Mat-2.4108 Independent Research Projects in Applied Mathematics

Pricing of electricity futures: A literature review

February 17, 2014

Juha Kännö

Instructor and supervisor:
Prof. Ahti Salo

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1 Introduction

1.1 Background and motivation

In a liberalized electricity wholesale market power is traded like almost any other commodity. Electricity differs inherently from other goods in that it cannot be stored in large quantities. Hence, the supply of electricity fed into the grid must constantly match consumption to ensure the stability of the power system. In physical electricity markets, sellers and buyers commit themselves to provide or consume the settled volumes. Physical markets are typically arranged as day-ahead markets, where the sellers and buyers each day submit bids for each hour the following day. The bids are collected by a power exchange that determines which generators are to be dispatched, and then calculates the clearing price, or the spot price. This arrangement provides the transparent pricing for wholesale electricity trade and ensures that the physical supply and demand of electricity are economically matched (Bunn, 2000; Weron, 2007).

Because electricity cannot be stored, it is likely that the spot price is strongly driven by fundamentals connected to supply and demand (e.g. Geman and Roncoroni, 2006). Demand has very low price-elasticity (Bye and Hansen, 2008; Johnsen, 2001), and hence the spot prices are largely determined by the supply side. Power plants in the Nordic market have a wide range of short-run marginal costs, which mainly depend on the generation technology. When the demand reaches such levels that low-priced base load generation is not sufficient, more expensive plants will be dispatched and the spot prices can rise significantly during consumption peaks. Transmission bottlenecks and unexpected plant outages can lead to even higher prices for limited periods of time.

The nature of electricity supply and demand results in characteristic features in spot prices. Prices typically have a periodic profile, show occasional spikes, and revert to a mean level (e.g. Bunn and Karakatsani, 2003; Weron, 2007). The Nordic electricity market is unique in that around 50–60 % of annual generation originates from hydro power, with the largest hydro power plants located in Norway. Hence, factors such as inflow and hydrological balance[1] have a big impact on the pricing of electricity supply. Hydro power has a non-existent marginal production cost in the short run,

[1]Hydrological balance measures the difference of current hydro reservoir levels from a long-run seasonal average.

but the volume of water that can be used for generation within a certain period of time is limited. Hence, a hydro power producer considers the short-run marginal cost of the generation source that would substitute hydro power as an opportunity cost and determines the value of the generation accordingly. In the Nordic case the substitute is typically coal condensing generation, which links fuel and emission costs to the spot price.

Due to the volatility and uncertainty of future spot prices, there is a need for instruments that allow market participants to lock in (to hedge) a part of their electricity price for time periods beyond the day-ahead market. In the Nordic market, the price risk can be managed with derivative contracts. Standardized contracts are traded in an exchange operated by Nasdaq OMX Commodities. The main contract types are *futures*, *deferred settlement futures* (previously known as *forwards*), *electricity price area differentials* (*EPADs*, previously known as *Contracts for Difference*, *CfDs*), and *options* on the other contract types. [2]. Derivative contracts are available for periods of days, weeks, months, quarters and years up to 10 years ahead. The financial contracts do not involve physical delivery of energy, but are settled by cash payments only. Hence, speculators take part in financial trading together with power producers and large consumers, which are also called *asset-backed* market players.

The theory of commodity futures pricing was developed well before the emergence of electricity markets. Fama and French (1987) summarize two common views on commodity futures pricing. First, the theory of storage is based on the non-arbitrage pricing argument that the price of the future contract must be equal to the costs of borrowing money to buy the commodity from the spot market and storing it until the maturity of the future contract. Second, the future price can be viewed as the expected spot price upon maturity plus a market risk premium.

Both views have been applied in studies on the pricing of electricity futures. The topic is highly relevant, as financial contracts are actively traded. NordREG (2013) estimated that the turnover volume of the Nordic financial electricity market was 1662 TWh in 2012, which was 4.2 times the annual physical consumption in the Nordic market. Hence, there is need to understand how futures prices are formed, given fundamental data and expectations about future spot prices.

[2] In order to harmonize instrument names with common financial naming conventions, Nasdaq OMX Commodities renamed instruments formerly known as 'forwards' to 'deferred settlement futures', as 'forward' commonly refers to a product sold over the counter. There are some differences in how futures and deferred settlement futures are settled, referred by the term 'deferred settlement'. The changes took place on 30 September 2013. For reference, see http://nordic.nasdaqomxtrader.com/digitalAssets/86/86358_globaldataproductsnewsletter2013-17.pdf

1.2 Research objectives

This study examines how the theory of commodity futures pricing has been applied to electricity markets and attempts to answer the following questions:

1. What factors are used to explain the relationship between future and spot prices?
2. What approaches can be used to evaluate actual forward prices against expected spot prices in the Nordic electricty market?

The second question represents the view of a market player willing to hedge the price of future production or consumption. In this case the forward positions are kept open to delivery. Profit is made from the difference of future price and delivery spot price. For instance, if the contract price is above the average spot price during the delivery period of the contract, the seller of the contract earns a profit while the buyer makes a loss.

1.3 Structure of the study

The remaining part of this study is organized as follows. Section 2 describes the theory of commodity future pricing. Section 3 reviews literature on the pricing of electricity futures. Finally, section 4 presents summarizes the findings and present the conclusions of the study.

2 Commodity forward pricing theory

2.1 Theory of storage

The theory of storage explains the difference between contemporary spot and forward market prices with regard to interest rates, costs in holding a commodity and a convenience yield on physically holding a commodity (e.g. Fama and French, 1987). The price of a forward contract or any other derivative can determined with the concept of replication. Textbook references include Luenberger (1998) or Sundaram and Das (2010). Basically, other assets are used to construct a portfolio which has an identical outcome as the forward contract. By assuming that there is no arbitrage, the present value of the forward contract must be equal to the present value of the replicating portfolio.

Let us consider a forward contract with delivery price F and expiration at time T. Let 0 denote the current time. An investor taking a long position in the forward pays the price F at expiry and receives the underlying asset. The holding at date T can be replicated by taking a long position in the underlying asset at time 0 and holding it until T. In the latter strategy one pays S_0, the spot price of the underlying asset at time 0. By assuming no arbitrage, we have

$$d(0,T)F = S_0,$$

where $d(0,T)$ is the discount factor between 0 and T. Assuming a continuously compounding risk-free interest rate r, the discount factor is $d(0,T) = e^{-rT}$, and the forward price is defined as

$$F = S_0 e^{rT}. \tag{1}$$

Holding an asset may incur also other cash flows known as the *cost of carry*. For instance, there may be costs from storage or insurance, especially if the underlying is a physical commodity. On the other hand, an underlying security may pay out dividends, which can be considered as negative costs. Adding the cost of carry to equation (1) gives

$$F = S_0 e^{(r+c)T}, \tag{2}$$

where c is the continuously compounding factor of total carrying costs.

Based on equation (2), the forward price F increases with the maturity date T. However, the opposite can also be observed (Luenberger, 1998). Decreasing forward prices can be explained by the benefit of having the commodity physically in stock when there is a shortage of supply. For example, a farmer could make a profit by selling his supply of soybean meal and purchasing a forward contract. Still, he will not do it if the profit is less than the cost of not having soybean meal available for supplying other contracts, or for own use. This cost is referred as the *convenience yield*. To allow for this behaviour, the equation (2) can be modified as

$$F = S_0 e^{(r+c-y)T}, \tag{3}$$

where y is the continuously compounding convenience yield.

2.2 Market risk premium

The market risk premium provides an alternative view on the connection between spot and forward prices. The theory of storage—as the name already suggests—relies on the assumption that the underlying commodity can be stored. Because electricity is not freely storable, the storage model cannot be directly applied. The risk premium approach is independent of storability. It splits the forward price into the expected spot price at maturity and a risk premium. For buyers, the premium is the price they are willing to pay for protecting themselves from unwanted spot price movements. For sellers, the premium is a discount they are willing to accept, respectively (Fama and French, 1987).

Following the notation used by Marckhoff and Wimschulte (2009), the price of a forward contract at time t with maturity at T is

$$F_{t,T} = E\left[S_T|\Omega_t\right] + \pi_t^F, \tag{4}$$

where $E\left[S_T|\Omega_t\right]$ is the expected spot price at time T with respect to the information set Ω_t available at t. π_t^F is the risk premium associated with the forward contract at t. If the risk premium is zero, the forward price is an unbiased estimator for the future spot price.

3 Forward pricing in electricity markets

This study identified four factors which differentiate works on electricity forward pricing. First, some papers develop theoretic models, while others attempt to empirically validate the theories by applying them to actual market data. Second, the papers seem build either on the market risk premium approach or the theory of storage. Third, there is variation in the lengths of analysed the contracts: the shortest contracts cover days or weeks, while the longer contracts cover months, quarters or years. Fourth, the papers focus on markets which differ in terms of liquidity, concentration of market power, generation technologies used and other factors.

In what follows, the contributions of reviewed papers are briefly summarized and categorized according to the aforementioned factors.

Gjolberg and Johnsen (2001) attempt to explain the relationship between Nordic future and spot prices with the theory of storage. They focus on the storage levels of hydro reservoirs, and interpret the results in the light of storage costs and convenience yield. Authors conclude that the market reacts strongly to observed changes in storage levels, and that the forward prices overshoot spot prices so strongly that it is hard to explain by fundamentals. The results could be explained by inaccuracy of the model, or by the fact that the market is still young and learning, which could lead to seemingly irrational price behaviour.

Bessembinder and Lemmon (2002) present one of the earliest market risk premium models for electricity forwards. They apply an equilibrium approach and propose that the forward price will generally be decreased by the anticipated variance of spot prices, and increased by the anticipated skewness of spot prices. The model also implies that forward prices will exceed expected spot prices when either the demand or the volatility of demand is high, due to the increased probability of spiking prices. The empirical data comprises front month forward prices from the Pennsylvania–New Jersey–Maryland (PJM) power exchange from years 1997–2000 and California Power Exchange from 1998–2000.

Longstaff and Wang (2004) conduct an empirical study on day-ahead forward price data from the PJM market from 2000–2001. Regression of premia on different risk measures supports the predictions of Bessembinder and Lemmon (2002).

Botterud et al. (2002) analyse risk premia in historical prices of front week contracts in the Nordic market from the start of derivatives trading in 1995 until 2001. They argue that the risk premia result from the levels of risk aversion among producers and consumers. When most producers are risk-averse and want to fix their sales price, the forward price is likely below the expected spot price. Vice versa, when most consumers are risk-averse, the forward price is likely to exceed the expected spot price. Botterud et al. (2002) found that on average future prices exceeded the delivery prices. Producers, who can adjust their production according to price fluctuations, can make profit. Hence, it makes sense not to fix the price for all planned production. Consumers, on the other hand, have fewer possibilities to adjust consumption according the spot price. For them it is beneficial to hedge as much future consumption as possible. An excess demand for futures would explain the observed risk premia.

Kristiansen (2004) analyses risk premia of Contracts for Difference (CfDs)[3] in the Nordic market in 2000–2002. He finds both over and under-priced contracts and

[3]The underlying asset of the CfD is the difference of an area price and the Nordic system price. It is traded in the same manner as Nordic electricity forwards.

explains the premia by the levels of risk-averseness among producers of consumers, the argument also used by Botterud et al. (2002). Under-priced contracts belonged to the Oslo market area which houses large amount of hydropower producers. The negative premia are attributed to producers willing to hedge future production. Actual delivery prices are uncertain and depend on future inflows, which strongly affects the area price.

Benth et al. (2008) develop a theoretical framework for risk premia with similar concepts as the empirical study of Botterud et al. (2002). The risk premia are explained firstly by the levels of risk aversion of buyers and sellers, and secondly by the different timing of hedging activities between buyers and sellers. Market power is defined as "eagerness to hedge risk across different points in time". The model is applied to data from the German electricity market from 2002–2006. Producers' market power is found to be at strongest in the presence of spike risk and close to maturity; in these cases the consumers are more eager to hedge than producers. Furthermore, producers' market power seems to decrease when the time to maturity increases.

Marckhoff and Wimschulte (2009) study empirically risk premia in Nordic CfDs and *implied area price forwards* [4] from years 2000–2006. The regression of risk premia on the variance and skewness of delivery spot prices supports the model of Bessembinder and Lemmon (2002) for CfDs, as well as for system and implied area price forwards. The availability of hydro power is related the variance and skewness of spot prices and area price spreads. The examination of risk premia and time to maturity reveals an inverse relationship both for system and implied area price forwards. This supports the theoretical results of Benth et al. (2008).

Audet et al. (2004) present a stochastic model for the forward curve. One the model's use cases is that of creating a conditional forecast of the forward curve, given a forecast of the underlying spot price. Hence, the model can be used to estimate the risk premium which is the difference of the forward and expected spot price. All parameters are estimated from price data. The model is tested with Nordic market data from years 1999–2001. The authors note that forward curve dynamics depend on the hydrological situation, and the model could be developed further by incorporating changes in hydrological reservoirs into the forward curve parameters.

[4] The system price is the underlying of Nordic forward contracts. The underlying of the CfD is the difference between an area price and the system price. Hence, an implied area forward can be constructed by taking similar positions both in a (system) forward and a CfD for the desired market area.

Redl and Bunn (2011) and Redl (2011) provide a comprehensive empirical study of the determinants of risk premia in German and Nordic electricity markets. They propose that the price risks of fuels substantially affect the risk premia of electricity prices. They also note that market concentration not only increases expected spot prices but risk premia as well. The results were consistent with previous findings on the premia-increasing effects of spot price volatility and skewness.

Finally, Huisman and Kilic (2012) compare risk premia across Dutch and Nordic markets. The data covers monthly forward contracts with delivery one to six months ahead from 2005–2010. They argue that Nordic futures prices contain information about expected changes in spot prices, but do not show evidence of time-varying risk premia. In contrast, Dutch futures prices contain information about both expected changes in spot prices, and about time-varying risk premia. The authors attribute this difference to the fact that in the Nordic market much of electricity is produced by hydro, wind and solar generation, which use 'imperfectly storable fuels' compared to 'perfectly storable' thermal fuels, such as gas and coal prevailing in the Netherlands. Huisman and Kilic (2012) attribute the time-varying risk premia of the Dutch market to the price of natural gas. This result is consistent with the findings of Redl (2011) from the German market.

4 Summary and conclusions

The aim of this study was to review literature on the pricing of electricity forwards in order to identify what factors link future and spot prices, and determine potential approaches for evaluating actual future prices against expected spot prices.

Based on the reviewed literature, most papers build on the theory of market risk premium. This is natural due to the fact that electricity cannot be directly stored. Hydro power generation from reservoirs is the most flexible indirect storage solution for large volumes of electrical energy. Gjolberg and Johnsen (2001) attempted to explain the relationship of Nordic futures and spot prices by the levels of hydro reservoirs, but could not explain all price variation fundamentally. Other reviewed papers attempted to explain the market risk premium by the properties of the underlying spot price, or by factors rising from the structure of the electricity market.

Flexible hydro reservoirs benefit electricity producers more than consumers. Botterud et al. (2002) acknowledge that producers may profit from spot price fluctuations because they can generally adjust their production volumes to the prevailing price level more flexibly than consumers can adjust their load. Hence, there tends to be a larger number of risk-averse consumers than producers in the forward market, which helps explain forward prices above expected spot prices. Benth et al. (2008) present a framework that explains changes in market premia by a temporal shift in market power between producers and consumers.

With evidence from North American power exchanges, Bessembinder and Lemmon (2002) introduce a model where the risk premium is explained by volatility and skewness of spot prices. Both Marckhoff and Wimschulte (2009) and Redl (2011) find evidence that volatility and skewness have similar effects also on Nordic risk premia.

Empirical studies were based on risk premia calculated as the difference of the forward price and average realized spot price in the delivery period. This method assumes that the expectations for future spot prices are unbiased, which implies that the mean of spot forecast errors would be zero. It is questionable whether this holds in the Nordic market, because changes in the hydrological situation are strongly reflected by the expected spot prices. The hydrological situation can change dramatically during the trading period of a contract, and thus the long-term price expectations can also vary considerably.

The research on Nordic markets suggested that the volatility and skewness are dependent on the availability of hydropower. Hence, volatility and skewness of spot prices should be considered as proxies which indicate that dry periods will lower the availability of hydro power, requiring more expensive generation sources to be put online, which increases prices and the likelihood of price spikes. The sentiment of the reviewed papers seemed to be that rather than connecting Nordic risk premium models to the statistical properties of expected spot prices, the models should be connected directly to the fundamentals inducing the price behaviour. Emphasis should be put on variables describing the hydrological situation, such as reservoir and inflow levels, or deviation of actual levels from seasonal long-term average values. It could also the mean inclusion of measures of price risk from coal and gas markets.

As a final remark, the Nordic electricity market is growing and changing and the market players market are learning from experience. Therefore, analysis of market data from most recent years may reveal quite different patterns than the same analysis performed on data from the initial years of the exchange. The earliest reviewed papers analysed data from 1995, when the Nordic electricity derivatives trading was originally started. To date, the Nordic market players have witnessed hydrological situations ranging from extremely wet to dry, dramatic movements in global fuel markets and increasing transmission capacity both within the Nordic region, as well to neighbouring markets. Perhaps most recent and still ongoing change is the massive shift towards wind and solar generation, which replaces conventional generation and increases spot price volatility. Due to the constantly evolving environment, there is a continuous need to better understand the dynamics of Nordic electricity markets.

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