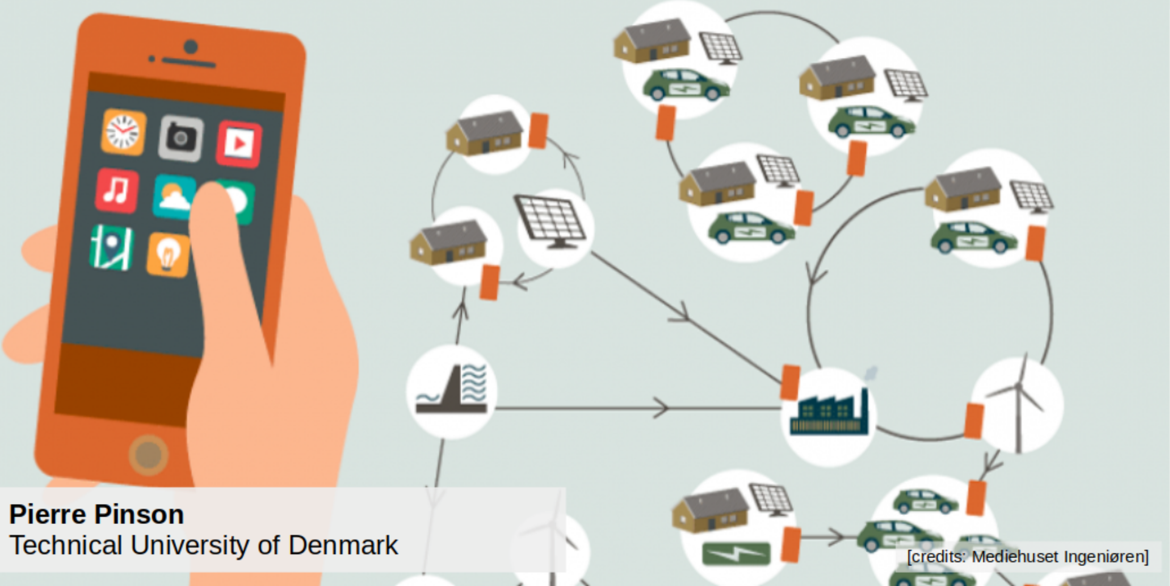
Module 2 – Electricity Spot Markets (e.g. day-ahead)

2.4 Zonal and network aspects

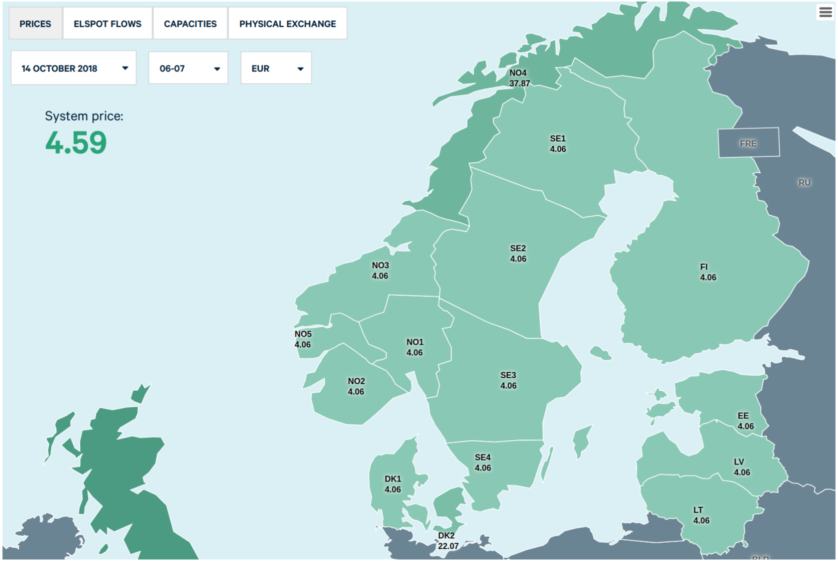


[credits: Mediehuset Ingeniøren]

Pierre Pinson
Technical University of Denmark

Prices may vary geographically

- Remember there is a network involved, and power has to flow...
- This was not accounted for so far!



Exchange capacity limitations

- There is a maximum amount of energy that may be exchanged from one location to the next
- When this limit is reached, one talks about **congestion** and prices for connected areas will differ
- Exchange capacity limitations are directly related to *network constraints* and *operational practice*

Approaches to handling exchange capacity limitations

- There are basically two philosophies, developed on both sides of the Atlantic Ocean, i.e., in Europe and the USA

	Europe	US
System Operator	TSO	ISO
Market Operator	Ind. Market Operator	ISO
Offers	Market products	Unit capabilities
Clearing	Supply-demand equilibrium	UCED problem
Network representation	Highly simplified	Fairly detailed
Prices	**Zonal**	**Nodal**

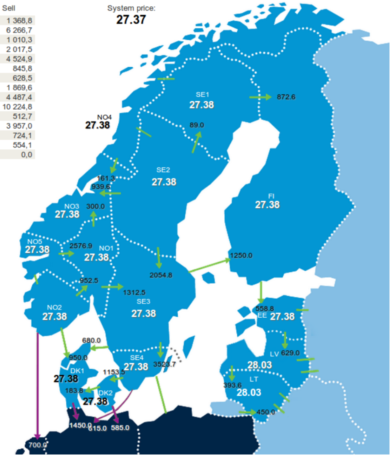
TSO: Transmission System Operator
ISO: Independent System Operator
UCED: Unit Commitment and Economic Dispatch

Illustration of zonal and nodal pricing

Scandinavia (Zonal):

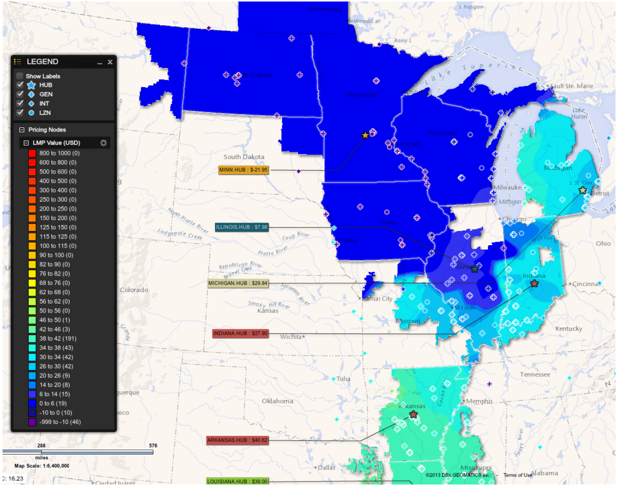
Elspot volumes

	Buy	Sell
NO1	3 285,7	1 368,8
NO2	4 364,2	6 266,7
NO3	2 411,2	1 010,3
NO4	1 856,2	2 017,5
NO5	1 948,0	4 524,9
DK1	2 659,6	845,8
DK2	1 598,2	628,5
SE1	1 086,0	1 869,6
SE2	1 404,0	4 487,4
SE3	8 138,4	10 224,8
SE4	2 882,9	512,7
FI	5 520,8	3 957,0
EE	653,9	724,1
LT	947,7	554,1
LV	235,4	0,0



Go visit: `http://nordpoolgroup.com`

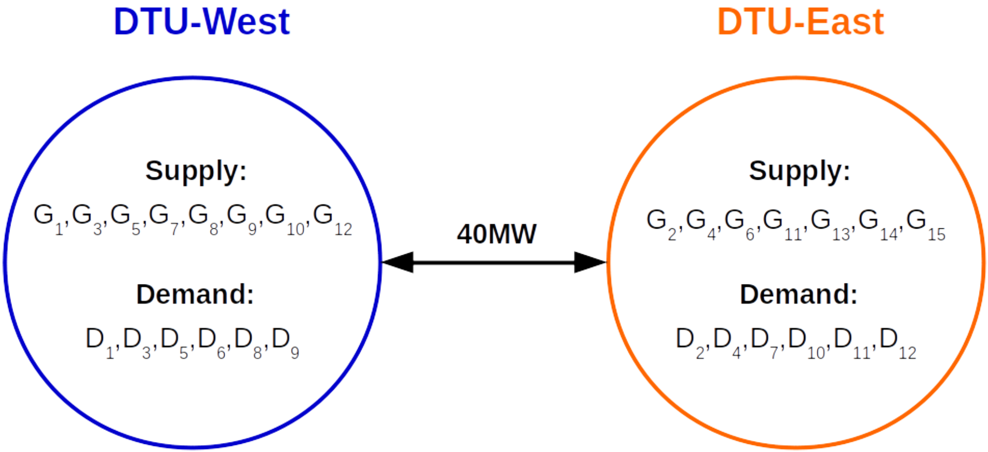
Midwest US (Nodal):



Go visit: https://www.misoenergy.org

From system price to area prices

- Let us revisit our previous market clearing example,
  - considering two areas **DTU-West** and **DTU-East**, and
  - with a transmission capacity of **40 MW** (so, only 40MWh can flow)



Localization of offers

Demand: (for a total of 1065 MWh)

Company	id	Amount (MWh)	Price (€/MWh)	Area
CleanRetail	D_1	250	200	DTU-West
El4You	D_2	300	110	DTU-East
EVcharge	D_3	120	100	DTU-West
QualiWatt	D_4	80	90	DTU-East
IntelliWatt	D_5	40	85	DTU-West
El4You	D_6	70	75	DTU-West
CleanRetail	D_7	60	65	DTU-East
IntelliWatt	D_8	45	40	DTU-West
QualiWatt	D_9	30	38	DTU-West
IntelliWatt	D_{10}	35	31	DTU-East
CleanRetail	D_{11}	25	24	DTU-East
El4You	D_{12}	10	16	DTU-East

And on the supply side

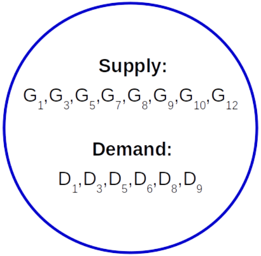
Supply: (for a total of 1435 MWh)

Company	id	Amount (MWh)	Price (€/MWh)	Area
RT®	G_1	120	0	DTU-West
WeTrustInWind	G_2	50	0	DTU-East
BlueHydro	G_3	200	15	DTU-West
RT®	G_4	400	30	DTU-East
KøbenhavnCHP	G_5	60	32.5	DTU-West
KøbenhavnCHP	G_6	50	34	DTU-East
KøbenhavnCHP	G_7	60	36	DTU-West
DirtyPower	G_8	100	37.5	DTU-West
DirtyPower	G_9	70	39	DTU-West
DirtyPower	G_{10}	50	40	DTU-West
RT®	G_{11}	70	60	DTU-East
RT®	G_{12}	45	70	DTU-West
SafePeak	G_{13}	50	100	DTU-East
SafePeak	G_{14}	60	150	DTU-East
SafePeak	G_{15}	50	200	DTU-East

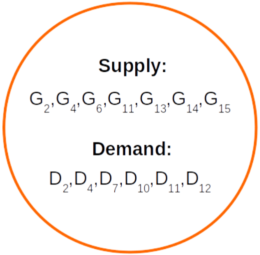
Localizing the previous market-clearing results

- Following previous market clearing results, one obtains

DTU-West



DTU-East



- Supply side: $\{G_1, G_3, G_5, G_7, G_8\}$ (but only 55 MWh for G_8) - Total: 495 MWh
- Demand side: $\{D_1, D_3, D_5, D_6, D_8, D_9\}$ - Total: 555 MWh

  $\rightarrow$ Deficit of **60 MWh**

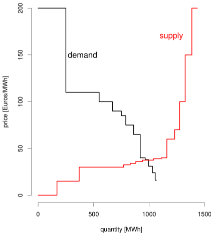
- Supply side: $\{G_2, G_4, G_6\}$ - Total: 500 MWh
- Demand side: $\{D_2, D_4, D_7\}$ - Total: 440 MWh

  $\rightarrow$ Surplus of **60 MWh**

BUT, only **40 MWh** can flow through the interconnection!

Intuition based on an import-export approach

- Due to transmission constraints, the market has to split and becomes two markets



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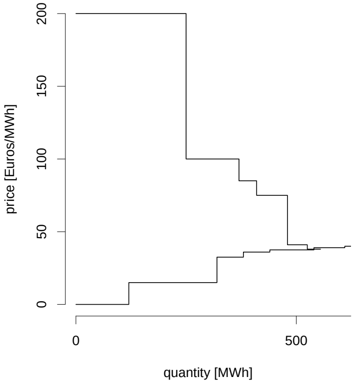
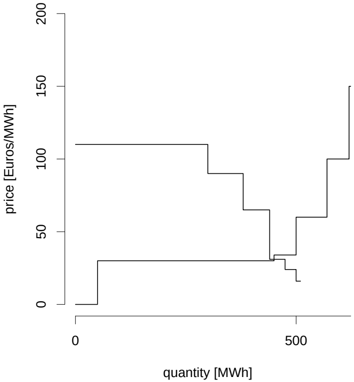
DTU-West



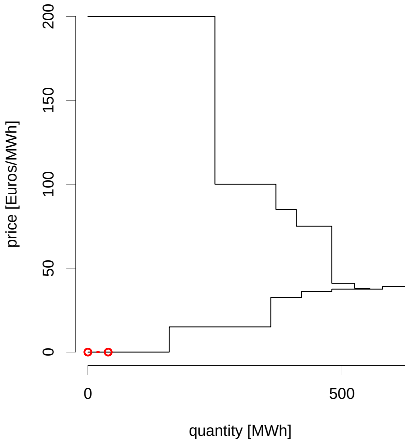
DTU-East



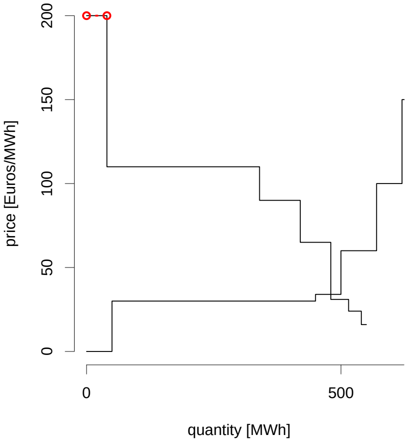
- In practice:
  - 2 market zones with their own supply-demand equilibrium
  - extra (price-independent) consumption/generation offers representing the transmission from one zone to the next to be added

Adding transmission-related offers

- Extra supply in the high price area, i.e., DTU-West (40 MWh coming from DTU-East)



- Extra consumption in the low price area, i.e., DTU-East (40 MWh for DTU-West)

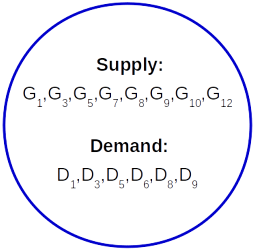


- Power ought to flow from the low price area to the high price area

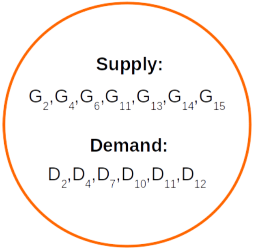
Market clearing results for both zones

- The same type of LP problems as introduced before is solved
  - for each zone individually,
  - with the extra consumption/generation offers representing the amount of energy transmitted

DTU-West



DTU-East



- Supply side: $\{G_1, G_3, G_5, G_7, G_8\}$ (but only 75 MWh for G_8) - Total: 515 MWh
- Demand side: $\{D_1, D_3, D_5, D_6, D_8, D_9\}$ - Total: 555 MWh

  $\rightarrow$ **Zonal price: 37.5 €**

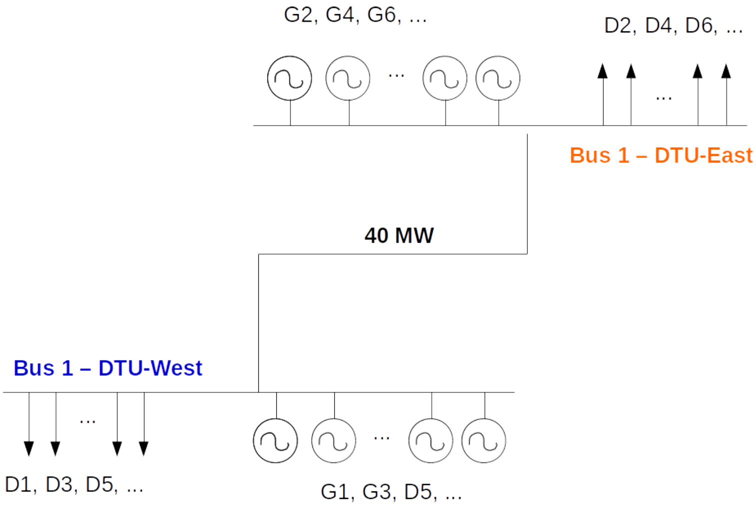
- Supply side: $\{G_2, G_4, G_6\}$ (but only 30 MWh for G_6) - Total: 480 MWh
- Demand side: $\{D_2, D_4, D_7\}$ - Total: 440 MWh

  $\rightarrow$ **Zonal price: 34 €**

More elegantly with flow-based coupling

- Instead of boldly splitting the market, one could instead acknowledge how power flows...
- This allows clearing a single market with geographically differentiated prices

- our DTU system with 2 zones can be modelled as a 2-bus system,
- loads and generators are associated to the relevant bus
- DC power flow is assumed as commonly done at transmission level



Formulating the market clearing

- The network-constrained social welfare maximization problem can be written as:

$$
\begin{aligned}
\max_{\{y_i^D\},\{y_i^G\}} \quad & \sum_i \lambda_i^D y_i^D - \sum_j \lambda_j^G y_j^G \\
\text{subject to} \quad & \sum_i y_i^{D,West} - \sum_j y_j^{G,West} = B\Delta\delta \\
& \sum_i y_i^{D,East} - \sum_j y_j^{G,East} = -B\Delta\delta \\
& 0 \leq y_i^D \leq P_i^D, \;\; i = 1, \ldots, N_D \\
& 0 \leq y_j^G \leq P_j^G, \;\; j = 1, \ldots, N_G \\
& -40 \leq B\Delta\delta \leq 40
\end{aligned}
$$

where:

- B is the absolute value of susceptance (physical constant) of the interconnection between DTU-West and DTU-East
- $\Delta\delta$ is the difference of voltage angles between the 2 buses

  $\rightarrow$ $B\Delta\delta$ represents the signed power flow from DTU-West to DTU-East

Obtaining the zonal prices

- As for the case of a single zone, the dual LP allows obtaining **market-clearing prices**
- These **2 prices** corresponds to the Lagrange multipliers for the **2 equality constraints** (i.e., balance equations):

$$
\begin{aligned}
\max_{\{y_i^D\},\{y_i^G\}} \quad & \sum_i \lambda_i^D y_i^D - \sum_j \lambda_j^G y_j^G \\
\text{subject to} \quad & \sum_i y_i^{D,West} - \sum_j y_j^{G,West} = B\Delta\delta \ : \ \lambda^{S,West} \\
& \sum_i y_i^{D,East} - \sum_j y_j^{G,East} = -B\Delta\delta \ : \ \lambda^{S,East} \\
& 0 \leq y_i^D \leq P_i^D, \ i = 1, \dots, N_D \\
& 0 \leq y_j^G \leq P_j^G, \ j = 1, \dots, N_G \\
& -40 \leq B\Delta\delta \leq 40
\end{aligned}
$$

Results for our auction example

- Results are the same than those based on the import-export approach

- Supply side: $\{G_1, G_3, G_5, G_7, G_8\}$ (but only 75 MWh for G_8) - Total: 515 MWh
- Demand side: $\{D_1, D_3, D_5, D_6, D_8, D_9\}$ - Total: 555 MWh

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- Demand side: $\{D_2, D_4, D_7\}$ - Total: 440 MWh

  $\rightarrow$ **Zonal price: 34 €**

- However, all zones are modeled at once, and the approach can scale readily

Final extension to nodal pricing

- In a US-like setup, each node of the power system is to be seen as an area
- For a system with K nodes, the network-constrained social welfare maximization market-clearing writes:

$$
\begin{aligned}
\max_{\{y_i^D\},\{y_i^G\}} \quad & \sum_i \lambda_i^D y_i^D - \sum_j \lambda_j^G y_j^G \\
\text{subject to} \quad & \sum_i y_i^{D,k} - \sum_j y_j^{G,k} = \sum_{l \in \mathcal{L}_k} B_{kl}(\delta_k - \delta_l), \;\; k = 1, \ldots, K \; : \; \lambda^{S,k} \\
& 0 \leq y_i^D \leq P_i^D, \;\; i = 1, \ldots, N_D \\
& 0 \leq y_j^G \leq P_j^G, \;\; j = 1, \ldots, N_G \\
& -C_{kl} \leq B_{kl}(\delta_k - \delta_l) \leq C_{kl}\,, \quad k, l \in \mathcal{L}_N
\end{aligned}
$$

where

- $\mathcal{L}_N$ is the set of nodes, $\mathcal{L}_k$ the set of nodes connected to node k
- B_{kl} are the line suseptances, $(\delta_k - \delta_l)$ the phase angle differences
- $\lambda^{S,k}$ are the K nodal prices

[Extra: Enerdynamics (2012). Locational Marginal Pricing. *Electricity Markets Dynamics online course* (video)]

Settlement under zonal and nodal pricing

- Market participants are subject to the price where they are physically located, i.e.,
  - *Consumption* side: $R_i^{DA,D} = -\lambda^{S,\text{location}} y_i^D$, $R_i^{DA,D} \leq 0$, (since being a payment)
  - *Supply* side: $R_j^{DA,G} = \lambda^{S,\text{location}} y_j^G$, $R_j^{DA,G} \geq 0$ (since being a revenue)

Payment and revenues for our example market clearing

- *Consumption* side (payments):
  - D_1 pays $250 \times 37.5 = 9375$ €, $(R_9^{DA,D} = -9375)$
  - D_2 pays $300 \times 34 = 10200$ €, $(R_9^{DA,D} = -10200)$, etc.
  - D_9 pays $30 \times 37.5 = 1125$ €, $(R_9^{DA,D} = -1125)$
- *Supply* side (revenues):
  - G_1 receives $120 \times 37.5 = 4500$ €, $(R_8^{DA,G} = 4500)$
  - G_2 receives $50 \times 34 = 1700$ €, $(R_2^{DA,G} = 1700)$, etc.
  - G_8 receives $55 \times 37.5 = 2062.5$ €, $(R_8^{DA,G} = 2062.5)$

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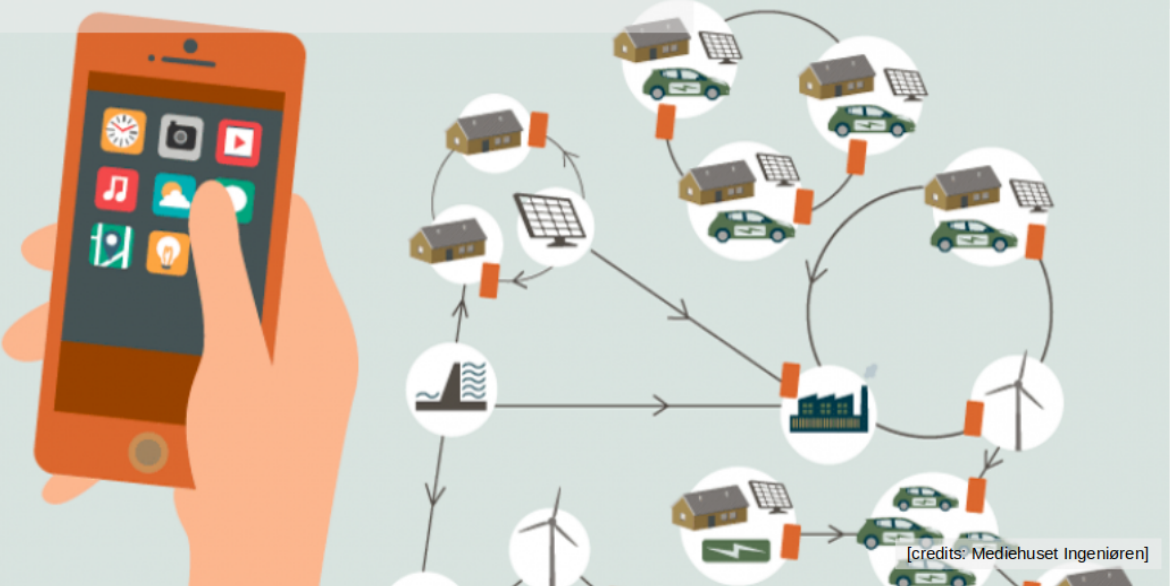
  - G_8 receives $55 \times 37.5 = 2062.5$ €, $(R_8^{DA,G} = 2062.5)$

- The market is **not budget balanced anymore**, since the sum of consumer payments is greater that the sum of supplier revenues
- The difference defines a **congestion rent** to be collected by the system operator(s)

Use the self-assessment quizz to check your understanding!



[credits: Mediehuset Ingeniøren]