\tau_\theta\\
\alpha_1 =& 3\lambda\mu_\xi(3 - 4N_R)\sigma_\theta^2\\
\alpha_2 =& 3\lambda(9c + 6\mu_\theta - 4cN_R + 4\mu_\theta N_R + a(4N_R - 9))\sigma_\xi^2\\
\alpha_3 =& \lambda(-3\mu_\xi(4N_R - 9)\sigma_\xi^2 - 10N_R\tau_\xi).
\end{aligned}$$

The sign of $\frac{\partial}{\partial k_W}\Delta f_{Pi}(k_W)$ is determined by its numerator, which is a fourth-order polynomial with non-positive second, third, and fourth-order terms. Similarly to Proposition 2, this implies the threshold existence of a $\overline{k}_W^{NA}$ such that $\frac{\partial}{\partial k_W}\Delta f_{Pi}(k_W) \leq 0$ for renewable capacity $k_W \geq \overline{k}_W^{NA}$. Letting $\tau_\theta = 0, \sigma_\theta^2 = 0$, the constant and first-order terms are non-negative. We therefore have $\frac{\partial}{\partial k_W}\Delta f_{Pi}(k_W) \geq 0$ when $k_W \leq \overline{k}_W^{NA}$. The impact on the expected spot price is the opposite. By continuity, this occurs for $\sigma_\theta^2 \leq \overline{\sigma}_\theta^2$. □

Proof of Proposition 5. As in the proof of Proposition 3, the results follow from derivatives and cross-derivatives with respect to the parameters, for example:

$$\frac{\partial \mathbb{E}[p_s]}{\partial p_R} = \frac{54\lambda\sigma_\theta^2}{81\lambda(2\sigma_\theta^2 + k_W^2\sigma_\xi^2) + 3N_R(45 + 8\lambda(\sigma_\theta^2 + k_W^2\sigma_\xi^2))} \geq 0. \tag{22}$$

□

Proof of Proposition 6. As in the proof of Proposition 3, the results follow from derivatives and cross-derivatives with respect to the parameters. □