# Electricity Forward Premium: Renewable Integration and Skewness Preference

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July 31, 2023

**Abstract**

This paper demonstrates the relevance of incorporating renewable production and skewness preference in electricity forward pricing models. Starting from a mean-variance-skewness utility function, we prove that equilibrium forward premia are determined by idiosyncratic moments: variance and skewness of wholesale spot prices, as well as systematic mixed moments: covariance and coskewness between renewable output and spot prices. We find empirical evidence that coskewness and covariance are statistically significant and improve the explanatory power of regression by more than 30 percents. Spot price skewness is less important and negatively relates to forward premia due to a flatter supply curve of thermal plants. Further decomposing the risk factors into supply and demand shocks, we show that renewable supply volatility increases while skewness reduces forward premia. The results suggest the importance of considering the asymmetry of renewable supply shocks in explaining electricity forward premia.

**Keywords:** Electricity, Forward pricing, Skewness preference, Renewable, Risk hedging,
**JEL:** G11, G12, G13, Q41

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# 1 Introduction

Intermittent renewable electricity generation is growing globally to reduce reliance on fossil fuels. In 2022, 22.3% of electricity in EU is generated by solar and wind, which account for 14.6% in US and 14.5% in China respectively. Increasing renewable generation is expected to reduce electricity spot price from *merit-order effect* by its negligible marginal production cost. However, lack of demand response and economical storage, electricity price is very volatile, which becomes more severe in the energy transition.[1] To manage price variability, the market participants, namely generators and retailers, sign a forward contract to fix the power price. The nature of electricity that it cannot be economically stored implies the failure of cost-of-carry method to pricing electricity forward, so an adaptive equilibrium model is necessary to account for the renewables penetration. To understand the dynamics of forward prices and how involved parties are affected intrigue different parties: market participants are helped to make hedging and investment decision and negotiate contracts; policy makers can better understand the effect of energy transition on different parties and develop policies accordingly.

Moreover, it is acknowledged that risk aversion only partially captures the preference of a risk averse agent: people care about mean and variance of final wealth, but they present asymmetric awareness of risks to different directions. They dislike downside risk but show preference to positive skewness, which is called "prudence". While intermittent renewable sources are volatile and increase market risk, their output distribution presents long right tail, implying extremely high production and low price.[2] Hence, when determining forward hedging strategies, agents not only smooth profit volatility, but seek benefits (or avoid loss) of extreme scenarios.

With this motivation in mind, this paper builds an equilibrium power forward pricing model, incorporating renewable electricity generation and skewness preference. The theoretical result shows that equilibrium forward premium, the difference between forward price and expected spot price, is determined by a linear combination of spot price variance, skewness, as well as covariance and coskewness between renewable power generation and spot price. The idiosyncratic variance and skewness indicate the risk from conventional market that would vanish at the time of high renewable penetration, while the covariance and coskewness terms represent renewable market risk and the interaction between renewable and conventional generations.

Specifically, we find that equilibrium forward premia are negatively correlated with variance and covariance, while positively relate to coskewness. The effect of spot price skewness is positive if marginal production cost of thermal plants is non-concave and the sign is indefinite otherwise. In addition, we demonstrate the effects of renewable penetrations on the optimal hedging positions of thermal generators and retailers. Besides market occupation, thermal producers increase their sale by a larger price volatility and right-skewed renewable generation, while retailers increase their purchase with more volatility but this effect is partly offset due to left-skewed spot

[1] See figures in Appendix B.
[2] See figures in Appendix C.

prices.

The empirical evidence from German market shows strong support to our predictions. Ignoring the covariance and coskewness, spot price variance and skewness are weak to explain forward premia, demonstrating the vital role of renewable sources in the power market. Augmented with covariance and coskewness components increases the explanatory power of onpeak and baseload forward premia by 33 percent and 36 percents respectively. As anticipated, both variance of spot prices and covariance between renewable generation and spot price negatively affect forward premia, reflecting the fact that firms are risk averse and prefer to be assured in advance. As all components are rescaled to the same magnitude, the estimate of covariance term being around three times as much as that of variance implies a larger impact of renewable generation compared to the risk from conventional market. Furthermore, the data show a right-skewed renewable output and a negatively skewed spot price. A significantly positive estimate on coskewness suggests that generators (retailers) avoiding large loss (seeking benefits) from asymmetric renewable supply shock is relevant to forward valuation. Therefore, although renewable volatility raises forward premia, its positive skewness imposes a downward pressure.

Moreover, the spot price skewness coefficient turns out to be small and negatively significant. In a seminal paper, Bessembinder and Lemmon (2002) present an equilibrium model of electricity forward price in a market where electricity is only generated by thermal plants that face a strong convex supply curve. they claim that forward premium is negatively related to variance while positively related to skewness, implying an upward bias of forward price at the time of high demand due to cost spike. In reality, the marginal cost of thermal plants is linear and even concave in the low and middle level of production, and becomes more convex when approaching capacity limit. Due to merit order effect, renewable generation is contracted before conventional plants and this decreases the average convexity of its supply curve. Therefore, the argument in Bessembinder and Lemmon (2002) is reversed, leading to a small and negative coefficient of skewness.

Finally, we test the model predictions using data of recent energy crisis from 2021 to 2023, and the findings show agents present strong risk aversion but the preference for skewness is not robust. The coskewness term is still positive but not significant. This can be the result of limited sample size or the fact that people care much more about uncertainty than risk asymmetry in a state of upheaval. We also find the significance of coskewness increases with the span of forward price, implying that people behave irrationally in the short time after a shock but return to being prudent over time.

We contribute to the literature in three aspects. First, we theoretically and empirically show that both variability and skewness of renewable electricity generation affect optimal power forward position and equilibrium forward premia. The interaction between demand and supply risk, as well as the interaction between renewable and conventional productions are well tracked. A lot of empirical papers examine the predictions in Bessembinder and Lemmon (2002) and the results are scattered. Longstaff and Wang (2004) use day-ahead forward and real-time prices in PJM market from 2000 to 2002 to test the theory and find the results supporting Bessembinder and Lemmon (2002). However, by PJM data for a longer period, Haugom and Ullrich (2012) find the coefficients for variance and skewness are varying and they cannot find evidence that there exists significant risk premia. Viehmann (2011) shows there is significant positive premia during peak hours and negative ones during offpeak hours, using German day-ahead hourly and OTC price (2 hours before day-ahead auction), and the relationship between forward premia with variance and skewness is consistent with Bessembinder and Lemmon (2002).

Some other papers augment Bessembinder and Lemmon (2002) by incorporating other explanatory variables in a reduced form. For instance, Douglas and Popova (2008) add gas storage and show that increase in gas storage predicts a lower risk premium, and this effect is especially evident when demand for electricity is medium and demand for gas heating is low. Lucia and Torró (2011) use Nordic data from 1998-2007 and the results support a time varing premium: positive premium in winter when reservior level is low and zero in summer. By the same intuition, unexpected big shock would push a high premium. However, they find that after the turbulence in Nord pool market, the prediction by Bessembinder and Lemmon (2002) does not hold anymore. Redl and Bunn (2013) take multi-factor analysis of forward premium, showing that reserve margin, market power and underlying fuel price volatility all significantly increase premium. Similarly, Bunn and Chen (2013) investigate how various foundamental and behavioral factors affect the formation of risk premium. They find the main driver of peak premia is behavioral terms (lagged premium & price), while premium positively relates to volatility and negatively relates to skewness, which is opposite to Bessembinder and Lemmon (2002).

Our results provide some explanations to the mixed empirical results. The prediction in Bessembinder and Lemmon (2002) is not a rule of thumb, but varys according to the market structure. For instance, we show that the relationship between premia and spot price skewness is indefinite. Furthermore, omitting variables would result in insignificant and even reverse sign of coefficients. Finally, even not explicitly discussed in this paper, the length of forward contract also matters. The forward pricing model focus on long term forward contract while a day-ahead forward contract exhibits other characteristics that are not well integrated in the setup.

There are also studies concerning theoretical extensions. Buhler and Merbach (2009) develop a generalized dynamic version of equilibrium pricing model. Oliveira and Ruiz (2021) add market power and generation cost uncertainty. Ullrich (2007, 2013) add capacity constraint to the model. Gianfreda et al. (2022) derive equilibrium model with higher moments other than variance and skewness. Koolen et al. (2021) include renewable technologies and emphasize the technology-specific effect on spot and forward market. Schwenen and Neuhoff (2021) give a simple forward pricing model where there is only renewable supply risk and marginal cost of conventional generation is constant, and derive a negative relationship between forward premium and the covariance between renewable output and spot price. Puera and Bunn (2022) investigate the effect of forward market where risk-averse agents face competitive intermittent wind generation and duopoly thermal producers. The focus of their paper is how forward market affect spot market equilibrium rather than forward pricing. Besides the follow-up of Bessembinder and Lemmon (2002), other research such as Lucia and Schwartz (2002) and Benth and Paraschiv (2018) explore electricity forward pricing by assuming exogenous stochastic spot price process. Ito and Reguant (2016) derive electricity forward premia from market power rather than risk aversion.

Second, our model is a generalization and application of three-moment asset pricing model in forward market and power market. The main insight of Kraus and Litzenberger (1976) is that the standardized coskewness between market return and individual asset's return affects the latter's risk premium, the sign of which is opposite to market return skewness. Numerous studies explore its empirical implications, most of which are confined to stock and bond markets, such as Friend and Wesrerfield (1980), Banz (1981), Harvey and Siddique (2000), Langlois (2020), Colacito et al. (2016) among others. Some papers like Christie-David and Chaudhry (2001), Fernandez-Perez et al. (2018), and Hollstein et al. (2021) extend the model to commodity futures market. However, to our knowledge, all those papers consider a static portfolio selection, define the risk premia as the difference between risky asset's return and risk-free rate or other market proxy, and require knowledge of market performance. Hence, this paper is the first one to extend a three-moment pricing model to electricity forward market, investigating the relationship between spot and forward prices. Uninformed of market return, the power forward pricing is further expressed as both idiosyncratic and renewable systematic risk measurements, while the traditional form only has a structure of systematic components.

Finally, even the model is constructed in the context of electricity market, the findings of skewness preference also shed light on other energy commodity markets. Specifically, we show that on top of covariance between market risk and spot price, their coskewness also plays a role in risk hedging strategies, and this well explains the phenomena that people hedge a lot at good time while hesitate to take a large forward position when price and volatility are both high, which is hard to understand from the perspective of risk aversion. Note that in a single technology setup, the equilibrium premia are decomposed into variance and skewness of spot prices, just as in Bessembinder and Lemmon (2002). However, they obtain price skewness by convex production cost function, while in our model, it comes from both skewness preference and the shape of cost curve, which clarifies the underlying mechanism of different relationships between forward premia and spot price skewness.

The rest of this paper is organized as follows. Section 2 builds the model. Section 3 describes the data used in this paper. Section 4 and 5 give empirical results. Section 6 concludes.

# 2 Model

We build a two-stage equilibrium model for electricity spot and forward market. Three categories of risk-averse participants are active in the market: conventional generators, renewable generators, and retailers on behalf of end consumers. As a benchmark model, we assume the absence of government, arbitragers and storage. Furthermore, suppliers and retailers are independent and compete perfectly. There are two types of uncertainty: demand uncertainty from consumers, supply uncertainty from intermittent renewable generation. States are realized in the spot market.

## 2.1 Setup

Consider an electricity market with $N_I$ conventional generators denoted by $i \in \{1, ..., N_I\}$, $N_R$ renewable generators denoted by $r \in \{1, ..., N_R\}$, and $N_J$ ex-ante homogeneous retailers denoted by $j \in \{1, ..., N_J\}$ that sell power to residential consumers with exogenous fixed price $p_R$. Both types of generators and retailers can freely trade in spot power market and forward market. Let $p_S$ denote the spot power price and $p_F$ be the forward price. As the market is perfectly competitive, all firms are price takers.

Each conventional generator $i$ sells $Q_i^F$ in the forward market, and purchases if $Q_i^F < 0$. The quantity they trade in the spot market is denoted by $Q_i^S$, so total supply is $Q_i = Q_i^F + Q_i^S$. Conventional generators face a total cost function[3] $C_i = \frac{a}{c}(Q_i)^c$. Hence, the profit of conventional generators is:

$$\Pi_i = p_F Q_i^F + p_S Q_i^S - \frac{a}{c}(Q_i)^c \tag{1}$$

Similarly, renewable generator $r$ sell $Q_r^F$ in the forward market and $Q_r^S$ in spot market with zero marginal cost. Different from thermal plants, renewables are not dispatched and their actual production is restricted by uncertain capacity $K_r$. The profit function of renewable supplier is:

$$\Pi_r = p_F Q_r^F + p_S Q_r^S \tag{2}$$

$$Q_r^F + Q_r^S \le K_r \tag{3}$$

Retailers denoted by $j$ sell $Q_j^F$ (hence, purchase if $Q_j^F < 0$) in forward market and buy the difference between actual demand $D_j$ and forward trade in spot market.

$$\Pi_j = p_R D_j + p_F Q_j^F - p_S(D_j + Q_j^F) \tag{4}$$

In the second stage (spot market), as everything is certain, all parties maximize their profit, while in the first stage, utility is maximized. All firms have the same CARA[4] utility form $u(\Pi) = -e^{-A\Pi}$, where $A \ge 0$ is the parameter of risk aversion. By third order Taylor expansion and certainty equivalence, each firm can be viewed to have a mean-variance-skewness utility function so they maximize:

$$U(\pi_{\{i,j,r\}}) = E(\pi_{\{i,j,r\}}) - \frac{A}{2}Var(\pi_{\{i,j,r\}}) + \frac{A^2}{6}Skew(\pi_{\{i,j,r\}}) \tag{5}$$

[3]We ignore fixed cost as it does not affect the results.

[4]The main result does not change if we relax the utility form to exhibit HARA, namely

$$-\frac{u'(\Pi)}{u''(\Pi)} = a\Pi + b$$

Consistent with literature, risk-averse agents dislike profit variance but prefer positive skewness of profit. The three-moment utility function is valid when profit distribution is asymmetric. There are three possible sources of asymmetry: (1) asymmetric renewable supply shock, (2) asymmetric demand shock, (3) nonlinear conventional production cost.

## 2.2 Spot market equilibrium

In the spot market, renewable generators sell all capacity available and retailers purchase power until demand is satisfied. conventional generators sell power to maximize its profit and:

$$Q_i = \left(\frac{p_S}{a}\right)^x \tag{6}$$

where $x = \frac{1}{c-1}$. As market is clear, the total generation from conventional suppliers is equal to residual demand: $Q = D - K$, the difference between total demand $D = \sum_j D_j$ and total supply from renewable sources $K = \sum_r K_r$. To simplify the analysis, we impose that $K \leq D$. Hence, spot price is characterized by:

$$p_S = a\left(\frac{Q}{N_I}\right)^{1/x} \tag{7}$$

More supply from renewables reduces spot price, which is called *merit-order effect*. Furthermore, As $Var(K) > 0$, spot price volatility would increase unless demand and renewable production comove; the latter could be supported during peak time if power industry has a large share of solar PV. The impact on skewness is more complex. It partially depends on the direction of renewables' skewness: a right skewed renewable output distribution decreases the skewness (less positively or more negatively skewed) of spot price, and vice versa.

## 2.3 Forward market equilibrium

In the forward market, firms maximize expected utility expressed in (5) by choosing optimal forward position $Q^F_{i,j,r}$ and solving for the equilibrium condition:

$$p_F - E(p_S) = -ACov(R_{i,j,r}, p_S) + \frac{A^2}{2}Cos(R^2_{i,j,r}, p_S) \tag{8}$$

where

$$\begin{aligned}
R_i &= p_S(Q_i - Q_i^F) - \frac{a}{c}\left(Q_i\right)^c \\
R_j &= p_R Q_j - p_S(Q_j + Q_j^F) \\
R_r &= p_S(K_r - Q_r^F)
\end{aligned}$$

is the net return on spot sale (purchase). The covariance and coskewness are defined as:

$$Cov(R_{i,j,r}, p_S) = E\{[R_{i,j,r} - E(R_{i,j,r})][p_S - E(p_S)]\}$$
$$Cos(R^2_{i,j,r}, p_S) = E\{[R_{i,j,r} - E(R_{i,j,r})]^2[p_S - E(p_S)]\}$$

As all parties have the same probability belief [5], they choose forward position such that they burden the same risk, which must be market risk for market to clear. Therefore, when all firms have the same risk preference[6], the market equilibrium premium can be rewritten as:

$$p_F - E(p_S) = \frac{A}{N}\left[-Cov(\underbrace{p_R D - C(Q)}_{\text{total market profit}}, p_S) + \frac{A}{2N}Cos[(p_R D - C(Q))^2, p_S]\right] \tag{9}$$

As producers' sale revenue and retailer's purchase cost are cancelled out, the remaining market risk is the difference between retailers' revenue risk and producers' production cost risk[7]. In the forward-spot electricity market, forward can be viewed as a safe asset while spot is risky. To generators, they have long side of spot as initial wealth and choose how many forward to sell in forward market (hold in the spot market). To the contrary, retailers choose how many forward to buy in the forward market (in other words, the amount of spot to hold in spot market). Hence, when spot price is positively (negatively) correlated with market profit, aversion to risk means that to forward has a lower (higher) value. The sign of coskewness depends on skewness of spot price, when spot price is right skewed, which is preferred by agents, they will ask for a higher forward premium because in this case, to buy forward and hold spot is an attractive option so forward becomes more expensive in order to clear the market. On the other hand, when spot price is negatively skewed, firms prefer to sell forward and ask for a lower premium. The market profit can be decomposed into:

$$p_R D - C(Q) = \Pi_C + \Pi_K \tag{10}$$

where $\Pi_C = p_R Q - C(Q)$ is the market profit attributed to conventional production and $\Pi_K = p_R K$ is the profit by renewable production. Hence, the forward premium is:

$$p_F - E(p_S) = \frac{A}{N}\left[\underbrace{-Cov(\Pi_C, p_S) + \frac{A}{2N}Cos(\Pi_C^2, p_S)}_{\text{I: conventional}} \underbrace{-Cov(\Pi_K, p_S) + \frac{A}{2N}Cos(\Pi_K^2, p_S)}_{\text{II: renewable}} + \underbrace{\frac{A}{N}Cos(\Pi_C, \Pi_K, p_S)}_{\text{III: interaction}}\right] \tag{11}$$

[5]This is a strong assumption but still successfully captures the main characteristic of forward pricing.

[6]In the case of heterogeneous preferences, denote the risk tolerance as the inverse of risk aversion: $\tau_{i,j,r} = \frac{1}{A_{i,j,r}}$. The average risk tolerance is $\tau = \frac{\sum_i A_i + \sum_j A_j + \sum_r A_r}{N}$ and the average skew preference is $\frac{1}{2\bar{\tau}^2}$. In equilibrium, the coefficients before covariance and coskewness term become $-\frac{1}{\bar{\tau}}$ and $\frac{1}{2\bar{\tau}^2}$ respectively.

[7]Since production cost of renewable sources is assumed to be zero, production cost only comes from conventional generation. Existence of renewable generation cost does not change the main result.

Renewable generation affects forward price directly by output volatility and skewness, as well as indirectly through the composition of power market. In the absence of supply risk (when $K$ is constant), term II and III vanish and the equilibrium premium is reduced to the result in Bessembinder and Lemmon (2002)[8] if conventional market is not skewed. By equation (6),

$$\Pi_C = \frac{N_I}{a^x}(p_R p_S^x - \frac{1}{c} p_S^{x+1}) \tag{12}$$

Then, using second-order Taylor series expansions, we rewrite forward premium[9] as:

$$p_F - E(p_S) = \alpha Var(p_S) + \beta Skew(p_S) + \theta Cov(K, p_S) + \gamma Cos(K^2, p_S) + \eta Cos(K, p_S^2) + \Phi \tag{15}$$

where

$$\begin{aligned}
\alpha &= -\frac{A}{N}\varphi < 0 \\
\beta &= \frac{A^2}{2N^2}\varphi^2 - \frac{A}{N}\psi \\
\theta &= -\frac{A}{N}p_R < 0 \\
\gamma &= \frac{A^2 p_R^2}{2N^2} > 0 \\
\eta &= \frac{A^2 P_R}{N^2}\varphi > 0 \\
\psi &= \frac{xN_I}{2a^x}E(p_S)^{x-2}[(x-1)p_R - xE(p_S)] \\
\varphi &= \frac{N_I}{a^x}xE(p_S)^{x-1}[p_R - E(p_S)] > 0
\end{aligned}$$

and

$$\Phi = \frac{A^2\psi}{N^2}[\varphi(Kur(p_S) - Var^2(p_S)) + p_R(Cok(p_S^3, K) - Var(p_S)Cov(p_S, K)) + \frac{\phi}{2}(Hyp(p_S) - 2Var(p_S)Skew(p_S))] \tag{16}$$

indicates higher order central (mixed) moments. Kurtosis is highly correlated with variance and hyperskewness is correlated with skewness. Moreover, covariance

[8]Bessembinder and Lemmon (2002) give the result that:

$$p_F - E(p_S) = -\frac{A}{N}Cov(\Pi_C, p_S)$$

[9]In Bessembinder and Lemmon, the result is

$$p_F - E(p_S) = \alpha Var(p_S) + \beta' Skew(p_S) \tag{13}$$

where $\beta' = -\frac{A}{N}\psi$. If renewable is integrated and a symmetric profit distribution is assumed, the result is:

$$p_F - E(p_S) = \alpha Var(p_S) + \beta' Skew(p_S) + \theta Cov(K, p_S) \tag{14}$$

and coskewness between renewable output and price capture most of their interaction and other higher mixed moments become redundant. Hence, we simplify the model by focusing on second and third central and mixed moments while omitting higher moments.[10]

**Proposition 1.** *(Formation of forward premium) When the market has both demand and supply uncertainty, power forward premium is a linear combination of spot price variance "$Var(p_S)$", spot price skewness "$Skew(p_S)$", covariance "$Cov(K, p_S)$" and coskewness "$Cos(K^2, p_S), Cos(K, p_S^2)$" between spot price and renewable generation. The premium is negatively correlated with variance and covariance, and positively correlated with coskewness. It positively correlates to skewness when $c \geq 2$ and a negative correlation implies $1 < c < 2$.*

Note that the covariance and coskewness strengthen the ability to explain equilibrium forward premium only in the existence of both demand and supply risks. If there is no demand risk, price and supply are perfectly correlated so risk premium can be expressed as a combination of variance and skewness of wholesale spot prices:

$$p_F - E(p_S) = \alpha' Var(p_S) + \beta' Skew(p_S) \tag{17}$$

where

$$\begin{aligned}
\alpha' &= \frac{A}{N}\varphi' > 0 \\
\beta' &= \frac{A^2}{2N^2}(\varphi')^2 + \frac{A}{N}\psi' > 0 \\
\psi' &= \frac{N_I x^2}{2a^x}E(p_S)^{x-1} \\
\varphi' &= \frac{N_I x}{a^x}E(p_S)^x
\end{aligned}$$

The first two terms in equation (15) are the risk measures of conventional market, while the third and fourth proxies represent the risk from renewables. As coskewness between two variables are asymmetric, there is a fifth term, which stands for the interaction risk between conventional and renewable generation. Renewable generation in power market alters the pricing formation in two ways: first, higher penetration of renewables reduces the reliance on thermal plants, production cost of which is initially flat and then sharp on generation. Hence, upward spike in marginal production cost is less likely to happen so spot price as well as the impact of skewness is not necessarily positive; second, the relation between renewable output and spot price plays a role in pricing determination. The equilibrium spot price given by (7) implies systematic supply risk and spot price risk are negatively linked, $Cov(K, p_S) < 0$. Hence, a higher correlation between supply and spot price increases the premium, showing a higher value of holding spot. Moreover, the coskewness between supply and spot price is also considered in forward hedging strategies. Right skewed spot price means the ability

[10]Significance of higher moments can be easily tested. In our paper, we find them insignificant and not help to explain the forward premium.

to capture the supply skewness and this increases the value of holding it. In contrast, a negative coskewness means spot price hardly benefit from supply skewness so sellers are incline to sell more in forward market. Finally, the last term shows that a right (left) skewed renewable output relates to an upside (downside) spot volatility, which is liked (disliked) by agents who hold spot and infers a rise (reduction) of forward premium.

When share of conventional generation approaches zero, the variance, skewness, and interaction term vanish (i.e. $\alpha, \beta, \eta \to 0$), so premium pricing becomes a linear combination of $Cov(K, p_S)$ and $Cos(K^2, p_S)$. In this case, skewness of renewable output and spot prices should be negatively related. If renewable is positively (negatively) skewed, there are two countervailing (reinforcing) effects of renewable risk: (1) it increases forward premium because of risk aversion, (2) it decreases (increases) forward premium since spot return becomes frequently low (high). Therefore, a large positive premium occurs when renewable shocks change the marginal technology and/or a leftward deviation takes place, and vice versa. I summarize the above analysis as follows:

**Proposition 2.** *(Impact of renewables on forward premium) When renewable generation dominates, power forward premium is determined by covariance and coskewness between renewable output and spot price.*

$$p_F - E(p_S) = \theta Cov(K, p_S) + \gamma Cos(K^2, p_S) \tag{18}$$

*where $\theta < 0$ and $\gamma > 0$ are the same as in (15).*

Next, we explore the optimal forward position that can be characterized as follows,

$$Q^F_{i,j,r} = \frac{p_F - E(p_S)}{AVar(p_S)} + \frac{Cov(\rho_{i,j,r}, p_S)}{Var(p_S)} - \frac{A}{2}\frac{Cos(R^2_{i,j,r}, p_S)}{Var(p_S)} \tag{19}$$

where $\rho_{i,j,r} = R_{i,j,r} + p_S Q^F_{i,j,r}$. The optimal forward positions depend on three terms: expected basis term, risk hedging term, and prudence term. The expected basis term represents the firms' incentive to take advantage of expected forward-spot price difference. When forward price is higher than expected spot market, firms are willing to sell more in forward market, and vice versa. Note that this term is reversely affected by parameter of risk aversion. Intuitively, when $p_F > E(p_S)$, generators sell less and retailers buy more when they are more risk averse. On the other hand, when $p_F < E(p_S)$, generators sell more and retailers buy less when they are more risk averse. On top of that, hedging term reflects participants' spot trading risk in the absence of forward trading. In general, this term is positive for conventional generators, so they sell in the forward market to hedge their risk, and by contrast, negative for retailers, reflecting the fact that they should buy some forward to reduce their purchase risk in spot market.

The direction of hedging pressure from renewable revenue risk depends on how revenue and spot price is correlated. There are two countervailing effects: price effect and volume effect. When price effect dominates, renewable generators are positively exposed to profit risk so they have incentive to sell forward position. On the other hand, when volume effects dominates, increase of price implies lower profit so they take a higher risk to pursue a larger forward position. Moreover, as renewable supply shock increases the spot price volatility, it motivates conventional generators as well as retailers to trade more on forward market.

When preference for skewness seeking is included, generators would sell more (less) if coskewness term is negative (positive) as they want to avoid downside revenue loss from an extreme low spot price ((benefit from high price), while retailers buy less (more) if coskewness term is negative (positive) as they want to chase the high profit from an extreme low spot price (prevent large loss from high price), and forward price premium decreases (increases) reflecting the effect of prudence preference.

**Proposition 3.** *In the forward market,*

*(i) renewable shock affects conventional generators in three ways: (1) to occupy the market; (2) to increase spot volatility so generators sell more forward; (3) to decrease coskewness (less positive or more negative) so generators sell even more forward.*

*(ii) renewable shock affects retailers in two ways: (1) to increase spot volatility so buyers purchase more forward; (3) to decrease coskewness (less positive or more negative) so buyers purchase less forward.*

# 3 Data Description

We use German data from Jan 2015 to May 2021 to test the results obtained in previous section.[11] The original data is hourly spot price, daily one-month-ahead baseload and onpeak forward price traded on EEX, hourly demand and renewable (wind+solar) generation downloaded from SMARD. Onpeak period is hour 8:00-20:00. Baseload price is daily average price; peak price is average price across peak hours; the implied offpeak price and premium are calculated accordingly.

This part gives the summary statistics of demand, residual demand, renewable generation, spot prices, the covariance and coskewness between spot price and renewable output, and forward premium. The mean is calculated as monthly average. Standard deviation, standardized skewness, covariance and coskewness are calculated on a monthly basis using deviations of daily average from the expected monthly average. The summary is displayed as average across seasons and throughout full sample period. Spring is from March to May; Summer is from June to August; Fall is from September to November and Winter is defined as months December, January, and February.

## Table 1: Statistics of Demand (GWh) and Renewable Generation (GWh)

The first panel presents daily average demand, residual demand and renewable output that aggregates wind and utility-scale PV generation. The second and third panel reports the same variables, but average over peak time and offpeak time, respectively. For each variable, standard deviation and standardized skewness are also computed. All results are reported for each season and the whole year.

| | Daily Average | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | D | | | RD | | | K | | |
| Season | Mean | SD | Skewness | Mean | SD | Skewness | Mean | SD | Skewness |
| Spring | 56.54 | 2.99 | −1.66 | 38.77 | 7.42 | −0.78 | 17.78 | 6.73 | 0.68 |
| Summer | 55.10 | 1.54 | −0.83 | 40.41 | 4.88 | −0.93 | 14.68 | 4.83 | 1.09 |
| Fall | 58.10 | 1.97 | −1.34 | 42.72 | 7.20 | −0.53 | 15.38 | 7.14 | 0.64 |
| Winter | 60.66 | 3.90 | −1.21 | 43.09 | 9.30 | −0.33 | 17.60 | 8.37 | 0.36 |
| Overall | 57.64 | 2.64 | −1.27 | 41.20 | 7.26 | −0.64 | 16.45 | 6.81 | 0.68 |
| | Peak Average | | | | | | | | |
| | D | | | RD | | | K | | |
| Season | Mean | SD | Skewness | Mean | SD | Skewness | Mean | SD | Skewness |
| Spring | 62.78 | 3.70 | −1.86 | 39.49 | 8.56 | −0.73 | 23.29 | 7.53 | 0.55 |
| Summer | 62.11 | 1.73 | −0.91 | 40.78 | 6.05 | −0.77 | 21.32 | 5.93 | 0.93 |
| Fall | 65.01 | 2.22 | −1.51 | 46.66 | 8.05 | −0.51 | 18.35 | 7.84 | 0.57 |
| Winter | 67.11 | 4.43 | −1.27 | 48.47 | 9.88 | −0.36 | 18.67 | 8.84 | 0.41 |
| Overall | 64.27 | 3.08 | −1.40 | 43.80 | 8.19 | −0.59 | 20.48 | 7.57 | 0.61 |
| | Offpeak Average | | | | | | | | |
| | D | | | RD | | | K | | |
| Season | Mean | SD | Skewness | Mean | SD | Skewness | Mean | SD | Skewness |
| Spring | 50.31 | 2.41 | −1.21 | 38.05 | 6.74 | −0.75 | 12.26 | 6.37 | 0.71 |
| Summer | 48.08 | 1.51 | −0.91 | 40.04 | 4.22 | −0.84 | 8.05 | 4.15 | 0.99 |
| Fall | 51.19 | 1.87 | −1.13 | 38.78 | 6.78 | −0.54 | 12.41 | 6.79 | 0.69 |
| Winter | 54.20 | 3.48 | −1.06 | 37.72 | 9.10 | −0.30 | 16.53 | 8.25 | 0.32 |
| Overall | 51.01 | 2.35 | −1.08 | 38.60 | 6.77 | −0.61 | 12.42 | 6.44 | 0.67 |

## 3.1 Demand and Generation

Table 1 indicates that Germany has a higher demand for power in fall and winter compared to spring and summer. However, this difference is smaller for daily average residual demand since wind production is higher in winter, and that of peak demand is larger due to much lower solar production in winter. Moreover, we observe that residual demand is more volatile than demand, reflecting the supply volatility of intermittent renewable sources. Demand and renewable supply has weak relationship[12] ($Var(RD) \approx Var(D) + Var(K)$). Finally, note that demand is left skewed while renewable output is right skewd. The left skewness of residual demand very likely implies a left skewed spot price distribution.

## 3.2 Spot Price

Power prices exhibit daily and seasonal effects and are consistent with the residual demand variation reported in previous section. The highest peak price in winter shows the fact of large demand and low solar output, while a low offpeak price indicates large wind generation at night. Furthermore, price is more volatile in winter and spring, reflecting high uncertainty of wind output compared to solar PV. Finally, spot price is in general left skewed because of renewable penetration, but relatively symmetric during onpeak period of winter.

**Table 2: Statistics of Spot Price (€/MWh)**

Reported are the mean, variance and standard skewness of spot price, for peak hours, offpeak hours and throughtout the day. All results are reported for each season and in an overall basis.

| | Base | | | Peak | | | Offpeak | | |
|---|---|---|---|---|---|---|---|---|---|
| Season | Mean | SD | Skewness | Mean | SD | Skewness | Mean | SD | Skewness |
| Spring | 34.96 | 8.25 | −1.52 | 35.87 | 10.59 | −1.46 | 34.06 | 7.57 | −1.23 |
| Summer | 37.39 | 4.89 | −0.86 | 39.61 | 6.11 | −0.66 | 35.16 | 4.45 | −1.10 |
| Fall | 42.08 | 7.52 | −0.11 | 47.84 | 9.26 | 0.18 | 36.33 | 6.46 | −0.68 |
| Winter | 40.59 | 10.86 | −0.38 | 48.32 | 12.67 | 0.00 | 32.86 | 9.87 | −1.03 |
| Overall | 38.66 | 7.97 | −0.74 | 42.78 | 9.77 | −0.51 | 34.54 | 7.18 | −1.02 |

## 3.3 Mixed Moments between Spot Price and Renewable Generation

As expected, the *merit order effect* implies a negative correlation between spot price and generation from renewable sources. Moreover, this covariance is stronger at peak time as well as in winter since supply shock from renewables is more important at the

[11] A larger sample size is available, but we choose this period to isolate long-term dynamic effect and supply cost shock from summer of 2021 to spring of 2023.

[12] The correlation coefficient between demand and renewable generation is 0.08 for both peak and offpeak period.

**Table 3: Mixed Moments between Spot Price and Renewable Generation**

Reported are the mean covariance and coskewness between spot price and renewable generation, for peak hours, offpeak hours and throughtout the day. All results are reported for each season and in an overall basis. The unit for renewable production is in GWh, while we use €/MWh for spot price. The selection of unit is to make all moments in comparable size. Two nontrivial asymmetric coskewness are computed and the magnitude is reduced by dividing it by ten to make all moments comparable.

| | Cov$(K, p)$ | | | Cos$(K^2, p)$ | | | Cos$(K, p^2)$ | | |
|---|---|---|---|---|---|---|---|---|---|
| Season | Base | Peak | Off | Base | Peak | Off | Base | Peak | Off |
| Spring | -46.44 | −60.57 | −39.51 | -38.7 | −46.90 | −35.41 | 79.40 | 120.12 | 70.70 |
| Summer | -20.85 | −29.89 | −16.65 | -16.60 | −17.93 | −16.55 | 16.41 | 22.84 | 27.17 |
| Fall | -48.46 | −61.69 | −41.24 | -19.02 | −21.20 | −20.85 | 10.55 | −1.80 | 22.66 |
| Winter | -76.99 | −90.12 | −70.08 | -20.37 | −22.63 | −23.42 | 30.85 | 7.98 | 54.53 |
| Overall | -48.86 | −61.33 | −42.51 | -24.17 | −27.82 | −24.48 | 35.97 | 39.75 | 45.09 |

time of high demand and large production from wind sources. When demand is high, a negative supply shock will lead to a higher marginal price. Wind is more volatile than solar, and hence more correlated to spot prices.

The first coskewness Cos$(K^2, p)$ shows how upward volatility of renewable generation affects spot price. As positively skewed renewable production drives a left skewed spot price. This coskewness is negative, implying a low value to hold spot (low cost to purchase forward). Moreover, the second coskewness Cos$(K, p^2)$ indicates a comovement between the upside price volatility and renewable production, which is positive as renewable generation is right skewed.

## 3.4 forward Premium

The model gives the relationship between ex-ante forward premium and population statistics. We assume that ex-post premium is an unbiased estimate of ex-ante premium, which is calculated as the difference between forward price at month $t-1$ and sample mean of daily spot price in month $t$:

$$PREM_{t-1,j} = F_{t-1,j} - \frac{\sum_d S_{t,d,j}}{N_t}, \quad j \in \{\text{peak,offpeak,base}\} \tag{20}$$

We focus on one-month-ahead premium in this paper. One-month-ahead forward contract is continuously traded (except weekends) until the first day of delivery month. In order to avoid coincidence, we use three different ways to determine the forward price: (1) the closing price of last trading date; (2) the average of last seven day's forward price before delivery month; (3) the monthly average forward price before delivery month. Table 5 gives the results for baseload, peakload and offpeak premium.

We observe significant positive premium in winter and spring, and negative baseload premium except winter. This cannot be well explained by Besseminder and Lemmon

**Table 4: Seasonal Average Forward Premium (€/MWh)**

Reported are the average forward premium, for baseload, peakload and offpeak load. forward premium is calculated in three different ways: (i) the closing price of last trading day of one calendar month; (ii) the average closing price of last trading week of one calendar month; (iii) the monthly average closing price. Offpeak forward does not exist in practice, and is computed as the difference between baseload and onpeak forward price: off = 2∗base-peak. All results are reported for each season and in an overall basis.

| | forward Price Determination | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Last day | | | Last 7 days avg. | | | Monthly avg. | | |
| Season | Base | Peak | Off | Base | Peak | Off | Base | Peak | Off |
| Spring | −2.18*** | 1.45** | −5.82*** | −1.99*** | 1.97*** | −5.95*** | −1.48* | 2.71*** | −5.67*** |
| Summer | −3.65*** | −0.56 | −6.75*** | −3.81*** | −0.53 | −7.10*** | −4.18*** | −0.96 | −7.40*** |
| Fall | −1.72** | 1.11 | −4.54*** | −1.82** | 0.99 | −4.63*** | −1.97** | 0.81 | −4.75*** |
| Winter | 0.67 | 4.14*** | −2.79*** | 0.59 | 3.88** | −2.69*** | 0.80 | 4.27** | −2.67** |
| Overall | −1.68*** | 1.60*** | −4.95*** | −1.70*** | 1.65*** | −5.06*** | −1.63*** | 1.81*** | −5.08*** |

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

(2002) as winter peak price is rather volatile compared to other seasons and not skewed. Also, spring peak price is negatively skewed, which is not able to induce a positive forward premium.

Looking back to Table 3, the covariance in winter is strongest coincide with the large positive premium at peak time. The correlation is weakest in summer, when there is negative premium. Furthermore, spring and fall represent similar variance and covariance, but significantly different forward premium, which is explained by the skewness preference. Table 2 and 3 indicate a big difference of price skewness and coskewness between spring and fall, the former of which is notably stronger than other seasons.

# 4 Regression Results

In this part, we test the implications from theoretical part by simple OLS regression of premium on the explanatory variables as in (15):

$$PREM_t = \mu + \alpha Var(S_t) + \beta Skew(S_t) + \theta Cov(K_t, S_t) + \gamma Cos(K^2, p_S) + \eta Cos(K, p_S^2) + \epsilon_t \tag{21}$$

The sign of all coefficients except $\beta$ is definite. The sign of $\beta$ depends on the parameter $\psi$. If $\psi$ is non-positive, $\beta > 0$. If $\psi$ is positive, depending on the magnitude, $\beta$ can be either positive or negative. Therefore, to predict the sign of $\beta$, we start with estimating the parameter $c$ by taking logarithms of equation (7). The regression equation is:

$$\ln(S_t) = \lambda + (c-1)\ln(RD_t) + \zeta_t \tag{22}$$

while $\lambda = \ln(a/N_I^{\frac{1}{x}})$ is the constant term. Spot price and residual demand are calculated as daily average. The overall estimate is $c = 1.88$ for onpeak production and $c = 1.93$ for offpeak generation, irrespective of the seasonal effect.

**Table 5: Estimates on Cost Parameter "c"**

Reported are the estimates of parameter "c" that reflects the convexity of conventional generation cost function. Daily average spot price and residual demand data from Jan 2015 to May 2021 in German market are used for estimation. All results are reported for each season and in an overall basis. The numbers in parentheses are adjusted R square for each regression.

| Season | Base | Peak | Off |
|---|---|---|---|
| Spring | 1.77*** | 1.71*** | 1.64*** |
| | (0.22) | (0.25) | (0.14) |
| Summer | 2.01*** | 1.97*** | 1.96*** |
| | (0.34) | (0.42) | (0.24) |
| Fall | 1.77*** | 1.75*** | 1.86*** |
| | (0.37) | (0.38) | (0.41) |
| Winter | 1.92*** | 1.90*** | 2.13*** |
| | (0.42) | (0.38) | (0.43) |
| Overall | 1.88*** | 1.88*** | 1.93*** |
| | (0.34) | (0.40) | (0.31) |

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

As $x = \frac{1}{c-1}$, $1 < c < 2 \Leftrightarrow x > 1$. Therefore, the sign of parameter $\psi$ is indefinite, and so is $\beta$. Spot price skewness is composed of two terms: coskewness and covariance with conventional market risk. As skewness preference is assumed to be positive, the first term must be positive while the latter can amplify, offset or overweight the former one. To summary, we predict that:

**Hypothesis 1.** *The equilibrium power forward premium decreases with expected variance of spot prices, ceteris paribus.* $\alpha < 0$.

**Hypothesis 2.** *The equilibrium power forward premium decreases with expected covariance between spot prices and renewable output, ceteris paribus.* $\theta < 0$.

**Hypothesis 3.** *The equilibrium power forward premium increases with expected coskewness between spot prices and renewable output, ceteris paribus.* $\gamma > 0$, $\eta > 0$.

**Hypothesis 4.** *The equilibrium power forward premium may either increase, decrease or not change with expected skewness of spot prices, ceteris paribus.* $\beta \lesseqgtr 0$.

Table 6 reports the regression results. Renewable energy penetration challenges the validity of idiosyncratic variance and skewness to explain the formation of power forward premium, coefficients of which are not significant for baseload forward premium and very small for onpeak one. The lack of explanatory power on baseload forward premium reflects the fact that offpeak load is mostly satisfied by renewable generation, so the idiosyncratic moments, which represent risk from conventional generation, play a minor role.

## Table 6: Regression of Average Monthly Premium on Risk Factors

Reported are the estimates of forward premium on risk factors obtained in Bessembinder and Lemmon (2002), equation (14) which assumes symmetric distribution of profit, and equation (15) which assumes asymmetric distribution. Panel A, B, C are computed on the basis of baseload premium, peakload premium and offpeak premium, respectively. Asymmetric case 1 only includes $Cos(K^2, p)$, while asymmetric case 2 includes both $Cos(K^2, p)$ and $Cos(K, p^2)$. Forward premium is calculated in three different ways: (i) the closing price of last trading day of one calendar month; (ii) the average closing price of last trading week of one calendar month; (iii) the monthly average closing price. German data covering the period from Jan 2015 to May 2021 is used for estimation. The magnitude of estimates on risk factors are adjusted by multiplying by 10 in order to keep 2 decimals in reports.

| | Panel A: Baseload | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Last day | | | | Last 7 days avg. | | | | Monthly avg. | | | |
| Season | BL | Sym | Asy1 | Asy2 | BL | Sym | Asy1 | Asy2 | BL | Sym | Asy1 | Asy2 |
| Var($p$) | −0.03 | −0.37** | −0.54*** | −0.58*** | −0.01 | −0.58*** | −0.77*** | −0.81*** | −0.09 | −0.75*** | −0.96*** | −0.97*** |
| Skew($p$) | 0.00 | −0.02 | −0.05*** | −0.13** | −0.02 | −0.05** | −0.08*** | −0.16** | −0.04 | −0.08*** | −0.11*** | −0.14* |
| Cov($K, p$) | | −0.86*** | −1.39*** | −1.40*** | | −1.21*** | −1.82*** | −1.84*** | | −1.40*** | −2.05*** | −2.06*** |
| Cos($K^2, p$) | | | 0.62*** | 0.22 | | | 0.71*** | 0.33 | | | 0.76*** | 0.59 |
| Cos($K, p^2$) | | | | −0.40 | | | | −0.39*** | | | | −0.17*** |
| Cons | −1.89*** | −3.10*** | −3.12*** | −3.25*** | −1.80** | −3.51*** | −3.66*** | −3.53*** | −1.31 | −3.29*** | −3.31*** | −3.37*** |
| Adj. $R^2$ | −0.02 | 0.08 | 0.32 | 0.33 | −0.01 | 0.15 | 0.39 | 0.39 | 0.00 | 0.16 | 0.34 | 0.33 |
| | Panel B: Peakload | | | | | | | | | | | |
| | Last day | | | | Last 7 days avg. | | | | Monthly avg. | | | |
| Season | BL | Sym | Asy1 | Asy2 | BL | Sym | Asy1 | Asy2 | BL | Sym | Asy1 | Asy2 |
| Var($p$) | −0.05 | −0.38*** | −0.40*** | −0.45*** | −0.10* | −0.51*** | −0.55*** | −0.59*** | −0.14** | −0.57*** | −0.61*** | −0.62*** |
| Skew($p$) | −0.02 | −0.03*** | −0.04*** | −0.07*** | −0.03*** | −0.04*** | −0.06*** | −0.08*** | −0.04*** | −0.06*** | −0.07*** | −0.08*** |
| Cov($K, p$) | | −1.01*** | −1.34*** | −1.41*** | | −1.34*** | −1.68*** | −1.74*** | | −1.38*** | −1.72*** | −1.73*** |
| Cos($K^2, p$) | | | 0.57*** | 0.37** | | | 0.58*** | 0.40** | | | 0.58*** | 0.54** |
| Cos($K, p^2$) | | | | −0.19* | | | | −0.17 | | | | −0.04 |
| Cons | 1.93** | −0.57 | −0.80 | −0.90 | 2.29** | −1.04 | −1.27 | −1.36 | 2.85*** | −0.57 | −0.80 | −0.82 |
| Adj. $R^2$ | 0.01 | 0.20 | 0.35 | 0.36 | 0.07 | 0.33 | 0.44 | 0.45 | 0.12 | 0.31 | 0.39 | 0.38 |
| | Panel C: Offpeak | | | | | | | | | | | |
| | Last day | | | | Last 7 days avg. | | | | Monthly avg. | | | |
| Season | BL | Sym | Asy1 | Asy2 | BL | Sym | Asy1 | Asy2 | BL | Sym | Asy1 | Asy2 |
| Var($p$) | 0.04 | −0.29** | −0.32** | −0.59*** | 0.10 | −0.29* | −0.32** | −0.60*** | 0.16 | −0.20 | −0.24 | −0.81*** |
| Skew($p$) | 0.01 | 0.00 | −0.02 | 0.00 | 0.02 | 0.01 | −0.01 | 0.01 | 0.04 | 0.03 | 0.01 | 0.05 |
| Cov($K, p$) | | −0.73*** | −0.94*** | −1.27*** | | −0.87*** | −1.13*** | −1.47*** | | −0.81** | −1.08*** | −1.78*** |
| Cos($K^2, p$) | | | 0.44*** | 0.88** | | | 0.56*** | 1.02*** | | | 0.59*** | 1.52*** |
| Cos($K, p^2$) | | | | 0.35* | | | | 0.37 | | | | 0.75*** |
| Cons | −5.14** | −6.16*** | −5.96*** | −5.90*** | −5.55*** | −6.75*** | −6.49*** | −6.44*** | −5.73*** | −6.85*** | −6.58*** | −0.67*** |
| Adj. $R^2$ | −0.02 | 0.09 | 0.24 | 0.26 | −0.01 | 0.12 | 0.31 | 0.33 | 0.00 | 0.07 | 0.22 | 0.28 |

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

Augmenting covariance term significantly improve the performace of all variables (except skewness of offpeak prices) and the signs of estimates are consistent with model prediction. Specifically, as covariance and variance are negatively correlated, omitting covariance overestimates the coefficient of variance (so a small absolute value). In general, taking into account the covariance term increases the adjusted $R^2$ by 14 percent for baseload premium, and 21 percent for onpeak one. The increased importance of covariance on forward pricing during peak time demonstrates the fact that a positive renewable supply shock lowers spot price more than offpeak time.

Enhanced by coskewness term $Cos(K^2, p)$ further corrects the bias and increases the explanatory power of both baseload and onpeak forward premium regression, by 22 percent and 11 percent respectively. As predicted, firms value the positive renewable supply skewness. Hence, an extreme positive supply shock affects the premium in two opposite ways: it increases premium as aversion to risk, and decreases premium as preference to a low spot price. Since offpeak price is relativley low and less volatile, the skewness effect becomes more noticeable during that period.

Finally, to add another coskewness term $Cos(K, p^2)$ does not help much to explain the premium for baseload and peakload, but introduces severe collinearity problem as shown in Table 7. Recall that $Cos(K, p^2)$ shows the interaction between renewable generation risk, conventional generation risk and spot price. Therefore, highly correlated with skewness $Skew(p)$ and coskewness $Cos(K^2, p)$, the change of estimates on which is roughly equal to the coefficient on $Cos(K, p^2)$. However, the empirical redundancy does not mean $Cos(K, p^2)$ is trivial from theoretical perspective. As coskewness is asymmetric between two variables, full information requirement implies incorporation of both terms.

## Table 7: Correlation Matrix

Reported are the correlation matrix among variance, skewness, covariance, and two coskewness. Panel A gives the matrix for baseload risk factors, panel B is the matrix for onpeak, and panel C is computed on the basis of offpeak terms.

| | Panel A: baseload | | | | |
|---|---|---|---|---|---|
| | Var($p$) | Skew($p$) | Cov($K,p$) | Cos($K^2,p$) | Cos($K,p^2$) |
| Var($p$) | 1.00 | | | | |
| Skew($p$) | −0.66 | 1.00 | | | |
| Cov($K,p$) | −0.89 | 0.47 | 1.00 | | |
| Cos($K^2,p$) | −0.40 | 0.37 | 0.49 | 1.00 | |
| Cos($K,p^2$) | 0.62 | −0.88 | −0.52 | −0.73 | 1.00 |
| | Panel B: peakload | | | | |
| | Var($p$) | Skew($p$) | Cov($K,p$) | Cos($K^2,p$) | Cos($K,p^2$) |
| Var($p$) | 1.00 | | | | |
| Skew($p$) | −0.51 | 1.00 | | | |
| Cov($K,p$) | −0.88 | 0.36 | 1.00 | | |
| Cos($K^2,p$) | −0.51 | 0.51 | 0.56 | 1.00 | |
| Cos($K,p^2$) | 0.44 | −0.87 | −0.39 | −0.71 | 1.00 |
| | Panel C: offpeak | | | | |
| | Var($p$) | Skew($p$) | Cov($K,p$) | Cos($K^2,p$) | Cos($K,p^2$) |
| Var($p$) | 1.00 | | | | |
| Skew($p$) | −0.78 | 1.00 | | | |
| Cov($K,p$) | −0.86 | 0.64 | 1.00 | | |
| Cos($K^2,p$) | −0.47 | 0.46 | 0.50 | 1.00 | |
| Cos($K,p^2$) | 0.79 | −0.76 | −0.63 | −0.83 | 1.00 |

Even from empirical standpoint, the significance of the second coskewness is sample dependent. It is not necessary that multicollinearity messes up the result. For instance, the regression results of implied offpeak premium show that a second coskewness adds additional information, corrects the bias of other variables and improves the explanatory power. In fact, as the main purpose of the model in our paper is to show how risk measures predict equilibrium forward price rather than accurately identify the coefficient of each variable, we focus on the goodness of fit. If a new variable increases the explanatory power, it should be included in the pricing model, and vice versa. Note that covariance and variance are also highly correlated, which makes the significance of coefficients more impressive, as in this case, bias caused by omitted variable overweights the problem of collinearity, and covariance term provides abundant information that is orthogonal to variance and relevant to forward evaluation. Similar argument also holds when we include the first coskewness.

In order to better understand the effect of underlying shocks on forward premium, we rewrite the risk measurements in terms of supply and demand shocks through equation (7), and the regression equation[13] becomes:

$$PREM_t = b_0 + b_1 Var(D_t) + b_2 Skew(D_t) + b_3 Var(K_t) + b_4 Skew(K_t) + \epsilon_t \qquad (23)$$

**Table 8: Regression of Average Monthly Premium on Supply and Demand Shocks**

Reported are the estimates of forward premium on risk factors obtained in equation (23). Forward premium is calculated in three different ways: (i) the closing price of last trading day of one calendar month; (ii) the average closing price of last trading week of one calendar month; (iii) the monthly average closing price. German data covering the period from Jan 2015 to May 2021 is used for estimation.

| | forward Price Determination | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Last day | | | Last 7 days avg. | | | Monthly avg. | | |
| Season | Base | Peak | Off | Base | Peak | Off | Base | Peak | Off |
| Var($K$) | 0.07*** | 0.08*** | 0.05*** | 0.08*** | 0.09*** | 0.07*** | 0.09*** | 0.10*** | 0.08*** |
| Skew($K$) | −0.05*** | −0.05*** | −0.05*** | −0.06*** | −0.05*** | −0.07*** | −0.07*** | −0.06*** | −0.08*** |
| Var($D$) | −0.06 | −0.14 | −0.05 | −0.17 | −0.24 | −0.15 | −0.12 | −0.12 | −0.20 |
| Skew($D$) | 0.00 | −0.01 | −0.01 | −0.02 | −0.02 | −0.02 | −0.01 | −0.01 | −0.02 |
| Cons | −3.72*** | −1.60 | −6.16*** | −4.18*** | −2.18* | −6.55*** | −4.44*** | −2.47 | −6.74*** |
| Adj.$R^2$ | 0.29 | 0.27 | 0.19 | 0.31 | 0.28 | 0.28 | 0.25 | 0.20 | 0.27 |

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

[13] We omit the interaction terms because the correlation between demand and supply are very weak in our sample. We also run the regression with those terms and the results are not significantly changed. When demand and renewable supply are highly correlated, covariance and coskewness between these two shocks should also affect the results.

The result shows that renewable volatility increases while its skewness decreases the forward premium, which is in line with our previous analysis. Moreover, renewable skewness becomes more important during offpeak period compared to peak period, confirming our conjecture that retailers (sellers) are more risky (prudent) to take spot risk when demand is low and supply is abundant. Finally, it is striking that demand variation does not provide extra explanatory power. This implies that convexity of thermal plants' supply curve rather than demand variation itself affects the forward premium. In other words, when renewable sources constitute a significant portion of production, demand variation hardly contributes to upward cost spike, and hence does not affect risk premium.

# 5 Equilibrium During Turbulence

The summary statistics clearly shows a different pattern of spot price and forward premium after energy crisis.[14] Due to gas price hike, the expected spot price, spot price variance, skewness, covariance and coskewness all increase a lot. Furthermore, the exogenous parameter such as retail price, generation mix also change during the period of crisis. Hence, we extract this period from the regression in previous section and test it separately.

**Table 9: Regression of Average Monthly Premium on Risk Factors (Energy Crisis)**

Reported are the estimates of forward premium on risk factors obtained in equation (15) which assumes asymmetric distribution. Only $Cos(K^2, p)$ is included as coskewness term. Forward premium is calculated in three different ways: (i) the closing price of last trading day of one calendar month; (ii) the average closing price of last trading week of one calendar month; (iii) the monthly average closing price. German data covering the period from June 2021 to Feb 2023 is used for estimation. For each way, baseload, peakload and offpeak premium are used for regression. The magnitude of estimates on risk factors are adjusted by multiplying by 10 in order to keep 2 decimals in reports.

| | Last day | | | Last 7 days avg. | | | Monthly avg. | | |
|---|---|---|---|---|---|---|---|---|---|
| Season | Base | Peak | Off | Base | Peak | Off | Base | Peak | Off |
| Var($p$) | −0.07** | −0.06 | −0.08*** | −0.07 | −0.08 | −0.09* | −0.12** | −0.12** | −0.14** |
| Skew($p$) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Cov($K, p$) | −1.20** | −1.22* | −1.33*** | −1.38* | −1.64* | −1.38** | −2.28*** | −2.71*** | −2.06*** |
| Cos($K^2, p$) | 0.36 | 0.57 | 0.13 | 0.92 | 1.19 | 0.54 | 1.29 | 1.61* | 0.72 |
| Cons | −5.35 | 26.56 | −36.47** | 10.74 | 44.08 | −23.84 | 9.87 | 43.66 | −23.81 |
| Adj. $R^2$ | 0.21 | 0.03 | 0.42 | 0.07 | 0.06 | 0.12 | 0.29 | 0.29 | 0.32 |

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

In spite of small sample size, the results in table 9 give insights into firms' hedging behavior in times of turmoil. First, firms still show apparent risk aversion, but not

[14] See Appendix figure in D.

obvious on skewness preference. Furthermore, compared to offpeak premium, the model presents smaller explanatory power for onpeak premium, reflecting the reality that firms overreact during the periods of high uncertainty, especially when supply is tight. Finally, this irrational behaviour is modified over time, so the equilibrium model explains much better on an monthly average basis.

# 6 Conclusion

We conduct an investigation into the impact of asymmetric risk of renewable sources on firms' hedging strategies and equilibrium forward pricing in electricity markets. Particularly, we claim that power market participants not only care about the volatility introduced by intermittent renewables, but also evaluate its right-skewed distribution. As a positive supply shock leads to a lower spot price, the aversion to risk implies a high forward premium. However, the agents also realize that renewable generation is positively skewed, so buyers keep a smaller forward position in order to benefit from an extreme low spot price, which results in a lower forward premium. After accounting for the covariance and coskewness between renewable output and electricity spot price. The idiosyncratic risk measurements (i.e. the variance and skewness of spot power price) that reflect conventional market risk, still play a role in explaining the forward price formation. Specifically, spot price variances negatively relate to forward premia while the effect of skewness depends on the convexity of thermal plants' supply curve.

The empirical results obtained from German market support our predictions. Especially, we find a very small and negatively significant estimate on spot price skewness, reflecting the reality that renewable penetration reduces the average production costs of thermal plants by merit-order effect. Furthermore, the empirical analysis demonstrate the significance to incorporate renewable shocks and skewness preference in interpreting equilibrium forward premia. Variance and skewness of spot price barely explain forward premia while augmenting covriance term increases the adjusted $R^2$ by by 14 percent for baseload premium, and 21 percent for peak one. Incorporating coskewness futher increases the explanatory power of baseload and onpeak forward premium by 22 percent and 11 percent respectively.

To test the relationship between forward premium and underlying supply and demand shocks, we further run a regression on variance and skewness of demand and renewable sources, and the result indicates renewable variation positively affects forward premium while skewness decreases it. However, demand variance and skewness do not show a significant impact on risk premium.

Our paper sheds light on the mixed results of previous research. We believe that renewable adoption in the electricity market has changed the way producers and retailers determine their forward position, so regression setup that omits renewable variability and/or skewness would give results that are either not significant or opposite to theory, and proves to be weak to explain the forward premium formation. Some papers consider the level of renewable production or a reduced form regression, and the underlying mechanism is not yet well understood. Hence, our paper contributes to bridge this gap, both theoretically and empirically. Finally, even we explicit conduct an analysis in electricity market, the skewness preference and the model developed are also relevant to other markets, especially to explain the forward hedging decisions and equilibrium price formation.

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# Appendix

## A Proof of Equilibrium Forward Premium

$p_R D - C(Q) = \Pi_C + p_R K$, then:

$$Cos[(p_R D - C(Q))^2, p_S] = p_R^2 Cos(K^2, p_S) + 2p_R Cos(\Pi_C, K, p_S) + Cos(\Pi_C^2, p_S) \quad \text{(A.1)}$$

$$Cov(p_R D - C(Q), p_S) = Cov(\Pi_C, p_S) + p_R Cov(K, p_S) \quad \text{(A.2)}$$

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 $E(p_S)$ gives:

$$\begin{aligned} p_S^x &\approx E(p_S)^x + x[E(p_S)]^{x-1}(p_S - E(p_S)) + \frac{x(x-1)E(p_S)^{x-2}}{2}(p_S - E(p_S))^2 \\ &= [E(p_S)]^x \left[1 - x + \frac{x(x-1)}{2}\right] + x(2-x)E(p_S)^{x-1}p_S + \frac{x(x-1)}{2}E(p_S)^{x-2}p_S^2 \end{aligned} \quad \text{(A.3)}$$

Similarly,

$$p_S^{x+1} = [E(p_S)]^{x+1}\left[-x + \frac{x(x+1)}{2}\right] - (x+1)(x-1)E(p_S)^x p_S + \frac{x(x+1)}{2}E(p_S)^{x-1}p_S^2 \quad \text{(A.4)}$$

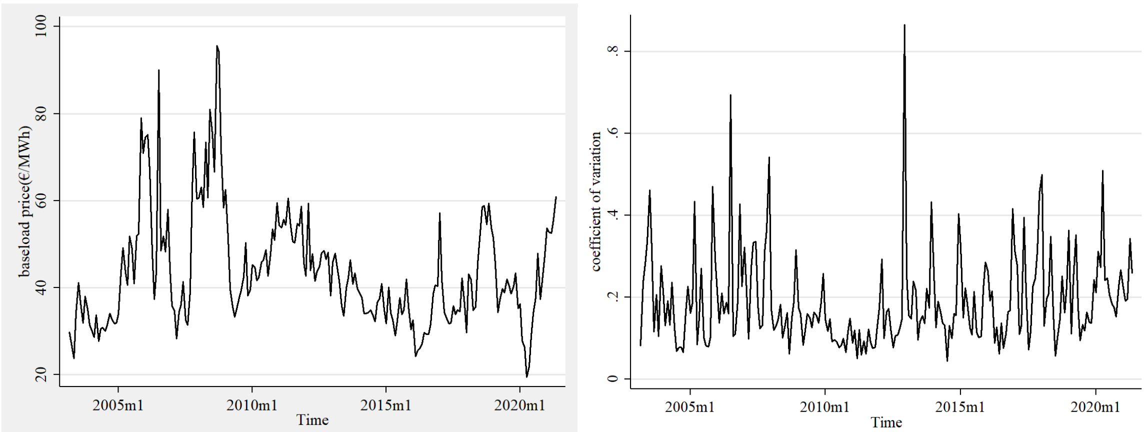
$\Pi_C = \frac{N_I}{a^x}(p_R p_S^x - \frac{1}{c}p_S^{x+1}) = cons + \phi p_S + \psi p_S^2$
$Cov(\Pi_C, p_S) = \varphi Var(p_S) + \psi Skew(p_S)$
$Cos(\Pi_C, K, p_S) = \varphi Cos(p_S^2, K) + \psi Cok(p_S^3, K) - \psi Var(p_S) Cov(p_S, K)$
$Cos(\Pi_C^2, p_S) = \phi^2 Skew(p_S) + 2\phi\psi(Kur(p_S) + 2E(p_S)Skew(p_S) - Var^2(p_S))$
$+ \psi^2(Hyp(p_S) + 4E(p_S)Kur(p_S) + [4E^2(p_S) - 2Var(p_S)]Skew(p_S) - 4E(p_S)Var^2(p_S))$

where

$$\phi = \frac{N_I}{a^x} x E(p_S)^{x-1}[(2-x)p_R - (1-x)E(p_S)]$$
$$\psi = \frac{xN_I}{2a^x} E(p_S)^{x-2}[(x-1)p_R - xE(p_S)]$$
$$\varphi = \frac{N_I}{a^x} x E(p_S)^{x-1}[p_R - E(p_S)]$$

Rearranging the terms gives the result in (15).

# B Baseload Price and Variation




**(a)** Baseload Price **(b)** Coefficient of Variation

**Figure 1:** Baseload Spot price and Variation Coefficient from Mar.2003 to May 2021

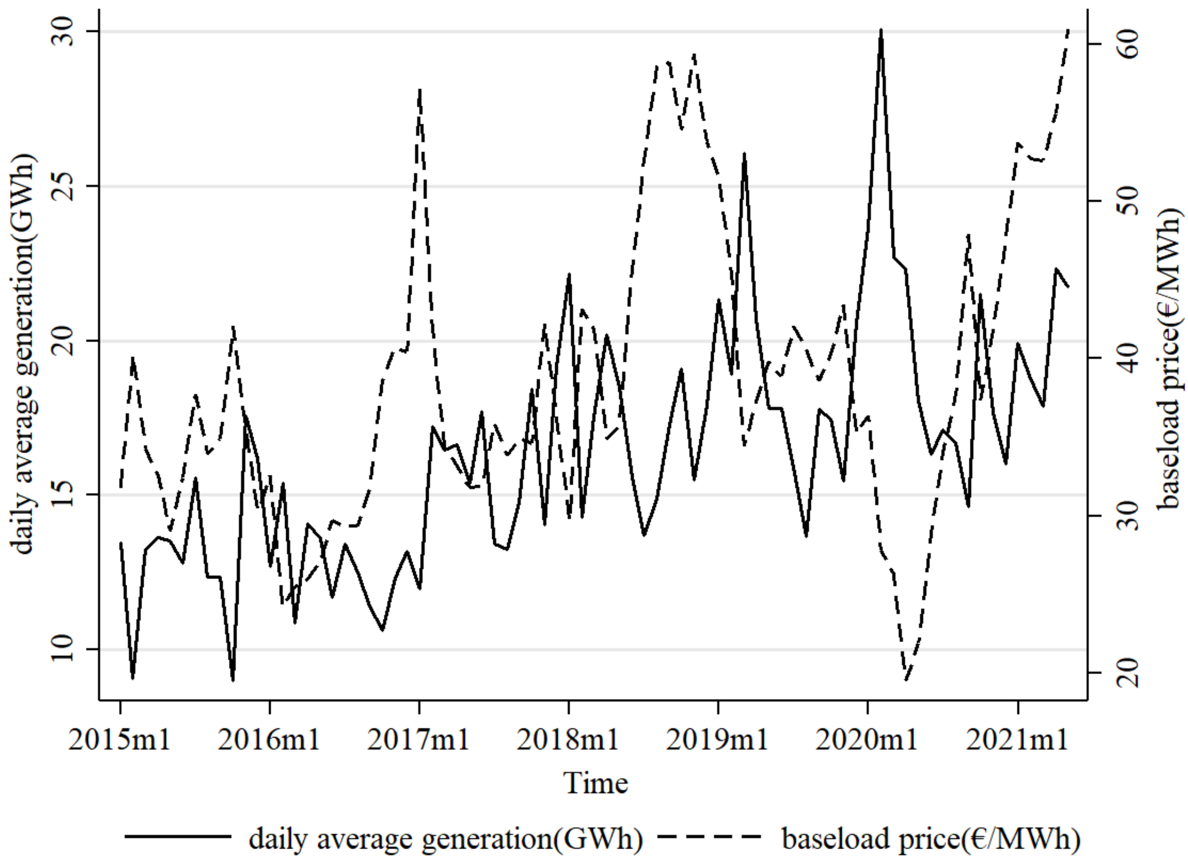



**Figure 2:** Negative Correlation between Renewable Output and Spot Price

# C Distribution of Renewable and Spot Price

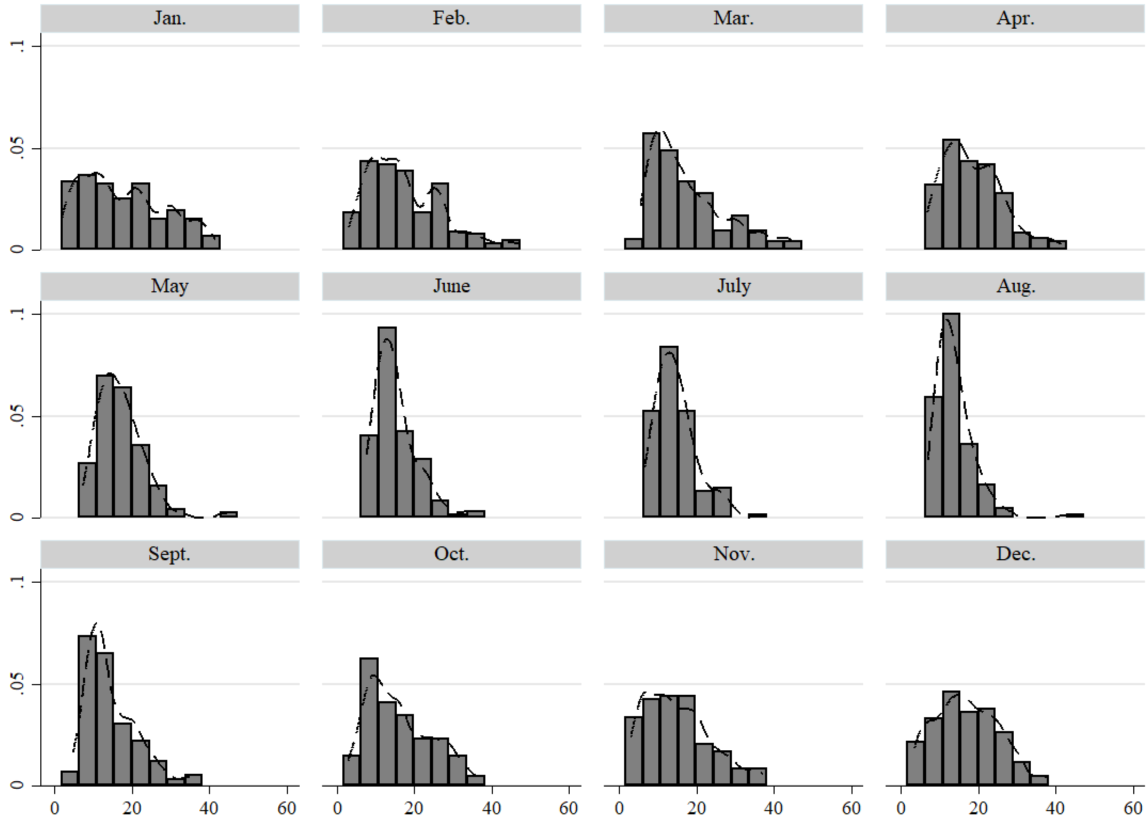



**Figure 3:** Distribution of Renewable Output Across Months

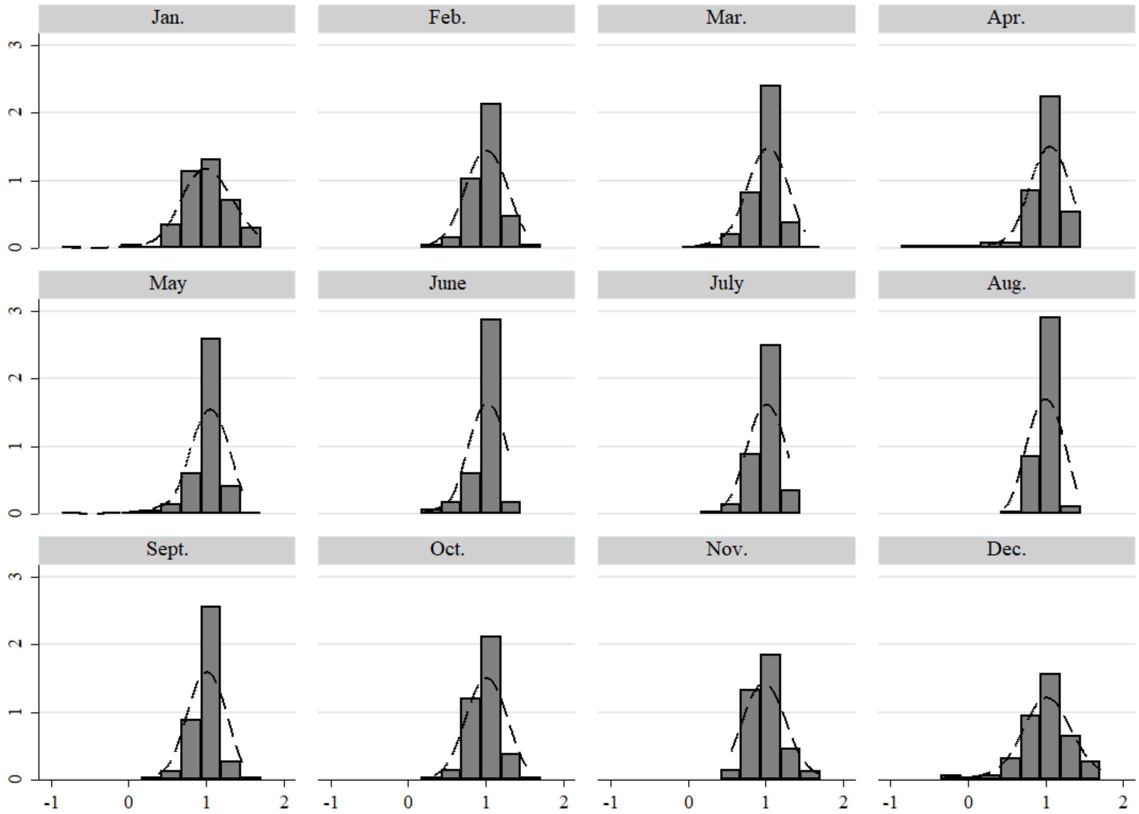
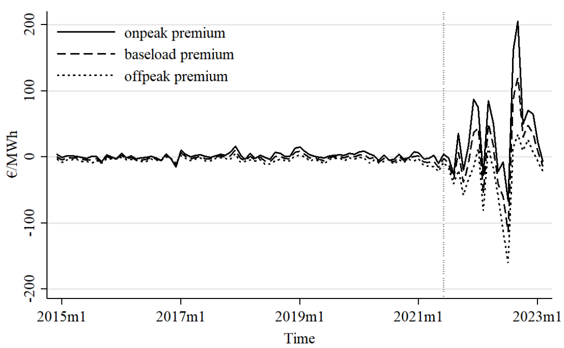
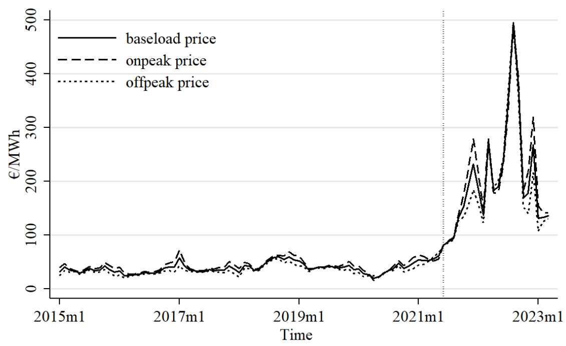



**Figure 4:** Distribution of Baseload Spot Price Across Months

# D Statistics at Energy Crisis




**(a)** Forward Premium




**(b)** Spot price

**Figure 5:** Spot price and Forward Premium Before and After Crisis