INTRODUCTION

- PCR (Price Coupling of Regions) has the scope of:
  ✓ creating a coordinated European electricity market,
  ✓ guarantee competition among operators,
  ✓ achieve environmental targets.

- PCR (Price Coupling of Regions) has three main legislative references.

- 3° legislative package (2009): ownership unbundling, NRA, ACER.

- European Network Codes (2009 - 10 codes among concerning all the relevant areas of electricity markets and system operations).

- CACM (2015 - capacity allocation and congestion management) methods for allocating capacity in day-ahead and intra-day timescales and outlines the way in which capacity will be calculated across the different zones.
INTRODUCTION

CACM contents

- DA markets
- ID markets
- Capacity calculation
- Bidding Zones configuration
- Rules for congestion income sharing
- Cost recovery arrangements

CACM implementation timeline

- CACM Entry into force
- ENTSO-E preliminary analysis
- Stakeholders feedback and general model selection
- TSOs to draft pricing methodology
- Consultation, update, internal approvals
- All NRAs approval
- Implementation phase (TSOs & PXs)

Deadline for all TSOs to submit pan-European pricing methodology to all NRAs
Implicit Allocation Mechanism

- With implicit auction, the transmission capacity is used to integrate the spot markets in the different bidding areas in order to maximize the overall social welfare in both (or more) markets.

- The flow on an interconnector is found based on market data from the marketplace/s in the connected markets. Thus the auctioning of transmission capacity is included (implicitly) in the auctions of electrical energy in the market.

- In implicit auctions, the transmission capacity between bidding areas (price areas/control areas) is made available to the spot price mechanism in addition to bid/offers per area, thus the resulting prices per area reflect both the cost of energy in each internal bidding area (price area) and the cost of congestion.

- Implicit auctions ensure that electrical energy flows from the surplus areas (low price areas) towards the deficit areas (high price areas) thus also leading to price convergence.
MARKET COUPLING MODELS IN EUROPE (DA MARKETS)

- Price Coupling of Regions (PCR) is the initiative launched by seven European power exchanges to develop a single price coupling solution for the calculation of electricity prices across Europe and the allocation of interconnection capacity in the market day before.

- The unique algorithm (EUPHEMIA) to determine fairly and transparently the prices of electricity on the day ahead and to allocate the interconnection capacity.

- An integrated European electricity market should increase liquidity, efficiency and social welfare.

  - **NORDPOOL SPOT**: Nordic countries (Norway, Sweden, Finland, Denmark, Estonia, Lithuania and Latvia)
  - **OTE**: Czech Republic
  - **APX-ENDEX**: UK, Netherlands
  - **BELPEX**: Belgium (part of APX)
  - **EPEX Spot**: Austria, France, Germany
  - **OMIE**: Portugal, Spain
  - **GME**: Italy, Slovenia
MARKET COUPLING MODELS IN EUROPE (DA MARKETS)

- PCR is based on an auction-based market model with implicit capacity allocation mechanism.
- Mandatory and non-mandatory pools co-exist.
- Unit-based and BRP market models co-exist.
- Different products can be traded in different market areas (single hours, blocks).
- Bidding Areas, Market Areas and TSO's Control Areas

In the management of coupled electrical markets, the way in which the TSOs provide interconnection capacity is crucial for the determination of national prices (European zones) and energy flows.

Within the European PCR, there are three different patterns of transit capacity allocation:

- **ATC (Available Transfer Capacity) MODEL**
- **FB (Flow Based Market Coupling) MODEL**
- **IBRID MODEL**

Within each of these approaches, the concept of 'Bidding Area' is fundamental.
- A bidding area is the smallest entity within a market where it is possible to submit purchase or sale orders.
In the ATC model, the various bidding areas of a market are ideally connected by interconnectors that represent the topology of the network synthetically. Energy between the different bidding areas can only flow through these interconnectors to the adjacent bidding areas.

The energy flow is limited by Available Transfer Capacity (ATC) values.
FB MODEL

- In the FB model we try to give a more accurate and truthful representation of the network of interconnections and consequently the flows.

- Transit constraints in the FB model are no longer expressed in terms of available transit capacity (ATC / NTC) as in the previous model but are modeled through two components:
  
  - **RAM** (Remaining Available Margin) vector that measures MWs still available for transit for each network mesh point;
  
  - Matrix **PTDF** (Power Transfer Distribution Factors) that has on the rows the different electrical links (or Critical Connection Elements) of the network and the columns the different Bidding Zones (or nodes) interconnected through the network. PTDF measures the power flow on the connection i-k as a result of the unit power input in node m while the injections in the other nodes are kept constant.

\[
PTDF \cdot \text{nex} \leq \text{RAM}
\]

Flow constraint in the FB model (where \text{nex} represents net exports from each node / Bidding Zone)
Within the European PCR there are currently two CWE and NEE areas that operate within them according to the FB model. These areas interact with the remaining market areas subject to coupling through an ATC mechanism. The target model should be the FB for all areas of the Integrated European Market.
**EUPHEMIA ALGORITHM - MARKET COUPLING PRINCIPLE**

- **Euphemia** is the algorithm developed to solve the problem of the coupling of the day-ahead power markets, in the MC region.
- Euphemia tries to maximize the social welfare of the system, i.e.

\[
\text{max } \left( \text{Consumer Surplus} - \text{Producer Surplus} \right)
\]

s.t.

*Power Network Constraints*

*(Other Constraints)*

- Consumers and producers submit their (limit) orders to the market as price-quantity couples, for each trading period $h$.

- A **demand order** $(p, q)$ for the period $h$, means that a consumer wants to buy $q$ MWh at a price less or equal to $p$, for the period $h$.

- A **supply order** $(p, q)$ for the period $h$, means that a producer wants to sell $q$ MWh at a price greater or equal to $p$, for the period $h$.

- Demand and supply orders from all market participants belonging to the same bidding area are aggregated into the demand curve and the supply curve.
PUN orders are a particular type of demand orders.

PUN orders are cleared at the PUN price (PUN), rather than the bidding area market clearing price.

The following equation must hold

\[
PUN \sum_{z} Q_z = \sum_{z} Q_z P_z \pm \Delta
\]

where

- \( Q_z \) is the volume consumed in bidding area \( z \)
- \( P_z \) is the market clearing price of bidding area \( z \)
- \( \Delta \) is the PUN imbalance tolerance
Euphemia is an iterative algorithm that tries to maximize the social welfare of the system. It can be divided into three sub-problems:

- **Welfare Maximization Problem (Master Problem):** Euphemia tries to select demand and supply orders that maximize the social welfare and respect the problem constraints.

- **Price Determination Sub-Problem:** Euphemia tries to determine, for each bidding area, the appropriate market clearing price.

- **PUN Search Sub-Problem:** Euphemia tries to determine the PUN price and removes paradoxically accepted orders.

---

**Master Problem**

- **Input**
  - Demand and supply curves
  - Network constraints (ATC, PTDF, RAM)
  - Network topology
- **Output**
  - Optimal selection of accepted orders
  - Energy flows between bidding areas

**Price Determination Sub-Problem**

- **Input**
  - Network constraints
  - Network topology
  - Master Problem solution
  - PUN imbalance constraint (if possible)
- **Output**
  - Market Clearing Prices
  - If a feasible solution does not exist, back to Master Problem (Flow Based Intuitive solution)

**PUN Search Sub-Problem**

- **Input**
  - Master Problem solution
  - Price Determination Sub-Problem solution
- **Output**
  - PUN price
  - Optimal selection of accepted PUN orders
For each period $h$, let’s define

- $(q_{i}^{d,k}, p_{i}^{d,k})$ the $i^{th}$ offer in the demand curve of the bidding area $k$
- $(q_{j}^{s,k}, p_{j}^{s,k})$ the $j^{th}$ offer in the supply curve of the bidding area $k$
- $t_{kl}$ the transit from bidding area $k$ to bidding area $l$

with $i = 1, ..., N_{d}^{k}$, $j = 1, ..., N_{s}^{k}$ and $k = 1, ..., Z$.

The Welfare Maximization Problem is

$$\max_{x} W(x) = \max_{x} \sum_{k=1}^{Z} \sum_{i=1}^{N_{d}^{k}} q_{i}^{d,k} p_{i}^{d,k} x_{i}^{d,k} - \sum_{k=1}^{Z} \sum_{j=1}^{N_{s}^{k}} q_{j}^{s,k} p_{j}^{s,k} x_{j}^{s,k}$$

subject to

- Balance constraints
  $$\sum_{j=1}^{N_{s}^{k}} q_{j}^{s,k} x_{j}^{s,k} - \sum_{i=1}^{N_{d}^{k}} q_{i}^{d,k} x_{i}^{d,k} = \sum_{l=1}^{Z} t_{kl} - \sum_{l=1}^{Z} t_{lk} \ \forall \ k = 1, ..., Z$$
- Flow-Based region constraints
  $$\sum_{k \in F_{B}} PTDF_{j,k} \left( \sum_{l \in F_{B}} t_{kl} - \sum_{l \in F_{B}} t_{lk} \right) \leq RAM_j \ \forall j = 1, ..., nRAM$$
- ATC constraints
  $$t_{kl} \leq T_{kl} \ \forall k, l = 1, ..., Z$$
- Variables constraints
  $$1 \geq x_{h} \geq 0 \ \forall h = 1, ..., \sum_{k=1}^{Z} N_{d}^{k} + N_{s}^{k}$$
  $$t_{kl} \geq 0 \ \forall k, l = 1, ..., Z$$
The FB constraint can be written in a more convenient way

$$\sum_{l,k \in FB} (PTDF_{jk} - PTDF_{jl}) t_{kl} \leq RAM_j \ \forall j = 1, \ldots, nRAM$$

This constraint is useful when the algorithm has to find and remove non-intuitive Flow-Based solutions.

We say that a critical branch \( j \) is congested if

$$\sum_{k \in FB} PTDF_{jk} \left( \sum_{l \in FB} t_{kl} - \sum_{l \in FB} t_{kl} \right) = RAM_j$$
With some effort, Welfare Maximization Problem can be written in matrix form

\[
\max_{x,t} W(x, t) = \max_x c^T x
\]

subject to

\[
A(x, t) \leq b
\]

\[
A_{eq}(x, t) = b_{eq}
\]

\[
(x, t) \geq 0
\]

This is a classical Linear Programming problem, with both equality and inequality constraints and can be easily solved using the well known simplex method. Let's call \((\bar{x}, \bar{t})\) a feasible solution of the Welfare Maximization Problem

\[
(\bar{x}, \bar{t}) = \arg \max_{x,t} W(x, t)
\]
Market Clearing Price of the bidding area $k$ and period $h$ ($MCP^h_k$) can be seen as the shadow price, associated with the production of 1 MWh in the bidding area $k$, i.e., $MCP^h_k$ gives the variation of the optimal value of the objective function $W(\bar{x}, \bar{t})$, if 1 MWh is produced more than the optimal solution $(\bar{x}, \bar{t})$, in the bidding area $k$.

In the Linear Programming framework, $MCP^h_k$ is the dual variable associated with the balance constraints. They can be found solving the dual problem of the Welfare Maximization Problem (primal problem), subject to the so called complementary slackness conditions.

When it’s possible, PUN imbalance constraint is added to the dual problem.
EUPHEMIA ALGORITHM - PRICE DETERMINATION SUB-PROBLEM

Dual problem of the Welfare Maximization Problem

\[
\min_y \left( b_{eq}, b \right)^T (y_{eq}, y_{ineq})
\]

subject to

\[
-(A_{eq}^T, A^T)(y_{eq}, y_{ineq}) \leq c
\]

\[
y_{ineq} \geq 0
\]

\[
y_{eq} \text{ unconstrained}
\]

complementary slackness conditions

When a PUN price has already been calculated, the **PUN imbalance constraint** is added to the problem

\[
\left| PUN \sum_k Q_k - \sum_k y_{eq}^k Q_k \right| \leq \Delta
\]
Let \( \bar{y} = (y_{eq}, y_{ineq}) \) be an optimal solution of the dual problem, for the period \( h \). Then

\[
MCP_k = y_{eq}^k
\]

The optimal solution \((\bar{x}, \bar{t})\) of the primal problem and the associated optimal solution of the dual problem \(\bar{y}\) are **intuitive optimal solution** if they satisfy the **intuitiveness constraint**

\[
(MCP_k - MCP_l) t_{kl} \leq 0 \quad \forall k, l = 1, ..., Z
\]

If solutions \((\bar{x}, \bar{t})\) and \(\bar{y}\) are not intuitive solutions, then Euphemia tries to solve the Welfare Maximization Problem, using different Flow-Based constraints. In particular, if \( j \) is a **congested critical branch**, then the Flow-Based constraints become

\[
\sum_{l \in F_B} \max(PTDF_{jk} - PTDF_{jl}, 0) \ t_{kl} \leq RAM_j
\]
EUPHEMIA ALGORITHM - PUN SEARCH SUB-PROBLEM

- Optimal selection of accepted orders $\bar{x}$
- Optimal selection of energy flows $\bar{\ell}$, between connected bidding areas

Welfare Maximization Problem

Price Determination Sub-Problem
- Market Clearing Price $MCP_k$ for each bidding area $k$
- Solution satisfies intuitiveness constraint: energy flows from bidding area with lower price to bidding area with higher price

PUN Search Sub-Problem
- New optimal selection of accepted (PUN) orders $\bar{x}$
- The solution $\bar{x}$ satisfies the PUN imbalance constraint
PUN Search is an **iterative procedure**.

- Fix $\Delta$ (**PUN imbalance tolerance**) and try to find a $PUN$ price that minimize PUN imbalance

$$I(PUN) = PUN \sum_k Q_k - \sum_k MCP_k Q_k$$

- In the iterative process, Euphemia remove paradoxically accepted PUN orders from the optimal solution $\bar{x}$, i.e., PUN orders that are cleared at market clearing price and not at $PUN$ price. The process stops when Euphemia finds a $PUN$ price such that $|I(PUN)| \leq \Delta$.

- Euphemia iteratively solves the **Welfare Maximization Problem**, the **Price Determination Sub-Problem** and the **PUN Search Sub-Problem**, until a feasible optimal solution meets all constraints.
Euphemia has to take into account:

- stepwise demand and supply curves,
- linear piecewise curves,
- hybrid curves.
**Euphemia Algorithm - Complex Orders**

**Minimum Income Condition (MIC) Orders**
- Set of hourly sub-orders.
- Subject to Minimum Income Condition constraints, defined by two terms
  - Fix term (FT) in €
  - Variable term (VT) in €/MWh
- If \((q_i^h, p_i^h)_{i=1,...,N}^h\) is the set of hourly orders of a period \(h\), then the MIC condition is

\[
FT + \left( \sum_h \sum_{i=1}^{N_i^h} q_i^h \right) VT \leq \sum_h \left( \sum_{i=1}^{N_i^h} q_i^h \right) MCP^h
\]
- If a MIC order is activated, each of the hourly sub-orders behaves like a normal hourly order, else each of hourly sub-orders is fully rejected.

**Load Gradient**
- Set of hourly sub-orders
- The amount of energy that is matched by the hourly sub-orders in one period is limited by the amount of energy that was matched by the hourly sub-orders in the previous period.
- Maximum increment/decrement allowed.
- Period 1 is not constrained by the energy matched in the last hour of the previous day.
- Load Gradient orders can be combined with MIC orders
A block order is defined by:

- number of periods,
- one price limit for all periods,
- possibly different volumes for every period,
- minimum acceptance ratio (curtailable block order).

If a block order is defined by a price $p$ and volumes $q^{h_1}, ..., q^{h_m}$, for $h_1, ..., h_m$ periods, then it’s out-of-the-money and fully rejected if

$$p > \sum_{i=1}^{m} MCP^{h_i} \quad \text{(sell order)}$$

or

$$p < \sum_{i=1}^{m} MCP^{h_i} \quad \text{(buy order)}$$

else, if the block order is in-the-money or at-the-money it can be rejected, fully or partially accepted (with respect to the minimum acceptance ratio).
Interpolated orders, complex orders, block orders add complexity to MC problem.

The Welfare Maximization Problem become

\[
\max_{x,y} W(x, y) = \max_x \sum_{k=1}^{Z} \sum_{i=1}^{N_d^k} q_i^{d,k} p_i^{d,k} x_i^{d,k} - \sum_{k=1}^{Z} \sum_{j=1}^{N_s^k} q_j^{s,k} p_j^{s,k} x_j^{s,k}
\]

\[
+ \max_x \sum_{k=1}^{Z} \sum_{i=1}^{N_d^k} q_i^{d,k} \left( p_{i,0}^{d,k} + x_i^{d,k} \frac{p_{i,1}^{d,k} + p_{i,2}^{d,k}}{2} \right) x_i^{d,k} - \sum_{k=1}^{Z} \sum_{j=1}^{N_s^k} q_j^{s,k} \left( p_{j,0}^{s,k} + x_j^{s,k} \frac{p_{j,1}^{s,k} + p_{j,2}^{s,k}}{2} \right) x_j^{s,k}
\]

\[
+ \sum_{\text{block,complex}} q p y
\]

The objective function \( W(x, y) \) is quadratic function in the variables \( x \).

The variables \( y \) are integer. In particular \( y \in \{0,1\} \).
## Potential Applications of a «Euphemia Like» Simulation Model

### What If Analysis
- **Content:** Replicate market clearing algorithm for past dates changing some inputs to assess final impact.
- **Goal:** Assess market power of specific competitors or assets or technologies; study system’s non linearities.
- **User:** Unit dispatcher, asset portfolio managers, cross border capacity portfolio managers.

### Forecasting
- **Content:** Replicate market clearing algorithm for future dates (typically short term) with guessed inputs to forecast output price/prices.
- **Goal:** Exploit trading opportunities (futures vs delivery).
- **User:** Short term traders.

### Sensitivity Analysis
- **Content:** Use market clearing algorithm for future dates (typically short term) with shocked inputs to measure output price/prices sensitivities wrt input change.
- **Goal:** Exploit trading opportunities (futures vs delivery).
- **User:** Short term traders.
## Tools for Bidding & Short Term Trading Decision Support

## Methodologies to Create a «Euphemia Like» Simulation Model

<table>
<thead>
<tr>
<th>Fundamental Model</th>
<th>Classical Econometric</th>
<th>Machine Learning</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CONTENT</strong>: exact replication of market mechanics eventually guessing unknown inputs.</td>
<td><strong>CONTENT</strong>: classical econometric linear models with autoregressive and exogenous components.</td>
<td><strong>CONTENT</strong>: neural network, support vector regression, regression and decision trees, pattern recognition.</td>
</tr>
<tr>
<td><strong>PROS</strong>: perfect understanding of market dynamics, model non linearities, possibility to exactly calculated what if scenarios and output sensitivities.</td>
<td><strong>PROS</strong>: simple to implement and calibrate, simple interpretation of results</td>
<td><strong>PROS</strong>: simple to implement and calibrate, simple interpretation of results, very good model for classification, usable for predictive and prescriptive analysis.</td>
</tr>
<tr>
<td><strong>CONS</strong>: complexity, strong dependence from initial conditions, difficulties to understand and explain errors.</td>
<td><strong>CONS</strong>: difficult to proxy an highly non linear phenomenon with a simple linear model, poor quality of results, scarce robustness.</td>
<td><strong>CONS</strong>: black boxes, good in sample results poor out of sample results.</td>
</tr>
</tbody>
</table>
CONTACTS

MAIL
info@phinergy.biz

TELEFONO
Mobile: 349 6354525
Fisso: 049 8697510

INDIRIZZO
Via della Croce Rossa 112
35129 Padova
Phinergy was born in June 2014 from the experience of its founders. Phinergy's mission is to offer its customers specialized services and consultancy in the areas of energy trading and risk management, employing only the finest international technical skills. Phinergy is an innovative startup incubated by StartCube, the incubator of companies at the University of Padua.

Enrico Edoli is founder and CEO of Phinergy.
During his career, he worked as an external quantitative analyst for trading and risk management support in various energy companies in Italy. He has published several technical articles and a book related to quantitative energy finance and he is also lecturer of a course in Mathematical Finance at the University of Padova.
Enrico has a degree in Mathematics and a PhD in Applied Mathematics achieved both at the University of Padua.

Stefano Fiorenzani is founder and Chairman of Phinergy.
He is a recognized expert in Energy Trading and Risk Management, with a career spanning numerous top European energy companies and financial institutions. He has published several scientific and business articles and three books on advanced methods in the Energy Finance area.
He holds a degree in Economic Science, a Master of Science in Financial Economics and a PhD in Mathematical Finance.