# The Power Forward Premium: Renewable Energy Sources and Skewness Preferences *

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**Abstract**

This paper proposes an equilibrium model for power forward and futures prices. We extend the framework of Bessembinder and Lemmon (2002), wherein producers are non-intermittent, fossil-fuelled power plants and agents have mean-variance preferences. Our model allows for uncertain supply from renewable energy sources (RES) and agents having mean-variance-skewness preferences. The model that we propose has four factors that explain the forward premium. Besides factors related to spot price variance and skewness as found by Bessembinder and Lemmon (2002), we find evidence for covariance and coskewness between RES supply uncertainty and spot prices. We provide empirical support for the factors and their predicted signs explaining the forward premiums observed in the German power market.

*Keywords:* power markets, forward premiums, skewness preferences, renewable energy sources

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## 1. Introduction

Since the end of the 1990's, two major changes have taken place in worldwide power markets. The first change was the liberalisation of power markets, such that power prices are determined by demand and supply in competitive spot and forward markets. The second change is the energy transition. Where power was predominantly produced by fossil fuels in many countries, these conventional energy sources (CES) face increasing competition from renewable energy sources (RES) such as wind mills and solar parks. This transition from power supplied by CES to RES in liberalised markets can be seen as an economic revolution, as the economic characteristics of CES and RES differ. Although they produce the same good (power), the marginal production costs and the intermittency of supply are different. CES have positive marginal production costs as they burn fuels and need emission rights to produce one additional unit of power. Also, CES supply is non-intermittent and can be adjusted (relatively) flexibly. RES such as wind mills and solar panels have negligible marginal production costs as they only require more wind or solar radiation to produce one extra unit of power. RES supply from wind and solar sources is intermittent as output depends on varying wind and solar radiation conditions. In this paper, we examine the impact of increasing the market share of an intermittent technology with negligible marginal cost in power forward and spot markets.[1]

The growth of RES in liberalised power markets impacts the market price of power in two ways. First, it leads to lower market prices ceteris paribus as the low marginal production costs of RES shift the supply curve to the right. Second, it leads to increased price volatility when power storage capacity is not sufficient and/or power demand does not follow the supply from RES. These changes in price dynamics caused by RES should have an impact on the prices of forward contracts that involve the delivery of power during some future time period.[2] As long as power storage capacity and demand response are not sufficient to counterbalance the uncertain variation in demand and supply from RES, the theory of storage cannot be applied to price power forward contracts.[3] Instead, researchers followed the expectation theory by assuming models that relate forward prices to expected future spot prices and forward premiums. This is the common approach to price forward contracts in power markets. An important paper in this respect is the one from Bessembinder and Lemmon (2002) (hereafter: BL). They propose an equilibrium forward price model for markets where power is produced by CES, demand is uncertain, and storage capacity is negligible. They show that the forward price equals the expected average spot price during the

[1] Therefore, we limit ourselves to intermittent RES, although other types of RES exist, such as non-intermittent hydro power stations.

[2] We assume that forward and futures contracts are equivalent.

[3] The theory of storage assumes that a good can be stored and carried from one period to another.

delivery period plus two premiums related to the variance and skewness of spot prices, due to asymmetric exposure to power demand risks.

As the energy transition leads to an increasing market share of RES, we are motivated to revisit their work and to examine to what extent their results would change if one allows for RES in addition to CES. We are not alone. Several studies have revisited, tested, and/or applied the BL model. Bühler and Müller-Merbach (2009) develop a generalized dynamic version of the BL model. Oliveira and Ruiz (2021) add market power and production cost uncertainty. Ullrich (2007) add capacity constraints to the model. Gianfreda et al. (2022) derive an equilibrium model that retains higher-order moments beyond variance and skewness in a Taylor expansion. Koolen et al. (2021) show the impact of different technologies on spot and forward prices. Schwenen and Neuhoff (2024) come close and derive forward prices from a framework that includes RES supply uncertainty. However, their approach is limited as they do not allow for demand uncertainty, and they assume flat (not convex) CES marginal production. They find that the covariance between power spot prices and supply from RES can also explain the forward premiums other than the variance and skewness of spot prices.

Others have empirically examined what factors explain forward premiums. Longstaff and Wang (2004) examine forward premiums as the difference between day-ahead prices and intraday spot prices in the PJM market from 2000 to 2002 and find results supporting BL. Haugom and Ullrich (2012) analyse a longer time period and find that the coefficients for variance and skewness vary over time. They do not find evidence of significant forward premiums overall. Viehmann (2011) finds support for the predictions of BL in the German power markets. Douglas and Popova (2008) observe that, although power cannot be stored (yet), we can store fuels with which power is produced such as natural gas. They show that higher gas inventory levels coincide with lower forward premiums. Huisman and Kilic (2012) use this idea of the storability of underlying fossil fuels to show that forward premiums depend on whether the markets use predominantly supply from CES or RES. Lucia and Torró (2011) examine data from Nordic markets wherein hydropower is a dominant form of RES. They find evidence for time-varying forward premiums: positive in winter when low reservoir levels make supply risk high, but zero premiums in summer when water is abundant and risk is low. Redl and Bunn (2013) show that reserve margin,[4] market power,[5] and underlying fuel price volatility all significantly influence the forward premium. Bunn and Chen (2013) find

[4]Reserve margin is the difference between installed production capacity minus demand (system load). It is a measure of market tightness and could also affect the market power.

[5]Market power is measured as the ratio of the power spot prices and the fundamental marginal cost estimate.

that the main drivers of peak forward premiums are lagged premiums and prices.[6] They find that forward premiums positively relate to spot price volatility and negatively to skewness in the British power market, being the opposite of what BL predict.

We are aware of these mixed results from the literature, with some being in line with BL and others not. The BL paper was published in 2002, and the contribution was that it explained forward prices in liberalised power markets wherein storage of power was limited. At that time, the supply from RES was limited in many markets (except for countries like Norway with a large share of hydropower production capacity), and the liberalised markets were young. Since 2002, power markets have evolved with the entrance of new players, agents that learned about price dynamics, and the growth of RES. Koolen et al. (2022) observe price and quantity data from an experimental trading environment and show that CES change their strategies in forward and spot markets when confronted with RES. These energy market developments may explain why mixed support for the BL factors was observed.

In this paper, we propose a framework that extends BL in two ways. First, we introduce uncertain (intermittent) supply from RES, and RES producers that operate separately from conventional producers, and only trade in power spot markets. Second, we assume that agents have skewness preference in their utility function besides the mean and variance. We motivate the mean, variance, and skewness preferences assumption by observing that the empirical probability distribution function (PDF) of RES supply quantities, and therefore spot prices, is skewed. The PDF of RES supply quantity is skewed because of capacity constraints. When the expected supply from RES is maximal (on sunny and windy days), actual quantities can only decrease, not increase, which produces a negatively skewed RES distribution. The opposite is true for days when we expect supply from RES to be low, and the shock will increase the quantity, resulting in a positively skewed RES distribution. Hence, depending on expected weather conditions, the PDF of RES is skewed. The summary statistics in Table 1 in the data section show that the empirical distribution function of demand is negatively skewed and that of RES supply is positively skewed. It also shows that the power spot prices are negatively skewed. We argue that agents in power markets with RES are

[6] In power markets, baseload refers to continuous supply across all hours of the day, while peak load denotes delivery during high-demand periods (typically weekdays, 8 AM–8 PM), with peak prices generally higher due to the reliance on more costly production sources. Off-peak hours are simply the baseload hours, excluding the defined peak period.

aware of these skewness effects and account for skewness when making decisions.[7]

In developing the model, we first investigate the market agents' hedging behaviour as a result of RES supply. The low marginal costs of RES crowd out CES in the spot market. Therefore, conventional producers with CES have a stronger incentive to sell in the forward market to maintain market share, which exerts downward pressure on the forward price. The skewness of RES supply has a different impact on the profits of conventional producers and retailers. For instance, when RES supply is positively skewed and spot prices are negatively skewed (that is empirically shown), it benefits retailers but harms conventional producers. Consequently, conventional producers may respond by selling even more forward contracts.

We then proceed with deriving a reduced-form expression for the equilibrium forward price. We show that the forward price is a linear combination of the expected spot price, spot price variance, and skewness (as in the BL model), plus new components related to the covariance and coskewness between RES supply quantities and spot prices. In addition, we provide an explanation for the mixed findings for BL in the literature. We show that, when allowing for RES and skewness preferences, the signs for spot price variance and spot price skewness can be positive and negative (i.e., not strictly negative and positive, respectively, as predicted by BL). Among other reasons, the role of skewness depends on the market aggregate supply curve defined by marginal production costs as perceived by retailers. An increase in RES production lowers the residual demand, defined as total demand minus RES production, that must be supplied by CES. If the installed CES capacity remains unchanged, production shifts to the flatter (less steep) part of the aggregate supply curve. In this case, a sudden increase in demand is less likely to trigger a spot price spike. Consequently, retailers face lower hedging pressure than under the BL setting, which reduces the positive effect of skewness on the forward price.

Lastly, we empirically test our forward price model on data from the German power market. We find that the empirical results align with our theoretical predictions. We conclude that the supply risk coming from intermittent RES introduces interactions between spot prices and the uncertain supply from RES, which has an impact on the forward price. This effect is robust to both ex-ante and ex-post specifications. We propose that, besides the variance and skewness of spot prices from BL, covariance and coskewness between spot price and RES supply should be considered as new

[7] In other words, when agents make hedging decisions, they not only think about smoothing profit volatility but also seek benefits (or avoid losses) from extreme prices. Skewness also matters because price jumps expose agents to asymmetric risks that they can't hedge away in spot markets.

components that explain the price of power forward contracts.

The rest of this paper is organized as follows. Section 2 builds the model. Section 3 describes the data and empirical methodology used in this paper. Section 4 discusses empirical results. Section 5 concludes.

## 2. Model

We develop a two-period equilibrium model that extends the one of BL. Consider three types of agents: conventional power producers, renewable producers, and retailers. They make decisions at two times. At time $t_F$, they decide quantities to buy or sell in the forward market. At time $t_S$, they decide quantities to buy or sell in the spot market ($t_F$ is before $t_S$). We assume perfectly competitive markets, such that all agents are price takers. Let $p_S$ be the spot price and $p_F$ be the forward price for one unit of power. Furthermore, we assume the absence of government, arbitrageurs, and storage. All these assumptions are in line with BL.

We begin by describing the agents and their profit functions. Then, we discuss demand and RES supply uncertainty and its impact on equilibrium power spot prices. We proceed with motivating the utility functions of the agents. After that, we analyse how they decide quantities to trade in forward markets. Finally, we derive the equilibrium forward price.

### *2.1. The agents*

Consider three types of risk-averse agents. First, there is a representative conventional power producer, denoted by $I$, that converts a fossil fuel to power. Second, there is a representative retailer, denoted by $J$, that sells power to consumers for an exogenous fixed price $p_R$. The retailer has no production capacity and purchases power in the forward and spot markets.[8] These two agents correspond to the agents in the BL model.[9] We extend their framework by introducing a representative renewable power producer, denoted by $R$, who uses RES such as wind and solar. We do not consider a producer that owns both CES and RES. Renewable producers often receive policy support and have a different risk profile compared with conventional producers, hence being

[8] Hence, there is no vertical integration and all transactions occur through the forward and spot markets.

[9] However, instead of modeling $N_I$ conventional producers and $N_J$ retailers explicitly, we use representative agents. This is without loss of generality under the assumption of homogeneous agents, since the aggregate behavior of many identical firms can be captured by a single representative producer and a single representative retailer. This aggregation absorbs $N_I$ and $N_J$ into the aggregate production cost function, aggregate demand function, and the risk-preference parameters, so that equilibrium outcomes depend only on aggregate capacity, demand, and risk attitudes. This ensures that the results are independent of the arbitrary number of identical participants, while retaining the essential mechanisms of the BL framework.

operated separately. This extension of BL is not trivial, as the marginal costs and production flexibility of RES differ from those of CES. RES require no fuel, emit no CO2, and have no marginal production costs as a consequence. To the contrary, CES have positive marginal costs, including fuel costs and emission rights. Another difference is that supply from RES is intermittent as production quantities depend on varying weather conditions. Their production quantity cannot be flexibly adjusted, whereas CES offer the flexibility to ramp up and down production quantities to match demand.[10]

### *2.2. The profit functions*

We proceed with the profit functions of the representative agents. The representative conventional producer $I$ sells a quantity $Q_I^F$ in the forward market and $Q_I^S$ in the spot market (negative values for $Q_I^F$ and/or $Q_I^S$ reflect purchases). Therefore, the conventional producer supplies a total quantity $Q_I = Q_I^F + Q_I^S$. The production cost function is

$$C(Q_I) = \frac{a}{c} Q_I^c, \qquad a > 0,\ c > 1, \tag{1}$$

where we ignore fixed costs that do not affect the results. The profit of the conventional producer is

$$\Pi_I = p_F Q_I^F + p_S Q_I^S - \frac{a}{c} Q_I^c. \tag{2}$$

The profit function of the representative renewable producer $R$ is derived similarly. We assume that renewable producers only trade $Q_R^S$ in the spot market and do not trade in the forward market, so $Q_R^F = 0$.[11] The marginal production cost of RES is zero. As RES production is intermittent, the actual production quantity $K$ is uncertain. The profit function of the renewable producer is

$$\Pi_R = p_S Q_R^S, \qquad Q_R^S \leq K. \tag{3}$$

[10] The production of RES can be curtailed, which offers some ramp-down flexibility. In this paper, we don't consider the curtailment flexibility unless the renewable supply exceeds the total power demand.

[11] This assumption is justified by the fact that renewable producers have less incentive to hedge in forward markets than conventional power producers. The reduced incentive to hedge results from governments that support RES with (partially) guaranteed selling prices. For instance, in Germany, almost all types of RES were eligible for a government-set feed-in tariff before 2014, after which the feed-in tariff was determined in an auction with a tender quantity cap. Awarded projects remain under price protection, while unawarded projects are more likely to be deferred to subsequent rounds rather than built without a price guarantee. See `https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/Ausschreibungen/Solaranlagen1/BeendeteAusschreibungen/start.html?utm_source=chatgpt.com` and `https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/Ausschreibungen/Wind_Onshore/BeendeteAusschreibungen/start.html?utm_source=chatgpt.com`. Furthermore, renewable producers do not know their production quantities for sure, making it harder to determine the quantity to be sold in forward markets to hedge price risk. Moreover, the RES market is less centralised than the CES market with many relatively small wind and solar parks that—because of their size—do not have direct access to futures markets. This makes hedging more costly.

Beyond the producers, the representative retailer $J$ trades in the markets. The retailer takes a forward position $Q_J^F$, which is typically negative since the retailer is a net buyer of power, and purchases the difference $D + Q_J^F$ in the spot market. The profit function of the retailer is

$$\Pi_J = p_R D + p_F Q_J^F - p_S(D + Q_J^F). \tag{4}$$

### *2.3. Demand and supply uncertainty*

When the agents have to choose their quantities to trade in the forward and spot markets, they face uncertainty that comes from two sources: consumer demand $D$ (like in the BL model) and supply $K$ from intermittent RES. We assume that both $D$ and $K$ will be revealed at a time before the spot price is determined but after the time when agents make decisions in the forward markets (i.e., $D$ and $K$ are revealed somewhere between $t_F$ and $t_S$). To simplify the analysis, we assume that $K \leq D$.[12] Both total demand and supply from RES are uncertain, i.e., $\mathrm{Var}(D) > 0$ and $\mathrm{Var}(K) > 0$.

We argue that a RES shock is not simply a negative demand shock. While a RES shock is influenced by weather, a demand shock can arise from many sources, with weather being only one of them. Table 1 supports this argument by showing the low correlation between $D$ and $K$.

### *2.4. Spot market equilibrium*

In the spot market, renewable producers sell all power produced by RES, retailers purchase power to satisfy demand, and conventional producer $i$ sells power to maximize profit. As the market clears, total production from conventional producers equals residual demand: $Q = D - K$. The market-clearing spot price is determined by the CES producers maximising their profits:

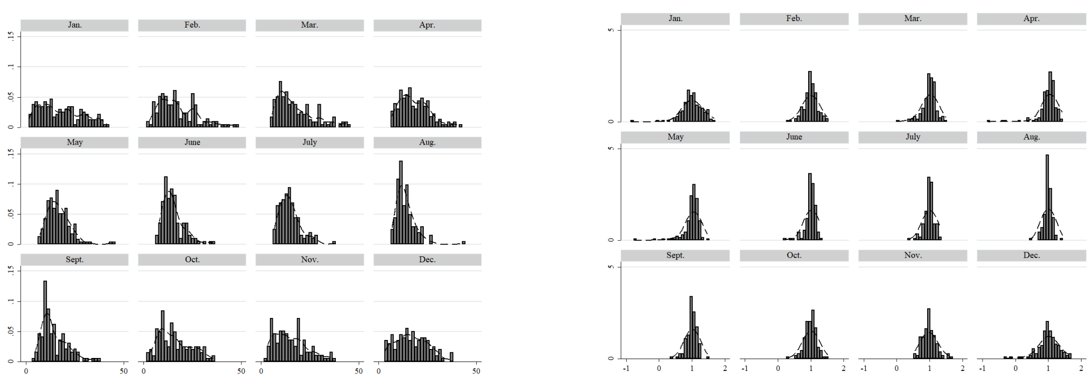
$$p_S = a(Q)^{1/x}, \qquad x = \frac{1}{c-1}. \tag{5}$$

With this market-clearing spot price function, we can analyse what happens to the spot price when more supply from RES is added to the market. Given demand, an increase in the RES power production decreases residual demand. Less quantity has to be produced by positive marginal costs CES. As a consequence, the spot price decreases. The variance of spot price changes as well. The variance of residual demand is $\mathrm{Var}(Q) = \mathrm{Var}(D) + \mathrm{Var}(K) - 2 \times \mathrm{Cov}(D, K)$. When supply from RES increases, $\mathrm{Var}(Q)$ increases unless total demand and supply from RES co-move (i.e., $\mathrm{Cov}(D, K) > 0$). In the early stage of the energy transition, the focus is on adding RES to existing power systems and not on storage or demand response.[13] As a consequence, $\mathrm{Cov}(D, K)$ is close to

[12] Otherwise stated, we assume that any supply from RES that exceeds total demand is curtailed.

[13] In 2022, wind and solar accounted for about 22% of power production in Europe, while contributions from battery storage and demand response remained negligible.

zero and spot prices become more volatile when supply from RES increases.[14] Later, when more power storage facilities and demand response systems are added to energy systems, the covariance between $D$ and $K$ will increase as more (less) supply from renewables leads to higher (lower) demand (demand response) and/or power being injected in (withdrawn from) storage facilities. Then, the spot price volatility will decrease because of this positive covariance. An increase in the supply from RES also affects the skewness of the spot price distribution. In a world with only CES, power is produced with a convex production cost function ($c > 2$). This convexity implies that a positive demand shock results in a larger absolute price change than a negative demand shock. The effect is most pronounced when the reserve margin is very small. Then, positive demand shocks can result in extremely high prices. As a consequence, the distribution of spot prices is positively skewed (see BL, Barlow (2002), and Borenstein (2002) for some early references). When supply from RES increases, less quantity is produced by CES. They will produce at a marginal production cost that comes from a region in the cost curve that is flatter.[15] Positive and negative demand shocks will then have a more equal impact on power prices than before, resulting in reduced positive skewness. See Figure 1.




(a) RES supply.

(b) Spot prices.

Figure 1: **Distributions of RES supply and spot prices.**

Panel (a) shows the empirical distribution of RES supply across months. Panel (b) shows the distribution of spot prices across months. The sample covers the period January 2015 through April 2021.

[14]When we refer to the covariance between demand and RES production, we mean the comovement of their unexpected shocks. The well-known pattern that solar generation co-moves with power demand in the afternoons is predictable and therefore not considered uncertain. Since power demand is highly inelastic and RES production is intermittent and largely uncontrollable, the covariance is typically very small.

[15]To be precise. We consider the medium-run scenario where CES capacity remains fixed. In the long run, CES capacity would also adjust in response to larger RES capacity.

*2.5. The agents preferences*

We have established how agents determine quantities to buy and sell in the spot market at time $t_S$. We now proceed with how they determine quantities of forward contracts to buy and sell at time $t_F$. As $t_F$ is before $t_S$ and before total demand $D$ and supply from RES $K$ are realized, agents make their decisions under uncertainty about demand, supply, spot prices, and thus their profits. Therefore, we must specify the agents' utility from uncertain future profits. Where BL assume that all agents share a mean–variance utility function, we instead assume they follow a mean–variance–skewness utility function:

$$U(\Pi) = E(\Pi) - \frac{1}{2\gamma}\,\mathrm{Var}(\Pi) + \frac{1}{3\phi}\,\mathrm{Skew}(\Pi), \tag{6}$$

where $\gamma > 0$ is the risk tolerance parameter and $\phi > 0$ is the skewness tolerance parameter. A smaller $\gamma$ implies a larger degree of risk aversion. A smaller $\phi$ represents a more pronounced skewness preference. Consistent with the literature, risk-averse agents dislike profit variance (hence the negative sign for Var) but prefer positive skewness in the profit distribution (hence the positive sign for Skew). A positive $\phi$ reflects agents' preference for taking risks that involve low-probability, high-return events, and a willingness to pay insurance premiums to avoid rare but extreme losses.

In asset pricing, skewness preference has strong theoretical and empirical foundations. Thorectically, this cubic utility function is justified by preferences for higher-order moments from a risk-averse agent (Kraus & Litzenberger, 1976).[16] Harvey and Siddique (2000) show that conditional skewness is an important factor in explaining the cross-section of stock returns, with systematic skewness priced in the market and commands a risk premium. Also, Boyeret et al. (2010) demonstrate that investors are willing to pay a premium for assets with high expected idiosyncratic skewness.[17]

The inclusion of skewness in the utility function is relevant only if the profit distribution is asymmetric, i.e., when $\mathrm{Skew}(\Pi) = \mathbb{E}\big[(\Pi - \mathbb{E}[\Pi])^3\big] \neq 0$. This condition is easily satisfied in power markets because the conventional producer's cost function, and hence its profit function, is nonlinear in spot prices. This also applies to retailers, who face both price and quantity risk, resulting in asymmetric profit distributions. Furthermore, we argue that as shown in Figure 1, the skewness

[16]For instance, if we assume a CARA utility form $u(\Pi) = -e^{-A\Pi}$, a third-order Taylor expansion and certainty equivalence imply a mean-variance-skewness utility function such that $\gamma = \frac{1}{A}$ and $\phi = \frac{2}{A^2}$.

[17]Skewness preference is also referred to as prudence in saving decisions (Kimball, 1990). In the prospect theory model, this assumption is rationalized as loss aversion, describing people's tendency to prefer avoiding loss over gaining equivalent gains (Tversky & Kahneman, 1986, 1992). While these models emphasize downside risk, we also allow for a lottery preference, i.e., the desire for extremely high payoffs. See Barberis and Huang (2008).

of the RES supply distribution propagates into the distribution of spot prices and, consequently, into profits.[18]

To see this, consider the following three expected weather scenarios. Scenario 1 considers "average" weather conditions for renewables. The weather is not extremely windy, and/or only thin clouds cover the sky. Supply from RES is average and both RES and CES supplies are used to meet demand. A change in the supply from RES can be compensated by CES ramping up or down production without having too much impact on spot prices. Scenario 2 contrasts with scenario 1 as it considers bad weather conditions for renewables: no wind and thick clouds (i.e., no solar radiation to supply power with). The expected supply from RES will be zero. A renewable supply shock, due to a sudden breeze or a ray of sunlight breaking through the clouds, can only result in an increase in supply from RES. The conditional distribution of residual demand and the distribution of spot prices will be skewed to the left (ceteris paribus). This implies that, given demand, the profit distribution of conventional producers becomes less positively skewed (or more negatively skewed), whereas the profit distribution of retailers becomes less negatively skewed (or more positively skewed). Scenario 3 covers the alternative weather extreme: perfect weather conditions for renewables: wind and no clouds. The expected supply from renewables is at a maximum. A renewable supply shock can only be negative, and the distribution of residual demand will be skewed to the right. As a consequence, the distribution of spot prices is skewed to the right even more than in scenario 1, and the profit distribution of conventional producers would become more positively skewed (or less negatively skewed), whereas the profit distribution of retailers becomes more negatively skewed (or less positively skewed).

To sum, profit distributions in power markets are inherently asymmetric, and the transmission of skewed RES supply into spot prices could change the asymmetry of profit and this could be perceived by market participants as in other financial and commodity markets. Therefore, we think that mean-variance preferences (as BL assume) are too restrictive to model power markets with RES, and we propose to include skewness in the agent preferences in equation 6.

### *2.6. Forward market equilibrium*

In this section, we derive the equilibrium forward prices. We begin with the optimal forward positions $Q_I^F$ (for the conventional producer) and $Q_J^F$ (for the retailer) that yield their maximum

[18] For conventional producers, since their profit function is convex in the spot price, the skewness of the spot price distribution is amplified in their profit distribution. For retailers, the effect can be either amplified or dampened, depending on the interaction between demand risk and price risk.

expected utility.[19]

*2.6.1. The optimal forward positions*

The utility-maximising forward positions of the representative agents are implicitly given by

$$Q^{F^*}_{I(J)} = \underbrace{\gamma \cdot \frac{p_F - \mathbb{E}(p_S)}{\mathrm{Var}(p_S)}}_{\text{basis term}} + \underbrace{\frac{\mathrm{Cov}(\rho_{I(J)}, p_S)}{\mathrm{Var}(p_S)}}_{\text{hedging term}} + \underbrace{\frac{\gamma}{3\phi} \cdot \frac{\partial \mathrm{Skew}(\Pi_{I(J)})/\partial Q^F_{I(J)}}{\mathrm{Var}(p_S)}}_{\text{skewness term}}, \tag{7}$$

where

$$\rho_I = p_S Q_I - \frac{a}{c} Q_I^c, \qquad \rho_J = (p_R - p_S)D,$$

are the *but-for-hedging* profits, i.e. profits earned with zero forward position.

The optimal forward positions in equation 7 depend on three terms: a basis term, a hedging term, and a skewness term. The basis term captures each agent's incentive to exploit the forward–spot price difference. When the forward price exceeds the expected spot price, agents sell more in the forward market. The basis term is proportional to the risk tolerance parameter $\gamma$ (recall that a smaller $\gamma$ indicates higher risk aversion). More risk-averse agents sell fewer forwards. The hedging term is the normalised sensitivity of an agent's profit to changes in the spot price when unhedged (i.e. when the forward position is zero). The profits of the conventional producer increase when spot prices rise, which makes the hedging term positive. The producer sells more forward contracts when profits are more sensitive to spot price changes. In contrast, the retailer faces losses when spot prices rise. For the retailer, the hedging term is negative. To manage profit risks, the retailer purchases more forward contracts when profits are more sensitive to spot price changes.

The basis and hedging terms are the same as in BL. This does not mean that the optimal forward positions would be the same as those according to the BL model, as we have seen that supply from RES influences spot price uncertainty. When we allow for skewness preference, the equation for the optimal position deviates from the BL as a third term emerges. This is the skewness term that reflects an agent's incentive to take advantage of the asymmetry of the profit distribution function. To see how agents benefit from skewness in our model, assume that they hold the optimal position as in the BL model, i.e., the forward position that they would have under mean-variance

[19] To find a solution, we need to ensure that the mean-variance-skewness utility function 6 is concave.[20] Therefore, we restrict the utility maximising forward position $Q^F \in [\underline{q}, \bar{q}]$ such that $\frac{\partial U^2(\Pi(Q^F))}{\partial (Q^F)^2} \leq 0$. This has two consequences. First, the agents are not allowed to buy or sell an infinite number of forward contracts. Second, aversion to profit volatility takes a larger weight than preference for skewness, implying that the optimal forward position with mean-variance-skewness preferences should not be too far from the optimal position when only mean-variance preferences are assumed.

preferences. It must hold that $\frac{\partial[E(\Pi)-\frac{1}{2\gamma}\text{Var}(\Pi)]}{\partial Q^F}=0$. But if $\partial\text{Skew}(\Pi)/\partial Q^F \neq 0$, a small change in the forward position increases an agent's utility. The agent adjusts its optimal forward position until the marginal loss from the basis and hedging terms equals the marginal benefit from the skewness term.[21] The extent to which an agent adjusts its forward position depends on the risk and skewness tolerance parameters $\gamma$ and $\phi$. If agents are very risk-averse ($\gamma \approx 0$), the skewness term becomes negligible. The more an agent values extreme profits (a smaller $\phi$), the more important the skewness term becomes in determining the forward position.

To understand how skewness preference affects the optimal positions of conventional power producers and retailers, we need to determine the sign of $\frac{\partial\text{Skew}(\Pi)}{\partial Q^F}$. Taking the derivative of profit skewness w.r.t the forward position gives

$$\frac{\partial\text{Skew}(\Pi)}{\partial Q^F} = -3\text{Skew}(p_S)(Q^F)^2 + 6\text{Coskew}(\rho, p_S^2)(Q^F) - 3\text{Coskew}(\rho^2, p_S), \tag{8}$$

where

$$\begin{aligned}\text{Coskew}(\rho^2, p_S) &= \mathbb{E}\{[\rho - \mathbb{E}(\rho)]^2[p_S - \mathbb{E}(p_S)]\},\\ \text{Coskew}(\rho, p_S^2) &= \mathbb{E}\{[\rho - \mathbb{E}(\rho)][p_S - \mathbb{E}(p_S)]^2\}.\end{aligned}$$

The RHS of equation 8 has a quadratic form in $Q^F$. Therefore, the profit skewness does not necessarily change monotonically with the forward position $Q^F$. To see this, consider the case that $\text{Skew}(p_S) < 0$.[22] When there is no quantity risk, meaning that the *but-for-hedging* profit is linear in the spot price, the minimum of equation 8 is zero. As a consequence, $\frac{\partial\text{Skew}(\Pi)}{\partial Q^F} \geq 0$, i.e., an increase in the forward position increases profit skewness. The intuition is straightforward: a negatively skewed spot price distribution implies a small probability of extremely low spot prices, allowing the agent to make a large profit by selling in the forward market and buying in the spot market. We refer to it as the price effect.

However, both conventional producers and retailers face quantity risk because they must meet consumers' power demand. For retailers, the quantity risk is unexpected surges or drops in power demand. Conventional producers are faced with total demand risk and manage sudden changes in the supply from RES, hence the uncertainty of residual demand risk. If the residual demand is positively skewed, conventional producers increase their forward sales. Otherwise, if the residual demand is negatively skewed either because of a positively skewed RES or a negatively skewed

[21] When $Q^F = Q^{F^*}$, $-\frac{\partial[E(\Pi)-\frac{1}{2\gamma}\text{Var}(\Pi)]}{\partial Q^F} = \frac{\partial\frac{1}{3\phi}\text{Skew}(\Pi)}{\partial Q^F}$ at $Q^F = Q^{F^*}$.

[22] The analysis of the case that spot price is positively skewed, $\text{Skew}(p_S) > 0$, is similar.

demand distribution, conventional producers face the risk of being crowded out of the spot market. Hence, they need purchase power in the spot market to offset the forward position, which reduces profit skewness. For retailers, when total demand is unexpectedly high, they may be forced to buy additional power at high spot prices, reducing profit skewness, creating an incentive to reduce their exposure in the forward market, and vice versa. We refer to it as the quantity effect. Therefore, the net effect depends on which effect is larger.

**Proposition 1.** *Skewness preference affects optimal forward positions through both price and quantity effects.*

1. ***Price effect:***
   - *Skew*$(p_S) < 0$*: both conventional producers and retailers sell more forwards.*
   - *Skew*$(p_S) > 0$*: both conventional producers and retailers sell fewer forwards.*
   - *Skew*$(p_S) = 0$*: no effect.*
2. ***Quantity effect:***
   - *Skew*$(Q) < 0$*: conventional producers sell fewer forwards.*
   - *Skew*$(Q) > 0$*: conventional producers sell more forwards.*
   - *Skew*$(Q) = 0$*: no effect on conventional producers.*
   - *Skew*$(D) < 0$*: retailers sell fewer forwards.*
   - *Skew*$(D) > 0$*: retailers sell more forwards.*
   - *Skew*$(D) = 0$*: no effect on retailers.*

*2.6.2. The equilibrium forward price*

As shown in Appendix A, the equilibrium forward price is determined by the market-clearing condition: $Q_I^F + Q_J^F = 0$. We summarize the results below.[23]

**Proposition 2.** *Define*

$$\tau_{I(J)} = \frac{Coskew(\rho_{I(J)}, p_S^2)}{Var(p_S)} - \frac{\phi}{2\gamma}, \tag{9}$$

$$p_{I(J)} = \mathbb{E}(p_S) - \frac{1}{\gamma} Cov(\rho_{I(J)}, p_S) + \frac{1}{\phi} Coskew(\rho_{I(J)}^2, p_S), \tag{10}$$

$$w_{I(J)} = \frac{\tau_{J(I)}}{\tau_I + \tau_J}. \tag{11}$$

*Only if* $\tau_I + \tau_J < 0$*, the equilibrium forward price exists and is given by:*

$$p_F = w_I p_I + w_J p_J + \frac{\phi}{4} \frac{Skew(p_S)}{Var(p_S)^2} \frac{(p_I - p_J)^2}{(\tau_I + \tau_J)^2}. \tag{12}$$

[23] In the absence of skewness preference, $\phi = \infty$, the forward price reduces to the simple average $p_F = \frac{1}{2}(p_I + p_J)$.

$\tau_I$ and $\tau_J$ represent composite risk measures for the conventional producer and retailer, respectively. It has two components: $\frac{\text{Coskew}(\rho_{I(J)}, p_S^2)}{\text{Var}(p_S)}$, which measures the *but-for-hedging* profit sensitivity per unit of spot-price variance (i.e., exposure to tail risk normalized by volatility), and $\frac{\phi}{2\gamma}$, the ratio of skewness preference versus variance aversion. It is positive when the skewness tolerance parameter $\phi$ is sufficiently small—implying a strong preference for skewness—or when *but-for-hedging* profits largely increase with spot price volatility. Intuitively, a larger $\tau$ indicates a weaker incentive to hedge. Their sum, $\tau_I + \tau_J$, captures the industry risk preferences. When the sum is positive, at least one of the agents does not have sufficient incentive to hedge, so there is no matched forward position. Hence, a forward equilibrium exists only if aggregate variance aversion dominates skewness preference, i.e., when $\tau_I + \tau_J < 0$. The equilibrium forward positions are:

$$Q_I^F = \frac{\phi}{2\text{Var}(p_S)} \frac{p_I - p_J}{\tau_I + \tau_J}, \tag{13}$$

$$Q_J^F = -Q_I^F. \tag{14}$$

Normally, the conventional producer sells forwards while the retailer buys forwards, implying $p_I < p_J$.[24] When both the producer and retailer exhibit variance aversion dominating skewness preference, i.e., $\tau_I < 0$ and $\tau_J < 0$, $p_I$ and $p_J$ can be interpreted as the *reservation prices* at which the conventional producer and retailer, respectively, optimally choose a zero forward position. Since the optimal forward position is increasing in the forward price, the equilibrium forward price must lie strictly between $p_I$ and $p_J$, $p_I < p_F < p_J$. The weight $w_{I(J)}$ shows the relative risk measure, and the less risk-sensitive agent should have a larger weight. Intuitively, if an agent is risk-neutral, they trade on the forward market for arbitrage reasons. Hence, when the forward price is far from their reservation price, they will continue trading until all arbitrage opportunities are eliminated.

Now consider the case where either $\tau_I \geq 0$ or $\tau_J \geq 0$, but $\tau_I + \tau_J < 0$. In this situation, even though an equilibrium may still exist in theory, the concavity of the utility function—which ensures a well-behaved optimum—becomes weak. This local maximum is typically small and fragile: even minor deviations from the equilibrium position increase utility, making the optimum unstable. For example, if the producer exhibits a strong skewness preference and anticipates a positively skewed spot price distribution, it will prefer to buy forward and liquidate in the spot market, while the retailer also wants to buy forwards for hedging. Since no counterparty is willing to take the short

[24] Reverse trading is possible, with the producer buying forwards and the retailer selling forwards, so $p_I > p_J$. For clarity, we focus on the typical case.

side, the forward market cannot clear.[25]

*2.6.3. Reduced form representation of the forward premium*

By the equilibrium spot price given in equation 5 and the spot market clearing condition, the *but-for-hedging* profits, $\rho_I$ and $\rho_J$, can be expressed as:

$$\rho_I = \frac{1}{(x+1)a^x} p_S^{x+1},$$
$$\rho_J = (p_R - p_S)K + (p_R - p_S)\frac{p_S^x}{a^x}.$$

To compare with BL and derive a theoretical prediction testable by the central moments of wholesale spot prices and the mixed moments between renewable production and wholesale spot prices, we assume that the normalized risk measures $\tau$ and the weights $w$ remain constant under changes of spot price variance. Then, we approximate $p^x$ and $p^{x+1}$ using second-order Taylor series expansions shown in Appendix B and rewrite the equilibrium forward premium as

$$\begin{aligned} p_F - \mathbb{E}(p_S) = {} & \alpha \mathrm{Var}(p_S) + \beta \mathrm{Skew}(p_S) \\ & + \theta \mathrm{Cov}(K, p_S) + \xi \mathrm{Coskew}(K^2, p_S) + \eta \mathrm{Coskew}(K, p_S^2). \end{aligned} \tag{15}$$

where

$$\begin{aligned}
\alpha &= -w_I \frac{[\mathbb{E}(p_S)]^x}{\gamma a^x} - w_J \left[ \frac{x[\mathbb{E}(p_S)]^{x-1}(p_R - \mathbb{E}(p_S)) - [\mathbb{E}(p_S)]^x}{\gamma a^x} - \mathbb{E}(K) \right], \\
\beta &= w_I \left[ \frac{(x-1)^2[\mathbb{E}(p_S)]^{2x}}{\phi a^{2x}} - \frac{x[\mathbb{E}(p_S)]^{x-1}}{2\gamma a^x} \right] \\
&\quad + w_J \left[ \frac{\psi^2}{\phi a^{2x}} - \frac{x[\mathbb{E}(p_S)]^{x-2}\left[(x-1)p_R - (x+1)\mathbb{E}(p_S)\right]}{2\gamma a^x} \right] \\
&\quad + \frac{\phi}{4\gamma(\tau_I + \tau_J)^2} \left( \frac{1}{a^x} \left[ x\,\mathbb{E}(p_S)^{x-1}\big(p_R - \mathbb{E}(p_S)\big) \;-\; 2\,[\mathbb{E}(p_S)]^x \right] \;-\; \mathbb{E}(K) \right)^2, \\
\theta &= -\frac{w_J}{\gamma}(p_R - \mathbb{E}(p_S)), \\
\xi &= \frac{w_J}{\phi} p_R^2, \\
\eta &= w_J \left[ \frac{2\psi p_R}{a^x \phi} + \frac{1}{\gamma} \right], \\
\psi &= p_R x(2-x)[\mathbb{E}(p_S)]^{x-1} + (x+1)(x-1)[\mathbb{E}(p_S)]^x.
\end{aligned}$$

The first observation from the equilibrium forward premium 15 is that the variance and skewness of spot prices are not sufficient in explaining the forward premium. In our framework, uncertainty

[25] In other words, when agents exhibit strong skewness preference, their distinct roles as producer and retailer become irrelevant, and they treat power forwards as purely financial assets rather than instruments to manage trading risk.

comes from demand $D$ and RES supply $K$. When demand and supply shocks are not perfectly correlated, as argued in section 2.4 and empirically shown in Table 1, $K$ explicitly appears in the equilibrium equation 15.

Another observation is that, although the variance and skewness factors were found by BL, their coefficients change with the inclusion of RES and skewness preference. BL predict $\alpha < 0$. This can be explained as follows. The conventional producers are willing to sell forward contracts for hedging reasons. On the other side, retailers' aversion to price risk drives them to purchase forward contracts. When conventional producers and retailers have the same risk preference, these two hedging pressures offset, and there is no bias on the forward price. However, since high spot prices correlate with high power demand, the additional profit margins produce a counteracting incentive for retailers to sell forward contracts. This leads to a net selling of forward contracts, thereby exerting downward pressure on the forward premium ($\alpha < 0$). However, the expression for $\alpha$ in equation 15 shows that the BL rationale may not hold if conventional producers face greater quantity risk than retailers ($\tau_I < \tau_J$), giving them an incentive to sell fewer forwards and thereby driving up the forward premium, or if the expected RES supply $K$ is sufficiently large, incentivizing retailers to buy more forwards to hedge the uncertainty from RES, which also increases the forward premium. As a consequence, we cannot determine the sign of $\alpha$ when we allow for supply from RES and/or skewness preferences.

RES supply and skewness preference affect the parameter of spot price skewness $\beta$ as well. Note that $\beta$ depends on both the risk tolerance $\gamma$ and skewness tolerance $\phi$. When risk tolerance is sufficiently large, $\beta$ is positive and driven by skewness preference. Otherwise, there is a tradeoff between the incentive to hedge price variance and to profit from price skewness. BL predict $\beta > 0$ because retailers are exposed to more profit risk from unexpected demand surges (negative demand shock and negative price shock) than conventional producers that benefit from high spot prices. Therefore, retailers have a larger incentive to buy forward contracts, which increases forward prices. However, as RES supply grows, reliance on CES decreases. The conventional producers operate in a flatter region of their marginal cost function, leading to less frequent high spot prices. Hence, there is less demand for hedging the price variance and the forward price decreases. However, when the share of RES in power production becomes sufficiently large, the price variance increases again, and retailers will hedge for this risk. Because the variance of spot price is now related to a more negatively skewed spot price distribution, the hedging incentive in $\beta$ has a negative rather than positive attribute as in BL. When the risk tolerance is smaller than skewness tolerance, $\beta$ could turn negative and drive up the forward price. In general, the net effect on the sign of $\beta$ cannot be predicted ex-ante. The complex composition of the parameters $\alpha$ and $\beta$ may explain the mixed empirical findings from the BL model in the existing literature.

Our contribution is that we suggest three components that explain the forward premium beyond spot price variance and skewness. The components capture the relationship between spot prices and RES supply. The first is the covariance between RES supply and spot prices. This component was found by Schwenen and Neuhoff (2024) as well. They propose (and find empirical support) that the forward premium increases when the covariance between supply from renewables and the spot price decreases (becomes less negative). That is, they expect $\theta < 0$, as we do. More supply from RES lowers the spot price, so the covariance is negative. This implies that CES produces less quantity, and the total supply of forward contracts decreases as a consequence. The forward premium then increases. It is worth noting that we found the covariance factor under different assumptions for the market. Schwenen and Neuhoff (2024) do not model demand uncertainty. Instead, they model spot price uncertainty without specifying where that price uncertainty comes from. Furthermore, their agents do not have skewness preferences. Therefore, the support of the covariance factor in explaining the forward premium is more robust.

The other two components that we find in equation 15 are the co-skewness factors that result from retailers' skewness preference. The first co-skewness, $\text{Coskew}(K^2, p_S)$, reflects information about how uncertainty of the supply from RES (as expressed by $K^2$) affects changes in spot prices. RES supply uncertainty can manifest in two ways. When the distribution of RES supply has a right tail, there is a low probability of a large RES supply increase and an extremely low spot price. Because retailers prefer low spot prices, they sell in the forward market, creating downward pressure on the forward price and premium. Conversely, if the RES supply distribution function is negatively skewed, there is a likelihood of an extremely high spot price, and retailers purchase more forwards, thereby driving up the forward price. Therefore, the model predicts that $\xi > 0$.

The second coskewness term captures the relationship between spot price uncertainty ($p_S^2$) and RES supply. The sign of its coefficient $\eta > 0$ cannot be determined. There are two key effects to explain. First, when an increase in the supply from RES increases spot price variance, retailers' risk aversion makes them purchase more forward contracts, and the forward price increases to clear the market. Second, although spot price variance increases, its impact depends on the skewness of the spot price distribution. If the increased variance is associated with a decline (rise) in spot prices that benefits (harms) retailers, they will have less (more) incentive to buy forward, leading to a decrease (increase) in the forward price. This effect resembles the role of $\text{Coskew}(K^2, p_S)$. The sign of $\eta$ depends on the relative strength of these two forces: $\eta > 0$ if risk aversion (variance term) dominates, and $\eta < 0$ if skewness preference plays a larger role.

It is important to note that all parameters in 15 depend on time-varying variables such as expected spot prices and supply from RES. Furthermore, we cannot expect that the level of other parameters, such as the agent's risk and skewness tolerance, the CES production costs, and the retail price, will remain constant over time. Hence, we expect the magnitude of the effects of the risk measures to vary over time, while the predicted signs follow the same intuition. We summarise the main implications of the parameters in proposition 3.

**Proposition 3.** *When both demand and supply from RES are uncertain and market participants have mean-variance-skewness preferences, the forward premium of a power forward contract is a linear combination of spot price variance $Var(p_S)$, spot price skewness $Skew(p_S)$, covariance $Cov(K, p_S)$, co-skewness $Coskew(K^2, p_S)$, and co-skewness $Coskew(K, p_S^2)$. The forward premium is negatively correlated with the covariance and positively correlated with the co-skewness between spot price variance and renewable production, $\theta < 0, \xi > 0$. The signs of parameters $\alpha, \beta$, and $\eta$ are indefinite.*

## 3. Empirical methodology and data

We proceed with applying the forward premium equation 15 to market data, where the premium is defined as $p_F - \mathbb{E}(p_S)$. This is the ex-ante forward premium relating the forward price to the expected spot price during a future delivery period, while the expected spot price is not directly observed in data. Hirshleifer (1989) distinguishes between ex-ante and ex-post forward premiums. Ex-ante forward premiums provide information about whether the related risks are priced. Ex-post forward premiums, defined as the forward price minus the realised average spot price, provide insight into the realised premiums earned for taking the risks. We test the model both ex-ante and ex-post.

We begin with how we test our model ex-post. The regression equation is

$$\begin{aligned} p_{F_{t,T}} - p_{S_T} = {} & \alpha \, \mathrm{Var}(p_{S_T}) + \beta \, \mathrm{Skew}(p_{S_T}) \\ & + \theta \, \mathrm{Cov}(K_T, p_{S_T}) + \xi \, \mathrm{Coskew}(K_T^2, p_{S_T}) \\ & + X_t + \mathrm{MFE}_T + \epsilon_T. \end{aligned} \tag{16}$$

Here $p_{F_{t,T}}$ is the price of the futures contract for delivery in month $T$, observed on the last trading day of the preceding month ($t \in T-1$).[26] The realised spot price $p_{S_T}$ is the monthly average

[26] We use the forward price from the last trading day, as it reflects the most accurate information about the delivery month. We also tested using (i) the average futures price over all trading days in $T-1$ and (ii) the average over the last trading week. The results are robust.

spot price in $T$. We have hourly day-ahead spot prices, and we distinguish between base and peak load futures contracts. We compute the daily average base and peak prices first. Let $p_{S_{t,h}}$ be the spot price for delivery of one MWh during hour $h$ on day $t$.[27] Define $B_t$ and $P_t$ as the sets of base hours and peak hours. $n_{B_t}$ is the number of baseload hours and $n_{P_t}$ is the number of peak load hours on day $t$.[28] $n_T$ is the number of relevant days in month $T$.[29] The daily averages are

$$p_{S_{B,t}} = \frac{1}{n_{B_t}} \sum_{h \in B_t} p_{S_{t,h}}, \qquad p_{S_{P,t}} = \frac{1}{n_{P_t}} \sum_{h \in P_t} p_{S_{t,h}}.$$

The monthly averages are

$$p_{S_T} = \frac{1}{n_T} \sum_{t \in T} p_{S_{B,t}} \quad \text{(baseload)}, \qquad p_{S_T} = \frac{1}{n_T} \sum_{t \in T} p_{S_{P,t}} \quad \text{(peak load)}.$$

We follow the same logic to compute the other variables in the regression equation. For example, $\mathrm{Var}(p_{S_T})$ is the variance calculated as deviations of daily averages from the monthly averages (either for base or peak load prices whichever applies)

Observe that we have not included $\mathrm{Coskew}(K, p_S^2)$ from equation 15 in the regression equation. The reason is that we observed that both co-skewness variables are highly correlated in our sample, leading to multicollinearity issues. We proceed with $\mathrm{Coskew}(K^2, p_S)$. The reason for this is that we predict a positive sign for this variable, whereas the sign for the other is undetermined. Furthermore, we think that $\mathrm{Coskew}(K^2, p_S)$ has a clearer economic interpretation as it relates to the uncertainty of supply from RES and the spot price.[30]

Lastly, equation 16 includes $X_t$ and $\mathrm{MFE}_t$. $X_t$ represents control variables (we'll introduce them later). $\mathrm{MFE}_t$ represents month dummy variables (we'll discuss these later as well). We applied the same methodology for calculating the monthly averages for demand $D$, residual demand $Q$, and power quantities supplied by renewables $K$.

[27] As we use day-ahead prices for spot prices, the spot prices are actually observed one day before delivery.

[28] $B_t$ contains 24 hours for most days except for days when time is adjusted for daylight saving time.

[29] Note that the number of days for peak load is less than for base load as peak load only applies to working days.

[30] The correlation between $\mathrm{Coskew}(K^2, p_S)$ and $\mathrm{Coskew}(K, p_S^2)$ is close to $-1$, so including both variables merely reallocates the estimates on $\mathrm{Coskew}(K^2, p_S)$ and $\mathrm{Coskew}(K, p_S^2)$. The covariance term $\mathrm{Cov}(K, p_S)$ captures the relationship between the level of RES supply and the spot price. The coskewness term $\mathrm{Coskew}(K^2, p_S)$ extends this by adding the effect of uncertainty in RES supply on spot prices. By contrast, $\mathrm{Coskew}(K, p_S^2)$ measures how the level of RES supply interacts with uncertainty in the spot price itself.

When we test our model ex-ante, the regression equation is as follows:

$$\begin{aligned} p_{F_{t,T}} - E_t(p_{S_T}) = {} & \alpha \mathrm{Var}_t(p_{S_T}) + \beta \mathrm{Skew}_t(p_{S_T}) \\ & + \theta \mathrm{Cov}_t(K_T, p_{S_T}) + \xi \mathrm{Coskew}_t(K_T^2, p_{S_T}) + \\ & + X_t + \mathrm{MFE}_t + \epsilon_t. \end{aligned} \tag{17}$$

The forward premium is $p_{F_{t,T}} - E_t(p_{S_T})$, meaning the difference between the forward price observed for delivery during month $T$ observed at time $t$ and the average spot price for month $T$ as expected at time $t$. There is no general way on how to measure the expected spot price for a future time period. Agents in the energy market use different proprietary models to make expectations. We choose a very simple approach. We measure the expected spot price $E_t(p_{S_T})$ as the (rolling) average spot price observed over the previous 30 days before $t$. The drawback of this backward looking method is that it ignores any "predictable" changes in the spot prices (for instance, when $T$ is a month with a normally higher demand than for month $T-1$ one would expect a higher spot price during month $T$). To account for such effects, we add month dummy variables (the month fixed effects $\mathrm{MFE}_t$). We apply the same backward looking method to measure the risk factors variance, skewness, covariance, and co-skewness (hence the time subscripts $_t$ for those variables as the rolling estimates vary over different $t$'s. The advantage of the rolling estimates in the ex-ante analysis is that we can use observations from every day in the month prior to the delivery period and don't have to rely on the last trading day only as we do for the ex-post analysis. Next, we provide insight in the data that we use.

### *3.1. Data*

Our sample consists of data from the German power markets (EPEX for spot contracts and EEX for futures contracts) provided by ENTSO-E, SMARD, and Refinitiv.[31] The sample covers the period January 2015 through April 2021.

The data consists of daily observations of the following variables:

- day-ahead hourly power prices (we refer to them as spot prices),
- day-ahead hourly supply quantities from wind and solar RES,
- day-ahead hourly power demand,

[31] Although we refer to Germany, we mean the bidding zone. The power day-ahead prices are determined per bidding zone. The German bidding zone covered Germany, Luxembourg, and Austria until October 2018. After that, it covered Germany and Luxembourg. As the share of German power in this bidding zone is much higher than the share of Luxembourg power, we refer to Germany.

- one-month-ahead power baseload and peak load futures prices,
- one-month-ahead coal (API2 Coal, \$/MT) futures prices,
- one-month-ahead natural gas (RFV Natural Gas, €/MWh) futures prices,
- carbon emission allowances futures prices (EUA, €/ton).

We use marginal production costs of fossil fuelled power plants as control variables ($X_t$ in equations 16 and 17, where natural gas and coal are the fossil fuels primarily used in Germany. We estimate the marginal costs of natural gas producers ($C_{g,t}$) and coal producers ($C_{c,t}$) as

$$C_{g,t} = P_{G,t}/0.5 + 0.35 \times P_{EUA,t}$$
$$C_{c,t} = E_t \times P_{C,t}/(24 \times 0.29 \times 0.4) + 0.95 \times P_{EUA,t}$$

wherein $P_{G,t}$ is the price of gas in €/MWh, and $P_{C,t}$ is price of coal in \$/metric tonne. The values 0.35 tons/MWh and 0.95 tons/MWh are the carbon emission rates for gas and coal producers respectively (see Fabra and Requant (2014)). 0.5 and 0.4 are the respective efficiencies of gas and coal fired CES (see Fleten et al. (2015)). The numbers 24 and 0.29 are needed to convert from MMbtu to MWh (one metric ton is about 24 MMbtu, and 0.29 is the conversion factor from MMbtu to MWh. $E_t$ is the €/\$ exchange rate (published by WM Company and Thomson Reuters). The marginal costs $C_{g,t}$ and $C_{c,t}$ are expressed in €/MWh after unit conversion.

### *3.2. Summary statistics*

Panel A of Table 1 provides descriptive statistics of the data described in section 3.1. Panel B and Panel C of Table 1 report risk measures calculated based on the method described in section 3, for baseload and peak load, respectively. Focusing on baseload, we observe that the average hourly demand was 59.75 GWh. Obviously, during peak hours, the average demand is higher than during a base load hour. Demand $D$ is negatively skewed. Supply from RES $K$ is positively skewed, and is higher during peak hours as both solar and wind produce during peak hours, whereas solar cannot produce during nighttime (off-peak). Residual demand is more variable than demand and supply from RES. This can be explained by the fact that the correlation between demand and RES supply is weak in our sample.[32] As a consequence, $\mathrm{Var}(Q) \approx \mathrm{Var}(D) + \mathrm{Var}(K)$.

Spot prices are negatively skewed. Also, we find that the covariance between renewable supply and spot prices is negative in both base and peak hours. This is consistent with equation 5 that the spot price depends on residual demand ($D - K$). Increases in RES supply reduce the residual

[32] The correlation coefficient between demand and renewable production is almost zero during base load hours and 0.07 during peak hours.

Table 1: **Summary statistics**

Panel A reports descriptive statistics of day-ahead hourly power prices (spot prices), day-ahead hourly supply quantities from wind and solar RES, day-ahead hourly power demand, one-month-ahead power baseload and peak load futures prices, one-month-ahead coal and natural gas futures prices, carbon emission allowances futures prices, and ex-post baseload and peak load forward premiums. Panel B and Panel C report ex-post risk measures calculated in section 3.1, for baseload and peak load, respectively. The coskewness is scaled by multiplying by 0.1. Standard deviations, standardized skewness, covariance, and coskewness are computed on a monthly basis using deviations of daily averages from monthly averages, and reported results are averaged across all months in the sample. Note that the standard deviations in Panels B and C are not comparable with those in Panel A.

**Panel A: Data description**

| Variable | Mean | Std. dev. | Min | Max | Obs |
|---|---|---|---|---|---|
| Spot price (€/MWh) | 35.44 | 17.10 | -130.09 | 200.04 | 55,385 |
| Demand (GWh/h) | 59.72 | 10.88 | 32.81 | 86.41 | 54,330 |
| RES supply (GWh/h) | 16.84 | 10.47 | 0.60 | 63.05 | 54,330 |
| Gas futures (€/MWh) | 16.57 | 4.83 | 3.92 | 29.65 | 1,600 |
| Coal futures ($/MT) | 67.39 | 17.26 | 38.45 | 102.60 | 1,600 |
| EUA futures (€/ton) | 15.40 | 10.26 | 3.91 | 48.74 | 1,599 |
| Baseload futures (€/MWh) | 37.05 | 9.47 | 17.02 | 64.27 | 1,652 |
| Peak load futures (€/MWh) | 44.59 | 11.92 | 18.97 | 80.05 | 1,652 |
| Base forward premium (ex-post, €/MWh) | 1.32 | 3.92 | -7.82 | 11.32 | 76 |
| Peak forward premium (ex-post, €/MWh) | 1.52 | 4.98 | -16.50 | 16.43 | 76 |

**Panel B: Risk measures — baseload**

| Measure | Demand | RES supply | Residual demand | Spot price | N |
|---|---|---|---|---|---|
| Mean | 59.75 | 16.85 | 42.90 | 35.42 | 76 |
| Std. dev. | 5.57 | 5.73 | 8.83 | 8.44 | 76 |
| Std. skew | -0.80 | 0.99 | -0.47 | -0.90 | 76 |
| $\mathrm{Cov}(K, p)$ | – | -50.45 | – | -50.45 | 76 |
| $\mathrm{Coskew}(K^2, p)\times 0.1$ | – | -21.61 | – | -21.61 | 76 |

**Panel C: Risk measures — peak load**

| Measure | Demand | RES supply | Residual demand | Spot price | N |
|---|---|---|---|---|---|
| Mean | 69.84 | 20.85 | 48.99 | 42.68 | 76 |
| Std. dev. | 3.17 | 7.58 | 8.26 | 9.61 | 76 |
| Std. skew | -1.16 | 0.51 | -0.50 | -0.43 | 76 |
| $\mathrm{Cov}(K, p)$ | – | -62.23 | – | -62.23 | 76 |
| $\mathrm{Coskew}(K^2, p)\times 0.1$ | – | -24.94 | – | -24.94 | 76 |

demand to be supplied by conventional producers, which lowers the spot price. The covariance is more negative during peak hours, as RES shocks have more impact at times with high demand. When demand is high, a negative supply shock will lead to a higher marginal price. The coskewness terms $\text{Coskew}(K^2, p)$ are also negative. This implies that increased uncertainty in supply from RES yields lower spot prices. We explain this from a positively skewed supply from renewables driving negatively skewed spot prices. Finally, forward premiums are on average positive and slightly higher for delivery during peak hours.

## 4. Empirical results

In this section, we test our hypotheses focusing on the estimates for the regression models 16 and 17. We begin with discussing the results for the ex-ante forward premiums. Table 2 shows the results for the base load futures contracts. Column (1) shows the parameter estimates only including the BL variables. The parameter estimate for variance has a negative sign, as predicted by BL, but is not significant. The parameter estimate for skewness is significant, but is negative whereas BL predicted it to be positive. We explain this difference in sign from the convexity of the marginal production costs function that BL assume. Their model does not include RES, but RES capacity has increased over time. As RES shift the supply curve to the right, skewness effects caused by the steep incline on the right side of the convex production cost function will occur less frequently. Hence, the impact of skewness has changed and the impact is negative apparently.[33] Allowing for year fixed effects and fuel costs in column (2) does not change the parameter estimates much.

Columns (3) and (4) in Table 2 show the results for covariance and coskewness variables.[34] Our model predicts the parameter for covariance $\theta$ to be negative and the parameter for coskewness $\xi$ to be positive. This is exactly what we observe in column (3): the sign for covariance is negative and for coskewness is positive. Both are significantly different from zero. Furthermore, the sign for the BL variables variance and skewness are negative and both are significant. Especially the parameter estimate for variance has become more negative when we allow for covariance and skewness in the model. The estimate for skewness does not change. The model with covariance and skewness fits the model better as the $R^2$'s reported in columns (3) and (4) are higher than in (1) and (2) respectively. Allowing for the control variables improves the fit, but does not change the parameter estimates much.

[33] Recall that we cannot predict the sign of the skewness parameter ($\beta$) in regression equation 17.

[34] Because the fuel cost data are missing for one trading day, the sample size is reduced by one when fuel costs are included as controls.

Table 2: **Ex-ante forward premium (baseload)**

This table presents the parameter estimates for the ex-ante forward premium (equation 17) in baseload contracts. The results are obtained from daily data from January 2015 to April 2021. Columns (1) and (2) present the results for the BL model. Columns (3) and (4) show the results for the model derived in this paper. Columns (2) and Col(4) include yearly fixed effects and fuel costs as control variables. The magnitude of variance and coskewness are rescaled by 0.1, and the skewness is rescaled by 0.01. HAC standard errors are reported in parenthesis.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| $\text{Var}(p_S)$ $(\times 0.1)$ | -0.01 | -0.08 | -0.45*** | -0.48*** |
| | (0.07) | (0.07) | (0.05) | (0.06) |
| $\text{Skew}(p_S)$ $(\times 0.01)$ | -0.05*** | -0.05*** | -0.07*** | -0.08*** |
| | (0.02) | (0.01) | (0.01) | (0.01) |
| $\text{Cov}(K, p_S)$ | | | -0.14*** | -0.13*** |
| | | | (0.01) | (0.01) |
| $\text{Cosk}(K^2, p_S)$ $(\times 0.1)$ | | | 0.04*** | 0.05*** |
| | | | (0.01) | (0.01) |
| Month FE | YES | YES | YES | YES |
| Year FE | NO | YES | NO | YES |
| Fuel costs | NO | YES | NO | YES |
| $R^2$ | 0.46 | 0.55 | 0.59 | 0.65 |
| Adj. $R^2$ | 0.46 | 0.54 | 0.59 | 0.65 |
| N | 1579 | 1578 | 1579 | 1578 |

$^*: p < 0.1$, $^{**}: p < 0.05$, $^{***}: p < 0.01$

Table 3 shows the results for the peak load contracts. Comparing with the base contracts, we observe similar results with the single difference being the parameter estimate for variance in the BL specification of the regression model in columns (1) and (2) which are significant. All signs are the same as for base load contracts and as predicted for covariance and coskewness. Adding those variables improves the fit. Allowing for control variables improve the fit further, but has no impact on the parameter estimates.

From observing the results in Tables 2 and 3, we conclude that four factors explain the forward premium in power forward contracts. Beyond the variance and skewness of spot prices, as was predicted by BL, covariance and co-skewness are significant premiums as well.

Table 3: **Ex-ante forward premium (peak load)**

This table presents the parameter estimates for the ex-ante forward premium (equation 17) in peak load contracts. The results are obtained by daily data from January 2015 to April 2021. Columns (1) and (2) present the results for the BL model. Columns (3) and (4) show the results for the model derived in this paper. Columns (2) and Col(4) include yearly fixed effects and fuel costs as control variables. The magnitude of variance and coskewness are rescaled by 0.1, and the skewness is rescaled by 0.01. HAC standard errors are reported in parenthesis.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| $\mathrm{Var}(p_S)$ ($\times 0.1$) | -0.07* | -0.14*** | -0.33*** | -0.33*** |
| | (0.04) | (0.04) | (0.05) | (0.05) |
| $\mathrm{Skew}(p_S)(\times 0.01)$ | -0.06*** | -0.06*** | -0.06*** | -0.05*** |
| | (0.01) | (0.01) | (0.01) | (0.01) |
| $\mathrm{Cov}(K, p_S)$ | | | -0.10*** | -0.08*** |
| | | | (0.02) | (0.02) |
| $\mathrm{Cosk}(K^2, p_S)$ ($\times 0.1$) | | | 0.02* | 0.02** |
| | | | (0.01) | (0.01) |
| Month FE | YES | YES | YES | YES |
| Fuel costs | NO | YES | NO | YES |
| Year FE | NO | YES | NO | YES |
| $R^2$ | 0.58 | 0.67 | 0.64 | 0.71 |
| Adj. $R^2$ | 0.58 | 0.67 | 0.64 | 0.70 |
| N | 1579 | 1578 | 1579 | 1578 |

$^{*}: p < 0.1$, $^{**}: p < 0.05$, $^{***}: p < 0.01$

We continue discussing the empirical results for the ex-post forward premiums. Tables 4 and 5 show the results for base and peak load contracts, respectively. Recall that for the ex-post results, we only use futures prices observed on the last trading day of the month. The spot prices and the forward premium factors are the realised values and not the expected values, as for the ex-ante results. First, we focus on the results for base load contracts in Table 4. The estimates of the parameters in the BL version of the model in column (1) are both not significantly different from zero. When we include the covariance and co-skewness factors in column (3) all parameters are

Table 4: **Ex-post forward premium (baseload)**

This table presents the parameter estimates for the ex-post forward premium (equation 16) in base load contracts. The results are obtained by data observed on the last trading days of the months between January 2015 to April 2021. Columns (1) and (2) present the results for the BL model. Columns (3) and (4) show the results for the model derived in this paper. Columns (2) and Col(4) include monthly and yearly fixed effects and fuel costs as control variables. The magnitude of variance and coskewness are rescaled by 0.1, and the skewness is rescaled by 0.01. HAC standard errors are reported in parentheses.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| $\mathrm{Var}(p_S)$ $(\times 0.1)$ | 0.12 | -0.00 | -0.68*** | -0.68*** |
| | (0.12) | (0.16) | (0.10) | (0.12) |
| $\mathrm{Skew}(p_S)$ $(\times 0.01)$ | 0.01 | -0.04 | -0.08** | -0.08** |
| | (0.06) | (0.06) | (0.04) | (0.04) |
| $\mathrm{Cov}(K, p_S)$ | | | -0.17*** | -0.17*** |
| | | | (0.02) | (0.03) |
| $\mathrm{Cosk}(K^2, p_S)$ $(\times 0.1)$ | | | 0.06*** | 0.04*** |
| | | | (0.02) | (0.01) |
| Month FE | NO | YES | NO | YES |
| Fuel costs | NO | YES | NO | YES |
| Year FE | NO | YES | NO | YES |
| $R^2$ | 0.04 | 0.42 | 0.38 | 0.59 |
| Adj. $R^2$ | 0.02 | 0.19 | 0.34 | 0.41 |
| N | 76 | 76 | 76 | 76 |

$^{*}: p < 0.1, ^{**}: p < 0.05, ^{***}: p < 0.01$

significant. As it was the case for the ex-ante results, adding control variables does not change the parameter estimates much (although they improve the fit of the model). The signs for covariance and co-skewness are as predicted by our model. The same results hold for the peak contracts in Table 5.

Table 5: **Ex-post forward premium (peak load)**

This table presents the parameter estimates for the ex-post forward premium (equation 16) in peak load contracts. The results are obtained by data observed on the last trading days of the months between January 2015 to April 2021. Columns (1) and (2) present the results for the BL model. Columns (3) and (4) show the results for the model derived in this paper. Columns (2) and Col(4) include monthly and fixed effects and fuel costs as control variables. The magnitude of variance and coskewness are rescaled by 0.1, and the skewness is rescaled by 0.01. HAC standard errors are reported in parenthesis.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| $\mathrm{Var}(p_S)$ ($\times 0.1$) | -0.07* | -0.20*** | -0.42*** | -0.46*** |
| | (0.03) | (0.04) | (0.06) | (0.07) |
| $\mathrm{Skew}(p_S)$ ($\times 0.01$) | -0.03 | -0.05** | -0.04*** | -0.05*** |
| | (0.02) | (0.02) | (0.01) | (0.01) |
| $\mathrm{Cov}(K, p_S)$ | | | -0.13*** | -0.12*** |
| | | | (0.03) | (0.03) |
| $\mathrm{Cosk}(K^2, p_S)$ ($\times 0.1$) | | | 0.06*** | 0.04** |
| | | | (0.02) | (0.01) |
| Month FE | NO | YES | NO | YES |
| Fuel costs | NO | YES | NO | YES |
| Year FE | NO | YES | NO | YES |
| $\mathrm{R}^2$ | 0.08 | 0.51 | 0.40 | 0.64 |
| Adj. $\mathrm{R}^2$ | 0.05 | 0.32 | 0.37 | 0.49 |
| N | 76 | 76 | 76 | 76 |

$^{*}: p < 0.1$, $^{**}: p < 0.05$, $^{***}: p < 0.01$

The results show that the forward premium factors as proposed by our model explain the forward premiums in the prices of futures contracts observed from Germany. These factors improve the fit of the models compared to models wherein only the BL factors are included. Where demand uncertainty was the only cause of risk in the BL model, we include RES supply uncertainty as an additional source of uncertainty that CES producers and retailers have to deal with. The results in this paper show that risk caused by this uncertainty is priced.

## 5. Concluding remarks

In this paper, we propose an equilibrium model for the price of power forward contracts. Our starting point is the equilibrium model derived by Bessembinder and Lemmon (2002), wherein producers are non-intermittent fossil-fuelled power plants and all agents have mean-variance preferences. Nowadays, most power markets face a large growth in supply from renewable energy sources (RES) such as wind mills and solar parks. This motivated us to derive an equilibrium model with supply from RES included. The inclusion of RES has a non-trivial effect on power forward prices as the economics of RES are different from conventional energy sources (CES): RES supply is intermittent, and marginal production costs are close to zero. Hence, the spot price drops but is more volatile. In addition, we argue that the probability distribution of RES supply is skewed, which translates into skewness in spot prices and, consequently, in profits. We introduce mean–variance–skewness preferences to capture how agents respond to the skewness in profit distributions induced by RES variability.

The equilibrium forward price model that we propose has four factors that explain the forward premium. Besides factors related to spot price variance and skewness as found by Bessembinder and Lemmon (2002), we find evidence for two other factors related to the covariance and coskewness between RES supply and spot prices. We provide empirical support for the factors and their predicted signs explaining the forward premiums observed in the German power market.

A secondary result is that our model predicts that the sign for skewness, which Bessembinder and Lemmon (2002) predicted to be positive, cannot be determined as it depends on the convexity of the supply curve. The low marginal production costs of RES shift the supply curve to the right, such that demand is supplied from a flatter region of the supply curve. We find that the sign for the skewness factor is negative. This is one explanation for the mixed results found for the Bessembinder and Lemmon (2002) model in the literature.

We believe that our results benefit market participants. When they derive expected spot prices to make investment decisions in power markets, our results help to better filter those expectations from the prices of futures contracts. It also helps to judge better whether to hedge a risk or not as it shows more factors that an agent is being compensated for. One could argue that the validity of our model is limited as it is built on a market setting wherein power storage capacity is limited and/or power demand is price-inelastic in the short term. Once power markets have sufficiently large storage capacity and agents change their consumption quantities when supply from RES change, the variance and skewness of spot prices and the relationship between with supply from RES and spot prices will eventually disappear. As a consequence, the importance of the factors explaining the power forward premium disappears and forward prices will behave more in line as predicted by the theory of storage. We think that this won't happen soon as it requires huge investments and behaviour changes. Until then, we think that power market agents can benefit from the results of our model as it provides a better understanding of power forward premiums.

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## Appendix

### Appendix A. Proof of Equilibrium Forward Pricing

Substituting the derivative of skewness into the first-order condition for forward positions (see Eqs. 7 and 8) yields a quadratic equation in $Q^F_{I(J)}$:

$$\frac{\mathrm{Skew}(p_S)}{\mathrm{Var}(p_S)}\,(Q^F_{I(J)})^2 - 2\,\tau_{I(J)}\,Q^F_{I(J)} + \frac{\phi}{\mathrm{Var}(p_S)}\,(p_{I(J)} - p_F) = 0, \tag{A.1}$$

where

$$\tau_{I(J)} = \frac{\mathrm{Coskew}(\rho_{I(J)}, p_S^2)}{\mathrm{Var}(p_S)} - \frac{\phi}{2\gamma}, \tag{A.2}$$

$$p_{I(J)} = \mathbb{E}(p_S) - \frac{1}{\gamma}\mathrm{Cov}(\rho_{I(J)}, p_S) + \frac{1}{\phi}\mathrm{Coskew}(\rho^2_{I(J)}, p_S). \tag{A.3}$$

*Existence.* Equation (A.1) admits real solutions only if the discriminant is non-negative:

$$\Delta = \tau^2_{I(J)} - \phi \cdot \frac{\mathrm{Skew}(p_S)}{\mathrm{Var}(p_S)^2}\,(p_{I(J)} - p_F)\ \geq\ 0. \tag{A.4}$$

*Roots.* When $\Delta \geq 0$, the quadratic admits two algebraic solutions:

$$Q^F_{I(J),\pm} = \frac{\tau_{I(J)} \ \pm \ \sqrt{\tau^2_{I(J)} - \phi \cdot \frac{\mathrm{Skew}(p_S)}{\mathrm{Var}(p_S)^2}\,(p_{I(J)} - p_F)}}{\mathrm{Skew}(p_S)/\mathrm{Var}(p_S)}. \tag{A.5}$$

*Second-order condition.* The second derivative of expected utility with respect to the forward position is

$$U''(Q^F_{I(J)}) = \tau_{I(J)} - \frac{\mathrm{Skew}(p_S)}{\mathrm{Var}(p_S)}\,Q^F_{I(J)}. \tag{A.6}$$

Defining the threshold

$$\bar{Q}^F_{I(J)} = \frac{\mathrm{Var}(p_S)}{\mathrm{Skew}(p_S)}\tau_{I(J)}, \tag{A.7}$$

we can write

$$U''(Q^F_{I(J)}) = -\frac{\mathrm{Skew}(p_S)}{\mathrm{Var}(p_S)}\,(Q^F_{I(J)} - \bar{Q}^F_{I(J)}). \tag{A.8}$$

- If $\mathrm{Skew}(p_S) > 0$, the SOC requires $Q^F_{I(J)} > \bar{Q}^F_{I(J)}$. The larger root $Q^F_{I(J),+}$ satisfies this condition and is the maximizer; the smaller root is a minimizer.
- If $\mathrm{Skew}(p_S) < 0$, the SOC requires $Q^F_{I(J)} < \bar{Q}^F_{I(J)}$. The smaller root $Q^F_{I(J),-}$ satisfies this condition and is the maximizer; the larger root is a minimizer.
- If $\mathrm{Skew}(p_S) = 0$, Eq. (A.1) reduces to a linear equation with a unique solution, which automatically satisfies the SOC.

Hence, the solution that maximizes the agent's utility is:

$$Q^F_{I(J)} = \frac{\tau_{I(J)} + \sqrt{\tau^2_{I(J)} - \phi \cdot \frac{\mathrm{Skew}(p_S)}{\mathrm{Var}(p_S)^2}\,(p_{I(J)} - p_F)}}{\mathrm{Skew}(p_S)/\mathrm{Var}(p_S)}. \tag{A.9}$$

The market-clearing forward price should be determined such that the sum of forward positions across thermal producers and retailers is zero.

$$Q^F_I + Q^F_J = 0$$

The algebra gives the result

- **If** $\tau_I + \tau_J < 0$**:**

$$p_F \ = \ \frac{\tau_I p_J + \tau_J p_I}{\tau_I + \tau_J} \ + \ \frac{\phi}{4}\,\frac{\mathrm{Skew}(p_S)}{\mathrm{Var}(p_S)^2}\,\frac{(p_I - p_J)^2}{(\tau_I + \tau_J)^2}. \tag{A.10}$$

- **If** $\tau_I + \tau_J = 0$**:**
  - no equilibrium $p_F$, because the second order condition of the optimal position is equal to zero, meaning no local maximum is achieved.
- **If** $\tau_I + \tau_J > 0$**:**
  - no equilibrium $p_F$, because the square root cannot be negative.

Substituting equations (A.10) into equation (A.4) shows that the non-negative condition holds automatically.

## Appendix B. Proof of Reduced Form Equilibrium

Taylor series says:

$$f(x) \approx f(x_0) + f'(x_0)(x - x_0) + \frac{f(x_0)}{2}(x - x_0)^2$$

Hence, to approximate $p_S^x$ around $\mathbb{E}(p_S)$ gives:

$$\begin{aligned} p_S^x &\approx \mathbb{E}(p_S)^x + x[\mathbb{E}(p_S)]^{x-1}(p_S - \mathbb{E}(p_S)) + \frac{x(x-1)[\mathbb{E}(p_S)]^{x-2}}{2}(p_S - \mathbb{E}(p_S))^2 \\ &= [\mathbb{E}(p_S)]^x \left[1 - x + \frac{x(x-1)}{2}\right] + x(2-x)[\mathbb{E}(p_S)]^{x-1}p_S + \frac{x(x-1)}{2}[\mathbb{E}(p_S)]^{x-2}p_S^2 \end{aligned} \tag{B.1}$$

Similarly,

$$p_S^{x+1} = [\mathbb{E}(p_S)]^{x+1}\left[-x + \frac{x(x+1)}{2}\right] - (x+1)(x-1)[\mathbb{E}(p_S)]^x p_S + \frac{x(x+1)}{2}[\mathbb{E}(p_S)]^{x-1}p_S^2 \tag{B.2}$$

For simplification, we define:

$$\begin{aligned} A &= -(x+1)(x-1)[\mathbb{E}(p_S)]^x \\ B &= \frac{x(x+1)}{2}[\mathbb{E}(p_S)]^{x-1} \\ C &= p_R x(2-x)[\mathbb{E}(p_S)]^{x-1} \\ D &= p_R\frac{x(x-1)}{2}[\mathbb{E}(p_S)]^{x-2} \\ E &= p_R x(2-x)[\mathbb{E}(p_S)]^{x-1} + (x+1)(x-1)[\mathbb{E}(p_S)]^x \\ F &= p_R\frac{x(x-1)}{2}[\mathbb{E}(p_S)]^{x-2} - \frac{x(x+1)}{2}[\mathbb{E}(p_S)]^{x-1} \end{aligned}$$

Then, we can rewrite the covariance between $\rho_i$ and $p_S$ as

$$Cov(\rho_i, p_S) = \frac{1}{(x+1)a^x}Cov(p_S^{x+1}, p_S) = \frac{1}{(x+1)a^x}[A + 2\mathbb{E}(p_S)]Var(p_S) + \frac{1}{(x+1)a^x}BSkew(p_S) \tag{B.3}$$

For coskewness, we keep only up to third-order central and mixed moments.

$$Coskew(\rho_i^2, p_S) = \frac{1}{(x+1)^2a^{2x}}Cos(p_S^{x+1}, p_S^{x+1}, p_S) = \frac{A^2}{(x+1)^2a^{2x}}Skew(p_S) \tag{B.4}$$

Hence,

$$\begin{aligned} p_I &= \mathbb{E}(p_S) - \frac{1}{\gamma}Cov(\rho_i, p_S) + \frac{1}{\phi}Coskew(\rho_i^2, p_S), \quad \forall \quad i \in \{1, 2, ..., N_I\} \\ &= \mathbb{E}(p_S) - \frac{\mathbb{E}(p_S)^x}{\gamma a^x}Var(p_S) + \left[\frac{(x-1)^2[\mathbb{E}(p_S)]^{2x}}{\phi a^{2x}} - \frac{x[\mathbb{E}(p_S)]^{x-1}}{2\gamma a^x}\right]Skew(p_S) \end{aligned}$$

Similarly, we get

$$\begin{aligned}
p_J &= \mathbb{E}(p_S) - \frac{1}{\gamma}\mathrm{Cov}(\rho_J, p_S) + \frac{1}{\phi}\mathrm{Coskew}(\rho_J^2, p_S) \\
&= \mathbb{E}(p_S) - \frac{1}{\gamma}\left[\frac{x[\mathbb{E}(p_S)]^{x-1}(p_R - \mathbb{E}(p_S)) - [\mathbb{E}(p_S)]^x}{a^x} - \mathbb{E}(K)\right]\mathrm{Var}(p_S) \\
&\quad + \left[\frac{E^2}{\phi a^{2x}} - \frac{x[\mathbb{E}(p_S)]^{x-2}\big((x-1)p_R - (x+1)\mathbb{E}(p_S)\big)}{2\gamma a^x}\right]\mathrm{Skew}(p_S) \\
&\quad - \frac{1}{\gamma}\big(p_R - \mathbb{E}(p_S)\big)\mathrm{Cov}(K, p_S) \\
&\quad + \frac{1}{\phi}p_R^2\mathrm{Cos}(K^2, p_S) \\
&\quad + \left[\frac{2Ep_R}{a^x\phi} + \frac{1}{\gamma}\right]\mathrm{Cos}(K, p_S^2).
\end{aligned}$$

Substituting the results into equation (12) and rearranging the terms give the reduced form representation as shown in equation (15).