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Energy storage dimensioning and feasibility analysis for household consumption scheduling based on fluctuations of Nord Pool Spot price

***Abstract**. This paper describes the analysis of price fluctuations in the Nord Pool Spot (NPS) Estonia (EE) area. Also the electrical energy storage dimensioning and feasibility analysis for consumption scheduling on the basis of the NPS EE area price is discussed.*

***Streszczenie.** W artykule przedstawiono analizę fluktuacji cen na obszarze objętym przez Nord Pool Spot (NPS) Estonia. Dodatkowo zaprezentowano metody wymiarowania oraz analizę wykonalności układów magazynowania energii na podstawie danych dotyczących zużycia energii w systemie NPS EE. (**Wymiarowanie i analiza wykonalności magazynów energii dla obiektów mieszkalnych na podstawie fluktuacji cen w Nord Pool Spot**).*

Keywords: consumption scheduling; household; Nord Pool Spot; energy storage dimensioning; feasibility.
Słowa kluczowe: in the case of foreign Authors in this line the Editor inserts Polish translation of keywords.

Introduction

The deregulation of electricity industry is giving way to global trends toward the commodization of electric energy. [1][2]. This trend has intensified in Europe and North America, where market forces have pushed legislators to begin removing artificial barriers that have shielded electric utilities from competition. The price of electricity is far more volatile than that of other commodities normally noted for extreme volatility. Relatively small changes in load or generation can cause large changes in price and all in a matter of hours (with real-time dynamic prices in seconds or minutes). Unlike in the financial markets, electricity is traded every hour of the year - including nights, weekends and holidays. Unlike other commodities, electricity cannot be stored efficiently. Therefore, delicate balance must be maintained between the generation and consumption for 8760 hours a year.

There is, however, a great difference between electricity and the other energy (and commodity) markets in that the variable costs of production vary so greatly between different types of installation – Wind and Hydropower with a virtual nil cost at one extreme and Gas Turbines at the other end of the scale. In order to satisfy fluctuating consumer demand at the lowest cost, a broad variety of generating techniques are required. Some installations are capital intensive but can be run year round and are relatively fuel efficient (hydro, nuclear, coal-fired). Other units such as co-production of heat and power are used less frequently to cover winter heating demand at times of higher prices. Whilst energy intensive units such as Gas Fired Turbines are used for brief periods of very high price and demand.

Although the principle of generation electricity is simple, generating electricity for an area as large as Europe means a complex balancing process. One of the biggest problems faced by the system operator is congestion. When congestion occurs, zonal prices supersede power exchange's market clearing price, which is based on the aggregated energy supply and demand curve intersection point for each hour [3]. In such a case, electricity prices can increase or decrease dramatically. The primary role of a market price is to establish equilibrium between supply and demand. This task is especially important in the power markets because of the inability to store electricity efficiently and the high costs associated with any supply failure. NPS runs the largest market for electrical energy in the world, offering both day-ahead and intraday markets to its participants. 330 companies from 20 countries trade on the Exchange. In 2009 the NPS group had a turnover of 288TWh [4]. The spot market at NPS is an auction based exchange for the trading of prompt physically delivered electricity. The spot market carries out the key task of balancing supply and demand in the power market with a certain scope for forward planning. In addition to this, there is a final balancing process for fine adjustments in the real time balancing market. The spot market receives bids and offers from producers and consumers alike and calculates an hourly price which balances these opposing sides. NPS publishes a spot price for each hour of the coming day in order to synthetically balance supply and demand. Every morning Nord Pool participants post their orders to the auction for the coming day. Each order specifies the volume in MWh/h that a participant is willing to buy or sell at specific price levels (€/MWh) for each individual hour in the following day. The SESAM (Elspot trading system) calculation equation (1) is based on an application of the social welfare criteria in combination with market rules. SESAM is maximizing the value of the objective function subject to physical constraints; like volume constraints, area balances, transmission and ramping constraints.

$$Max\sum_{n}\left\{\int_{0}^{d^a} D^a(x)dx - \int_{0}^{s^a} S^a(y)dy\right. \qquad (1)$$

where a – represents an area, d^a – demand in the area a, and D^a – demand function in the area a, s^a – supply in the area a, S^a – supply function in the area a, and n – number of areas.

The system price (SP1) for each hour is determined by the intersection of the aggregate supply and demand curves which are representing all bids and offers for the entire Nordic region [4]. In addition to area price there is also an annual fixed fee and a variable trading fee for all market participants. In the political debate surrounding energy, this type of price formation is labeled a marginal price setting. This gives a false impression that the establishment of prices in the electricity market is different from the price formation process in other commodity markets. The only difference lies in the significantly higher requirements for the secure delivery of electricity because it must be delivered at the precise moment it is needed by the consumer. The inelasticity caused by the inability to store electricity is the reason of this difference.

Storage dimensioning for consumption scheduling based on the Nord Pool Spot (NPS) average daily price

To find the possibilities for consumption scheduling it was constructed an average day from actual data from the NPS trading system. It was studied a period of seven months starting in April 2010. Average price was calculated with the well-known formula of a generalized mean.

$$\bar{x} = \sqrt[m]{\frac{\sum_{i=1}^{n} x_i^m}{n}} \qquad (2)$$

where X_i – price of electrical energy at time i

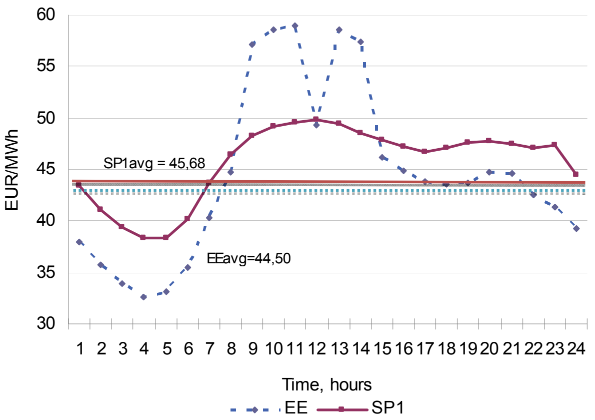

Fig. 1. Average daily price at the EE area and SP1 area

One hour is the smallest time interval when prices can change, because on spot electricity trading prices are set constant for delivery of power during a certain hour. Analysis shows that fluctuations in the system area are smaller (around 11.00€/MWh) than in the EE area (the amplitude of the price during the day is much higher at 26.35€/MWh) (Fig. 1). The high price amplitude in the local market provides opportunities to use consumption scheduling models in residential areas to gain economy.

Energy consumption in households in the UK is reported in [5] and in Estonia in [6]. Peak hours for UK households are from 06-08 and 13-18. Main peak hours for Estonian average households are at 7-8 and 19-21 on workdays (WD) and 12-14 and 19-21 at weekends (HD). It is quite easy to see the possible use of energy storage to smoothen the loads at morning or midday use and even the evening use at weekends. However, some exact calculations are needed in terms of the possibilities to conserve energy at low price before evening peak hours on workdays [7].

According to equation 2 the average NPS price during the measured period (April 2010 to October 2010) in the Estonia (EE) area is calculated as 44.50€/MWh. The NPS price curve is not similar on workdays and at weekends. The maximum price on workdays is 65.93€/MWh and the minimum is 33.35€/MWh. At weekends the maximum and minimum prices are 43.05€/MWh and 29.76€/MWh, respectively. Average price below the EE area average (44.50€/MWh) is 38.02€/MWh (-14.55%) on workdays and 38.26€/MWh (-14.03%) at weekends. Average price above the EE area average is 53.50 €/MWh (20.22%) on workdays and does not exceed the average at weekends.

If all shiftable loads on workday (WD) are "switched on" under average price, then at least 1.1 kWh storage system is needed for shifting of energy consumption (Fig. 2).

If all shiftable loads on holiday (HD) are "switched on" under average price, then at least 11.8 kWh of energy consumption should be supplied from the storage system (Fig. 3). If an average price deviation is allowed (43.05 - 29.76)*10% = 1.33€ (10 % from maximum and minimum price difference), then 4.83 kWh should be supplied from the electrical energy storage.

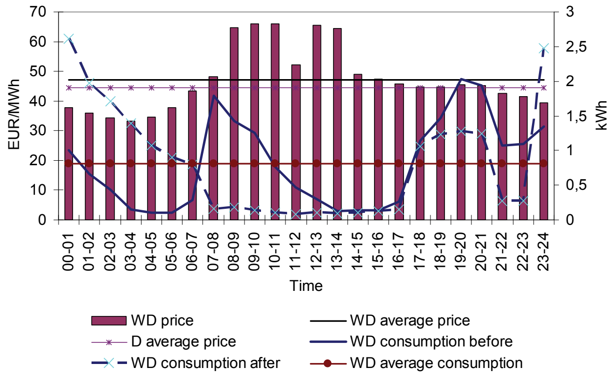

Fig. 2. Average workday price fluctuation compared to electricity consumption before and after scheduling of shiftable loads

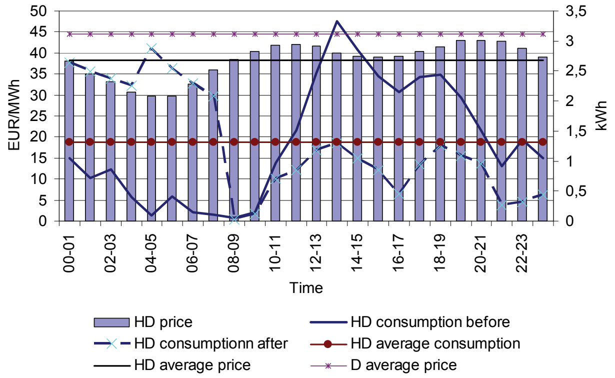

Fig. 3. Average holiday price fluctuation compared to electricity consumption before and after scheduling of shiftable loads

Average price deviation and distribution of price range

As shown on figure 4, the deviation calculated by the simple formula (3) from the average price to analyze possibilities to use off-peak hours to store energy or shift the load to off-peak hours. We needed an assurance of off-peak hours available to recharge the batteries or other storage equipment. We found that the average duration of peaks that are higher than the average area price is 9.59 hours and the average duration of off-peaks is 13.48 hours. That means there is plenty of time to recharge storage equipment during the off-peak time.

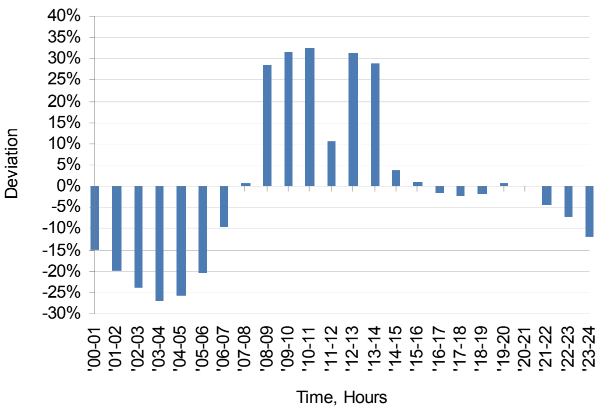

Fig. 4. Average EE area price deviation

Deviation from an average price is higher at peak hours, but peak hours last less than off-peak hours. It is most profitable to save energy between the 23...06 o'clock, then the price is lower than 10% compared to average. There is also a possibility to save energy between 16...19 o'clock when the price is about 2-3% lower than average.

$$S = \frac{\sum_{n=1}^{k} \frac{x_i}{n} - X_F}{X_F} \tag{3}$$

where X_i – price of electrical energy in the instance *i* (from 0-24 hours), and X_F – average area price.

As seen in fig. 5 the distribution of prices is symmetric and leptokurtic. With the leptokurtic distribution, the price will have a relatively low amount of variance, because return values are close to the mean. This could mean that energy producers will not try to invest to storage facilities as there could be quite small return on investment. This gives us an opportunity to continue our research on the profitability of using energy storing and shifting on the demand side.

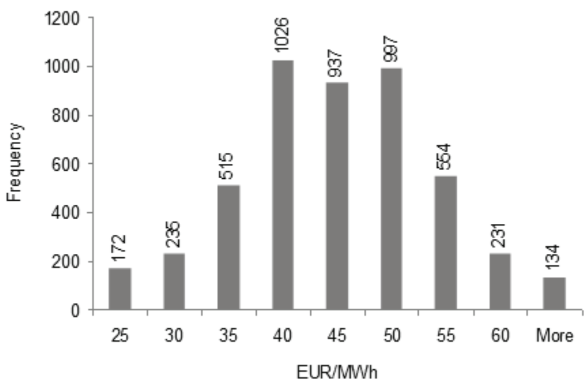

Fig. 5. Distribution of price range in the EE area

Feasibility analysis

Today batteries could be the best solution for consumption shifting in an average apartment [6]. Their feasibility for households can be estimated by the system cost and profit calculation. To find a profitable ES, it is necessary to take into account parameters and costs described in papers [8] and [9]. In current analysis are described Lead-Acid (LA), Nickel Cadmium (NiCd), Lithium Ion (LiIon), Sodium Sulphur(NaS), Vanadium Redox Flow(VR), Polysulfide Bromide Flow (PSB) and Zinc Bromide (ZnBr) batteries.

10 year usage of energy storage (1 charge/discharge cycle per day) will give approximately 3650 cycles then charging takes place in the low price period at night and discharge takes place in the high price period during daytime. In case of constant Depth of Discharge (DoD) value, the required energy capacity is different from initial energy capacity. The simple equation 4 establishes the final required energy capacity for consumption scheduling with particular DoD.

$$E_{1,\max} = \frac{E_I}{DoD} \tag{4}$$

Where $E_{1,max}$ – required maximum energy capacity, and E_I – initial required energy capacity.

Table 1 shows the result of DoD and energy capacity calculation with 3650 cycles for different batteries with 7 and 12 kWh of Initial Required Energy Capacity (IREC). It shows that highest discharge depth can be applied in case of NaS battery, which reduces the final required energy capacity until 7.68 kWh. Thus, daily maximum load shifting to low price involves one charging/discharging cycle of ES with 7 kWh of energy capacity. Daily cost savings C_{cyc} for one charge/discharge cycle with estimated price deviation are shown in (5).

$$C_{cyc} = E_{2,\max} \cdot \Delta x \tag{5}$$

where E_{2max} – ES maximum energy capacity for financial saving, Δx – amplitude of price during the day (26.35€/MWh).

Table 1. DoD and energy capacity calculation with 3650 cycles

	Li-Ion	LA	NiCd	ZnBr	VR	NaS
DoD, %	72,76	14,58	43,63	45,62	76,66	91,10
IREC 7 (kWh)	9,62	48,02	16,04	15,34	9,13	7,68
IREC 7 (kWh)	16,49	82,32	27,50	26,31	15,65	13,17

The result of equation 5 is 0.186 € (7 kWh x 0.0264 €/kWh). It means that one charging/discharging cycle of ES for investigated apartment will save 0.19€

Table 2 demonstrates ES total cost calculated for initial required energy capacity of 7 kWh and peak power 7 kW. There are columns with calculated number of cycles for investment return and costs per 1 cycle. The last column of table 2 is price difference multiplying factor. It shows by how many times current price difference must be increased for ES recoupment. As we can see none of batteries storages is able to return the investment and make profit within current life-time (cycles). It means, with current price differences, there are only two opportunities to achieve profitability. The first one is reducing the total cost of energy storage system (cheaper components, cheaper maintenance), which should give possibility to return investment in limited period of time i.e. 7 – 10 years. The second method is increasing lifetime of ES (more cycles, higher efficiency), which should give possibility to return investment in period of time about 20 – 30 years, before it fails or breaks down.

According to table 2 the most prospective ES is Sodium Sulphur (NaS) Battery. It has medium energy capacity cost and slightly expensive power capacity cost (up to 380€ / kW). While it is quite new product on the market, the cost could be reduced. Today, the main difficulty is that developing companies generally target this technology for utility-scale (>1000 kW) stationary applications. Developing of NaS system solutions for small consumers can bring this type of storages to households market.

The increasing usage of renewable energy sources (and/or increasing production of renewable sources) on the market could increase price differences and profitability of ES systems. Also, introduction of full real-time dynamic pricing system (e.g. price changing period is 5 minutes or less), with increased amplitude of price, could reduce profitability time of electrical ES systems for households.

Table 2. Investments return calculation for battery energy storages

Battery type	Energy storage cost €	Cost per cycle €	Amount of required cycles to return the investment	ES actual lifetime cycles with DoD 50%	Price difference multiplying factor to return investments with lifetime cycles
NaS	4109	0,41	21625	10000	2,2
LA	3399	8,94	17889	380	47,1
NiCd	7948	2,65	41833	3000	13,9
Li-Ion	6772	0,97	35642	7000	5,1
ZnBr	3161	0,93	16635	3400	4,9
PSB	3979	0,99	20944	4000	5,2
VR	3394	0,64	17862	5300	3,4

Conclusion

We observed the EE area price during 4802 hours starting from 1 April 2010 when Estonia entered the NPS market. During that time an average hourly price for the EE price area was 44.5€/MWh and it is slightly lower than the price in the system area. The price curve is similar on weekdays and at weekends. At weekends the average hourly price remains under an average area price. An average off-peak time lasts for 13.48 hours, which is long enough to store energy with cheaper storage equipment or shift the power usage to a less expensive time period without losing customer's comfort requirement. The minimum energy reserves that an electrical energy storage system should have for described household energy consumption shifting, based on the Nord Pool Spot (NPS) average daily price should be between 4.83....11.8 kWh (average about 7 kWh).

Described analysis shows that there is no ES solution for a household which would return total initial investments and make a profit in a lifetime period. With current battery lifetimes and current DoDs, battery storages will bring profit only with the difference growing between energy prices by 2.2 for NaS as a minimum and by 47.1 for LA as a maximum one. Nevertheless, the similarity of the calculated parameters of household energy storage with the parameters of existing hybrid electric vehicle batteries makes the technology used in vehicles attractive for residential areas. Today, the most feasible solution is load shifting with simple scheduling systems (without electrical energy storage). Profitability time of investments for simple scheduling systems is up to 2 years. For example, investment for the shifting equipment of water heater is less than 1 year.

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