1. Electricity Market in Poland

1.1. Market reforms

In Poland market reforms has been introduced to the power supply industry by passing the Energy Law in 1997. The next step lead to the establishment of the Energy Regulatory Authority and the introduction of the Ministry of Economies ordinances allowing for the first stage of liberalisation.

In December 1999, the Economic Committee of the Polish Government approved the electricity market structure. The Power Exchange started the operation in June 2000. From the 1st of September 2001, the Balancing Market began its operation using a day ahead, one-hour interval balancing mechanism. The presumed structure, trade and balancing rules of the Polish Electricity Market makes it one of the most advanced electricity markets in Europe [1].

1.2 Market structure

The structure of the Polish Electricity Market presented to the government four years ago assumed two main levels of energy trade: wholesale and retail. The wholesale market embraces: power producers, energy traders, power exchanges and the balancing market operated by the Transmission System Operator (TSO). The retail market comprises of the Distribution System Operators (DSO) selling energy to tariff (T) and TPA customers, energy traders and the direct access of energy producers to TPA customers. The Power Exchange facilitates wholesale market trade.

The main structure of the electricity market is shown in Figure 1 with the following notation: red lines mean trade and physical flow of electricity, blue lines denote wholesale trade, and green lines indicate trade with TPA customers [1].
The market project approved by the Government presumed the electricity trade is carried out in three main forms: (i) bilateral contracts covering 80-85% of the total energy production, (ii) Power Exchange transactions counting for 10-15% and (iii) balancing market transactions assumed to be about 5% of the total electricity demand. The trading interval for contract and transaction settlement is one hour; therefore the balancing mechanism has to incorporate one-hour intervals. The cost of must-run generation is to be calculated by the TSO and covered by transmission network charges. In the first stage, the balancing market operated as a day-ahead market with balancing bids submitted by 10:00h (recently changed to 11:00) in a day before energy delivery.

1.3. Energy trade

The market structure allows for various forms of electricity trade. For example, an electricity producer can sell his production in the form of bilateral contracts to energy traders, distribution companies or directly to customers with TPA. He can also offer his energy in the Power Exchange day-ahead market. The remaining energy can be bid in the balancing market. Similarly, energy purchasers, for example customers with TPA, can buy electricity directly from power producers or from energy traders or other distribution companies.

Customers with TPA can participate in the Power Exchange and the Balancing Market; however, the large cost of such participation makes them unlikely to join these markets in nearest future.

Market participants can enter various forms of forward contracts offered by the Power Exchange. Similar contracts are offered by two energy trade sites on the Internet.
1.4. Trade and energy schedule

In a day before energy delivery (Day N-1), market participants can submit bids to the day-ahead market run by the Power Exchange. Such bids should be submitted before 8:00h. The Power Exchange announces the results of the session before 9:00h. Another hour remains to submit bids to the Balancing Market, up to 10:00h – Figure 2.

Having the information on contract positions and balancing bids, the TSO starts the balancing procedures. First, it verifies the consistency of contract positions and the bids submitted. Secondly, using the balancing bids and information about technical constraints, the TSO computes commitment and dispatch of generating units. The calculation results in the one-hour interval generation schedule for Day N. However, one-hour intervals used for energy trading are too large for generation unit control, due to large variations in daily electricity demand. The TSO recalculates the one-hour interval schedule to the 15-minute interval schedule in order to provide adequate control signals. It is assumed that the average values of four 15-minute signals, in a given hour, is equal to the energy in this hour set by the one-hour interval generation schedule [2].

Fig. 2 Trade and energy delivery schedule

2. Balancing Market

2.1. Information on contract positions

Market participants, both producers and electricity purchasers provide to the TSO information on their contract positions, indicating the amount of electricity sold or purchased and their contract partners – Table 1 and 2.

The sum of all contracts and Power Exchange transactions counts for the participant contract position. The trade in the Balancing Market covers difference between the real electricity production, and the contract position declared by power producers. Similarly, this market trades the difference between the electricity use and the contract position declared by energy buyers.

Table 1 Information on the contract position submitted by a power producer for one of his generating units for one hour of Day N.

<table>
<thead>
<tr>
<th>Contract partner</th>
<th>DisCo 1</th>
<th>DisCo 2</th>
<th>Energy Trader A</th>
<th>Energy Trader B</th>
<th>Power Exchange</th>
<th>Sum = Contract position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy in MWh</td>
<td>30</td>
<td>65</td>
<td>100</td>
<td>50</td>
<td>20</td>
<td>265</td>
</tr>
</tbody>
</table>
Table 2  Information on the contract position submitted by a power buyer (DisCo) for one hour of Day N.

<table>
<thead>
<tr>
<th>Contract partner</th>
<th>Generating Unit X1</th>
<th>Generating Unit X1</th>
<th>Generating Unit X1</th>
<th>Energy Trader B</th>
<th>Power Exchange</th>
<th>Sum = Contract position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy in MWh</td>
<td>100</td>
<td>150</td>
<td>120</td>
<td>70</td>
<td>30</td>
<td>470</td>
</tr>
</tbody>
</table>

2.2. Balancing bids

Additional to the information on contract positions generating units provide balancing bids for each hour of Day N – Table 3. A balancing bid consists of 10 bands providing flexibility in price and energy declarations. There are two categories of bands. The category “R” indicates energy sold in bilateral contracts or Power Exchange transactions. The prices attributed to these bands indicate how much an energy producer is ready to pay to the TSO, if his generating unit is scheduled below the level of the contract position declared. In the bands denoted by “P”, a power producer can offer additional energy to the TSO. The prices attributed to bands “P” point how much a power producer expects to be paid for additional production [3].

The structure of balancing bids provides large flexibility for power producers in their declarations. They can split the energy contracted into several “R” bands with various energy amounts and prices. This scheme reduces the energy producer risk of being entirely excluded from the schedule when the TSO cannot realise the contract positions declared. Power producers can also offer additional amount of energy to the TSO if it is required more generation to balance energy demand.

Electricity trade is carried out in energy net values. However, power generation units are controlled using gross values of energy. Power producers themselves decide on the difference between gross and net values. The last band is used to evaluate the cost of starting-up energy in the dispatch computer program. However, the payment for starting-up energy is calculated using the balancing price (CRO).

There are several restrictions imposed on the parameters of balancing bids. Energy in the first band should not be smaller than the generating unit’s technical minimum. The sum of energy in all the bands cannot be higher than the maximum generating capacity. Prices should increase monotonically across the bands. Currently, the lowest price is set to 50PLN/MWh (about 12.5US$), while the highest price is equal to 1500PLN/MWh (about 375US$).

Table 3  Example of a balancing bid submitted for a given generating unit for one hour in Day N.

<table>
<thead>
<tr>
<th>Band</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price (PLN/MWh)</td>
<td>50</td>
<td>55</td>
<td>60</td>
<td>100</td>
<td>105</td>
<td>110</td>
<td>120</td>
<td>130</td>
<td>150</td>
<td>1499</td>
</tr>
<tr>
<td>Energy net (MWh)</td>
<td>300</td>
<td>40</td>
<td>30</td>
<td>40</td>
<td>15</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Energy gross (MWh)</td>
<td>312</td>
<td>42</td>
<td>33</td>
<td>42</td>
<td>16</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>Band type</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
</tbody>
</table>

3. Commitment and dispatch in a day-ahead balancing market

The commitment and dispatch carried out in a day ahead has a form of a plan prepared for the next day by TSO. The TSO takes into account the balancing bids submitted by power stations and technical condition of generating units, as well as network constraints. The linear-binary programming has been applied to solve the commitment and a dispatch problem [4]. The LP engine XPRESS provided by the Dash Associates Limited was implemented to find the minimum of the objective function subjected to network constraints.
3.1 Modelling the problem

Each generating unit provides the balancing bid for every hour. The balancing bid consists of 10 bands, in which a bidder can set energy price and energy volume as net and gross energy. When a balancing bid is sketched in a step function, it can be seen that each step can be modeled as one variable – Fig 3.

There are several constraints imposed on the range of independent variables. They include:

1. The variable in the first band can be equal to a minimum power of a generating unit or Zero.
   \[ E_{h,j,1} = \begin{cases} P_{\text{min}} t \\ 0 \end{cases} \]
   This constraint represents the physical limitation, that a power generating unit cannot work stable below its \( P_{\text{min}} \) level. This leads to the application of binary programming.

2. For the other variables, their values should be in a range between Zero and the maximum value declared for a given band \( 0 \leq E_{h,j,i}^* \leq E_{h,j,i} \).

The notation used is as follows: “\( h \)” – the hour for each bid submitted; “\( j \)” – the index of a generating unit; “\( i \)” – the band number, “\( t \)” – time interval equal to one hour.

The total number of independent variables counts for:

\[
N_{\text{Independent \ Total}} = N_j \times N_{\text{bands}} \times N_{\text{hours}}
\]

where: \( N_j \) - a number of generating units; \( N_{\text{bands}} \) - a number of bands; \( N_{\text{hours}} \) - a number of hours, i.e. an optimization time horizon.

In our case, \( N_j = 100 \), \( N_{\text{bands}} = 10 \), \( N_{\text{hours}} = 24 \), the product counts for 24000 independent variables.

![Fig. 3 Graphical representation of a balancing bid](image-url)
3.2. The objective function

The objective function is formulated as a sum of products of the bid price and energy, which can be dispatch from band “i”. This embraces nine bands. The last band is used to bid the start-up price. This price is not paid to generators; however it is used in commitment and dispatch computations. Setting the tenth band as the start-up price allows for the flexibility of balancing bids, as a bid provider can give his willingness to be committed by setting a low start-up price.

\[
F_{\text{objective}} = \min \left\{ \sum_{h=1}^{H_k} \sum_{j=1}^{N_j} \sum_{i=1}^{9} c_{h,j,i} \cdot E_{h,j,i} + c_{h,j,10} \cdot E_{h,j}^{\text{start-up}} \right\}
\]

where: \( E_{h,j,i} \) - dispatch in hour „h”, generating unit „j”, energy from band „i”; \( c_{h,j,i} \) - bid price in hour „h”, generating unit „j”, in band „i”; \( E_{h,j}^{\text{start-up}} \) - start-up energy in hour “h”, generating unit “j” resulting from one of three starting unit characteristics; \( N \) - number of generating units, which have submitted the bids; \( H_k \) - time horizon equal to 24 hours.

In the objective function we do not differ the bands and they all are treated in the same way. This means that the algorithm can handle the balancing market with zero bilateral trade. This feature makes the algorithm universal for a bilateral market and a pool market.

3.3. Setting reserve

The information on the required level of primary and secondary reserve is distributed to market participants by TSO two days before energy generation. The contracts for Ancillary Services bind generating units to include power relating to primary and secondary reserve directly to a balancing bid. In such a case the energy in the first band of the balancing bid is adjusted as follows:

\[
E_{h,j,1} = P_{\text{min}} + t + P_{\text{reserve Prim}} * t + P_{\text{reserve Sec}}
\]

\[
\sum_{i=1}^{9} E_{h,j,i} = P_{\text{max}} - t - P_{\text{reserve Prim}} * t + P_{\text{reserve Sec}}
\]

The system is relatively simple; however, it reduces flexibility of dispatch, as the energy in the first band is larger than amount of the energy offered in all bands.

Tertiary reserve (hour reserve) is included into the algorithm as a constraint in the following way. This means that the difference between energy offered by all committed units and the energy dispatched in all committed units should be larger than the assumed level of the tertiary reserve. In other words, the spinning reserve should be larger than the assumed level.

\[
\sum_{j=1}^{N_j} \sum_{i=1}^{m} E_{h,j,i} - \sum_{j=1}^{N_j} \sum_{i=m+1}^{9} E_{h,j,i} \geq P_{\text{reserve Tert}}(h) \cdot t \text{ for } h = 1...24
\]

3.4. Technical constraints

The commitment and dispatch is carried out taking into account several technical constraints relating to generating units. The main technical constraints handled by the algorithm include:

- Minimum and maximum power
- Ramp rates
- Starting up characteristics from three state: hot, warm and cold
- Minimum off time

We do not include in technical constraints a minimum on time.
3.5. **Network constraints**

There are several categories of network constraints used in the algorithm. These constraints come from a special module called GMOS. Mathematical relations are as follows.

**Minimum number of generating units working in a node or in a group.**

\[
\sum_{i=1}^{N_p} DP_{h,i,l} \geq L_{h,p}^{\text{min}}
\]  

where: \( DP_{h,i,l} \) - decision variable equal to \( 0 \) or \( 1 \); when \( DP_{h,i,l} = 1 \), when a generating unit has been committed and dispatch power is at least equal to \( P_{\text{min}} \); \( L_{h,p}^{\text{min}} \) - minimum number of committed units in a node or a group \( p \) in hour \( h \).

**Maximum number of generating units working in a node or in a group.**

\[
\sum_{i=1}^{N_p} DP_{h,i,l} \leq L_{h,p}^{\text{max}}
\]

where: \( DP_{h,i,l} \) - decision variable equal to \( 0 \) or \( 1 \); when \( DP_{h,i,l} = 1 \), when a generating unit has been committed and dispatch power is at least equal to \( P_{\text{min}} \); \( L_{h,p}^{\text{max}} \) - maximum number of committed units in a node or a group \( p \) in hour \( h \).

**Minimum power generated in a node or in a group of generating units**

\[
\sum_{i=1}^{N_p} \sum_{k=1}^{10} E_{h,j,i} / t \geq PJ_{h,p}^{\text{min}}
\]

where: \( E_{h,j,i} \) - energy dispatched from a generating unit „j” in hour \( h \); \( PJ_{h,p}^{\text{min}} \) - minimum power of all generating units in a node or a group \( p \) in hour \( h \).

**Maximum power generated in a node or in a group of generating units**

\[
\sum_{i=1}^{N_p} \sum_{k=1}^{10} E_{h,j,i} / t \leq PJ_{h,p}^{\text{max}}
\]

where: \( E_{h,j,i} \) - energy dispatched from a generating unit „j” in hour \( h \); \( PJ_{h,p}^{\text{max}} \) - minimum power of all generating units in a node or a group \( p \) in hour \( h \).

3.6. **Preparing commitment and dispatch for a day-ahead market**

Preparation of the commitment and dispatch in a day-ahead market embraces a several steps such as:

- Calculation of commitment and dispatch for the predicted system demand \( P_{\text{system}}^{\text{predicted}} (h) \) for each hour for a day-ahead market
- Calculation of commitment and dispatch for the increased system demand
  \[ P_{\text{system}}^{\text{increased}} (h) = P_{\text{system}}^{\text{predicted}} (h) + \Delta P_{\text{increase}} (h) \]  
- Calculation of commitment and dispatch for the decreased system demand
  \[ P_{\text{system}}^{\text{decreased}} (h) = P_{\text{system}}^{\text{predicted}} (h) - \Delta P_{\text{decrease}} (h) \]  
- Preparation of the ranking list from the difference between commitment and dispatch for the predicted system demand and the demand increased and decreased.

The calculation of the ranking list is necessary and the LPD algorithm is used only once a day before power generation. In mean time, the predicted system demand can be changed and the system
dispatchers should have ranking lists allowing for the increase or decrease of power generation, as well as for the commitment or de-commitment of new generating units.

4. Conclusions

The LPD module, with the supporting module GMOS for network constraints modeling, begun its operation on the 1st September 2001. Since then, it has been working without any problems, allowing for commitment and dispatch in a day-ahead balancing market in Poland. The authors of this paper were responsible for the design and the implementation of both modules. The computer programs for the LPD and GMOS modules were developed by the Energoprojekt-Consulting SA.

Bibliography