How the European day-ahead electricity market works

ELEC0018-1 - Marché de l'énergie - Pr. D. Ernst

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Starting question

How is electrical energy traded in Europe?
Organization of the electrical power system (simplified)

**Generation Companies**
- Generate electricity, provide balancing services,...

**System Operators**
- Ensure reliability and security of the electrical network
- Operates the electricity markets: facilitates energy trading and allocates cross-border capacity

**Market Operators**
- Facilitates energy trading and allocates cross-border capacity

**Retailers**
- Buy electricity from producers, sell electricity to end-users

**Large Consumers**
- Buy electricity from producers, Generate their own electricity, sell their extra generation

**OTC**
Previous organization (simplified)

Generation Companies

Generate electricity, provide balancing services,…

Ensure reliability and security of the electrical network

Consumers

Sell electricity to end-users
Why an Electricity Market?

Break monopolies and open electricity generation and retail to competition.

Facilitate exchanges between countries. This does not only require creating a markets in each country, but also coupling those markets.

Give incentives for building capacity / consuming electricity where appropriate. Market results provide time series of prices per area and period of the day, volumes that are exchanged, etc. This is part of necessary information to determine the appropriate capacity investments (at least in principle...).
What is an Electricity Market?

A centralized platform where participants can exchange electricity transparently according to the price they are willing to pay or receive, and according to the capacity of the electrical network.

**Fixed gate auction**

- Participants submit sell or buy orders for several areas, several hours,
- the submissions are closed at a pre-specified time (closure)
- the market is cleared. Uniform clearing price: market prices are (well, *should be ...*) sufficient to determine whether orders are accepted or rejected
- Example: day-ahead. This is the topic of this lecture.

**Continuous time auction**

- Participants continuously submit orders. Orders are stored,
- Each time a deal is feasible, it is executed,
- Example: intra-day.
Markets by time horizon and activity

Futures    Day-ahead    Intra-day    Balancing

Towards real-time
Markets by time horizon and activity

- Intra-day
  - Futures
  - Day-ahead
  - Intra-day
  - Balancing

- Towards real-time

- Generation companies/retailers submit supply/demand orders
- TSOs allocate cross-border capacity
- Cleared once per day around 1PM
Day-ahead market operation and coupling

Each zone (or **bidding area**) has its own **Power eXchange (PX)** which collects participants orders.

France and Germany : EPEX spot, Belgium and the Netherlands: APX-Endex, etc.

**Market coupling**

- Perform clearing once per day for all coupled zones
  - hence orders can be matched between markets
  - and cross-border capacity is thus implicitly allocated.
- A price difference between countries must be explained by the congestion of some transmission lines.

Note: before market coupling, cross-border (i.e. inter-market) capacities were allocated through explicit auctions before deals were actually performed.

Detail: in general, each PX is responsible for the allocation to its participants (**portfolio allocation**). It has its own tie rules to lift indeterminacies.
Market operators / Power exchanges
History of the coupling project
Quantitative insight: Yearly consumption (2012)

- Total EU-28: $2.8 \times 10^3$ TWh
- Belgium: 82 TWh

Source: [2]
Evolution of consumption [GWh]

Source: [2]
Energy traded on the day-ahead market (DAM)

Source: [1]
Traded volume in DAM/ total consumption

Source: [1,2]
500MWh < Consumption < 2000 MWh

Without taxes

With taxes

Source: [2]
Electricity prices for household consumers [Euro/kWh]

Without taxes

With taxes

Source: [2]
Outline of the lecture

1. Definitions and market rules
2. Selected topics in Mathematical Programming
3. Formalization of the day-ahead market coupling problem
4. A few words about the solution method implemented in EUPHEMIA
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Orders: expressing the willingness to buy or sell

For now, assume

- participants submit orders that can be matched to any proportion
- $p^0$: price at which the order starts to be accepted
- $p^1$: price at which the order is totally accepted
- only one period
- the quantity is an energy amount, expressed in MWh (MegaWatt X hour)

Later on, we will denote the fraction of $q$ accepted by $x \in [0, 1]$
A single period, single location, day-ahead market

Market Clearing Price (MCP)

Price

Sell

Buy

Aggregated sell and buy curves
“Clearing” the market amounts to determining which orders should be accepted and at which price

- But what are the properties of the computed prices? Ideally, they should be such that all orders that are
  - **in-the-money** are fully accepted
  - **out-of-the-money** are fully rejected
  - **at-the-money** are accepted
    - at a proportion \( \frac{MCP - p_0}{p_1 - p_0} \) if \( p_0 \neq p_1 \)
    - at any proportion if \( p_0 = p_1 \)
Exercise with hourly order curves

- The order book is composed of

<table>
<thead>
<tr>
<th>Order</th>
<th>Type</th>
<th>Quantity</th>
<th>$p_0$</th>
<th>$p_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Supply</td>
<td>10</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>Supply</td>
<td>15</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>Demand</td>
<td>5</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Demand</td>
<td>10</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

- Determine the supply and demand curves and compute the MCP.
Solution

Market Clearing Price (MCP)

Suppliers

Demanders

Market Clearing Price (MCP)
Graphical view of welfare (shaded area)

Market Clearing Price (MCP)

Price

Surplus of buyers

Surplus of sellers

Sell

Buy

Quantity
Block orders

A block order is defined by

- one price
- a set of periods
- quantities for those periods
- (a minimum acceptance ratio)

Why?

- Producers want to recover start-up costs, model technical constraints,
- consumers want to secure their base load.

Severe complications

- Couples periods
- Introduces “non-convexities”
Exercise with block orders (a single time period)

Optimizing welfare would lead to the acceptance of the two block orders. How do you set the price? Which orders are accepted?
The rule in Europe: no Paradoxically Accepted Block (PAB)

No order can be accepted while loosing money, even if it increases the total welfare.

On the other hand a block order could be rejected although it is in the money: Paradoxically Rejected orders.

Exercise: create an example where the optimal solution contains a Paradoxically Rejected Block order.
The exchanges between markets are restricted

**ATC model**: connectors are defined between some pairs of bidding areas. Electricity can be exchanged via these connectors, but exchanges are limited.

![Diagram of the power exchange connections between France, Germany, Belgium, and the Netherlands.]

This is not a realistic model, since there are other transmission lines and power flows according to Kirchhoff laws (non-linear).
Two markets, no congestion
Two markets, no congestion

Infinite capacity

Price

Quantity

Market A

Uniform global price

Price

Market B

Quantity
Two markets, no congestion

Market B exports to market A (all demand matched from supply of market B)
Two markets, no congestion

Market B exports to market A (all demand matched from supply of market B)
Two markets, congestion

Max 10 MW

Price difference

Transfer limited

Market A

Market B

Price

Price

Quantity

Quantity
Two markets, congestion

Market B exports to market A, but not enough to equalize prices
Refining the network model

**Flow based model**

- Instead of an ATC model, a more realistic representation is achieved by expressing linear constraints on net exports of bidding areas.

- Coefficients of net exports, called **Power Distribution Coefficient Factors (PTDF)**, are obtained thanks to an approximate sensitivity analysis around the expected working point of the system.

- Issues with the economic interpretation of prices.

Losses and tariffs on DC inter-connectors

Network ramping, ...
“Flow based” network model

Goals:

• express **better** the physical constraints of the network

• Allocate more capacity

• increase welfare
How?

A set of critical branches (CBs) are considered. Critical branches are lines, cables or devices that can be heavily impacted by cross-border exchanges. These are not only cross-border lines.

The expected loading of CBs is evaluated based on long term nominations. Part of the remaining margin can be allocated to day-ahead markets.

The impact of cross border exchanges on CBs is modelled through the net export of the bidding areas in the same balancing area.

Balancing area: set of bidding areas for which sum of net exports is zero. Can exchange energy with other balancing area, but accounted in another variable. E.g. CWE, FR + BE + NL + DE
NordPool Spot

Linked blocks

- Acceptance of one block conditioned by acceptance of other blocks

Flexible blocks

- e.g. a block of one hour that may be accepted at any period
GME (Italy)

Italy is split in several sub-markets

We must determine one common clearing price for all demand orders whatever the sub-market $m$: $PUN$ (Prezzo Unico Nazionale)

Supply orders are remunerated at zonal price $P_m$

Assume $Q_m$ is the quantity matched in zone $m$

Goal: zero imbalance

$$PUN \sum_m Q_m = \sum_m P_m Q_m$$
OMIE
(Spain – Portugal – Morocco)

“Complex Order” defined by

• Several supply curves for several periods

• A Minimum Income Condition

$$\sum_{h} Q_h P_h \geq E + V \sum_{h} Q_h$$

• Bounded variations between consecutive periods

$$|Q_h - Q_{h-1}| \leq LG$$
Price/volume indeterminacies

• When curves cross on a vertical segment, there is a price indeterminacy
  • Rule: try to be as close as possible from the mid point of the intersection interval

• Similarly, when curves cross on a horizontal segment, there is a volume indeterminacy
  • Rule: maximize traded energy

• Note: there are other curtailment rules (local matching, ...)
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Optimization

Find the best solution to a problem (the best according to a pre-specified measure, a function) and satisfying some constraints.

Example: find the longest meaningful word composed of letters in the set {T,N,E,T,E,N,N,B,A}

https://www.youtube.com/watch?v=lsFAokXCxTI

The problem is usually cast in mathematical language.

The solution method is usually automatic, that is an algorithm implemented on a computer.
Linear programing (LP)

Objective and constraints are linear expressions, and variables have continuous domains.

Example:

\[
\begin{align*}
\max_{x_1, x_2 \geq 0} & \quad 5x_1 + 11x_2 \\
\text{s.t.} & \quad x_1 \leq 6 \\
& \quad x_1 - 3x_2 \geq 1 \\
& \quad 3x_1 + 2x_2 \leq 19
\end{align*}
\]  

Properties:

- The feasible domain is a polyhedron.
- Optimal solution(s) lie on the boundary of that polyhedron.
Graphical representation of a Linear Program
Graphical representation of a Linear Program

Bounds
Graphical representation of a Linear Program
Graphical representation of a Linear Program
Graphical representation of a Linear Program

Constraints

Objective increases in this direction

Bounds

Feasible domain
Duality in linear programming

To each LP (called the primal) corresponds a dual problem

**Primal**

\[
\begin{align*}
\text{max } & \quad c^T x \\
\text{s.t. } & \quad Ax \leq b \\
\text{and } & \quad x \geq 0
\end{align*}
\]

**Dual**

\[
\begin{align*}
\text{min } & \quad b^T y \\
\text{s.t. } & \quad A^T y \geq c \\
\text{and } & \quad y \geq 0
\end{align*}
\]

- \( A \) is the constraints matrix, \( c \) a vector of cost coefficients and \( b \) a vector of right hand side coefficients
- each variable \( (x_i) \) in the primal corresponds to a constraint in the dual
- each constraint of the primal corresponds to a variable \( (y_j) \) in the dual
Complementary slackness

At optimality, the following relations hold:

$$y_i (a_i^\top x - b_i) = 0$$
$$x_j (A_j^\top y - c_j) = 0$$

For all rows $i$ and all columns $j$ of $A$, where $a_i$ is row $i$ of matrix $A$ and $A_j$ is column $j$ of matrix $A$ (vectors are always understood as column vectors).

This means that, at optimality, either a primal (resp. dual) constraint is tight (satisfied to equality) or the corresponding dual (resp. primal) variable is zero.
Solving very large LPs

**Simplex**

- moves from one vertex (extreme point) of the feasible domain to another until objective stops decreasing
- very efficient in practice but can be exponential on some special problems
- can keep information of one solution to quickly compute a solution to a perturbed problem (useful in a B&B setting), dual simplex, ...

**Barrier**

- iteratively penalizes the objective with a function of constraints, to force successive points to lie within the feasible domain
- polynomial time, very efficient especially for large sparse systems
- but no extremal solution hence crossover required in a B&B setting
Convex optimization

Those results generalize to problems more general than LP, that is when the objective and the feasible domain are convex.

There is a theoretical guarantee that there exist algorithms to solve those problems efficiently.

Example: (convex) Quadratic Programming (QP) are problems where the objective is quadratic and constraints are linear. The simplex and barrier algorithms can be adapted to QP.
Mixed Integer programming (MIP)

Idem as before, except that some variables must take integer values.

In general, relaxing the integrality requirement and solving the resulting continuous optimization problem does not yield a feasible solution to the original problem. Simple rounding procedures do not necessarily restore feasibility, and even if it does, do not guarantee optimality. However, the continuous relaxation provides a bound on the optimum of the original problem.

Simple enumeration of combinations of integer variable values is computationally undoable. Branch-and-bound is a clever way to do enumeration. It progressively imposes integer values and uses the solution to intermediate continuous relaxations to obtain bounds and thus avoid exploring some combinations, without losing optimal solutions.
Example of MIP

\[
\begin{align*}
\text{max} & \quad 5x_1 + 11x_2 \\
\text{s.t.} & \quad x_1 \leq 6 \\
& \quad x_1 - 3x_2 \geq 1 \\
& \quad 3x_1 + 2x_2 \leq 19 \\
& \quad x_1, x_2 \in \mathbb{Z}_+ 
\end{align*}
\]  
(C.3) (C.4) (C.5) (C.6) (C.7)

The solution of the continuous relaxation is not integer
Branch and bound example

Fractional solution

(a) Node 0: \( z^{*,0} \approx 42.82 \) and \( x^{*,0} \approx (5.36, 1.45) \).
Branch and bound example

Fractional solution

(a) Node 0: $z^*,0 \approx 42.82$ and $x^*,0 \approx (5.36, 1.45)$. 

$0 \leq x_1 \leq 5$
Branch and bound example

Fractional solution

(b) Node 1: $z^*,1 \approx 39.67$ and $x^*,1 = (5, 4/3)$.

Fractional solution

(a) Node 0: $z^*,0 \approx 42.82$ and $x^*,0 \approx (5.36, 1.45)$. 
Branch and bound example

Fractional solution

\[ (b) \text{ Node } 1: z^{*,1} \approx 39.67 \text{ and } x^{*,1} = (5, 4/3). \]

Fractional solution

\[ (a) \text{ Node } 0: z^{*,0} \approx 42.82 \text{ and } x^{*,0} \approx \langle 5.36, 1.45 \rangle. \]
Branch and bound example

Fractional solution

(b) Node 1: $z^*,1 \approx 39.67$ and $x^*,1 = (5, 4/3)$.

(c) Node 2: $z^*,2 = 36$ and $x^*,2 = (5, 1)$.

Integer solution

Fractional solution

(a) Node 0: $z^*,0 \approx 42.82$ and $x^*,0 \approx (5.36, 1.45)$. 
Branch and bound example

Fractional solution

(b) Node 1: $z^{*,1} \approx 39.67$ and $x^{*,1} = (5, 4/3)$.

(c) Node 2: $z^{*,2} = 36$ and $x^{*,2} = (5, 1)$.

Fractional solution

(a) Node 0: $z^{*,0} \approx 42.82$ and $x^{*,0} \approx (5.36, 1.45)$.

Integer solution
Branch and bound example

(a) Node 0: \( z^{*,0} \approx 42.82 \) and \( x^{*,0} \approx (5.36, 1.45) \).

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(c) Node 2: \( z^{*,2} = 36 \) and \( x^{*,2} = (5, 1) \).

Prune by infeasibility

Fractional solution
Branch and bound example

(b) Node 1: $z^*,1 \approx 39.67$ and $x^*,1 = (5, 4/3)$.

(c) Node 2: $z^*,2 = 36$ and $x^*,2 = (5, 1)$.

Prune by infeasibility

(a) Node 0: $z^*,0 \approx 42.82$ and $x^*,0 \approx (5.36, 1.45)$. 

Fractional solution

 Integer solution
Branch and bound example

Fractional solution

\[ x_2 \]
\[ x_1 \]

(b) Node 1: \( z^{*,1} \approx 39.67 \) and \( x^{*,1} = (5, 4/3) \).

\[ x_2 \]
\[ x_1 \]

Fractional solution

Prune by infeasibility

Integer solution

\[ x_2 \]
\[ x_1 \]

(c) Node 2: \( z^{*,2} = 36 \) and \( x^{*,2} = (5, 1) \).

\[ x_2 \]
\[ x_1 \]

Prune by bound

(a) Node 0: \( z^{*,0} \approx 42.82 \) and \( x^{*,0} \approx (5.36, 1.45) \).

\[ x_1 \]

Prune by infeasibility

(d) Node 4: \( z^{*,4} = 35.5 \) and \( x^{*,4} = (6, 1/2) \).
Outline of the lecture

1. Definitions and market rules
2. Selected topics in Mathematical Programming
3. Formalization of the day-ahead market coupling problem
4. A few words about the solution method implemented in EUPHEMIA
Features considered in the remainder of this lecture

- ATC coupling problem with hourly orders and block orders only.
- I.e. we do not consider GME, OMIE, smart orders, nor flow based network model.
Nature of the mathematical problem

It is a mathematical program with complementarity constraints (MPCC) and in addition it contains integer decision variables.

It enters the category of Mixed Integer Non-Linear Programs, meaning that the continuous relaxation of the problem is non-convex.

As we will see in the next section, Euphemia approximates the problem as a Mixed Integer Quadratic Program (MIQP) that is convex (Q is positive semi-definite) and then checks the solution is compliant with the “true” problem.
The **primal** market coupling problem

maximize Welfare

subject to 1. Clearing Constraints
2. Network constraints
3. Order definition constraints

Clearing constraints express the equality of generation and demand

Main decision variables:

- acceptance ratio of orders
Objective function: maximize social welfare

Exercise (solution on next page): Assume each order $i$ of a set $I$ is defined by

- its quantity $q_i$
- its start and end prices $p^0_i$ and $p^1_i$
- its type (supply or demand)

Write down the expression of welfare as a function of accepted quantities (for simplicity, do not account for block orders).
Welfare is a quadratic expression

\[ \text{Welfare} = \sum_{i \in I_{\text{demand}}} q_i x_i \left( p_i^0 + \frac{p_i^1 - p_i^0}{2} x_i \right) - \sum_{i \in I_{\text{supply}}} q_i x_i \left( p_i^0 + \frac{p_i^1 - p_i^0}{2} x_i \right) \]
Welfare is a quadratic expression

\[
\text{Welfare} = \sum_{i \in I_{\text{demand}}} q_i x_i \left( p_i^0 + \frac{p_i^1 - p_i^0}{2} x_i \right) - \sum_{i \in I_{\text{supply}}} q_i x_i \left( p_i^0 + \frac{p_i^1 - p_i^0}{2} x_i \right)
\]
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\]
Exercise

Define the necessary variables and formulate all the primal constraints (clearing, ATC, block order definition).
Without block orders, the problem has the following properties

- The formulation is convex (QP) and can be decomposed hour by hour
- Dual solution yields market prices and congestion prices

<table>
<thead>
<tr>
<th>Primal constraints</th>
<th>Dual variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clearing</td>
<td>Market Clearing Price (MCP)</td>
</tr>
<tr>
<td>Inter-connector capacity</td>
<td>Inter-connector congestion price</td>
</tr>
<tr>
<td>Orders acceptance UB</td>
<td>Order “surplus” ( (S_i) )</td>
</tr>
</tbody>
</table>
Example: dual model without network and block orders and interpretation of complementary slackness

\[
\min_{MCP, S_i \forall i \in \mathcal{I}} \sum_{i \in \mathcal{I}} S_i
\]

s.t.
\[
S_i \geq q_i (MCP - p_i)
\]
\[
S_i \geq 0
\]

Complementarity relations

No Paradoxically Accepted (PA) order

\[
Accept_i (S_i - q_i (MCP - p_i)) = 0
\]

No Paradoxically Rejected (PR) order

\[
S_i (1 - Accept_i) = 0
\]

Exercise: from the primal model of the previous exercise, find back the dual model expressed above.
Solutions naturally satisfy market rules

<table>
<thead>
<tr>
<th>Order type</th>
<th>MCP</th>
<th>Acceptance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>supply</td>
<td>$&gt; p^1$</td>
<td>1</td>
</tr>
<tr>
<td>supply</td>
<td>$&lt; p^0$</td>
<td>0</td>
</tr>
<tr>
<td>any</td>
<td>$\geq p^0$ and $\leq p^1$</td>
<td>$(\text{MCP}-p^0) / (p^1-p^0)$</td>
</tr>
<tr>
<td>demand</td>
<td>$&lt; p^1$</td>
<td>1</td>
</tr>
<tr>
<td>demand</td>
<td>$&gt; p^0$</td>
<td>0</td>
</tr>
</tbody>
</table>
Incorporating block orders

Complications

integer variables, thus QP $\rightarrow$ MIQP

time coupling

Paradoxically Accepted Blocks (PAB)

Market says it is not acceptable to lose money, but it is acceptable to be rejected although could have made money, without compensation
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About Euphemia

- Property of PCR members
- Developed by n-Side
- In operation since February 4, 2014. Before that the former solution COSMOS operated from November 9 2010 in the CWE region.
  - Now almost 4 years without failure
- Typical size of instances:
  - 50,000 orders
  - 700 blocks
- COSMOS solved real instances in less than 10 seconds. Now the algorithm takes several minutes.
Main idea

For a fixed selection of blocks, the Market Coupling Problem can be written as a QP

Solving this problem yields

• quantities (primal)
• prices (dual)

If there is no PAB with respect to those prices

• the block selection and the prices form a feasible solution to the Market coupling problem

Else we must find another block selection.
Branch-and-cut algorithm description (1)

When a node yields an integer solution for the primal
The dual of the relaxed problem (integer variables fixed) is constructed from the primal solution by complementarity.
Branch-and-cut algorithm description (3)

A constraint preventing prices that cause PAB is appended to the dual problem.
The objective is modified to yield prices as close as possible to the center of the price indeterminacy intervals.

**Price problem**
- Modified objective to lift price indeterminacies
- Dual constraints
- + no PAB constraints
Branch-and-cut algorithm description (5)

if that problem is feasible, we have a candidate solution for the market coupling problem

Primal

Set bounds on dual variables by complementarity

Acceptable

Dual

Price problem
Modified objective to lift price indeterminacies
Dual constraints
+ no PAB constraints

Feasible
Branch-and-cut algorithm description (6)

Else a cut is added to the current node to prevent this block selection.
About the implementation in Euphemia

- Implemented
  - in Java
  - using CPLEX and Concert Technology
- tuned cutting and node selection mechanisms
- achieves a precision of 10^-5 on all constraints
  - Embedded mechanisms to repair numerically difficult problems
References

[1] EPEX spot annual report 2013