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REGULAR ARTICLE

The dynamics and distribution of the area price in the Nord Pool

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Abstract The Nord Pool is often cited as a standard and successful electric power exchange. It was first created in Norway and developed into the power change system covering the Nordic countries. The Nord Pool provides a physical market where electricity producers and consumers/distributors meet by submitting bids for sale and purchase for 24 h time segment. If there does not exist a restraint of transmission capacity across the member countries, a single price—system price—is calculated by the intersection of the demand and supply curves, whereas if there exists congestion of transmission lines, area price instead of system price emerges. We are interested in analyzing how often and how far the two prices diverge and the probability distribution of the price ratio between system and area price. We found that the price ratio does not follow the normal distribution but the distribution is fat-tailed.

1 The purpose of study

The regulatory reform in 1980s that favored deregulation and liberalization in the US and Europe spread to the electricity industry that used to sustain public utility status—local monopoly—for a long time. Electric power supply is usually composed of three

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sectors: power generation, transmission and distribution. The traditional electricity companies are integrated monopolies from generation to distribution. The sector of power generation has become competitive through technological innovation whereas transmission is still regarded as natural monopoly. In the recent 20 years the institutional device has been introduced in order to help competition prevail in the electricity industry. The device was the creation of power exchange or spot market for the wholesale trade of electricity where the demand and supply of distributors meet in the day-ahead market.

There is a distinction between stock market and power exchange. The former is institution designed for exchange of stocks by numerous dealers who make bids every second whole day. The latter is devoted to physical electricity contracts usually accompanied by next-day delivery.

This type of market transaction has most developed in the Nordic countries. It has its historic origin. Norway is a special country where almost all electricity depends upon hydro power. Hydro power can be stored in reservoirs but subject to fluctuations caused by the weather condition or the amount of rainfall. The Norwegians have voluntarily developed the futures trade system in order to hedge this volatility. Under the EU regime of electricity industry reform, Norway was the first to restructure its industry and introduced the Energy Act in 1990. Thus the power exchange was created and called Nord Pool and other countries joined this power exchange system: Sweden (1996), Finland (1997) and Denmark (2002).

The Nord Pool is now often cited as a standard and successful power exchange where day-ahead commodities are traded for 24 h time segment. If there does not exist a restraint of transmission capacity among member countries, a single price or "system price" is hit by the intersection of the demand and supply curves. Nowadays, however, there exists a serious problem. The Nord Pool inherited the excess capacity of transmission built in the days of natural monopoly when each country was isolated. But according to the restructuring of electricity companies, electric power generation and transmission were unbundled. Transmission and distribution are regulated and national independent TSO's (Transmission System Operator) are responsible for system operation and management of spot markets. The electric power producers are no more integrated and they do not have any incentive or responsibility for investing in transmission lines. There comes a problem of transmission investment initiatives.[1]

If the member countries are not well coordinated for planning transmission investment, the existing excess capacity will be exhausted so long as the demand for electric power is growing. On top of the physical demand for electricity, the development of financial market calls for the increase of interconnection lines across regions.

In this paper we focus on the price behavior of the Nord Pool from two standpoints. Firstly due to the lack of transmission capacity it is often observed that the system price cannot be attained and electricity is sold by the area price. Namely the divergence between system and area price is not rare but usual. Secondly we investigate how far these two prices are divergent. The notion of power exchange that rely upon competitive spot markets or price mechanism naturally assumes that the distribution of

[1] This problem is discussed recently in the case of new construction of transmission lines between the Nord Pool and the Netherland (Giesbenty and Mulder 2008).

price follows the normal distribution. In other words the probability of the emergence of extreme prices is ruled out because we should rely upon a fragile price system for the supply of electricity.

2 Analysis

2.1 The congestion of transmission lines

The member countries of the Nord Pool are interconnected by the cross boarder transmission lines as illustrated in Fig. 1. The transmission lines in each country used to be built for fulfilling the domestic demand and not designed to accept extra electric currents from neighboring counties. Thus the Nord Pool system encounters the problem of capacity constraint of transmission lines.

In principle the Nordel provides ancillary services to realize a seamless Nordic electricity market by the cooperation among four Nordic TSO's.[2] So far as this balancing system works well, the demand and supply match every moment and an equilibrium price will dominate in each area of the Nord Pool member countries.

In Norway the system price prevails almost 100% and the discrepancy between system and area price can be negligible. In other countries, however, area prices are found to deviate from the system price to non-negligible extent, sometimes tenfold or sometimes one tenth of the system price.

We are interested in analyzing this phenomena because the volatility of electricity price has a significant economic and social impacts upon electricity users. The huge discrepancy between system and area price is to happen when the transmission lines across border are congested as the capacity constraint is stringent.

If there exists congestion of transmission lines between countries, the entry and/or exit of electricity between them are blocked. This creates bottlenecks from time to time and the local area price will be higher or lower than the system price depending upon the nature of congestion.

In one case when local demand in an area is temporarily increased and its price rises, electricity supply from another area will come in and price will the lowered if the transmission line is not occupied. This mechanism, however, will not work if the interconnecting lines to come in are congested. We call this "in-congestion".

In the other case when the local demand in an area decreases and its price is lowered, electricity providers will find it profitable to shift their supply to other region if the interconnecting lines are not congested. Otherwise those providers must stay in that area and compete with other producers. Because electricity instantly vanishes if not consumed at the moment of production, producers cannot but undercut their prices. The congestion of transmission line to go out from an area to another is called "out-congestion" in our analysis.

Now we define the measure of in-congestion and out-congestion based on the data provided by the Nord Pool ASA from 2001 to 2007.

[2] The Nordel consists of Statnett, Fingrid, Eneginet.dk and Svenska Kraftnät.

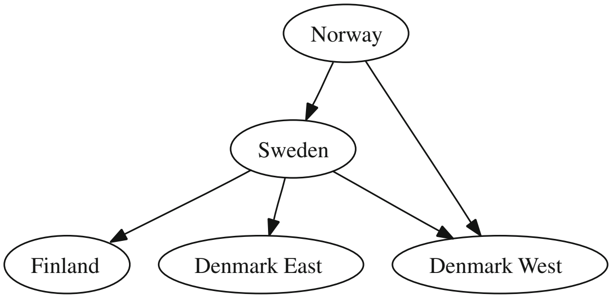

Fig. 1 Typical state of power transmission in the daytime. At nighttime electricity flow in the opposite direction

In-congestion: As regards to any one of the area transmission lines to which foreign electric currents to get in, the currents net flow is equal to transmission capacity.

Out-congestion: As regards to any one of the area transmission lines from which the area electric currents to get out, the currents net flow is equal to transmission capacity.

When the demand in one area increases, supply from other area will increase unless the transmission capacity prevents it. According to the definition of in-congestion, we expect the area price will rise by the bottleneck created by the congestion in at least one of the transmission lines. Likewise when the demand decreases in one area, producers will try to sell its product in another area and get off that region if the transmission capacity permits it. According to the definition of out-congestion, we expect the area price will be reduced by price undercutting among producers if at least one of the transmission lines is busy.

In our analysis we assume that the divergence between two prices will be reinforced by the emergence of transmission congestion as is defined in-congestion and out-congestion above. We now examine the probability distribution of the price ratio of area and system prices on the conjecture as follows.

1. In the case of in-congestion, increasing incidence of bottlenecks may cause higher probability that area price exceeds system price (the price ratio is greater than unity). This does not exclude the possibility that the price ratio is less than unity because in other transmission lines price undercutting can happen.
2. In the case of out-congestion the incentive of price undercutting among producers will increase. This will cause the higher probability that area price is lower than system price (the price ratio is less than unity). This does not exclude the possibility that in other areas area price is higher than system price.

In the next section we depict the probability distribution of price ratios with regarded to the four member countries by selecting the most representative areas in each country.

2.2 The probability distribution of the price ratio

When we look at the degree of prevalence of the system price in the Nord Pool as a whole, it is found that the divergence between system and area price is not exceptional but usual. The frequency of this divergence has dramatically increased and the equality the two prices in the whole region is found only 2.3% (1,262 h out of 53,874 h).

Then we disaggregate the Nord Pool into four countries to see the probability that the two prices are equal, we find that the probability of divergence from unity cannot be neglected as shown in Table 1.

This result implies that because electricity is a special goods that cannot be stored, there will be inevitable time lags in response to demand conditions. Produces may exploit monopoly rents or may undercut prices from time to time even when there is no in- or out-congestion.

In order to compare the four member countries we must first notice the difference of the source of power supply. Norway is exceptional because it almost 100% replies upon hydropower whereas the other three countries have different structure. Sweden relies upon hydropower (about 50%) and nuclear and hydropower plants. Finland mainly depends upon thermal power but has both nuclear and hydropower plants. Denmark depends mainly upon thermal power but wind power is also important.

As regards to the areas in the Nord Pool, Norway has multiple areas but we selected the southern part area here. Denmark has East and West areas which have no direct connection between them and we selected Denmark West. Sweden and Finland have one fixed areas (Fig. 2).

First we look at Norway (Fig. 2a). It is clear that in Norway in- and out-congestion do not have a particular impact upon the probability distribution of the price ratio. The matching of demand and supply is usual and the divergence between area and system price is minimal compared to other countries.

In Finland the effect of in- and out-congestion are most remarkable (Fig. 2b). In the case of in-congestion the price ratio is greater than unity whereas it is smaller than unity in the case of out-congestion. It is found that area price is five fold or one fifth of the system price at the probability about 0.1%.

In Sweden we can see the contrasting impacts of in- and out-congestion (Fig. 2c). In the case of in-congestion the price ratio is often less much than unity (sometimes one-tenth of the system price) even at the probability of 0.01%. This may come from the structural characteristic of Swedish power supply that relies on nuclear power.

In Denmark in- and out-congestion have noticeable impacts upon the price ratios (Fig. 2d). In case of in-congestion the price ratio is more than unity and even reaches ten fold of the system price at the probability of 0.1–0.01%. Likewise out-congestion reduces the price ratio to one-tenth at the tail of probability distribution. This comes

Table 1 Probability of divergence between system and area price

Area	$P_{\text{area}} < P_{\text{system}}$ (%)	$P_{\text{area}} = P_{\text{system}}$ (%)	$P_{\text{area}} > P_{\text{system}}$ (%)
Norway	17.4	73.5	9.1
Finland	25.5	66.5	8.0
Sweden	18.7	73.4	7.9
Denmark West	28.1	59.0	12.9
Denmark East	18.7	65.5	15.8

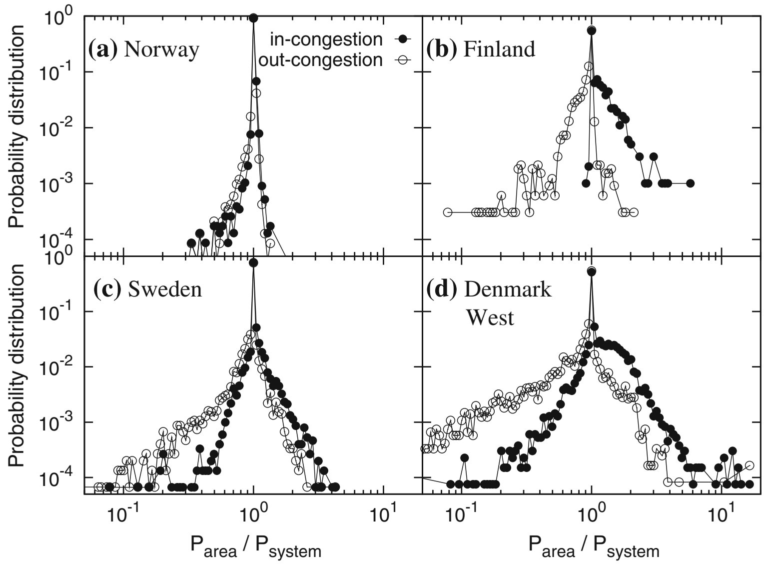

Fig. 2 Probability distribution of the price ratio of area and system price

from the Danish situation as follows. Denmark depends upon wind power that is vulnerable to the weather condition. In case of out-congestion wind power producers must undercut their prices remarkably whereas in case of in-congestion the demand from Germany bids the area price up to a considerable extent. These two factors that are specific to Denmark and non-existent to other countries may render more volatile price behavior of the area price.

To confirm that the price ratio does not depend on time, we use the Augmented Dickey-Fuller (ADF) test for unit root stationarity. As regards to the price ratio of all five areas, we can find that p-values for ADF test are smaller than 0.01, and consequently the null hypothesis of the unit root non-stationarity is rejected. Therefore, it is reasonable to assume that the price ratio does not possess evidence of unit root non-stationarity.

Moreover, we measure power spectral densities (PSDs) for the price ratio. As shown in Fig. 3, the PSDs have two peaks at frequencies corresponding to 8 and 16 h. These peaks are related to cycle of daytime (working time) and nighttime, respectively. The PSD can be characterized by a power law with a slope $\beta \geq -1$ in the low frequency limit, indicating stationary process. At higher frequency, the PSD becomes power law again, with a slope $\beta = -2$, implying a random walk behavior.

Finally we watch the cumulative probability distribution of area price among four countries. Figure 4 shows the cumulative distribution of normalized area price changes every hour defined as

$$g(t) = (\log(P_{\text{area}}(t+1)) - \log(P_{\text{area}}(t))) / \sigma_{\text{area}},$$

where σ_{area} is standard deviation of the are price changes. When in the Nord Pool the excessive divergence between the area price and the system price is watched, it is

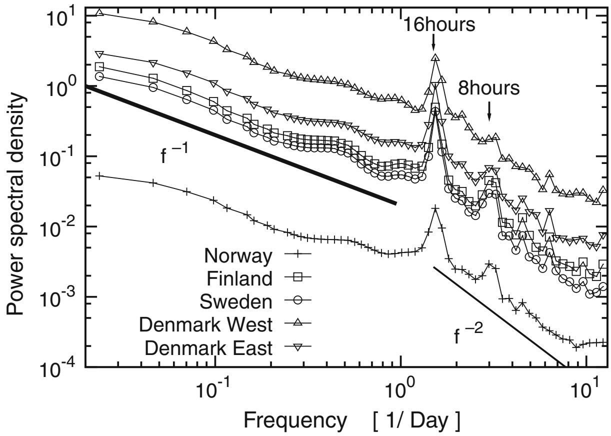

Fig. 3 Power spectral densities for price ratio of area and system price

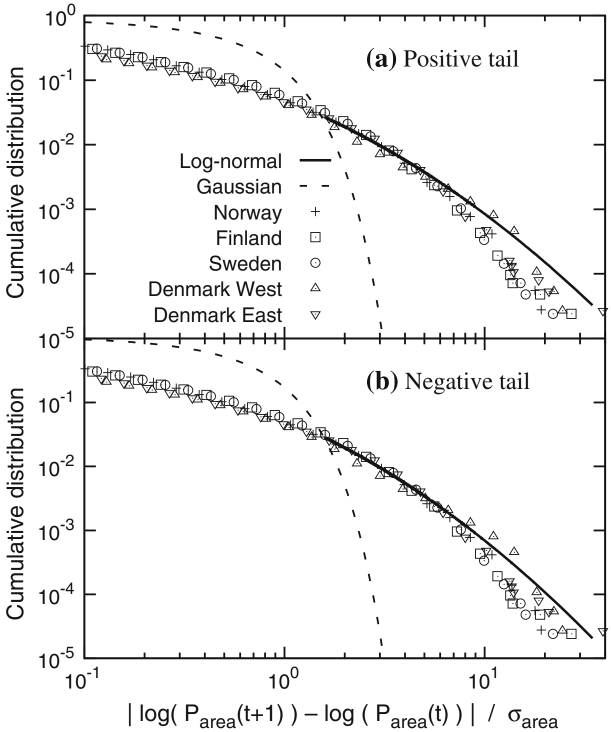

Fig. 4 Cumulative distribution functions of area price changes for positive tail ($P_{\text{area}}(t+1) > P_{\text{area}}(t)$) (**a**) and negative tail ($P_{\text{area}}(t+1) < P_{\text{area}}(t)$) (**b**). The line is the best fit with the log-Normal distribution. Standard normal distribution (Gaussian) is shown for comparison

adjusted by the trading system Elbas that makes a trade possible up to 60 min before the delivery hour. The ceiling and the floor of the area price are kept within reasonable bounds in order to avoid excessive volatility. As a result, unlike the case of foreign exchange rate (Ohnishi et al. 2008), the price distribution does not exhibit a true power distribution.

The Kolmogorov–Smirnov test compares two cumulative distribution functions (CDFs), and the maximum difference between these two CDFs yields a p-value. At the significance level of 5%, if the p-value lager than 0.05, the data passes the test, and consequently the null hypothesis that these two distributions follow the same function is accepted.

We compare our CDF to the CDF of a power law as

$$Pr(\geq x) \propto x^{-\alpha}, \quad x > x_{\min}$$

for x larger than a lower bound $x_{\min} = 1.6$. We estimate the value of the parameter of α using maximum likelihood method ($\alpha = 1.72 \pm 0.01$ for positive tail and 1.81 ± 0.01 for negative). For both positive and negative tails, the p-values is about 10^{-6}, indicating that the data dose not pass the test.

We also test for log-Normal distribution defined as

$$Pr(\geq x) \propto \exp\left[-\frac{(\ln x - \mu)^2}{2\sigma^2}\right], \quad x > x_{\min}$$

for x larger than a lower bound $x_{\min} = 1.6$. We estimate the value of the parameters μ and σ using method of least squares ($\mu = -1.672 \pm 0.001$ and $\sigma = 1.3740 \pm 0.0004$ for positive tail, and $\mu = -1.671 \pm 0.001$ and $\sigma = 1.3185 \pm 0.0005$ for negative). The p-values are 0.25 for positive and 0.11 for negative, indicating that the data pass the test and observed data follow the log-Normal distribution.

3 Conclusion

The Nord Pool has been regarded as an efficient power exchange covering the Nordic countries that contribute to enhance competition and security. The basic institutional premise is that the spot market is competitive in the sense that no one can control and distort efficient price formation. It is sometimes pointed out that there may exist anti-competitive pricing,[3] but it is generally taken for granted that the Nord Pool is fairly competitive.

We must, however, notice that there underlies another basic problem in pricing that may arise if the dynamic behavior of price over time does not follow the normal distribution. The normal distribution guarantees by 3σ rule that the exceptional event like price hike or meltdown will rarely happen. For example, probability of such phenomenon as of 3σ is 0.27%.

During the crisis of electricity shortage during 2002 and 2003, the Nordic people suffered from price hikes. Although, Amundson et.al argued that the Nord Pool survived the price turmoil, the fact remains that prices may burst in the future.[4]

[3] See Hylleberg (2004), Barnekow (2007).

[4] See Amundsen et al. (2006).

In this paper we examined the behavior of area price from 2001 to 2007 from the viewpoint of econophysics. We have found that the dynamic behavior of area price does not follow the normal distribution. In other words the shape of the distribution is fat-tailed or log-normal. Compared to the system price, the area price will fluctuate from one tenth to tenfold of the system price and their probability is not negligibly small as in the case of the normal distribution.

The source of price volatility mainly comes from the congestion of interconnecting transmission lines. It is often a subject of hot discussion whether each TSO can coordinate investment plans across the border. If they fail to sustain a well balanced investment plans, the problem of the capacity constraint upon transmission lines will become urgent. Our analysis suggests that the present state of price distribution itself represents a source of difficulty in the future.

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