

Electricity Markets: Summer Semester 2016, Lecture 4

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Transmission and distribution networks

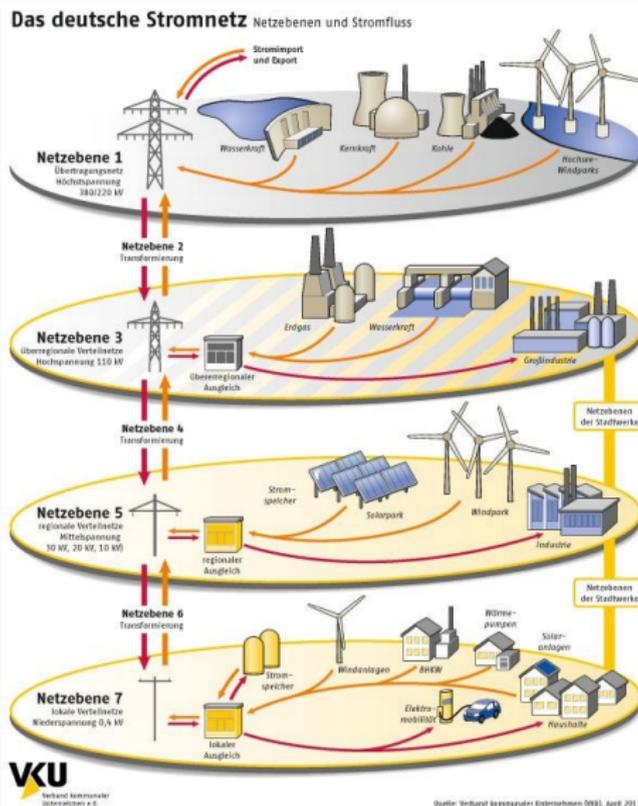
Transmission and distribution networks

Electricity usually is not consumed where it is produced, so it has to be transported via **transmission** and **distribution networks**.

Transmission networks: Transport large volumes of electric power over relatively long distances.

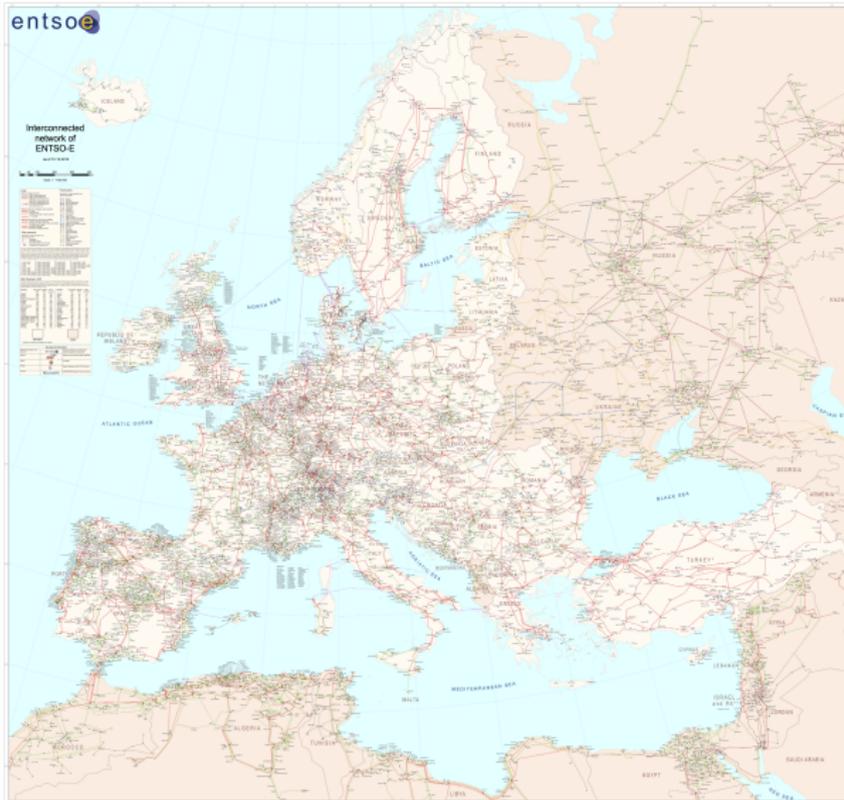
Distribution networks: Take power from the transmission network and deliver it to a large number of end points in a certain geographic area.

Transmission and distribution networks



Source: VKU

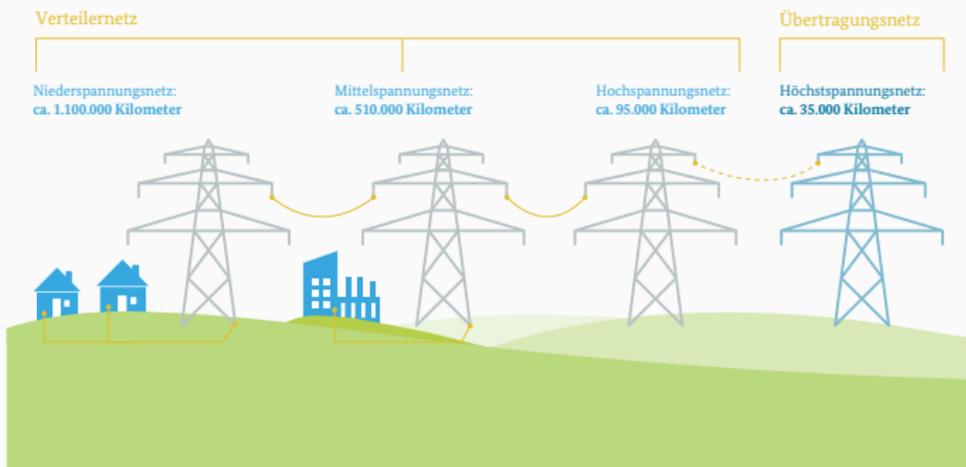
European Transmission Grid



Source: ENTSO-E

Transmission and distribution networks in Germany

**Das deutsche Strom-Verteilernetz ist
rund 1,7 Millionen Kilometer lang**



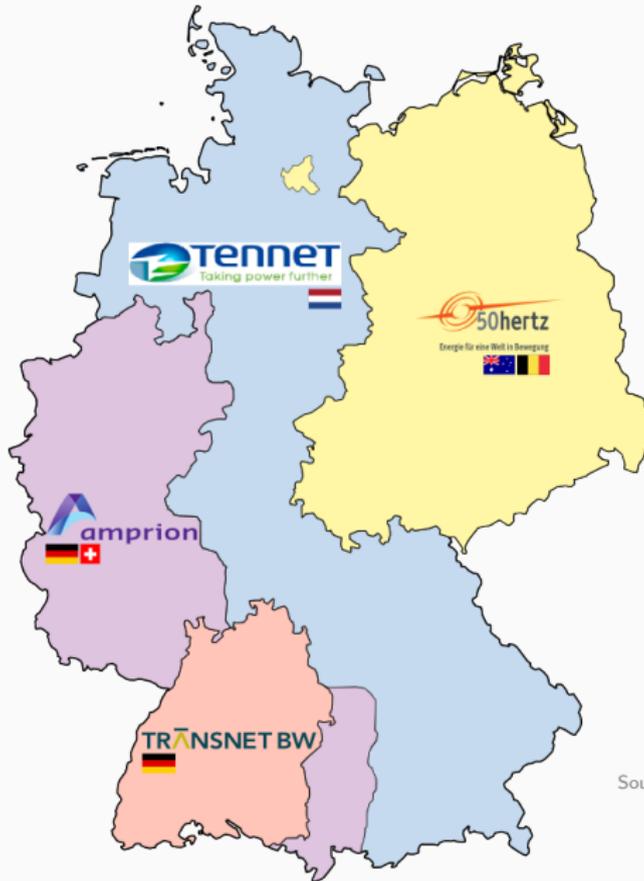
Source: BMWi

Transmission and distribution networks in Germany

Sector	Leading Companies	Market Share	Total Number of Providers
Transmission	Amprion Transnet BW (ENBW) TenneT 50Hertz Transmission	100% Combined	4
Distribution	EnBW E.ON RWE Vattenfall	The big 4 distribution companies own and operate a significant portion of the distribution system, though the exact level is not clear.	approximately 890* DSOs, about 700 of which are municipally owned <i>Stadtwerke</i>
Total Generation	EnBW E.ON RWE Vattenfall	56% installed capacity** (June 2014) ~59 % of electricity generated (2012).***	over 1000 producers (not including individuals)
Retail Suppliers	EnBW E.ON RWE Vattenfall	45.5% of total electricity offtake (TWh).****	over 900 suppliers

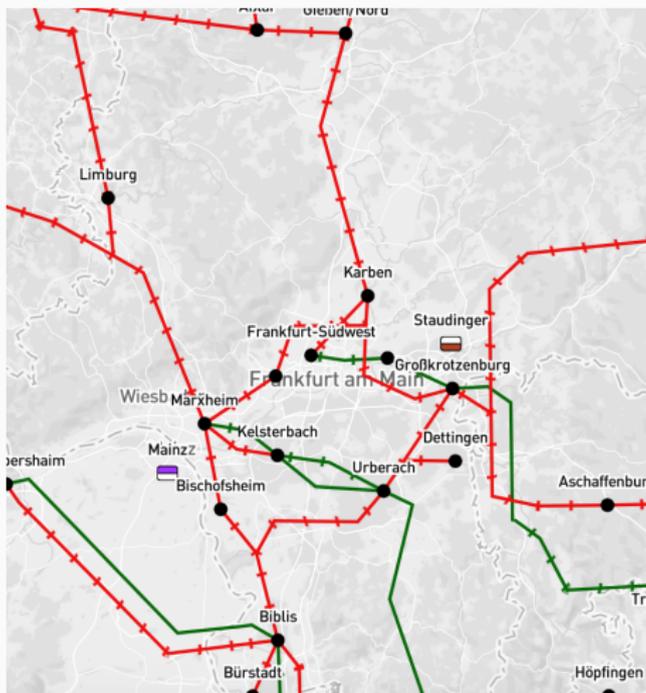
Source: Agora Energiewende / RAP

TSOs in Germany

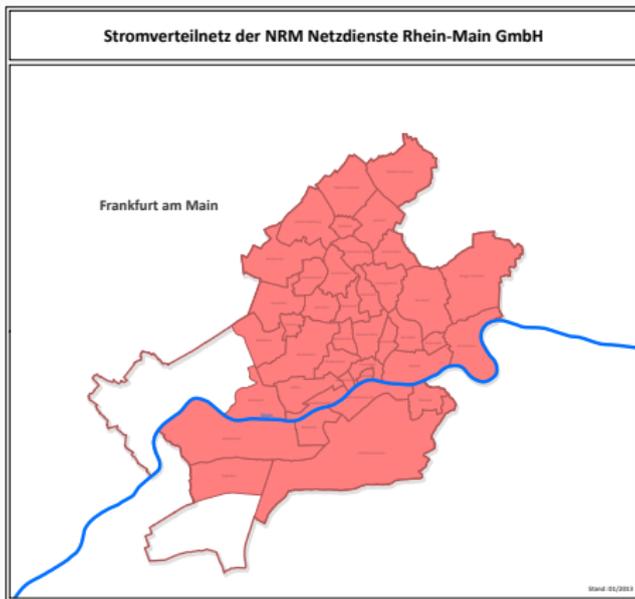


Source: Wikipedia (Francis McLloyd)

Transmission grid near Frankfurt



Source: ENTSO-E



NRM Netzdienste Rhein-Main (subsidiary company of Mainova)

Source: NRM Netzdienste Rhein-Main

Power grids and electricity markets

The (physical) balancing of supply and demand has to respect the **network constraints** of the system. These constraints have to be implemented by the **system operator**, but to some extent can also be included into the **market design**.

Transmission and distribution networks are (almost?) natural monopolies, which leads to substantial **market power**. These networks are typically state owned, cooperatives or heavily regulated (many interesting problems with respect to incentives, tariffs, etc.).

Network expansion is part of the **long-term** efficient operation of the system. Note the interdependency between network and generation investment.

Representing network constraints

Physical limits on networks

Thermal limits: Relate to the **maximum amount of power** which can be transmitted via a transmission line.

Voltage stability limits: Relate to the supply of reactive power to keep the system voltage close to a specific level.

Dynamic and transient stability limits: Relate to the stability of the system frequency, and the stability of the synchronized operation of the generators.

Representing transmission networks

Terminology: We represent the transmission grid as an network, consisting of **nodes** and **links**. The nodes may represent individual generators, groups of generators and consumers, whole geographic regions or just a point where different transmission lines meet. The links represent transmission lines, or more generally the possibility to transfer electric power between the respective nodes connected to the respective link.



Source: PyPSA

Basic implementation of thermal limits

A link l connecting two nodes allows to transport electrical power as a **power flow** F_l from one node to the other.

We implement the thermal limits on a line l as the **capacity** K_l , which gives the upper limit of power flow F_l on l :

$$\begin{aligned}F_l &\leq K_l \\ -F_l &\leq K_l\end{aligned}$$

This looks just like another constraint for KKT. Unfortunately, the power flows F_l are usually not free parameters, but are connected via physical laws from the generation and consumption pattern Q_i^S, Q_i^B at the nodes.

Efficient dispatch in a two-node system with constraints

Example

[The following example is taken from the book by Strbac and Kirschen.]

Consider two nodes representing regions, each with different total demand, using different types of generators:

First node: Fixed demand $Q_1^B = 500$ MW. The (inverse) supply function for the generators is given by

$$\pi_1 = MC_1 = 10 + 0.01Q_1 \text{ [€/MWh]}$$

Second node: Fixed demand $Q_2^B = 1500$ MW. The (inverse) supply function for the generators is given by

$$\pi_2 = MC_2 = 13 + 0.02Q_2 \text{ [€/MWh]}$$

For simplicity we assume that at both nodes the total generation limit is 5 GW.

Transmission line from node 1 to node 2 with capacity K .

Example: Separate markets

Transmission capacity $K = 0$:

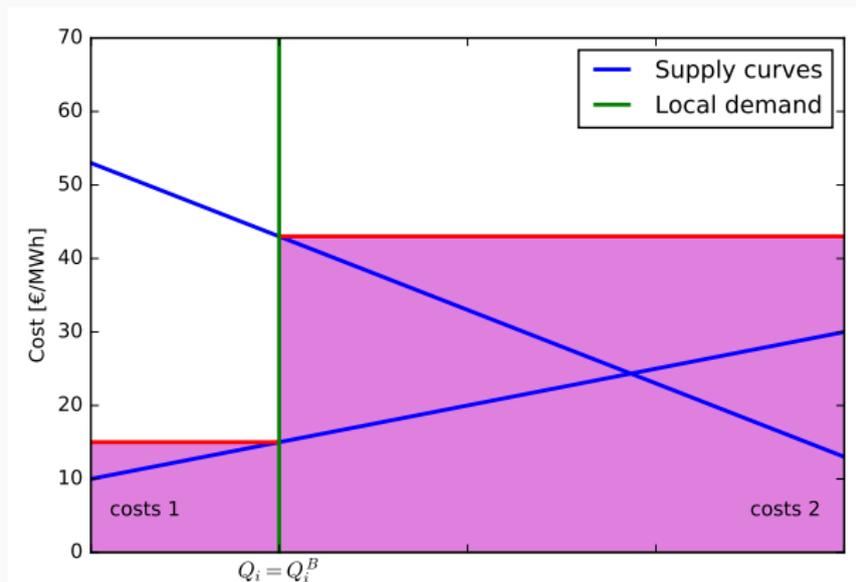
First node: Fixed demand $Q_1^B = 500$ MW. The competitive price is

$$\lambda_1 = MC_1(Q_1^B) = 10 + 0.01 \times 500 = 15 \text{ [€/MWh]}$$

Second node: Fixed demand $Q_2^B = 1500$ MW. The competitive price is

$$\lambda_2 = MC_2(Q_2^B) = 13 + 0.02 \times 1500 = 43 \text{ [€/MWh]}$$

Example: Separate markets



Example: Single market

Transmission capacity $K = \infty$:

There is now a total demand $Q^B = Q_1^B + Q_2^B$, leading to a single market clearing price λ . The generators at node 1 and node 2 adjust their output such that

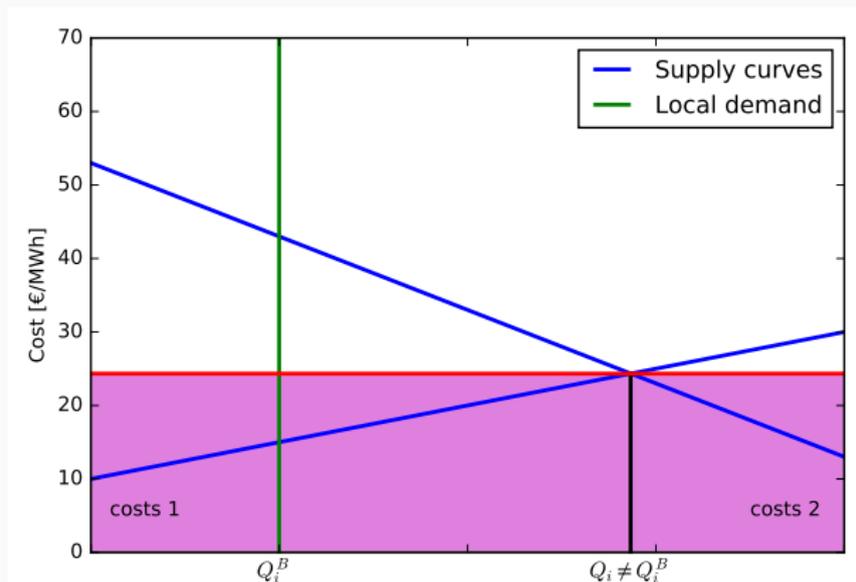
$$MC_1(Q_1) = MC_2(Q_2) = \lambda,$$

under the constraint that

$$Q_1 + Q_2 = Q^B$$

This leads to $Q_1 = 1433$ MW, $Q_2 = 567$ MW, and $\lambda = 24.33$ €/MWh.

Example: Single market



Example: Single market

The power flow F from node 1 to node 2 is given by

$$\begin{aligned} F &= (Q_1 - Q_1^B) = -(Q_2 - Q_2^B) \\ &= (1433 - 500) \text{ MW} = -(567 - 1500) \text{ MW} \\ &= Z_1 = -Z_2 \\ &= 933 \text{ MW} \end{aligned}$$

with $\{Z_1, Z_2\} = \{933 \text{ MW}, -933 \text{ MW}\}$ denoted as the **injection pattern**.

From the balancing condition it follows $Z_1 + Z_2 = 0$. We call a node with $Z > 0$ a **source**, and a node with $Z < 0$ a **sink**.

If $Z_1 > Z_2$, we have a flow from node 1 to node 2, if $Z_2 > Z_1$, we have a flow from node 2 to node 1 (source to sink).

Example: Single market

	Separate markets	Single market
Q_1^B [MW]	500	500
Q_1 [MW]	500	1433
Z_1 [MW]	0	+933
λ_1 [€/MWh]	15	24.33
Q_2^B [MW]	1500	1500
Q_2 [MW]	1500	567
Z_2 [MW]	0	-933
λ_2 [€/MWh]	43	24.33
$F_{1 \rightarrow 2}$ [MW]	0	933
$\sum_i \lambda_i \times Q_i$ [€]	72000	48660
$\sum_i \lambda_i \times Q_i^B$ [€]	72000	48660

Another example: Separate markets

Consider two nodes representing two regions with different total demand, using different types of generators:

First node: Fixed demand $Q_1^B = 200$ MW, one type of generators with marginal costs $c_1 = 10$ €/MWh and total generation limit $\hat{Q}_1 = 300$ MW.

Second node: Fixed demand $Q_2^B = 300$ MW, one type of generators with marginal costs $c_2 = 30$ €/MWh and total generation limit $\hat{Q}_2 = 400$ MW.

Transmission line from node 1 to node 2 with capacity K .

Optimal dispatch:

The generators at node 1 provide 200 MW to the consumers at node 1. Depending on the capacity of the transmission line, they export a power flow F between zero and 100 MW to the consumers at node 2. The generators at node 2 provide the remaining consumption at node 2, that is $300 \text{ MW} - F$.

Another example: Separate markets

Capacity $K = 0$:

First node generators produce the entire supply of consumers at node 1, $Q_1 = 200$ MW, but cannot export to node 2. Second node generators provide the entire supply of consumers at node 2, $Q_2 = 200$ MW. The competitive price at node 1 is $\lambda_1 = 10$ €/MWh, at node 2 it is $\lambda_2 = 30$ €/MWh.

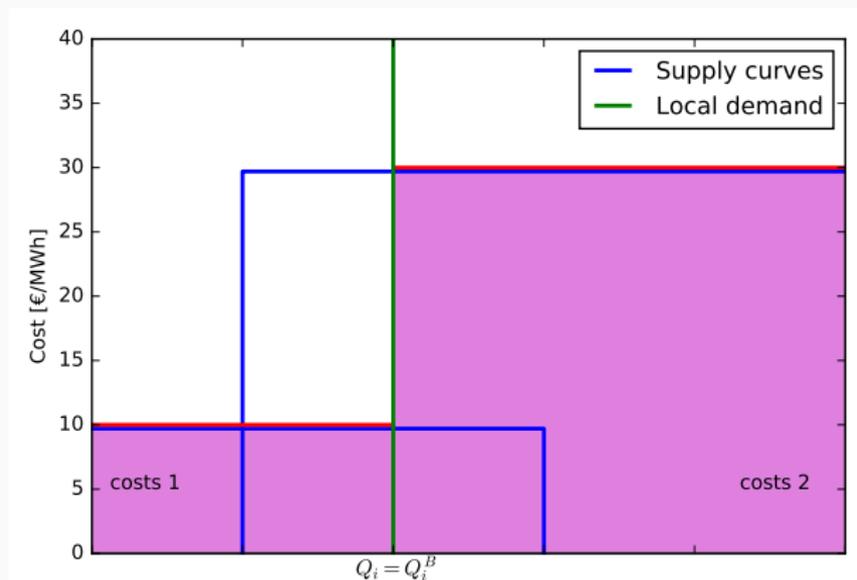
Total cost to consumers:

$$200 \text{ MW} \times 10 \text{ €/MWh} + 200 \text{ MW} \times 30 \text{ €/MWh} = 11000 \text{ €}.$$

$$\text{Generators at node 1: Revenue } 200 \text{ MW} \times 10 \text{ €/MWh} = 2000 \text{ €}.$$

$$\text{Generators at node 2: Revenue } 200 \text{ MW} \times 30 \text{ €/MWh} = 6000 \text{ €}.$$

Another example with two nodes, separate markets



Another example: Single market

Capacity $K = \infty$:

First node generators produce at the limit, $Q_1 = 300$ MW, second node generators provide the remaining $Q_2 = 200$ MW. The power flow is 100 MW. The competitive price at both nodes is $\lambda = 30$ €/MWh.

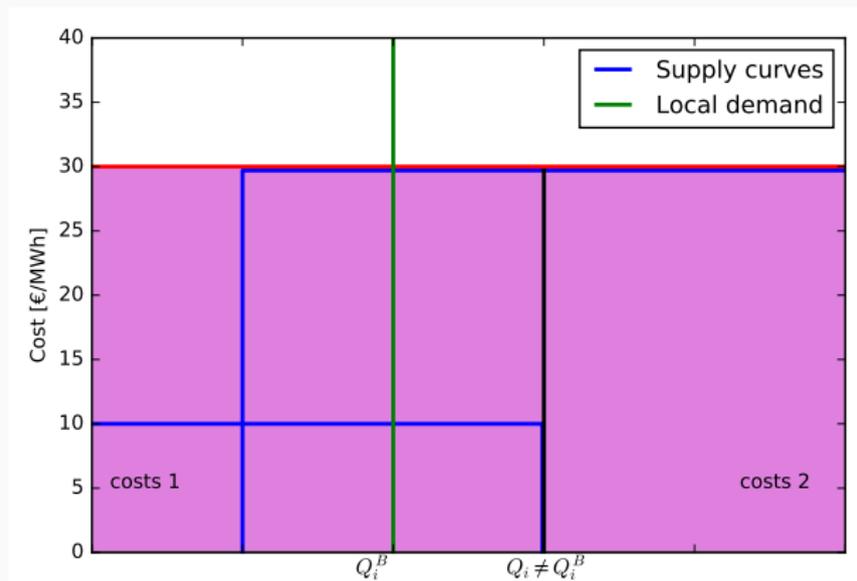
Total cost to consumers: $500 \text{ MW} \times 30 \text{ €/MWh} = 15000 \text{ €}$.

Generators at node 1: Revenue $300 \text{ MW} \times 30 \text{ €/MWh} = 9000 \text{ €}$.

Generators at node 2: Revenue $200 \text{ MW} \times 30 \text{ €/MWh} = 6000 \text{ €}$.

Due to the particular structure of the supply curves and the inelastic demand, market coupling has led to a higher price.

Another example: Single market



Back to the first example

Two nodes representing two regions, each with different total demand, using different types of generators:

First node: Fixed demand $Q_1^B = 500$ MW. The (inverse) supply function for the generators is given by

$$\pi_1 = MC_1 = 10 + 0.01Q_1 \text{ [€/MWh]}$$

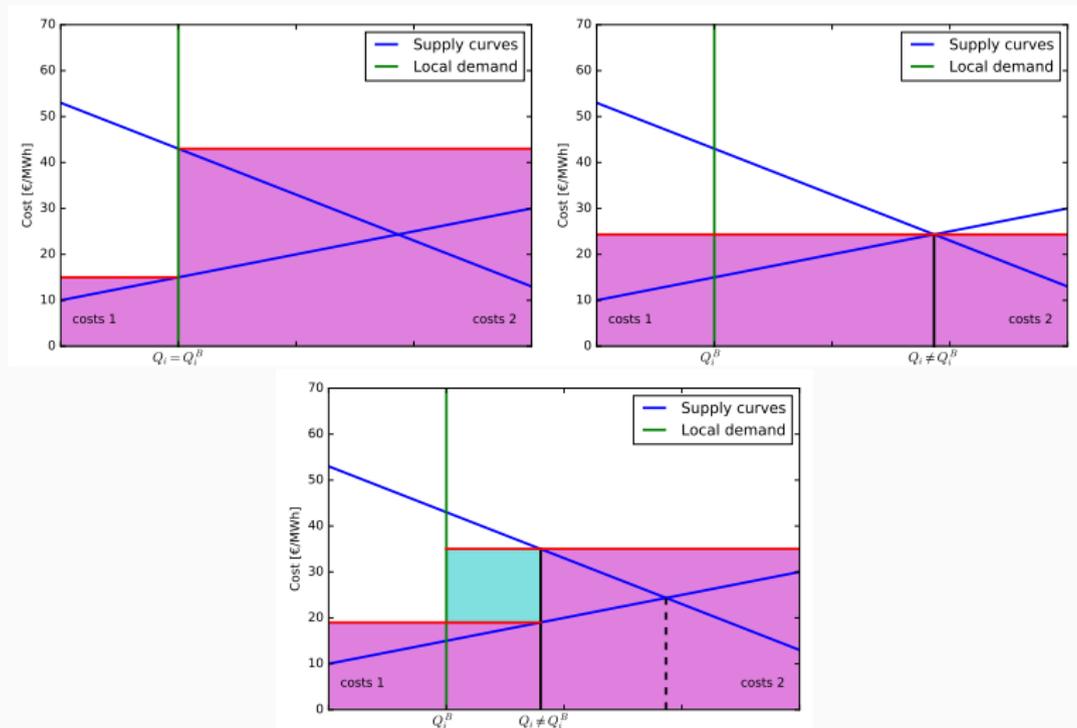
Second node: Fixed demand $Q_2^B = 1500$ MW. The (inverse) supply function for the generators is given by

$$\pi_2 = MC_2 = 13 + 0.02Q_2 \text{ [€/MWh]}$$

For simplicity we assume that at both nodes the total generation limit is 5 GW.

Transmission line from node 1 to node 2 with capacity $K = 400$ MW.

Example: Constrained single market



Example: Constrained market

Transmission capacity $K = 400$ MW:

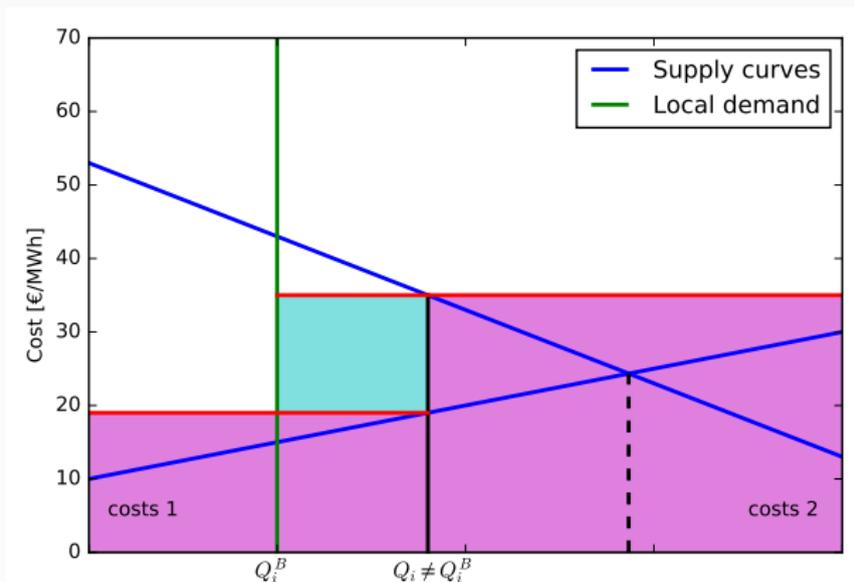
The transmission capacity is less than the power flow occurring for a single market with unconstrained transmission. The (cheaper) generators at node 1 export power until the line is **congested**. The (more expensive) generators then cover the remaining load at node 2.

$$MC_1(Q_1^B + K) = \lambda_1$$

$$MC_2(Q_2^B - K) = \lambda_2$$

This leads to $Q_1 = 900$ MW, $\lambda_1 = 19$ €/MWh, $Q_2 = 1100$ MW, and $\lambda_2 = 35$ €/MWh.

Example: Constrained market



Example: Constrained market

	Separate markets	Single market	Constrained market
Q_1^B [MW]	500	500	500
Q_1 [MW]	500	1433	900
Z_1 [MW]	0	+933	+400
λ_1 [€/MWh]	15	24.33	19
Q_2^B [MW]	1500	1500	1500
Q_2 [MW]	1500	567	1100
Z_2 [MW]	0	-933	-400
λ_2 [€/MWh]	43	24.33	35
$F_{1 \rightarrow 2}$ [MW]	0	933	400
$\sum_i \lambda_i \times Q_i$ [€]	72000	48660	55600
$\sum_i \lambda_i \times Q_i^B$ [€]	72000	48660	62000

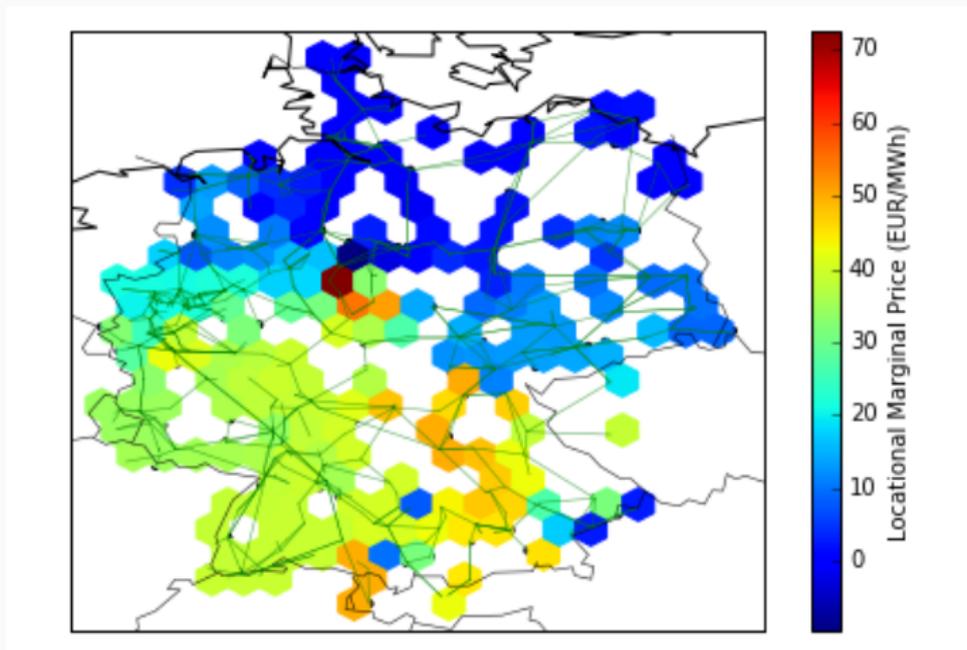
Locational marginal pricing

Due to the congestion of the transmission line, the marginal cost of producing electricity is different at node 1 and node 2. The competitive price at node 2 is higher than at node 1 – this corresponds to **locational marginal pricing**, or **nodal pricing**.

Since consumers pay and generators get paid the price in their local market, in case of congestion there is a difference between the total payment of consumers and the total revenue of producers – this is the **merchandising surplus** or **congestion rent**, collected by the market operator. For each line it is given by the price difference in both regions times the amount of power flow between them:

$$\text{Congestion rent} = \Delta\lambda \times F$$

Spoiler: LMP in a meshed network



Source: PyPSA
(Python for Power System Analysis)

Redispatch

Another way to handle congestion is to correct the single market outcome retrospectively using **redispatch**. Consider the previous example with line capacity $K = 400$ MW.

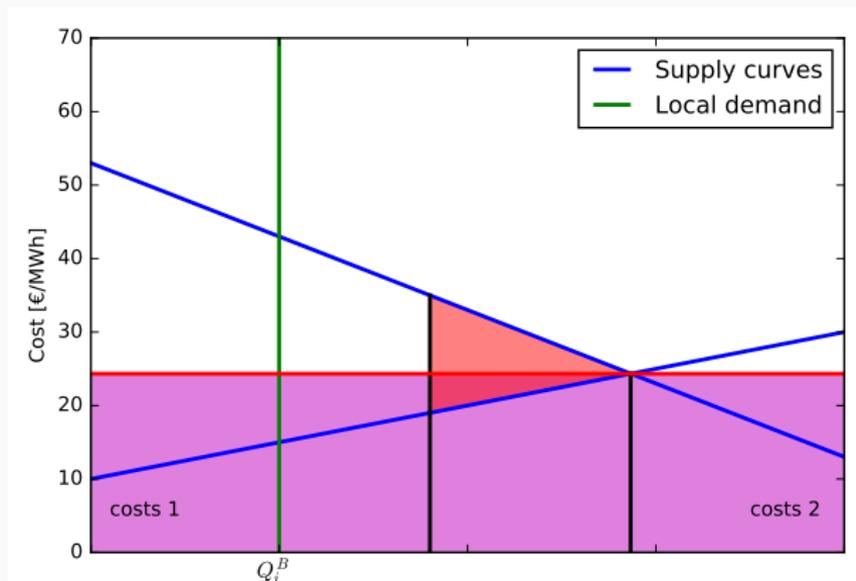
Single market result: $Q_1 = 1433$ MW, $Q_2 = 567$ MW, market price $\lambda = 24.33$ €/MWh, power flow 933 MW.

System operator has to adjust the dispatch:

$$\Delta Q_1 = -533 \text{ MW}$$

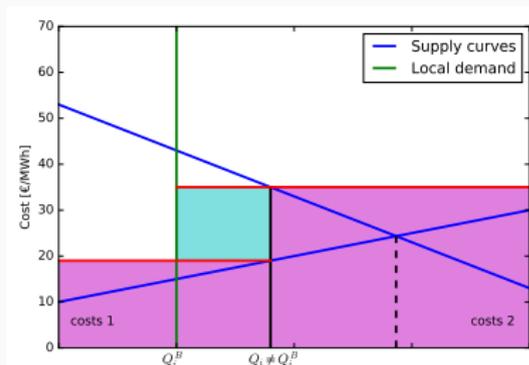
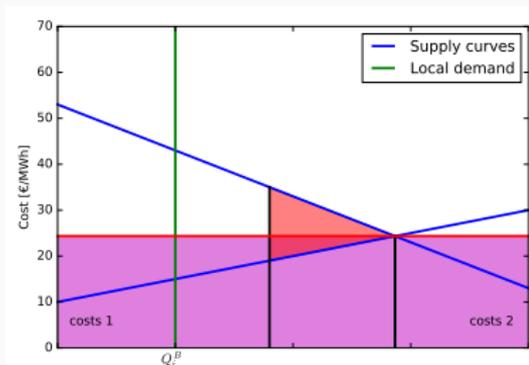
$$\Delta Q_2 = +533 \text{ MW}$$

Redispatch



Cost of redispatch: $0.5 \times (35 - 19) \times 533 = 4264$ [€/MWh]

Redispatch vs. Nodal pricing



Note that the cost of dispatch for the generators is identical for redispatch (left) and nodal pricing (right).

Redispatch in Germany

Redispatchmaßnahmen im Jahr 2014

Netzgebiet	Dauer in Std.	Menge getätigte Maßnahme in GWh	Gesamtmenge (getätigte Maßnahmen zzgl. Gegenschäft zum bilanziellen Ausgleich) in GWh	Saldierte Kosten für Redispatch in Mio. Euro
Regelzone TenneT	5.000	813	1.629	
Regelzone 50Hertz	3.230	1.751	3.502	
Regelzone Transnet BW	119	16	25	
Regelzone Amprion	104	20	41	186,7

Source: Bundesnetzagentur/
Bundeskartellamt

Redispatch in Germany

Strombedingte Redispatchmaßnahmen auf den am stärksten betroffenen Netzelementen im Jahr 2014 gemäß Meldungen der ÜNB



Source: Bundesnetzagentur/
Bundeskartellamt

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`http://fias.uni-frankfurt.de/~brown/courses/electricity_markets/`

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