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Modeling of dynamic market of energy with local energy clusters*

by

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Abstract: Clusters of energy are a new mechanism, meant to support development of modern power grids in Poland. In this article, we experimentally check the influence of a hypothetical presence of clusters on energy markets. We present a two level real time power market, where the power first is balanced within a cluster and then an inter-cluster trading is performed, in which the country power grid is a participant in the market. We show that it can be beneficial for all parties to maintain such a schema and that it is also a possible direction for further research.

Keywords: energy market, energy clusters, AA strategy

1. Introduction

The market of electricity is a very complex system which, despite the very active attempts to introduce free market mechanisms, still has strong features of oligopoly. The market has to satisfy different interest groups: the producers of power, the owners of the grid, the government that has to consider safety of power supply and, last but not least, the customers. On the top of this, power production has to match the demand at any time, at the same time guaranteeing the quality of the current. All of that has to fit with the dynamic development of distributed micro-power sources and clusters of energy.

Clusters of energy are legal entities that are allowed to trade electric power on a small, local scale. Clusters would gather geographically close producers and/or consumers in order to reduce the overhead of transport of electricity. In addition, a cluster would play a role in maintaining the good quality of power and its proper distribution. Apart from the technical problems with this solution, it is interesting to study the influence that such a model can have on the electricity market.

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In this paper, we analyse the effects of introducing clusters into the continuous bilateral energy market. It is not a full economic analysis as in Mohammadi (2012), rather it is simply an attempt to estimate the feasibility of introducing clusters in a certain type of market, which is a version of a pool market, Onaiwu (2009).The following two sections describe the model of the market (the trading scheme) and the strategies of the market participants. Section 4 shows the experiments that were performed to test the construction of the schema. The final section concludes the work.

2. Market model

2.1. Continuous double auction

The considered market is Continuous Double Auction (CDA), where transactions happen when buyer and seller agree on a price (see Luckok, 2003). The continuous double auction is one of the market mechanisms, frequently used in the stock market and also in the respective computer simulations (Tesauro and Das, 2001). The Adaptive-Aggressive (AA) strategy (Vytelingum et al., 2008) is used to calculate prices for market participants. This type of market consists of three kinds of entities:

- sellers, who offer their commodity at a certain price (their offer on the market is called *an ask*), along with the number of units of traded good they can sell,
- buyers, who put offers for purchasing the commodity (their offers are called *bids*) with some chosen prices and the number of units of commodity they need,
- the market agent (the broker) gathers the bids and the asks and orders them so as to find the bids with the highest price and the asks with the lowest. The broker arranges transactions if it turns out possible – when prices of subsequent ask offers are lower than or equal to the prices of the subsequent bid offers. The market agent also records important market events and outstanding offers (the current lowest ask is called the *outstanding ask*, and the highest bid is called the *outstanding bid*; both these values are important during the offer price – for bids and asks – formulation).

Buyers and sellers on the market are expected to behave *rationally*: their bids and asks should not be unprofitable and the ask-bid spread should be reduced during the market action, thus enabling the market prices to evolve toward an equilibrium price.

In general, there are several variants of CDA markets, depending on specifics of particular markets or traded goods. The most important is the cyclic trade. All market participants may give their offers, even asks and bids simultaneously, but only one of each type in one cycle. After collecting all offers, transactions are performed only if they are profitable for both participants*. Offers unmatched in one cycle continue to be active for a limited number of cycles, in this case their owners cannot bid again with the same types of offers. However, as it is possible to take into account the market events, it is rather advantageous to make a new offer in consecutive time cycle. In the energy context, the non-covered bids are always paired with the external power grid to ensure the overall perfect balancing. Time cycles in auctions are not associated with the real periods of time and time is not a crucial factor in this type of market. Surpluses and shortages can be sold/bought in subsequent iterations.

2.2. Two-level market for energy

It is predicted that within the next few years the legal situation in Poland will change in favour of a more liberal approach to energy trading and that the clusters would have real possibilities to gather prosumers, aggregate their energy and trade it. To realize this idea, the clusters not only need the changes in the national law, but also changes in infrastructure. To trade power, full knowledge is required about the amount of produced and consumed power at the point of entering or exiting of this energy to and from the power grid. In other words, the virtual "owner" of each kWh of energy has to be defined. It is then possible to virtually mark the kilowatt hours as sent from producer A to consumer B, thereby allowing to establish a transaction for a certain price. Additionally, there should be some fee to the owner of the power grid for the service of sending power from A to B. In the future, the clusters might develop their own local power grids on low-voltage levels and benefit from custom transfer pricing. It means that, if A and B belong to the same cluster and are connected by a low-voltage power grid, belonging to the cluster, their trading will not be visible from the external grid and no respective grid fees will apply.

In this paper, we consider the futuristic situation, in which the clusters own a part of the low-voltage power grid. In order to account for the clusters in the described market schema, the power trading is done in two stages:

1. First, "virtual" trading is performed within each cluster. The participants of a cluster are a part of the same low-level power grid and trading includes a fixed cost for using the infrastructure. The cost can be defined by clusters in many ways, but this is not in the scope of this article. We assume that the cluster's price for using the power grid infrastructure is cheaper than the fee of the national power grids. The participants of the cluster in the first level market are trying to balance energy within the cluster – if it is possible. If such a balance proves to be possible, then no second level bids or asks have to be done and there is a substantial profit from not incurring an extra cost for using the external infrastructure. But this situation is extremely rare. Usually, there will be some amount of power

*It is impossible to buy one's own energy, because asks and bids are always respectively above and below the cost curve and this kind of transaction is not profitable. Transactions with profit equal 0 are considered not rational in this approach.

that cannot be balanced: there will either be a surplus or a shortage of energy. From the point of view of external power grid the cluster as a whole is a prosumer – a single unit that is a participant of the second level market.

2. The second level of the market is a classic real time power market, in which one entity represents all members of the cluster. This can potentially create a bigger consumer (in case the cluster contains less production capacity than consumption capacity) or prosumer (if the cluster has a surplus of energy). At this stage, the trading involves the external grid, which means including standard costs for sending power, in turn making the powerflow more expensive.

After power gets sold or bought, the cluster divides the costs and profits proportionally. The division is based on establishing which units took part in generating the surplus or shortage of power in the microgrid. In this way, the internal balancing gets rewarded and should stimulate the members to create more ways of producing and storing power.

3. The strategies of the market participants - The Adaptive-Aggressive strategy of price formation

The Adaptive-Aggressive strategy, presented in Vytelingum et al. (2008) is a very sophisticated method of auction price development for all participants, regardless of their role in the process: seller or buyer. This method combines an estimation of market parameters, short- and long-term learning of market behaviour and the degree of participants' determination to carry out the transaction (aggressiveness).

One of the most important market parameters for describing its properties is the estimate of the equilibrium price $\hat{p}^*(T)$ at the closing of trading time T. It is calculated as the weighted moving average of last N transaction prices $p(t)$

$$\hat{p}^*(T) = \sum_{t=T-N+1}^{T} w(t)p(t) \tag{1}$$

$$w(t-1) = \rho w(t), \qquad \sum_{t=T-N+1}^{T} w(t) = 1$$

where $w(t)$ are weights, and $0 < \rho < 1$. From the above conditions it stems that

$$w(T) = \frac{1-\rho}{1-\rho^N}.$$

The value of $\rho = 0.9$ has been used upon the method author's suggestion in the simulations presented further in this paper.

Each trader has its own price λ_i, which constitutes a limit of its trading possibilities, depending on the transaction's profitability. According to the calculated value of $\hat{p}^*(T)$, two types of traders can be considered: an intra-marginal and an extra-marginal one. Additionally, market participants can also be naturally divided into buyers and sellers. Thus, four kinds of market participants can be derived, taking into account the following conditions (to simplify notation the subscript i, denoting the trader, is omitted):

for an intra-marginal buyer $\lambda > \hat{p}^*(T)$,
for an intra-marginal seller $\lambda < \hat{p}^*(T)$.
and
for an extra-marginal buyer $\lambda < \hat{p}^*(T)$,
for an extra-marginal seller $\lambda > \hat{p}^*(T)$.

As it can be seen, the intra-marginal buyer and seller are in good position for trading, the extra-marginal ones rather not. The notions of intra- or extra-marginal trader depend on time, as the estimate of the equilibrium price changes during the trade.

The final bid or ask price formation requires a lot of information about the market, which is used by the traders: the target price τ, the degree of aggressiveness r (see formula (2)) and the volatility parameter θ (see formula (4)).

The aggressiveness of the trader is an element of the short-time learning strategy and is controlled by the parameter $r \in [-1, 1]$. A trader with a value r close to -1 is called completely passive, meaning it will try to buy at price near 0 or sell at price near $o_{ask,\max}$ (with the maximum profit). A trader with $r = 0$ is called active and tries to buy and sell at price close to $\hat{p}^*(T)$ with moderate profit. Lastly, the trader with r close to 1 is called completely aggressive and tries to buy and sell at a price close to its $\lambda(t)$ price without or almost without profit. The degree of aggressiveness is being adapted according to the Widrow-Hoff rule (Hertz et al., 1991):

$$r(t+1) = r(t) + \beta_1(\delta(t) - r(t)) \tag{2}$$

where $0 < \beta_1 < 1$ is the learning rate, and $\delta(t)$ is the current desired aggressiveness. The desired aggressiveness is calculated to possibly improve the last shout, from the equation

$$\delta(t) = (1 \pm \zeta_r) r_{shout} \pm \zeta_a \tag{3}$$

where ζ_r is the relative and ζ_a the absolute change of r_{shout}. The value r_{shout} is the degree of aggressiveness that would form a price equal to the last shout. It is taken into account and changed, if any of the following conditions occurs:

For a buyer

If the last shout was followed by a transaction at price $q(t-1)$, and:
if $\tau(t-1) \geq q(t-1)$ then the buyer becomes more aggressive (λ_r and λ_a positive),
else the buyer becomes less aggressive (λ_r and λ_a negative).
If bid b was submitted and
if $\tau(t-1) \leq b$ then the buyer becomes more aggressive.

For a seller

If the last shout was followed by a transaction at price $q(t-1)$, and:
if $\tau(t-1) \leq q(t-1)$ then the seller becomes more aggressive (λ_r and λ_a negative),
else the seller becomes more aggressive (λ_r and λ_a positive).
If ask a was submitted and
if $\tau(t-1) \geq a$ then the seller becomes more aggressive.

The volatility parameter θ introduces dependence of the target price on price volatility α:

$$\theta^* = \theta_{\min} + (\theta_{\max} - \theta_{\min})(1 - \bar{\alpha} e^{\gamma(\bar{\alpha}-1)}) \tag{4}$$

where $\theta_{\min}$ and $\theta_{\max}$ are the minimal and the maximal value of updating θ, respectively, γ is a coefficient that determines the shape of this function, and $\bar{\alpha}$ is the normalized value of α, i.e.

$$\bar{\alpha} = \frac{\alpha - \alpha_{\min}}{\alpha_{\max} - \alpha_{\min}}.$$

The long-term learning strategy also uses the Widrow-Hoff rule to adapt the θ parameter:

$$\theta(t+1) = \theta(t) + \beta_2(\theta^* - \theta(t)) \tag{5}$$

where $0 < \beta_2 < 1$ is the learning rate.

The target price τ is very important for the traders and depends on the type and the role of the trader. It is the basis for calculation of traders' asks or bids in the auction (see: (11) and (10)):

- for an intra-marginal buyer

$$\tau(t) = \begin{cases} \hat{p}^*(t)\big(1 - \frac{e^{-r\theta}-1}{e^{\theta}-1}\big) & \text{if } -1 < r \leq 0 \\ \hat{p}^*(t) + (\lambda_b - \hat{p}^*(t))\frac{e^{r\theta}-1}{e^{\theta}-1} & \text{if } \quad 0 < r < 1 \end{cases} \tag{6}$$

  where λ_b is a buyer limit price;
- for an intra-marginal seller

$$\tau(t) = \begin{cases} \hat{p}^*(t) + \big(o_{ask,\max} - \hat{p}^*(t)\big)\frac{e^{-r\theta}-1}{e^{\theta}-1} & \text{if } -1 < r \leq 0 \\ \lambda_s + (\hat{p}^*(t) - \lambda_s)\big(1 - \frac{e^{r\theta}-1}{e^{\theta}-1}\big) & \text{if } \quad 0 < r < 1 \end{cases} \tag{7}$$

- for an extra-marginal buyer

$$\tau(t) = \begin{cases} \lambda_b\big(1 - \frac{e^{-r\theta}-1}{e^{\theta}-1}\big) & \text{if } -1 < r \leq 0 \\ \lambda_b & \text{if } \quad 0 < r < 1 \end{cases} \tag{8}$$

- for an extra-marginal seller

$$\tau(t) = \begin{cases} \lambda_s + (o_{ask,\max} - \lambda_s)\frac{e^{-r\theta}-1}{e^{\theta}-1} & \text{if} \quad -1 < r \leq 0 \\ \lambda_s & \text{if} \quad 0 < r < 1 \end{cases} \tag{9}$$

where λ_s is a seller limit price and $o_{ask,\max}$ is the maximum ask allowed in the market.

Now that all parameters necessary for the price formation are defined, they can be calculated using the following formulae:

For a buyer

$$bid(t) = \begin{cases} o_{bid} + \frac{\min(\lambda_b, o^{+}_{ask}) - o_{bid}}{\eta} & \text{in the first round} \\ o_{bid} + \frac{\tau - o_{bid}}{\eta} & \text{otherwise} \end{cases} \tag{10}$$

where $o^{+}_{ask} = (1 + \zeta_r)o_{ask} + \zeta_a$ and $1 \leq \eta < \infty$ is a constant.

For a seller

$$ask(t) = \begin{cases} o_{ask} - \frac{\max(\lambda_s, o^{-}_{bid}) - o_{ask}}{\eta} & \text{in the first round} \\ o_{ask} + \frac{\tau - o_{ask}}{\eta} & \text{otherwise} \end{cases} \tag{11}$$

where $o^{-}_{bid} = (1 - \zeta_r)o_{bid} - \zeta_a$.

In Vytelingum et al. (2010), the following values of constants, required in the method, have been used: $\eta = 3$, $\zeta_a = 0.01$, $\zeta_r = 0.02$, $\gamma = 2$, β_1, and β_2 drawn from the uniform distribution over the interval [0.2, 0.6]. These values were also kept in the here presented simulations. The traders must obey some rules to act as rational market players. A buyer submits a bid only if its limit price is higher than the current bid o_{bid}. A seller submits an ask only if its limit price is lower than the current ask o_{ask}. If the current ask is less than or equal to the buyer's target price, $o_{ask} \leq \tau$, then the buyer accepts it. If the current bid is greater than or equal to the seller's target price, $o_{bid} \geq \tau$, then the seller accepts it. The initial ask has been set in the simulation as $o_{ask,0} = o_{ask,\max}$. The initial bid has been set as $o_{bid,0} = 0$. The specificity of the electricity market required some minor changes on the stock exchange with CDA and AA. Since the demand and supply of market participants (except for the external supplier) must be met, an extra-time mechanism (of maximum 4 rounds) has been added to the market described above, where it is possible to buy/sell the shortages or the surpluses of energy. In addition, the offer prices are slightly moved towards the λ prices of participants. At the 4th extra round, offer prices are set as λ prices of participants, but the use of this case has been observed only once during simulations.

Table 1. The marginal costs of the participants on the market

participant	buying price	selling price
clusters (1,2,3)	0.22	0.18
prosumer 1	0.2602	0.15
prosumer 2	0.2655	0.15
prosumer 3	0.25434	0.15

Table 2. The maximum production capabilities of prosumers in the clusters

participant	cluster 1	cluster 2	cluster 3
prosumer 1	10 kWh	30 kWh	25 kWh
prosumer 2	10 kWh	30 kWh	0 kWh
prosumer 3	20 KWh	20 KWh	0 kWh

4. Experiments

4.1. Basic data

The test case presents a scenario where the clusters gather multiple prosumers that potentially can cover their total demand for electricity. For clarity, in the test case, there are only 3 clusters considered, each of them consisting of 3 prosumers/consumers. Their marginal costs are set to similar values as presented in Table 1. One of the prosumers in clusters 1, 2 and 3 has the maximum buying price of 0.2602 PLN and minimum selling price of 0.15 PLN, the second, respectively 0.2655 and 0.15 PLN, and the third one 0.25434 and 0.15 PLN.

The cluster is considered as an extra market participant that plays a role of balancing unit, which means that it sells and purchases all energy that was not traded between other users, its maximum buying price is 0.22 PLN and minimum selling price 0.18 PLN. There are in total 9 prosumers, but it was decided to make the prosumer prices very close to each other to, first, avoid an unrealistic behaviour of the market price and, second, be able to compare the 3 clusters. Table 2 presents the maximum production capabilities of each prosumer. The variability of production and consumption was generated by the simulators described in Radziszewska and Nahorski (2013) and (2014).

4.2. Results of the first level trading (local)

As can be seen in Fig. 1, all clusters have different amounts of energy that is put on the market – this is caused by assigning different production capabilities to all clusters. Cluster 1 shows, generally, an overproduction of power, which comes from water and wind sources. The transactions with high amounts of energy are coming mainly from production of energy from renewable power sources, like wind turbines and water micropower plants. The sinusoidal patterns in Fig. 1 show generated daily usage of power by consumers. Fig. 2 presents the change in

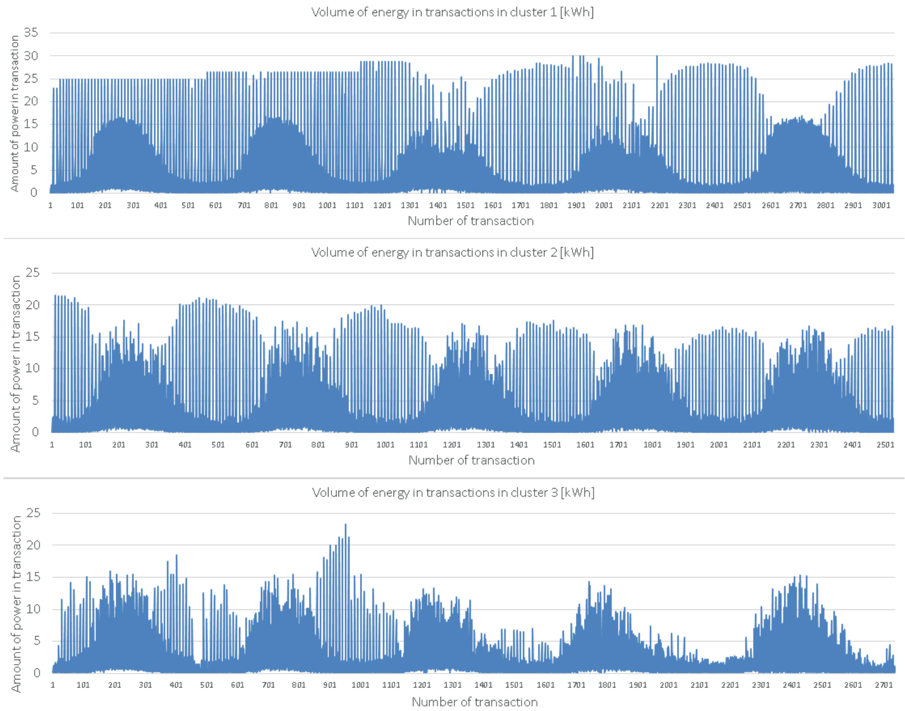

Figure 1. The volumes of energy traded within the clusters

price for 1 kWh of power. Generally, in cluster 1, where there is excess of power, the price is jumping between the marginal costs of participants. Such effect is reached when the Adaptive Aggressive strategy adjusts to the market situation where there is continuous excess of one good. In cluster 3 such situation is rare, so the prices are much less scattered and much more stable. The amounts of energy, sold by the participants to the clusters are shown in Fig. 3. Only the participants of cluster 3 are buying power, this fact being presented in Fig. 4.

4.3. Results of the second level trading

The second level market is simpler in the sense that the clusters are aggregating the power usage and production, therefore there are only 4 players on the market. The maximum buying prices and the minimum selling prices are presented in Table 3.

The volume of power in transactions, the price and amounts sold to and bought from the external power grid are presented in Fig. 6. The behaviour of the AA-algorithm can be clearly seen: when there is more supply of power, the price tends to reach the minimum value; when there is not enough power, the price tends to stabilize.

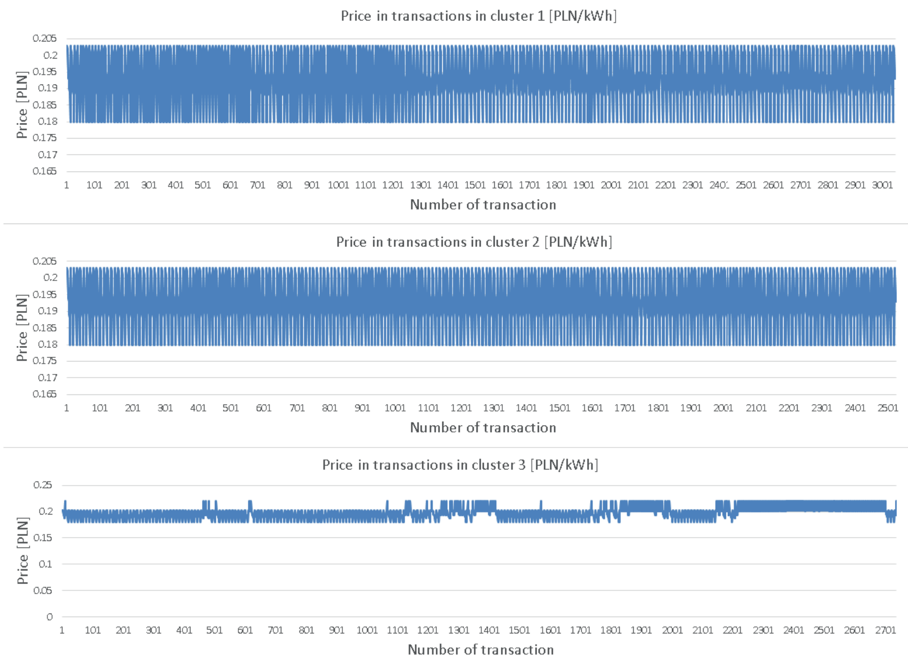

Figure 2. The prices of energy in transactions within the clusters

Table 3. The marginal costs of the participants on the market

participant	buying price	selling price
external power grid	0.15	0.21
cluster 1	0.23	0.16
cluster 2	0.22	016
cluster 3	0.24	0.16

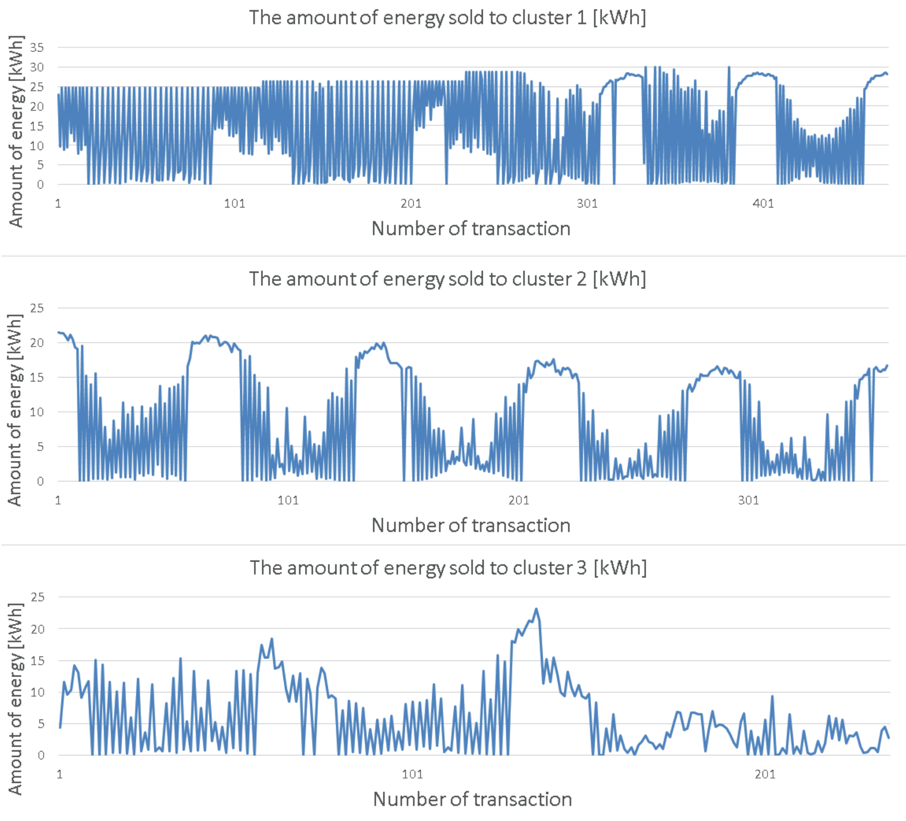

Figure 3. The amounts of energy in transactions within the clusters

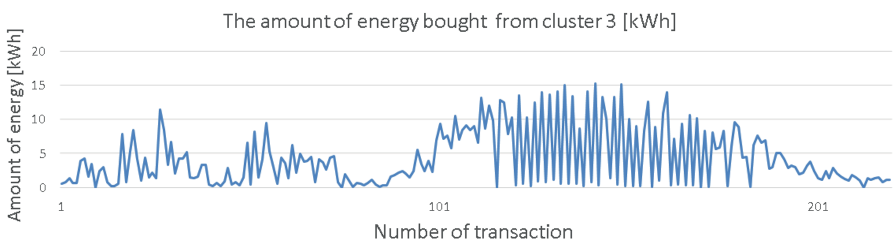

Figure 4. The amounts of energy in transactions within the clusters

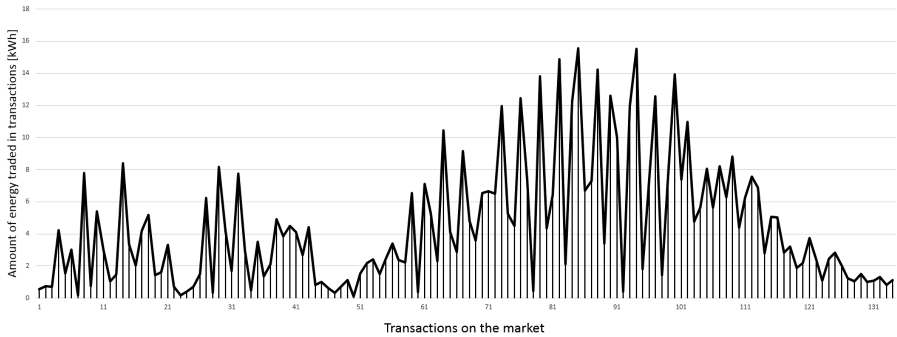

Figure 5. The volume of energy traded between clusters and the external power grid

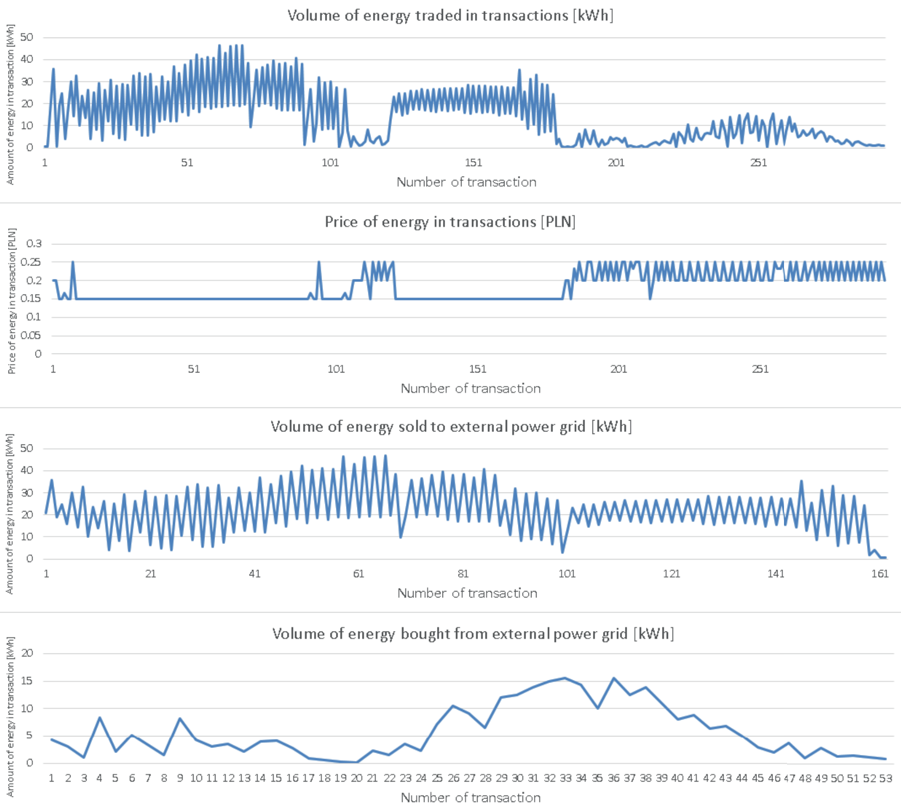

Figure 6. The volume of energy traded between clusters and the external power grid

4.4. Comparison of costs

In the current economic situation of all European countries, the new solutions for energy distribution should be profitable or at least cost neutral. Nowadays, there are many projects aimed at reducing the increase of power prices for people and companies. The assumption behind clusters is that the end users/prosumers do not suffer from power price increase, and at the same time energy or power is traded more locally.

The cluster participants should get some financial or service benefits for creating such legal entity. Cluster is not producing any power, but can negotiate better prices and better distribution costs. There are on-going discussions about the feasibility and role of clusters, but due to legal barriers there have not been yet any operating clusters to test the respective proposed approaches. The most popular idea is that the end prosumers are paying for energy as if there were no clusters, clusters try to negotiate better prices and if they succeed, the difference between the price paid by prosumers and the price paid to the grid constitutes the income of the cluster. Then, the cluster can use this profit to invest in the infrastructure, cover its own operational costs or distribute it among cluster participants.

Considering that the cost of sending 1 kWh of power through the national grid is 0.1 PLN/kWh, the cost for trading the amount of power simulated in our example (just under a week of operation) without clusters is 937.56 PLN. It is the sum of all energy that went through the national power grid, multiplied by the price of using the grid. In the solution with the clusters, the amount exchanged with the external power grids is smaller, owing to internal balancing within the clusters, and the cost of using the external power grid in this situation is 417.78 PLN. The difference in costs could be used in many ways; if it were returned to the prosumers, they would have slightly cheaper energy, investing it in the cluster can improve the infrastructure or fund the installation of power storage units.

5. Conclusion

In this article we are continuing our work from Stańczak et al. (2015) where we were analyzing the energy and CO2 markets. The work presented here extends further this research by considering clusters as representatives of the small prosumers on the power market. The scenario defned creates a two-stage market: first, there is the internal trading withing the cluster, second, the imbalances are traded between clusters and the national level power grid. Clusters reduce the amount of energy exchanged via the national power grid, leading to the reduced load on infrastructure.

The main barrier to the development of clusters is lack of proper legislation to allow clusters to be traders on the power markets. The essential incentive for creating clusters is the potential future profit for the community and for the micro-installation owners. The profit stems from the fact that the costs of using the country-level grid infrastructure are high, and are not expected to decrease in the near future; by taking over a part of this infrastructure (or lowering the scope of its use), the respective costs are lowered. This establishes the main - additional - income margin that will allow the clusters to develop. An accruing thereby financial incentive constitutes, as well, the motivation for prosumers to become members of a cluster: the resulting "dividend" of the cluster can be distributed across the participating prosumers to everyone's benefit.

The future work includes, on the one hand, calculating yearly costs of the presented solutions and, on the other, introducing a power storage unit to the cluster. The choice of the size of the power storage, considering its price, is a non trivial task, as it is not clear when such investment would pay off.

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