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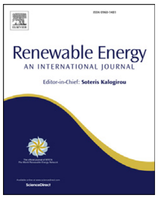

# Pricing forward contracts in power markets with variable renewable energy sources

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ABSTRACT

With the ongoing increase of variable renewable energy sources (VRES), such as wind or solar power, weather dependent production profiles induce uncertainty on the supply side and change operations at large in wholesale power markets. In this paper, we study how an increasing market share of VRES affects spot power price dynamics and the forward price premium. Using data from simulated power markets, we analyse the forward premium in three identical power markets with a varying market share of VRES supplied to the system. We demonstrate that markets with a high share of supply from VRES yield a significantly lower forward premium than markets with a low market share of wind or solar supply. Our results further confirm that, regardless of the market share of supply from VRES, forward power prices contain information about future spot power prices. These insights generate important implications for producers, retailers and other market participants exposed to wholesale price risk.

## 1. Introduction

This paper focuses on how the market share of supply from variable renewable energy sources (hereafter referred to as VRES), such as solar and wind, affects the premium priced in a forward contract for the delivery of power during a future period of time.[1] In their seminal work, Bessembinder and Lemmon [1] provide a theoretical equilibrium model that relates forward prices in power markets to the expected variance and skewness of spot prices. Empirical validations of this framework have however led to mixed results. Bunn and Chen [2] point out that empirical studies exhibit a wide range of results in terms of the size and sign of the forward premium, as they tend to focus on the sign and size of forward premiums rather than on underlying market fundamentals and production technologies. In this paper, we therefore assess whether uncertainty coming from both the demand and supply side affects the above forward price dynamics. We assess this by focusing on the changes in the forward premium under an increasing market share of VRES, which are variable and uncertain by nature.

Bessembinder and Lemmon [1] derive the power forward premium as the difference between the forward price and the expected spot price of power. They consider wholesale forward and spot power markets where homogeneous producers sell power to retailers, who in turn purchase that power and sell it to final consumers at a fixed unit price. Demand from final consumers is uncertain and ramping flexibility of producers is unrestricted. In equilibrium, Bessembinder and Lemmon [1] find that the forward power price will generally be a biased forecast of the future spot price, with the forward premium decreased by the expected variance of wholesale spot prices and increased by the expected skewness of wholesale spot prices. Otherwise stated, they show that:

$$F = E(S) - \kappa \times var(S) + \gamma \times skew(S), \tag{1}$$

where F is the forward price, S is the spot price, E(S) is the expected spot price, var(S) is the expected variance of spot prices, and skew(S) is the expected skewness of spot prices and $\kappa$ and $\gamma$ being positive parameters. The rationale behind the negative effect of expected spot price variance on forward premiums relates to risk-averse producers mitigating price risk by engaging in forward

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[1] When we mention forward contracts in this paper we refer to both forward and futures contracts.

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contracts. A positive skewness on the other hand yields a high probability of large upward price spikes, resulting in risk-averse retailers to hedge against spot price risk. In order to hedge against spot price uncertainty, risk-related hedging behaviour of producers and retailers thus drives downward and upward pressure on forward prices (Koolen et al. [3]).

In this paper, we study how the above forward market price dynamics are affected by an increasing market share of VRES[9]. There is a growing stream of literature investigating the impact of VRES on the volatility of power prices in sequential markets. Goodarzi et al. [4] find that high forecast errors from VRES yield higher trading volumes in spot markets. These increased volumes in turn affect the spot price, with possible spill-over effects in intraday and day-ahead markets. Astaneh and Chen [5] find that the volatility of forward prices increases with the share of VRES, as uncertainty on spot prices may indeed propagate into forward markets. Looking at day-ahead markets, Kyritsis et al. [6] and Rintamäki et al. [7] show that the variance of power prices directly depends on the market share of VRES. Although mixed findings have been reported with regards to increasing solar supply, depending on the timing of production in relation to demand (Kyritsis et al. [6], Reinhard et al. [8]), increased supply from VRES thus typically increases (spot) price volatility. In this paper, we relate the effect of VRES on forward pricing to the hedging needs of risk-averse producers, as anticipated forecast errors from VRES should decrease forward premiums. We thus expect an increasing market share of VRES to increase the variance of spot power prices and consequently, following (1), to impose a negative effect on the forward price premium.

Work on the effects of VRES on the (expected) skewness of power prices is relatively scarce. Gianfreda and Bunn [9] find an effect of VRES on the skewness of spot prices, describing that in the German day-ahead market price skewness turns from positive to negative under the influence of VRES. In a similar market setting, Huisman et al. [10] also show that with the increase of VRES, the tail on the left side of the power price distribution function (low prices) becomes increasingly fatter and the tail on the right side of the power price distribution function (high prices) become increasingly thinner. Huisman and Stet [11] show that the lower and higher quantiles of empirical power price distributions depend directly on the market share of supply from VRES. Furthermore, forecast errors on VRES may asymmetrically impact market prices depending on the reserve margin[2] level and the relative market share of VRES. For example, when the market share of VRES is predicted to be high, VRES overproduction may lead to low or even negative skewness, whereas underproduction may impact the price less due to the high reserve margin supplied by non-intermittent power producers that can ramp up production to rebalance the system. The same logic holds vice versa. When supply from VRES is predicted to be low, VRES underproduction may lead to extremely high spot power prices, and thus to high skewness levels, whereas overproduction will have a smaller effect on spot prices due to the high number of non-intermittent power producers who can reduce production to rebalance the system. Indeed, Kiesel and Paraschiv [12] document evidence on the asymmetric impact of VRES on intra-day and balancing market prices, finding proof for asymmetric effects from positive and negative forecast errors. It can thus be inferred that the introduction of VRES in spot markets[3] lowers the skewness of power prices by increasing the probability of low price spikes and decreasing the probability of high price spikes. Following (1), we expect risk-related hedging pressure of retailers therefore to decrease, resulting in a negative effect on the forward price premium.

The rest of this paper is organized as follows. We describe the methodology in the following section, embedding our work in the forward pricing theory. In Section 3, we describe the market framework, using data from a simulated market environment. We next discuss the results of the analysis and conclude by considering implications for market participants in renewable power systems.

## 2. Methodology

Fama and French [13] study the information embedded in the forward basis[4] in light of two alternative but not competing views: the theory of storage and expectations theory. In the first, traders can store and carry commodities until the delivery moment and the forward premium reflects storage, financing costs and a convenience yield for when traders expect frictions and prefer to have the physical asset instead of a contract. The other theory applies more directly to commodities for which storage is expensive or non-existing or for which quality depreciates over time. The forward basis then embeds information about an expected risk premium and expected change in the spot price between now and the delivery moment. Following the latter, let $F_{t,T}$ be the forward prices quoted at time t for delivery moment T. The forward basis is $F_{t,T} - S_t$, with $S_t$ being the spot price of the commodity at time t. Let $S_T$ be the spot price at the delivery moment T. Fama and French [13] propose two regression equations:

$$S_T - S_t = \alpha_1 + \beta_1 \times (F_{t,T} - S_t) + \varepsilon_{1,t}, \tag{2}$$

$$F_{t,T} - S_T = \alpha_2 + \beta_2 \times (F_{t,T} - S_t) + \varepsilon_{2,t}. \tag{3}$$

A positive $\beta_1$ signals that the forward basis contains information about the future change in the spot price, whereas a positive $\beta_2$ signals that the forward basis contains information about the to be realised risk premium. Note that by construction of equations (2) and (3), the summation of $\alpha_1$ and $\alpha_2$ is equal to zero and the summation of $\beta_1$ and $\beta_2$ is equal to one. The relation between $\beta_1$ and $\beta_2$ denotes that equations (2) and (3) will attribute the change in the forward basis to either the forecasting power of forward prices, to the expected change in spot prices or to a combination of both. Regarding the intercept of the equations proposed by Fama and French [13], unless they are both equal to zero, $\alpha_1$ and $\alpha_2$ will have opposite signs.

Fama and French [13] predict that in commodity markets with high storage costs, which is the case for power markets, forward prices are expected to contain information about future spot prices. We thus expect $\beta_1$ to be high, close to the value of one and, respectively, $\beta_2$ to be low, close to the value of zero. Huisman and Kilic [14] provide a fundamental explanation for the relation between forward and spot power prices by testing equations (2) and (3) in Dutch and NordPool power markets. Their results show that

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[9] In this paper, we consider the introduction of renewable power production via large utility-scale VRES. Note that small-scale renewables may induce a different effect due to the relation between risk-related hedging pressure of producers and retailers (Koolen et al. [3]). Furthermore, a tipping point may be observed depending on the level of reduced demand vs. demand uncertainty (Bessembinder and Lemmon [1]).

[2] We refer to reserve margin as idle non-intermittent production capacity at some point in time.

[3] The focus of the described papers concentrates on prices in day-ahead contracts, that involve the delivery of power during some period in the next day. In fact, a day-ahead contract is a one-day forward contract. However as the day-ahead market is widely regarded as the reference market for power pricing, it is reasonably to assume that the same relation holds for a spot market.

[4] We refer to the forward basis as the difference between the observed forward price for a contract that matures at a later date and the observed present spot price.

forward contracts with maturities between 1- and 6-months exhibit forecasting power over the spot day-ahead power prices with $\beta_1$ varying between 0.6 and 0.8 for the Dutch market and between 0.8 and 0.9 for the NordPool market. The difference in $\beta_1$ is attributed to the power mix differences between the two markets and the relative capacity of indirectly storing power through the underlying fuels. The Dutch power market, dominated by gas power producers, has capacity to indirectly store power through storing gas, thus leading to a lower $\beta_1$ estimate. In contrast, NordPool is dominated by hydro power plants which are more weather dependent and have a lower capacity to indirectly store power, resulting in a $\beta_1$ value closer to one. The results of Huisman and Kilic [14] thus confirm our view with regards to the value of $\beta_1$ in power markets that have no or limited (in)direct storage capacity.

Subtracting the current spot price from both sides of the equation (1) and using time subscripts, we obtain:

$$F_{t,T} - S_t = E(S_T) - S_t - \kappa \times var(S) + \gamma \times skew(S). \tag{4}$$

Equation (4) states that the forward basis embeds information about the expected change in the spot price and information about the variance and skewness of spot prices. Rewriting equation (4) in regression form gives us:

$$S_T - S_t = \alpha_3 + \beta_3 \times (F_{t,T} - S_t) + \varepsilon_{3,t}, \tag{5}$$

where we expect that $\beta_3 = 1$ and that $\alpha_3 = \kappa \times \text{var}(S) - \gamma \times \text{skew}(S)$ contains information about the expected variance and skewness of spot prices. Recall that $\kappa$ and $\gamma$ in equation (1) are positive parameters. We use this regression to test our claim that the combined impact of variance and skewness in Bessembinder and Lemmon [1] should lead to lower forward premiums in power systems with a higher share of VRES. We are thus interested to test whether $\alpha_3$ is larger in a power market with a high share of VRES than in a power market without VRES.

An alternative way to test for the same hypothesis is by making use of equation (3) where, for power markets with no storage, we expect $\beta_2 = 0$. If we include this information in equation (3), we obtain:

$$F_{t,T} - S_T = \alpha_2 + 0 \times (F_{t,T} - S_t) + \varepsilon_{2,t} = \alpha_2 + \varepsilon_{2,t}. \tag{6}$$

Equation (6) is equivalent with equation (1). If in equation (1) we subtract on both sides $E(S_T)$, we obtain:

$$F_{t,T} - E(S_T) = -\kappa \times var(S) + \gamma \times skew(S), \tag{7}$$

where on the left side of the equation we have the forward premium, similar to equation (6). If we incorporate this information in equation (7), this finally renders the following equation:

$$F_{t,T} - S_T = \alpha_4 + \varepsilon_{4,t}, \tag{8}$$

where $\alpha_4 = -\kappa \times \text{var}(S) + \gamma \times \text{skew}(S)$ is expected to be lower when the market share of VRES is high.

By estimating the parameters in equations (5) and (8) and analysing the patterns in $\alpha_3$ and $\alpha_4$ on markets with different levels of VRES in their power mixes, this work aims to provide evidence that an increasing market share of VRES decreases the forward premium in power markets. In other words, we test the hypothesis that $\alpha_3$ increases and that $\alpha_4$ decreases with the market share of VRES.

## 3. Market simulation environment and data

To examine whether an increase in the market share of VRES decreases the forward premium in power markets we examine forward and spot power prices in a simulated power market environment. We develop an experimental framework wherein human participants trade a specific good in a simulated market environment[5] and refer to such a market as the simulated market hereafter. The benefit of such an environment is that it allows us to isolate the effect of supply from VRES on the forward premiums from other factors such as changes in the power mix, marginal costs, and/or policies. We simulate three identical power markets, wherein the only difference between the markets is the share of supply from VRES, respectively 0%, 33%, and 67%. Each simulation run consists of two time periods. At time 1, agents trade forward contracts that involve the physical delivery of power at future time 2. At time 2, agents trade in the spot market after which delivery takes place.

There are four types of agents participating in the market setting. The first two distinguish the two types of power producers. The first is a non-intermittent power producer that supplies power with a production capacity of 900 MW. It converts a storable fuel into power and can flexibly adjust the volume produced with unlimited flexibility or ramping capacity (i.e. production volumes can vary freely between 0 MW and 900 MW). The only variable costs are fuel and emission right costs which combined are 50 €/MWh and which are fixed throughout the experiment. Fixed costs are zero, representing a sunk cost that does not affect trading decisions in a competitive market. All non-intermittent power producers have the same technology. The second type represents a VRES power producer that supplies power from a variable renewable energy source such as wind mills or solar panels at time 2. The supply of VRES is variable and each producer faces uncertainty in that the realised production is drawn from a normal distribution function with mean 900 MWh and a standard deviation of 45 MWh. All VRES power producers operate independently in order to simulate an entire market rather than a specific region. Both types of producers submit bids and offers in the forward market at time 1, but only the non-intermittent power producers submit bids and offers in the spot markets as they have the flexibility to increase or decrease production.

During the simulation, the relative market share of VRES varies over three different market structures. The first market has 15 non-intermittent power producers and no VRES. We refer to this setting as the **N** market. The second is the **L** market with a low market share of supply from VRES: 5 VRES and 10 non-intermittent power producers. The third market is the **H** market with 10 VRES and 5 non-intermittent power producers. The number of VRES producers in the market is the treatment variable which enables us to examine forward premiums when the market share of VRES increases.

The third agent represents consumers by an automatised agent that demands a volume of power at time 2. The demand is uncertain at time 1, being drawn from a normal distribution function with a mean demand of 11,500 MWh and standard deviation of 1,150 MWh. The demand is assumed to be price inelastic, which is common for power demand in the short run (Lijesen [16]). Although modeled as a single agent, it may represent a group of power retail companies that deliver power to households and enterprises. The consumer purchases expected consumption in the

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[5] We like to think of such market environment as a commodity market platform, with the only difference that we know the exact environment wherein these prices were determined. The setting, framework and boundary conditions are thus not set to answer a specific question, rather resulting prices and volume can serve to answer a range of research topics. For example, Koolen et al. [15] use the same dataset to examine the changes in the trading strategies of non-intermittent power producers when the supply from VRES increases in power systems.

**Table 1**
Summary of the market simulation setting.

| We use 5 identical simulations organized as follows: | | | |
|---|---|---|---|
| Market type | **N** market | **L** market | **H** market |
| Nb. of Rounds | 25 | 25 | 25 |
| Nb. of Producers: | | | |
| VRES | 0 | 5 | 10 |
| Non-intermittent | 15 | 10 | 5 |
| Nb. of bids/round: | | | |
| Forward market | 15 | 15 | 15 |
| Spot market[1] | 30 | 20 | 10 |
| Demand function in each round | Mean = 11, 500 MWh — St.Dev. = 1, 500 MWh | | |
| Maximum capacity per non-intermittent producer[2] | 900 MW | | |
| Expected output per VRES producer[3] | Mean = 900 MWh — St.Dev. = 45 MWh | | |

Note 1: Only non-intermittent power producers can submit bids in the spot market. Each can submit 2 bids: 1 sell and 1 buy offer; — Note 2: Non-intermittent power producers can ramp up their production when needed; — Note 3: VRES output is subject to weather conditions.

forward market[6] and final deviations in demand are settled in the spot market. The fourth agent is the automatised market and system operator which is a price taker. It collects all bids and offers and determines the market clearing price as market operator. As system operator, it buys or sells the needed amount of power in the spot market in order to balance demand and supply. It is assumed that the system operator has a very good signal of actual demand and supply from VRES such that it knows what volumes to buy or sell with absolute certainty.

Subjects were randomly allocated one of the first two agents in a counterbalanced order. Participants were recruited among graduate students that specialize in energy finance and received clear information on energy trading, power market design and financial decision making as part of the curriculum. In total 5 separate simulations were conducted. Each single simulation consisted of 3 sessions, one for each market structure. From each session data was collected on 25 rounds after controlling for learning rounds. While there are thus 125 observations available for each of the three market settings, only 120 observations can be used, as the first rounds of each of the 5 separate simulation sessions do not have a previous observation from which we can obtain $S_t$. Table 1 summarizes the data collection within the framework of our sequential power market simulation.

Table 2 presents a summary of the collected data per market setting. We notice that with the introduction of VRES, as we move from the **N** market towards the **H** market, the average level of cleared prices decreases on both the forward and spot markets. This is in line with our expectation, as the literature on the direct effect of VRES on power prices stipulates that the merit-order effect leads to lower mean power price levels (Würzburg et al. [17]). Looking at the mean volume, while on the forward market we do not observe a clear change from one market setting to another, on the spot market with the increase in share of supply from VRES there is an increase in the value of the absolute volume traded, suggesting increasing balancing needs as the market share of VRES increases.

**Table 2**
Summary statistics of the simulation data.

| | **N** market | **L** market | **H** market |
|---|---|---|---|
| | Mean settled price (EUR/MWh) | | |
| Forward market | 78.0 | 68.8 | 61.8 |
| Spot market | 75.8 | 70.6 | 68.0 |
| | Mean volume (MWh) | | |
| Forward market | 11,280 | 11,400 | 11,385 |
| Spot market[1] | 797 | 948 | 1,012 |

Note 1: Mean volume on spot market is calculated as the absolute cleared values on this market. The calculation includes both periods when the market found itself in a supply deficit and, respectively, surplus state.

We note two particularities that inherently follow from simulating power markets. First, the values of $S_t$ represent a proxy for the value of the spot price at time 1 of each round. The equations introduced by Fama and French [13] are meant to be applied on time series type of data. While in the collected experimental data the rounds follow each other in a sequential way, the simulation was not necessarily designed to be considered as a time series. Additionally, in an ideal setting, $F_{t,T}$ and $S_t$ prices should be quoted and available for trading in the same time. In the setting used, $S_t$ is quoted in the immediate period before quoting $F_{t,T}$ and not at the same time as $F_{t,T}$. The difficulties of getting spot price estimates were also incurred by Fama and French [13], as they relied on forward prices of contracts close to maturity as proxy for spot prices. The values for $S_t$ are used in the analysis to estimate equation (5). $S_t$ values are not used in equation (8) and hence this equation is not impacted by any potential bias in $S_t$. If the estimate used for past spot prices is a good proxy, we should be able to draw the same conclusions from either equation (5) or (8).

The second particularity is represented by the relative low number of observations in the original dataset. Power markets are known for exhibiting highly volatile prices. In such markets, one needs a high number of observations to draw significant conclusions. A solution to the matter of low number of observations is embedded in the experimental design. At time 2, once the forward market volume and price are cleared, each participant who acts as a non-intermittent power producer submits a sell and a buy spot market offer. This creates a merit order curve of 30, 20 and, 10 observations for respectively the **N**, **L** and, **H** markets. From these observations, based on the automised demand for the spot market, a spot price is cleared. Since this part is automised by the market and system operator, and bids are only reveled after final market closure, we argue that any of the bid offers in the spot merit order curve could have been the cleared spot price if the automised demand agent was required to select a different demand volume. We therefore argue that for each cleared forward price $F_{t,T}$, besides using the original values of cleared spot prices $S_T$, we can also use the entire merit order curve of $S_T$. By multiplying the number of 120 original cleared $F_{t,T}$ prices by the total number of spot merit order curve observations, the dataset used for estimating equations (5)

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[6] Risk-averse retail companies hedge margin income by lowering the risk from highly variable spot prices. Furthermore, the spot market is less liquid than the forward market as only producers that can flexibly adjust their output can offer power for spot delivery.

and (8) grows to 3600, 2400 and 1200 observations for respectively the **N**, **L** and **H** markets.[7] From here onwards, we will refer to the dataset where we use the entire merit order curve of $S_T$ as the extended dataset. The dataset where we use only the 120 simulated $S_T$ observations, is referred to as the original dataset.

## 4. Results

We use data from the above described market simulation to validate our hypothesis that the increase of supply from VRES in forward and spot power markets lowers the forward power price premium through the combined impact of VRES on the variance and skewness of spot prices. We do so in 2 different ways. First, by analysing the estimated values of the parameters in equation (5), and secondly by estimating equation (8). These estimates are obtained through ordinary least squares regressions for each market setting on a pooled sample from the five experiments. For equation (5) we expect that $\beta_3$ to equal one and $\alpha_3$ to be smallest for the **N** market, with zero supply from VRES, and highest for the **H** market, with the highest market share of supply from VRES. For equation (8) we expect $\alpha_4$ to be highest for the **N** market and lowest for the **H** market.

The results obtained by estimating equation (5) are summarised in Table 3, for the original dataset, and in Table 4, for the extended dataset which uses the entire merit order curve of $S_T$. In both tables, the results confirm our expectation for both the estimates of $\alpha_3$ and $\beta_3$. $\beta_3$ values are close to the value of one[8] for each of the market settings, regardless of both the amount of VRES in the power system and the type of dataset. This result proves that in power markets with little storage capacity, as is the case in most power markets, the forward basis, $F_{t,T} - S_t$, has forecasting power over future spot prices, $S_T$.

Further, in line with our expectation, we observe an increasing trend in the estimated mean of $\alpha_3$ moving from the **N** market to the **L** market and from the **L** market to the **H** market in both Tables 3 and 4 We find evidence for the indicated result in both the original and the extended dataset. Nevertheless, only for the extended dataset, where we use the entire merit order curve of $S_T$, the estimates for the **N** market and **H** market are significantly different from each other. For the original dataset, the high standard errors make any comparison between the markets only indicative and less reliable due to the low number of observations. These results confirm the expectation that with the increase of VRES in power markets, forward premiums become lower. Moreover, note that $\alpha_3 = \kappa \times \text{var}(S) - \gamma \times \text{skew}(S)$, the opposite of the forward premium expressed as per equation (1). Looking at Tables 3 and 4, this means that the forward premium estimated in our experimental framework is positive in the **N** market and becomes increasingly negative as we add a higher shares of VRES to the market. This decreasing effect is statistically significant for the results on the extended dataset.

**Table 3**
Results of estimating equation (5) on the different market structures using the original dataset.

| Eq. (5) estimated: | $S_T - S_t = \alpha_3 + \beta_3 \times (F_{t,T} - S_t) + \varepsilon_{3,t}$ | | |
|---|---|---|---|
| | **N** market | **L** market | **H** market |
| $\alpha_3$ | −0.758 | 2.574 | 5.730 |
| | (4.265) | (4.522) | (6.672) |
| $\beta_3$ | 1.057 | 0.982 | 1.044 |
| | (0.093) | (0.091) | (0.090) |
| Nb. observations | 120 | 120 | 120 |
| $R^2$ | 0.524 | 0.499 | 0.530 |
| F Statistic | 129.6 | 117.4 | 133.1 |

Note: Standard errors in parentheses.

**Table 4**
Results of estimating equation (5) on the different market structures using the extended dataset.

| Eq. (5) estimated: | $S_T - S_t = \alpha_3 + \beta_3 \times (F_{t,T} - S_t) + \varepsilon_{3,t}$ | | |
|---|---|---|---|
| | **N** market | **L** market | **H** market |
| $\alpha_3$ | −6.891 | 0.219 | 5.823 |
| | (0.974) | (1.252) | (2.197) |
| $\beta_3$ | 0.974 | 0.967 | 1.004 |
| | (0.021) | (0.025) | (0.030) |
| Nb. observations | 3600 | 2400 | 1200 |
| $R^2$ | 0.385 | 0.382 | 0.487 |
| F Statistic | 2250 | 1485 | 1136 |

Note: Standard errors in parentheses.

Tables 5 and 6 present the results on the estimates for equation (8). Equation (8) does not require the use of the proxy estimate for past spot prices $S_t$. The results on estimating $\alpha_4$ lead to the same conclusion regarding the relation between forward premiums in power markets and the share of VRES. In Tables 5 and 6, we observe in line with our expectation a decreasing pattern in the $\alpha_4$ estimates. The same as for $\alpha_3$ estimates, only in the extended dataset $\alpha_4$ estimates for the **N** market and **H** market are significantly different one from another. Also, similar to estimates for $\alpha_3$, we can deduce from the $\alpha_4$ estimates that the forward premium in the **N** market is positive and that it becomes negative in the **H** market as the share of VRES increases, with the results from the extended dataset yielding for the **N** market and **H** market significantly different values.

We note that although the results on the impact of supply from VRES on forward premiums are robust for the different market settings in our study, one should take into account a number of considerations when extrapolating the insights to actual power markets, depending on individual market characteristics. For example, when a significant amount of direct or indirect, through the underlying fuel, storage is available in the market, it may reduce the variable nature of power prices induced by VRES and reduce the frequency of extreme low prices.

Finally, the behavior of the forward premium is affected when non-intermittent power producers experience significant ramping costs in adjusting output profiles close to real-time. Note that currently many power markets still have limited capacity to store power and demand is relatively price inelastic. This implies that any forecast errors need to be offset by non-intermittent producers with the capability to flexible adjust their power output close to

**Table 5**
Results of estimating equation (8) on the different market structures using the original dataset.

| Eq. (8) estimated: | $F_{t,T} - S_T = \alpha_4 + \varepsilon_{4,t}$ | | |
|---|---|---|---|
| | **N** market | **L** market | **H** market |
| $\alpha_4$ | 0.633 | −2.575 | −5.500 |
| | (4.249) | (4.504) | (6.634) |
| Nb. observations | 120 | 120 | 120 |

Note: Standard errors in parentheses.

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[7] Although the minor downsides of this approach are i) the fact that in the extended newly created dataset each $F_{t,T}$ cleared price will be used for multiple $S_T$ values, and ii) the fact that implied spot demand volume will no longer follow a normal distribution, we believe these do not affect our results.

[8] Note that for each setting investigated, the estimate of $\beta_3$ is not significantly different from the value of one.

**Table 6**
Results of estimating equation (8) on the different market structures using the extended dataset.

| Eq. (8) estimated: | $F_{t,T} - S_T = \alpha_4 + \varepsilon_{4,t}$ | | |
|---|---|---|---|
| | **N** market | **L** market | **H** market |
| $\alpha_4$ | 6.949 | −0.221 | −5.801 |
| | (0.942) | (1.252) | (2.190) |
| Nb. observations | 3600 | 2400 | 1200 |

Note: Standard errors in parentheses.

real-time. Most of such market agents produce power using conventional, mostly fuel based, non-weather dependent technologies, such as coal or gas fired power plants. Although we believe that the main insights are robust to such extensions, underlying market fundamentals may impact the degree to which extent our results manifest itself.

## 5. Conclusions

We study the effects of an increasing market share of VRES on forward price dynamics in wholesale power markets. The introduction of VRES changes power market dynamics, as VRES typically bear lower marginal costs than traditional non-intermittent fuel-based power producers. Power output from VRES depends however on parameters that are uncertain by nature, like wind speed and solar radiation, and they have limited capacity to manage this variability, as curtailment is not preferred or incentivized in most power markets. This, in combination with the limited capacity of storing power and the variable inelastic demand, causes power price profiles for short-term delivery to vary drastically.

We study the above question in the framework of a simulated power market environment. This market set-up allows us to vary the share of VRES with a high degree of control and control for any other exogenous effects which may affect power price dynamics. We do so by analyzing simulated market data in three distinct market structures, ranging from a market with no VRES to a high VRES-supplied power system.

We study the effect of supply from VRES on power market prices in the scope of forward pricing. Forward markets help with the efficient allocation of resources for commodities that face uncertainty in price or quantity for a future time of delivery. Moreover, forward contracts are an important medium to allow market participants to deal with risk sharing over spot uncertainty close to real-time. Forward price premiums have been found to relate to spot price dynamics, most notably negatively to the variance and positively to the skewness of expected spot prices. In this paper, we find evidence that the expected higher variance and lower skewness introduced by an increasing share of VRES leads to lower forward premiums. We further demonstrate that in power markets without storage capacities, the forward basis contains information about the future spot price. This result is consistent regardless of the amount of supply from VRES in the power system.

The present paper indicates that with an increasing market share of VRES, there is an increasing need for storage and/or flexibility in power markets in order to reduce uncertainty and risks. The current limited capacity to store power and the largely inelastic demand imply that any imbalances caused by VRES output are offset by non-intermittent, mostly fuel based, power producers who provide the necessary flexibility needs to balance the system. In such systems, we find that higher shares of VRES in power markets may create a negative impact on the forward risk premium. In doing so, this work provides important insights for market participants, both producers and retailers, to effectively balance their portfolio in forward and spot markets as power systems become increasingly dependent on variable renewable energy sources.

## CRediT authorship contribution statement

**Ronald Huisman:** Conceptualization, Data Collection (Resources), Methodology, Investigation, Validation, Writing – original draft, Preparation, Writing – review & editing, Supervision. **Derck Koolen:** Conceptualization, Data Collection (Resources), Methodology, Software, Data curation, Investigation, Validation, Writing – review & editing. **Cristian teț:** Conceptualization, Methodology, Software, Data curation, Formal analysis, Visualization, Investigation, Validation, Writing – original draft, Preparation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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