“Intra-day and balancing markets”

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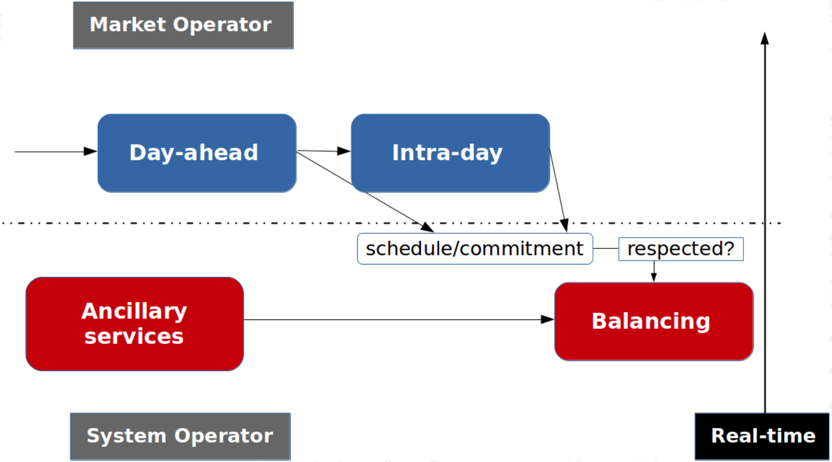
Learning objectives

Through this lecture and additional study material, it is aimed for the students to be able to:

1. Describe **intra-day and balacing market mechanism**
2. Model and solve **balancing market clearing**
3. Understand **differences between one-price and two-price balancing mechanisms**
4. Caculate **revenues and payments of market players** combining the various market floors

As part of the overall context...



We are closing the gap between all energy markets and actual operation

Outline

1. Basics and problem formulation
   - motivating these markets, and who does what?
   - a practical example
2. **Intra-day** (/adjustment) market
   - bilateral trading in practice
   - ELBAS (in Scandinavia) and its continuous electronic trading setup
   - illustration based on a practical example
3. **Balancing** market
   - in theory
   - in practice

1. **Basics and problem formulation**

From financial market to physical operation

- A day-ahead market is a financial market!
  - These are only transactions - No one is “forced” to generate or consume...
  - Both *market participants* and *system operator* are informed about market clearing outcomes (price and volumes for each market time unit)
  - In the European set-up, the market participants will then *self-dispatch*, i.e., determine themselves how they will generate or consume depending on volumes and prices
- The day-ahead market is cleared a fairly long time before actual operations (between 12 and 36 hours)
- Such a setup relies on the crucial concepts of
  - **Balance Responsible Parties** (BRP - to be explained in the next slide)
  - **Adjustment market**, i.e., intra-day market mechanism
  - **Balancing market**, i.e., (near) real-time market

Balance Responsible Party (BRP)

- From Energinet's website:

  "Production, consumption and trade activities must be assigned to the balance responsible parties (BRP) who must enter an agreement with Energinet.dk to assume responsibility for the specific activities, ie. production, consumption or trade. Upon entering the agreement on balance responsibility the BRP assumes the **financial responsibility** *for the imbalances they may incur."*

  A list of Danish BRPs is available at:
  `https://en.energinet.dk/Electricity/New-player/Oversigt-over-BA`

- Similar concepts and setups are used in other European countries, e.g., the Netherlands, Belgium, etc., with the respective system operators (e.g., TenneT, Elia, etc.) responsible for
  - assessing deviations, and
  - the eventual settlement

[Official regulation related to BRPs: Energinet Regulation C1 - Terms of Balance Responsibility]

[See also: Roles and responsibilities]

From day-ahead market clearing to actual operations

- Alternative ways for the scheduled supply and demand to minimize imbalances:
  - Compensate with other generation/consumption means within their own portfolio

    $\rightarrow$ **Re-dispatch of own units**
  - Find ways to adjust through agreements with other players between the day-ahead market clearing and actual operations

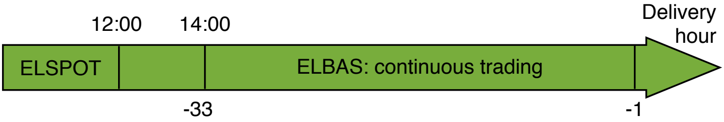
    $\rightarrow$ **Intra-day (/adjustment) market**
  - Let the system operator put the system back to balance

    $\rightarrow$ **Balancing market**

2. **Intra-day market**

Overview

- While the day-ahead market is
  - a pool,
  - based on an auction mechanism,
- the intraday market is based on **bilateral contracts**, even though centrally organized.
- Some reasons for that:
  - less players,
  - less liquidity,
  - the need for *corrective actions* may highly vary depending upon how new information disclosure occurs between day-ahead market clearing and actual operations...
- Organization: leaning towards *electronic trading* (introduced in a previous lecture)



[source: Nord Pool Group]

Simple example of bilateral trading: portfolio

- Let us introduce the portfolio of Rogue Trading® (abbreviated RT®):

Unit id.	Type	Nominal capacity	Flexibility	Marginal Cost (€/MWh)
N1	Nuclear	500	$--$	30
Bm1	Biomass	70	$+$	60
Bm2	Biomass	45	$++$	70
W1	Wind	120	$--$	0

- Flexibility summarizes the impact of operational constraints (i.e., minimum up and down time, ramping, minimum operating point, etc.)

- How to optimally trade with this portfolio based on bilateral contracts?

[Note: Example inspired by *Kirschen and Strbac (2004). Fundamentals of Power System Economics* (Sect. 3.4)]

Simple example... Existing contracts

- *Here and now*: 5th February, 13:00 - *Delivery period*: 6th of February, 11:00-12:00
- Existing contracts are:

Type	Buyer	Seller	Amount (MWh)	Price (€/MWh)
Long term (5 years)	QualiWatt	RT®	30	12
Long term (5 years)	IntelliWatt	RT®	200	35
Future (1-3 months)	RT®	DirtyPower	30	20
Future (1-3 months)	EVcharge	RT®	150	40
Future (1-3 months)	El4You	RT®	40	43

- RT® should generate: 390 MWh
- Prices are low... RT® should avoid using units Bm1 and Bm2
- Predicted wind power generation: 60 MWh for that hour
- Consequently, N1 is to generate 330 MWh

Simple example... Change of plan

- Update in the wind forecast - only 20 MWh to be generated... that means compensating for 40 MWh
- Nuclear is not flexible enough to adapt in time and Bm1 is down
- **Should Bm2 be used?** see the updated stacks of bids and offers:

Time	Buy/Sell	Id.	Amount (MWh)	Price (€/MWh)
1 March 2016, 11:00-12:00	Buy	D1	10	55
1 March 2016, 11:00-12:00	Buy	D2	50	50
1 March 2016, 11:00-12:00	Buy	D3	120	35
1 March 2016, 11:00-12:00	Buy	D4	80	27.5
1 March 2016, 11:00-12:00	Sell	G1	15	80
1 March 2016, 11:00-12:00	Sell	G2	55	65
1 March 2016, 11:00-12:00	Sell	G3	90	47
1 March 2016, 11:00-12:00	Sell	G4	40	45
1 March 2016, 11:00-12:00	Sell	G5	100	37

- *What would you do?*

Simple example... Option 1

- Instead of having to produce 40 MWh at a marginal cost of 70 €/MWh...

Time	Buy/Sell	Id.	Amount (MWh)	Price (€/MWh)
1 March 2016, 11:00-12:00	Buy	D1	10	55
1 March 2016, 11:00-12:00	Buy	D2	50	50
1 March 2016, 11:00-12:00	Buy	D3	120	35
1 March 2016, 11:00-12:00	Buy	D4	80	27.5
1 March 2016, 11:00-12:00	Sell	G1	15	80
1 March 2016, 11:00-12:00	Sell	G2	55	65
1 March 2016, 11:00-12:00	Sell	G3	90	47
1 March 2016, 11:00-12:00	Sell	G4	40	45
1 March 2016, 11:00-12:00	Sell	G5	100	37

- Let's just pick G4! (*we hit that offer...*)
- **Cost:** $45 \times 40 = 1800$ €

Simple example... Option 2

- Instead of having to produce 40 MWh at a marginal cost of 70 €/MWh...

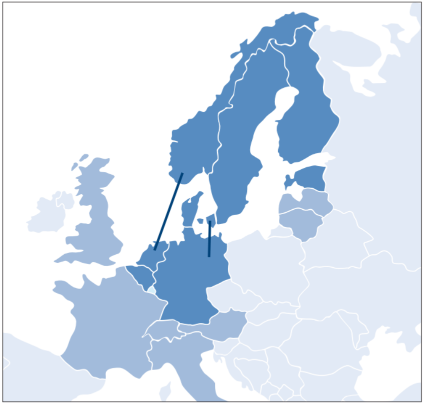
Time	Buy/Sell	Id.	Amount (MWh)	Price (€/MWh)
1 March 2016, 11:00-12:00	Buy	D1	10	55
1 March 2016, 11:00-12:00	Buy	D2	50	50
1 March 2016, 11:00-12:00	Buy	D3	120	35
1 March 2016, 11:00-12:00	Buy	D4	80	27.5
1 March 2016, 11:00-12:00	Sell	G1	15	80
1 March 2016, 11:00-12:00	Sell	G2	55	65
1 March 2016, 11:00-12:00	Sell	G3	90	47
1 March 2016, 11:00-12:00	Sell	G4	40	45
1 March 2016, 11:00-12:00	Sell	G5	100	37

- Let's play a bit more and combine G3 and D2!
- **Cost/benefit analysis:**

$$\left.\begin{array}{rl} \text{Cost:} & 90 \times 47 = 4230€ \\ \text{Income:} & 50 \times 50 = 2500€ \end{array}\right\} \text{Total Cost: } 4230 - 2500 = 1730€$$

- *Do you have a better one?*

The example of Elbas (Nord Pool)



Elbas areas, including licenced areas

Additional countries with Elbas members

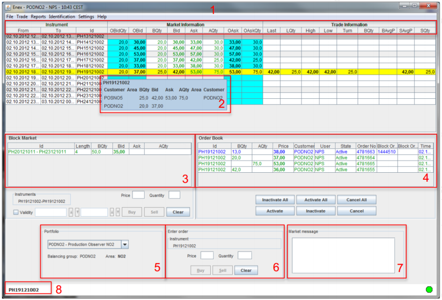
Interconnectors with implicit Elbas capacity out of Nord Pool Spot area

[source: Nord Pool Spot]

- **Elbas**: **El**ectricity **B**alance **A**djustment **S**ystem
- Centrally operated by Nord Pool, for internal and cross-border trading (upon availability of transmission capacity)
- Products: {Energy, Price}, for a given time unit or block bids (up to 3 successive time units)
- Gate closure (closing of trading opportunities before operations):
  - **2 hours** for Norway,
  - **1 hour** for Denmark, Sweden, Finland, Estonia,
  - **30 minutes** for interconnector to Germany (Kontek cable)
  - **5 minutes** in Belgium and the Netherlands (!!)

[See: Elbas User Guide - https://www.nordpoolspot.com/globalassets/download-center/intraday/intraday-user-guide.pdf]

Matching algorithm



[source: Nord Pool Spot]

And in the future: XBID

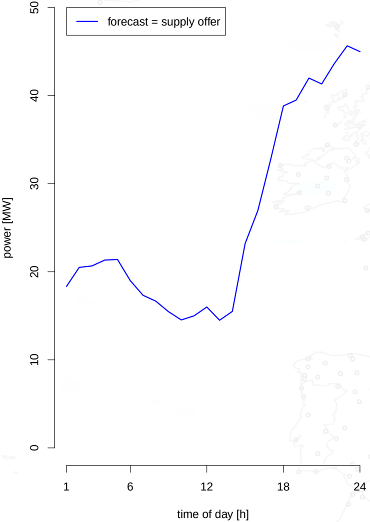
- All players use a web-based Java application serving as a GUI
- All offers can be declared there
- Every time a new offer is entered, the information given to all players is updated
- The key information is the set of "Ask/Bid" prices

  Bid price: at which you would buy
  Ask price: for which you are ready to sell
- Participants just "hit" offers they are willing to accept...

[See: Elbas User Guide - https://www.nordpoolspot.com/globalassets/download-center/intraday/intraday-user-guide.pdf]

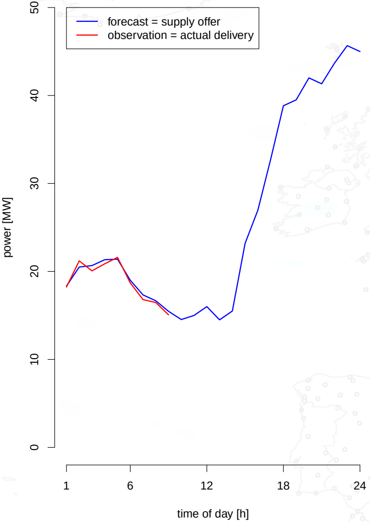
A practical example: 13.03.2014

- **WeTrustInWind** operates a 50MW wind farm (as in a previous lecture)
- Set of accepted supply offers from the day-ahead market (**12.03.2014 - 14:00**):



Time unit	MWh	€/MWh
...	...	...
18:00-19:00	40.1	45
19:00-20:00	41.0	57
20:00-21:00	42.3	72
21:00-22:00	45.6	75
22:00-23:00	46.5	73
...	...	...

- How does the situation look like?



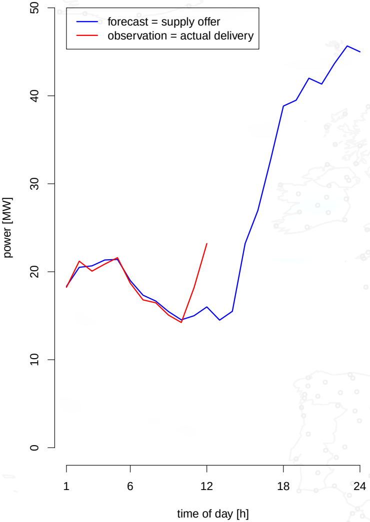
Schedule:

Time unit	MWh	€/MWh
...	...	...
18:00-19:00	40.1	45
19:00-20:00	41.0	57
20:00-21:00	42.3	72
21:00-22:00	45.6	75
22:00-23:00	46.5	73
...	...	...

Offers on our Elbas screen:

Time unit	buy/sell	MWh	€/MWh
...	...	...	...
18:00-19:00	sell	5.5	25
20:00-21:00	sell	20.3	13
20:00-21:00	buy	8.2	5
22:00-23:00	sell	12.5	23
...	...	...	...

- Hitting any offer?



Schedule:

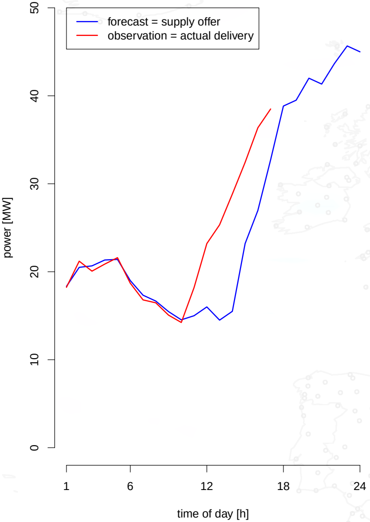
Time unit	MWh	€/MWh
...	...	...
18:00-19:00	40.1	45
19:00-20:00	41.0	57
20:00-21:00	42.3	72
21:00-22:00	45.6	75
22:00-23:00	46.5	73
...	...	...

Offers on our Elbas screen:

Time unit	buy/sell	MWh	€/MWh
...	...	...	...
18:00-19:00	sell	5.5	30
20:00-21:00	sell	20.3	18
20:00-21:00	buy	8.2	7
22:00-23:00	sell	12.5	27
...	...	...	...

Delivery day: 13.03.2014 - 17:00

- Hitting any offer?



Schedule:

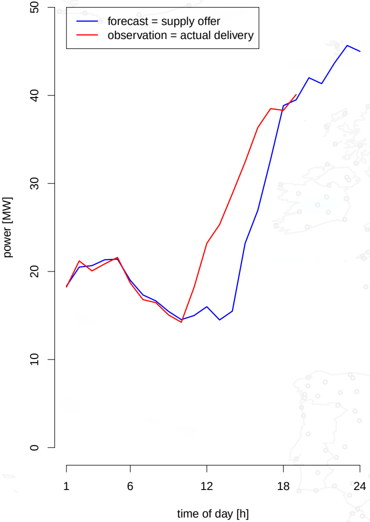
Time unit	MWh	€/MWh
...	...	...
18:00-19:00	40.1	45
19:00-20:00	41.0	57
20:00-21:00	42.3	72
21:00-22:00	45.6	75
22:00-23:00	46.5	73
...	...	...

Offers on our Elbas screen:

Time unit	buy/sell	MWh	€/MWh
...	...	...	...
18:00-19:00	sell	10	72
20:00-21:00	sell	20.3	58
20:00-21:00	buy	8.2	7
22:00-23:00	sell	12.5	27
...	...	...	...

Delivery day: 13.03.2014 - 19:00

- Hitting any offer?



Schedule:

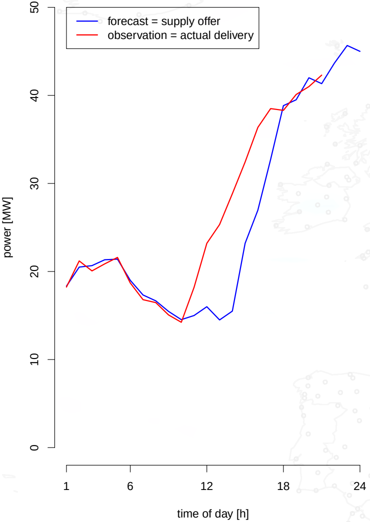
Time unit	MWh	€/MWh
...	...	...
18:00-19:00	40.1	45
19:00-20:00	41.0	57
20:00-21:00	42.3	72
21:00-22:00	45.6	75
22:00-23:00	46.5	73
...	...	...

Offers on our Elbas screen:

Time unit	buy/sell	MWh	€/MWh
...	...	...	...
20:00-21:00	sell	20.3	65
20:00-21:00	sell	4	32
20:00-21:00	buy	8.2	9
22:00-23:00	sell	12.5	47
...	...	...	...

Delivery day: 13.03.2014 - 21:00

- Hitting any offer?



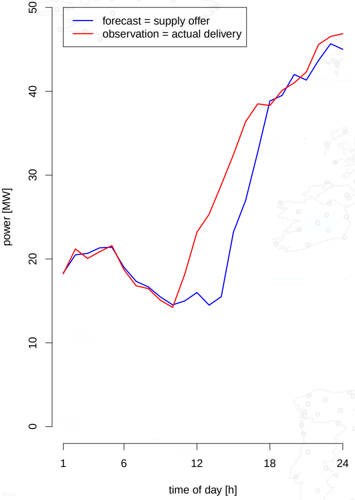
Schedule:

Time unit	MWh	€/MWh
...	...	...
18:00-19:00	40.1	45
19:00-20:00	41.0	57
20:00-21:00	42.3	72
21:00-22:00	45.6	75
22:00-23:00	46.5	73
...	...	...

Offers on our Elbas screen:

Time unit	buy/sell	MWh	€/MWh
...	...	...	...
22:00-23:00	sell	12.5	47
22:00-23:00	buy	7.2	35
22:00-23:00	sell	5.3	80
22:00-23:00	sell	28.5	32
...	...	...	...

End of the day (13.03.2014): Conclusions

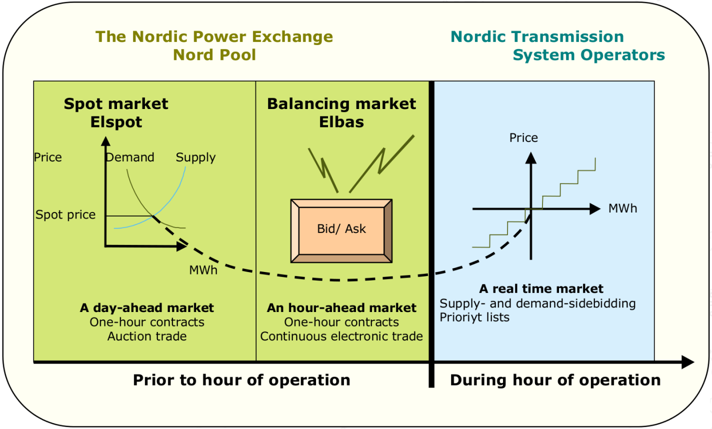


- It may be difficult to foresee the actual imbalance that would need to be fixed, eventually
- Decision-making in such adjustment markets can be
  - complex
  - and possibly stressful!
- One may clearly want to have more information than what we did in this example:
  - how the quantities and prices may develop in the intra-day market?
  - what do we expect to happen in the balancing market?
- A practical consequence is that, in general, volumes and liquidity in such intra-day markets are low...

3. **Balancing market**

The timeline, one last time!

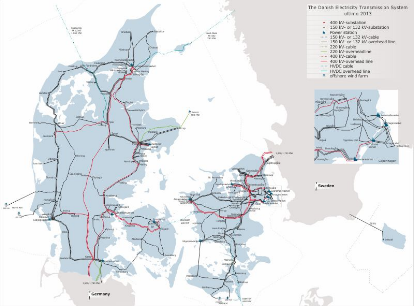
- Now we pass the ball to the Transmission System Operators (TSOs)...



[source: *Nord Pool A/S*]

The balancing market(s)

- The TSO has the **ultimate responsibility** to keep its **transmission system in balance**
- For instance in Denmark, Energinet's system covers
  - Transmission grid at the highest voltage level 400 kV
  - Regional electricity transmission grid on 132 kV east of the Great Belt and 150 kV west of the Great Belt



- More than a single market, this balancing stage may be seen as two markets:
  - *regulation market*, where the TSO buys/sells regulating power prior to the delivery hour
  - *balancing market*, linked to the real-time operations, and yielding balancing payments based on actual metering

  (Though we prefer to see them as a single market mechanism)

- This also links to some *ancillary services* (i.e., reserve capacities) that the TSO purchases - to be discussed during the next lecture...

[See, e.g., Energinet's regulation C2: The balancing market and balance settlement]

Who participates in these balancing market(s)?

- **Regulation market:**

  "A participant in the regulation market is offering to buy or sell regulating power, prior to the hour of operations"

  - the TSO, aiming to purchase regulating power
  - actors of the power systems, who *voluntarily* propose regulating power
  - those who *committed* to provide regulating power (through the reserve provision mechanism)
  - for Scandinavia, these resources are shared through the **NOIS** list (**N**ordic **O**perational **I**nformation **S**ystem)

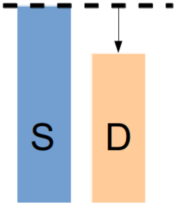
- **Balancing market:**

  "A participant in the balancing market is to cover the costs of his contribution to placing the system off-balance"

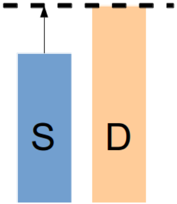
  

  - the TSO, responsible for the metering and settlement
  - all actors of the power system in the control area of the TSO

Is the system (really) in imbalance?



Downward regulation



Upward regulation

- There may be 3 possible situations, for the system as a whole:
  - **Positive imbalance**: Supply > Demand → need for *downward regulation*
  - **Negative imbalance**: Supply < Demand → need for *upward regulation*
  - **No imbalance**: Supply ∼ Demand → *no need for regulation*
- Similarly, supply and demand participants may also have positive and negative imabalance:
  - **Positive imbalance**: Actual generation > Scheduled generation (if supply) or ...
  - **Negative imbalance**: Actual generation < Scheduled generation (if supply) or ...
  - **No imbalance**: Actual generation ∼ Scheduled generation (if supply) or ...

Setting the scene

- **From the (previously cleared) day-ahead market:**
  - Balance of generation and consumption at quantity: P^S
  - Day ahead price: λ^S
  - Generators' schedules: $\hat{y}_j^G, \; j = 1, \ldots, N_G$
  - Demands' schedules: $\hat{y}_i^D, \; i = 1, \ldots, N_D$
- **Then reaching the balancing market:**
  - Imbalance to be handled: ΔP
  - Assume N_B balancing generators, able to move both up ($\uparrow$) and down ($\downarrow$)...
- **Their offers:**
  - *Upward* regulation: $P_j^{\uparrow}$, at price $\lambda_j^{\uparrow}, \; j = 1, \ldots, N_B$
  - *Downward* regulation: $P_j^{\downarrow}$, at price $\lambda_j^{\downarrow}, \; j = 1, \ldots, N_B$
- **One necessarily has:**
  - $\lambda_j^{\uparrow} > \lambda^S, \; j = 1, \ldots, N_B$
  - $\lambda_j^{\downarrow} < \lambda^S, , \; j = 1, \ldots, N_B$

Example list of balancing offers

- **This is a follow up on our basic example in the course on day-ahead markets!**
- *System price*: 37.5 € - *Accepted offers*: see lecture (link)
- *Deadline for offers*: 30th of January, 10:15 - *Delivery period*: 30th of January, 11:00-12:00
- Balancing offers include:

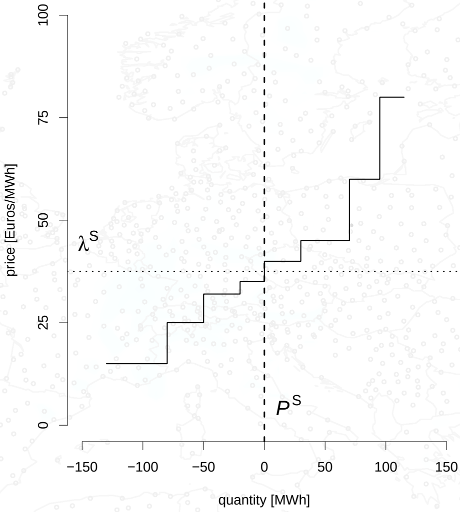
Company	id	$P_j^{\uparrow}$ (MWh)	$\lambda_j^{\uparrow}$ (€/MWh)	$P_j^{\downarrow}$ (MWh)	$\lambda_j^{\downarrow}$ (€/MWh)
BlueHydro*	B_1 (/G_3)	30	40	20	35
LastMinute	B_2	40	45	30	25
FlexiFast	B_3	25	60	30	32
DirtyPower*	B_4 (/G_8)	20	80	50	15

* *already scheduled after day-ahead market clearing*

- Here, only generators offer balancing - Demand could actually also contribute...

Graphically as a supply curve...

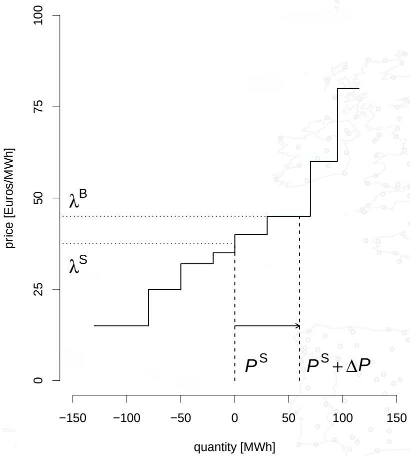
- This is the same type of supply curves than for day-ahead auctions, except that:
  - offers are for *adjustment* from the day-ahead quantity P^S (both upward and downward)
  - demand is here seen as inelastic (so, no demand curve - or seen as a vertical straight line)



Intuitively, two possible situations

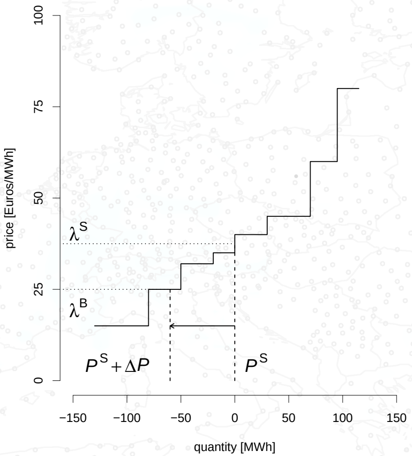
$\Delta P > 0$

(we need extra energy in the system)



$\Delta P < 0$

(we have too much energy in the system)



Writing the balancing auction as an LP

- Similarly to the day-market clearing, the auction can be solved through a Linear Program (LP):

$$
\begin{aligned}
\min_{\{y_j^\uparrow\},\{y_j^\downarrow\}} \quad & \sum_j \lambda_j^\uparrow y_j^\uparrow - \lambda_j^\downarrow y_j^\downarrow \\
\text{subject to} \quad & \sum_j y_j^\uparrow - y_j^\downarrow = \Delta P \ : \ \lambda^B \\
& 0 \leq y_i^\uparrow \leq P_i^\uparrow, \ j = 1, \ldots, N_B \\
& 0 \leq y_j^\downarrow \leq P_j^\downarrow, \ j = 1, \ldots, N_B
\end{aligned}
$$

- The balancing price λ^B can then be obtained by solving the dual LP
- It corresponds to the lagrange multiplier for the updated balance equation
- Using this balancing price directly for the settlement yields
  - *one-price imbalance settlement*
  - being referred to as a *one-price balancing market*

The one-price imbalance settlement

Basic properties:

$\Delta P > 0$	$\Delta P \sim 0$	$\Delta P < 0$
$\lambda^B > \lambda^S$	$\lambda^B = \lambda^S$	$\lambda^B < \lambda^S$

Consequences on settlement for those dispatched through the day-ahead market:

- $\Delta P > 0$:
  - Generator i producing less than scheduled must buy $\hat{y}_i^G - y_i^G$ at price λ^B
  - Demand j consuming more than scheduled must buy $\hat{y}_j^D - y_j^D$ at price λ^B
  - Generator i producing more than scheduled must sell $y_i^G - \hat{y}_i^G$ at price λ^B
  - Demand j consuming less than scheduled must sell $y_j^D - \hat{y}_j^D$ at price λ^B
- $\Delta P < 0$: ... basically, the same type of reasoning
- Meanwhile, balancing generators simply sell or buy at price λ^B

Example case 1: Outage of G_5

"Even though scheduled, the unit G_5 of KøbenhavnCHP will be down during that hour, and the operator could not get a match in the intra-day market..."

- All others are producing and consuming as planned.
- For the **balancing auction**, one has:
  - $\Delta P = 60$ MWh (since demand is higher than generation by 60 MWh for that hour)
  - $\lambda^B = 45$ €/MWh
  - Scheduled balancing generators: B_1 and B_2 (only 30 MWh upward)
- The **settlement** leads to:
  - G_5 paying $60 \times 45 = 2700$ €
  - $B_1(/G_3)$ and B_2 each receiving $30 \times 45 = 1350$ €
- Considering **both day-ahead and balancing** stages:
  - G_5 receives $60 \times 37.5 = 2250$ €, and has to pay $60 \times 45 = 2700$ €... That is a loss of 450 €(!)
  - B_1 $(/G_3)$ receives $200 \times 37.5 = 7500$ € (day-ahead) and $30 \times 45 = 1350$ € at the balancing stage

Example case 2: Wind forecast errors

"For both wind farms G_1 and G_2 (operated by $\mathrm{RT}^{®}$ and WeTrustInWind), the actual generation is not equal to that foreseen when clearing the day-ahead market, i.e."

- for G_1: $\hat{y}_1^G = 50$ MWh but actual generation is $y_1^G = 30$ MWh
- for G_2: $\hat{y}_2^G = 120$ MWh but actual generation is $y_2^G = 155$ MWh

- All others are producing and consuming as planned.

- For the **balancing auction**, one has:
  - $\Delta P = -15$ MWh (since generation is higher that demand by 15 MWh for that hour)
  - $\lambda^B = 35$ €/MWh
  - Scheduled balancing generators: B_1 (only 15 MWh downward)

- The **settlement** leads to:
  - G_1 paying $20 \times 35 = 700$ €
  - G_2 receiving $35 \times 35 = 1225$ €
  - B_1 paying $15 \times 35 = 525$ €

- Considering **both day-ahead and balancing** stages:
  - G_1 receives $50 \times 37.5 = 1875$ €, then pays $20 \times 35 = 700$ € - Gives 1175 €
  - G_2 receives $120 \times 37.5 = 4500$ €, then receives again $35 \times 35 = 1225$ € - Gives 5775 €
  - B_1 ($/G_3$) receives $200 \times 37.5 = 7500$ €, then pays $15 \times 35 = 525$ € - Gives 7175 €

Comments on the one-price balancing markets

- The total payment/revenue of day-ahead market participants for deviations from schedule equals the revenue/payment of the balancing generators
- Regarding deviations:
  - if one's own deviation contributes to setting the system off-balance (e.g., generator overproduce while there is too much power overall), **this leads to a loss**
  - but...
  - if one's own deviation is of the *helping the system go back to balance* (e.g., generator overproduce while there is a lack of power overall), **this leads to extra profit(!)**
- *What could be the consequences?*
- *And, how could we fix that?*

The two-price imbalance settlement

Basic properties: (well, the same for market clearing)

$\Delta P > 0$	$\Delta P \sim 0$	$\Delta P < 0$
$\lambda^B > \lambda^S$	$\lambda^B = \lambda^S$	$\lambda^B < \lambda^S$

Settlement is rethought:
$\rightarrow$ those putting the system off-balance are to be penalized
$\rightarrow$ those supporting the system (unintentionally) will not get extra rewards

- $\Delta P > 0$:
  - Generator i producing less than scheduled must buy $\hat{y}_i^G - y_i^G$ at price λ^B
  - Demand j consuming more than scheduled must buy $\hat{y}_j^D - y_j^D$ at price λ^B
  - Generator i producing more than scheduled must sell $y_i^G - \hat{y}_i^G$ at price λ^S
  - Demand j consuming less than scheduled must sell $y_j^D - \hat{y}_j^D$ at price λ^S
- $\Delta P < 0$: ... basically, the opposite type of reasoning
- Meanwhile, balancing generators simply sell or buy at price λ^B

Example case 1: Outage of G_5

"Even though scheduled, the unit G_5 of KøbenhavnCHP will be down during that hour, and the operator could not get a match in the intra-day market..."

- All others are producing and consuming as planned.
- For the **balancing auction**, one has:
  - $\Delta P = 60$ MWh (since demand is higher than generation by 60 MWh for that hour)
  - $\lambda^B = 45$ €/MWh
  - Scheduled balancing generators: B_1 and B_2 (only 30 MWh upward)
- The **settlement** leads to:
  - G_5 paying $60 \times 45 = 2700$ €
  - $B_1(/G_3)$ and B_2 each receiving $30 \times 45 = 1350$ €
- Considering **both day-ahead and balancing** stages:
  - G_5 receives $60 \times 37.5 = 2250$ €, and has to pay $60 \times 45 = 2700$ €... That is a loss of 450 €(!)
  - B_1 $(/G_3)$ receives $200 \times 37.5 = 7500$ € (day-ahead) and $30 \times 45 = 1350$ € at the balancing stage

Example case 2: Wind forecast errors

"For both wind farms G_1 and G_2 (operated by $\mathrm{RT}^{®}$ and WeTrustInWind), the actual generation is not equal to that foreseen when clearing the day-ahead market, i.e."

- for G_1: $\hat{y}_1^G = 50$ MWh but actual generation is $y_1^G = 30$ MWh
- for G_2: $\hat{y}_1^G = 120$ MWh but actual generation is $y_1^G = 155$ MWh

- All others are producing and consuming as planned.
- For the **balancing auction**, one has:
  - $\Delta P = -15$ MWh (since generation is higher than demand by 15 MWh for that hour)
  - $\lambda^B = 35$ €/MWh (while day-ahead price is $\lambda^S = 37.5$ €/MWh)
  - Scheduled balancing generators: B_1 (only 15 MWh downward)
- The **settlement** leads to:
  - G_1 paying $20 \times 37.5 = 750$ € (instead of 700 € in the one-price case)
  - G_2 receiving $35 \times 35 = 1225$ €
  - $B_1(/G_3)$ paying $15 \times 35 = 525$ €
- Considering **both day-ahead and balancing** stages:
  - G_1 receives $50 \times 37.5 = 1875$ €, then pays $20 \times 37.5 = 750$ € - Gives 1050 €
  - G_2 receives $120 \times 37.5 = 4500$ €, then receives again $35 \times 35 = 1225$ € - Gives 5775 €
  - B_1 $(/G_3)$ receives $200 \times 37.5 = 7500$ €, then pays $15 \times 35 = 525$ € - Gives 7175 €

Final remarks

- We gave here the big picture, and there may be additional aspects that could deserve consideration (for another time...), e.g.
    - There can be *both* up- and down-regulation situations at the same time...
    - The actual time step of operations is much smaller (for instance, 5 minutes) than the market time unit (say, 1 hour)
    - Demand-side could also be pro-active and participate in the balancing market
    - Network effects and inter-zone coordination can substantially impact the balancing mechanisms
    - etc.
- Let's have a look at the current situation in Scandinavia: Nord Pool's balancing page

Further readings

For those who want to go into the more mathematical aspects of balancing markets:

- J.M. Morales et al. (2014). *Integrating Renewables in Electricity Markets*, Chapter 4: "Balancing markets" (pdf)

For those interested in current challenges and discussion at the European level:

- F. Borggrefe and K. Neuhoff (2011). *Balancing and intraday market design: Options for wind integration* (pdf)

Thanks for your attention! - Contact: ppin@dtu.dk - web: pierrepinson.com