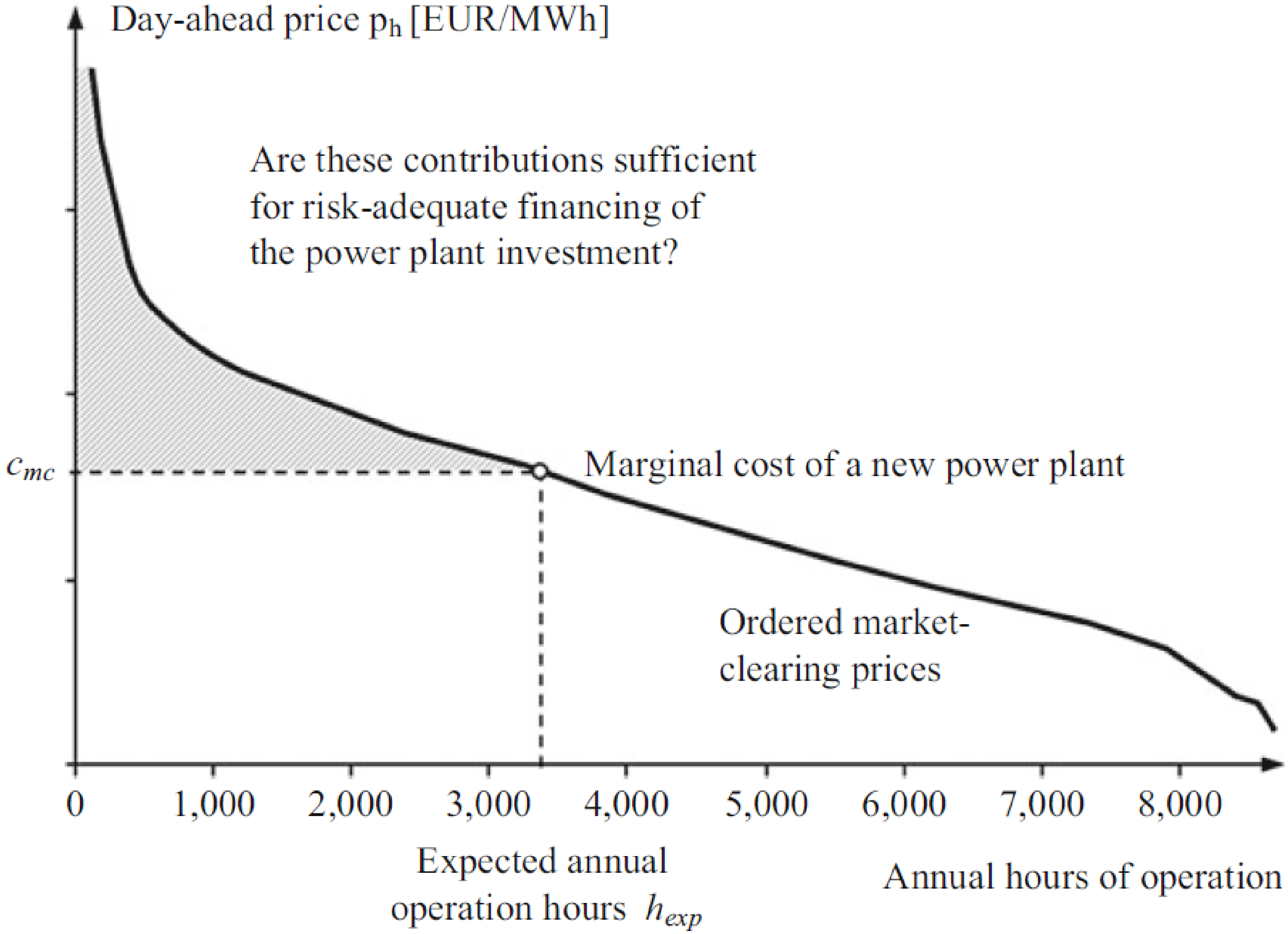
Integrated course „Energy Economics“
- Electricity Grid -

Chair of Energy Systems | Department of Energy Systems
Technische Universität Berlin

Continued: Investment into generation capacities

Annual Price Duration Curve



Erdmann / Praktiknjo / Zweifel (2017)

Task 1

Anwer the questions regarding the economics of technologies A and B based on the following techno-economic power plant data:

	Specific fixed costs	STMGC
	$\frac{Euro}{MW_{el} * a}$	$\frac{Euro}{MWh_{el}}$
A	140 000	40
B	80 000	50

a) Up to which number of full load hours is technology B cheaper than technology A?

$LTMGC = C_{fix} + STMGC \cdot FLH$

found from graph on next slide for STMGC = 40 €/MWhel

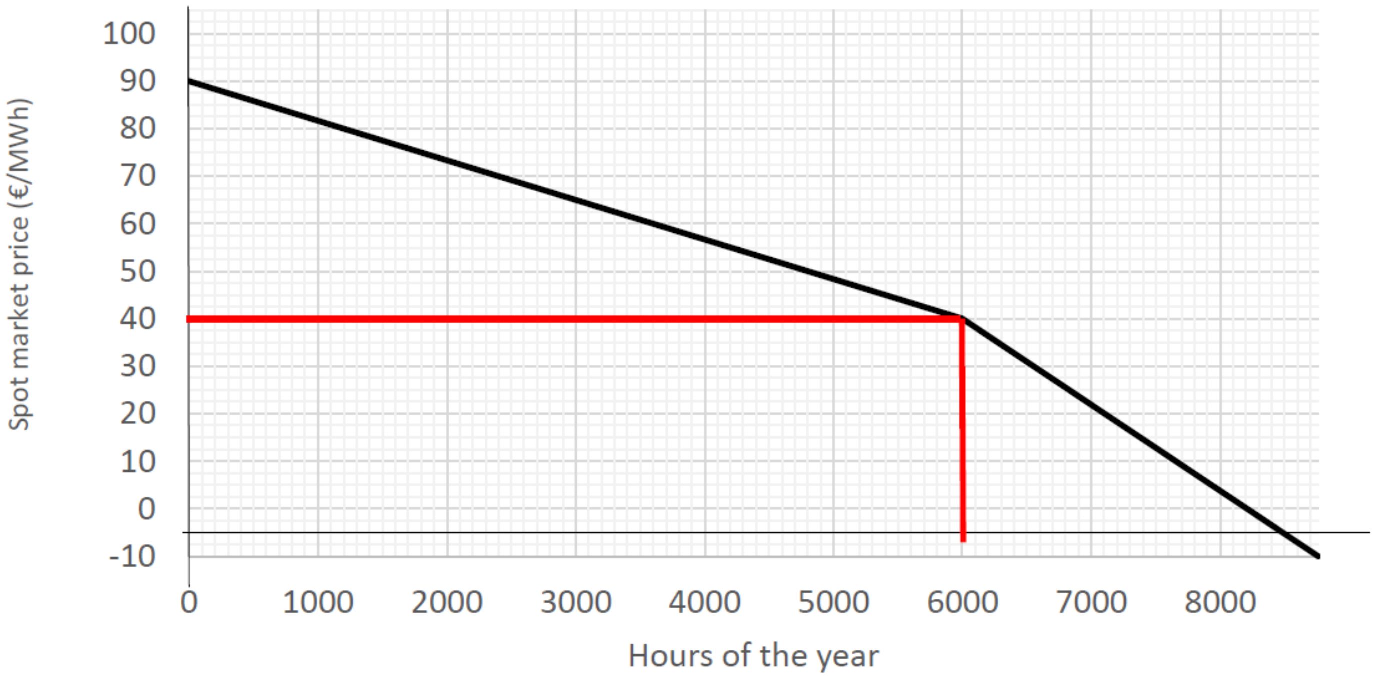
$LTMGC_A = LTMGC_B$

$140\,000\,€/MW_{el} \cdot a + 40\,€/MWh_{el} \cdot 6000\,h = 80\,000\,€/MW_{el} \cdot a + 50 \cdot FLH_B$

$FLH_B = \frac{380\,000 - 80\,000}{50} = 6000\,h$

Task 1

A:



Spot market price (€/MWh)
100
90
80
70
60
50
40
30
20
10
0
-10
0
1000
2000
3000
4000
5000
6000
7000
8000
Hours of the year

	Specific fixed costs	STMGC
	$\frac{Euro}{MW_{el} * a}$	$\frac{Euro}{MWh_{el}}$
A	140 000	40
B	80 000	50

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Task 1

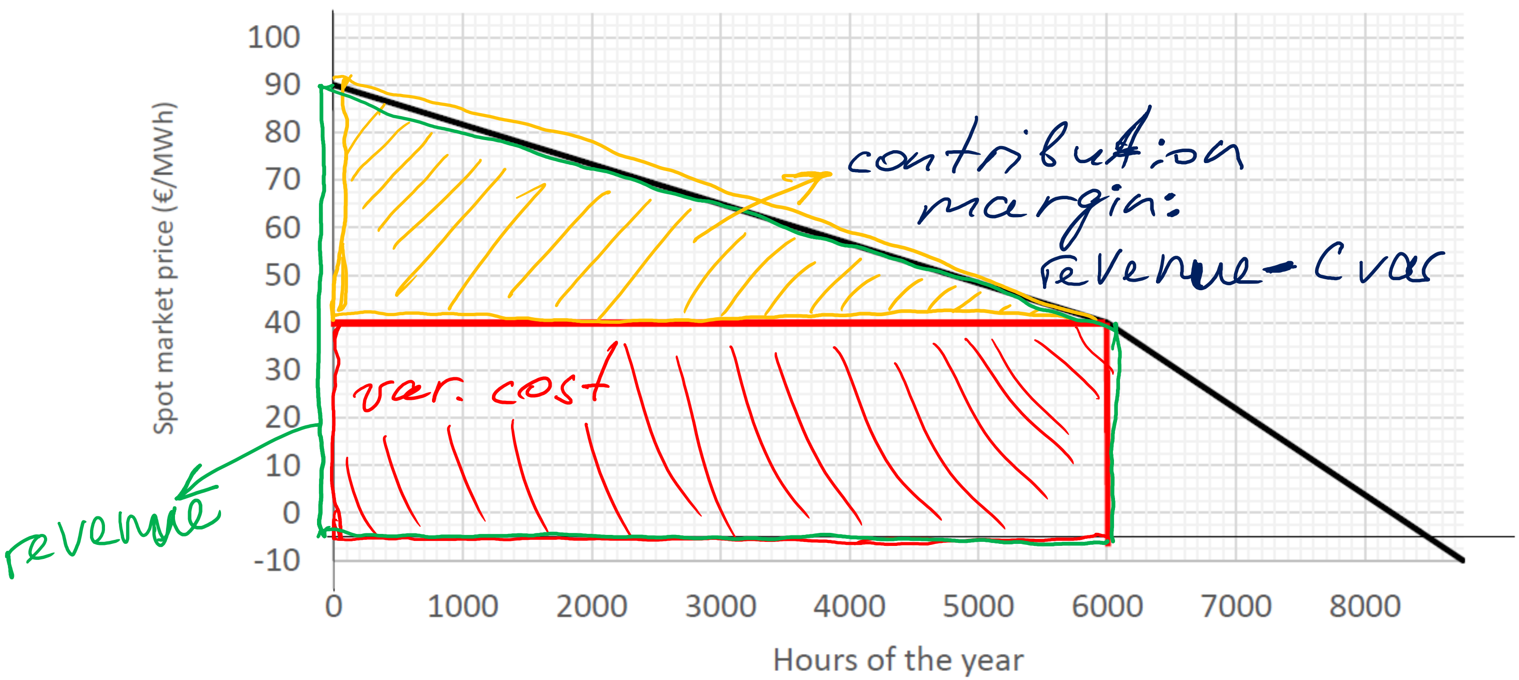
b) You sell electricity from power plant A on spot market which is characterised by a given price duration curve. Your generation unit has a rated capacity of 600 MW.

Calculate the power plant's:

- annual fixed costs in Euro
- annual variable costs in Euro
- annual contribution margin in Euro
- annual profit in Euro

Task 1

per MWel · a:



	Specific fixed costs	STMGC
	$\frac{Euro}{MW_{el} * a}$	$\frac{Euro}{MWh_{el}}$
A	140 000	40
B	80 000	50

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Task 1

- annual fixed costs in Euro

$C_{fix_A} = C_{fix_A} \cdot Cap;\ 140000\,€/MW_{el} \cdot a \cdot 600\,MW_{el} = 84\,000\,000\,€/a$

- annual variable costs in Euro

$C_{var_A} = STMGC_A \cdot FLH_A \cdot Cap;\ 40\,€/MWh_{el} \cdot 6000\,h \cdot 600\,MW = 144\,000\,000\,€/a$

- annual contribution margin in Euro

$CM_A = \frac{(90-40)\,€/MWh \cdot 6000\,h/a \cdot 600\,MW}{2} = 90\,000\,000\,€/a$

- annual profit in Euro

$\Pi_A = CM_A - C_{fix_A};\ 90\,000\,000\,€ - 84\,000\,000\,€/a = 6\,000\,000\,€/a$

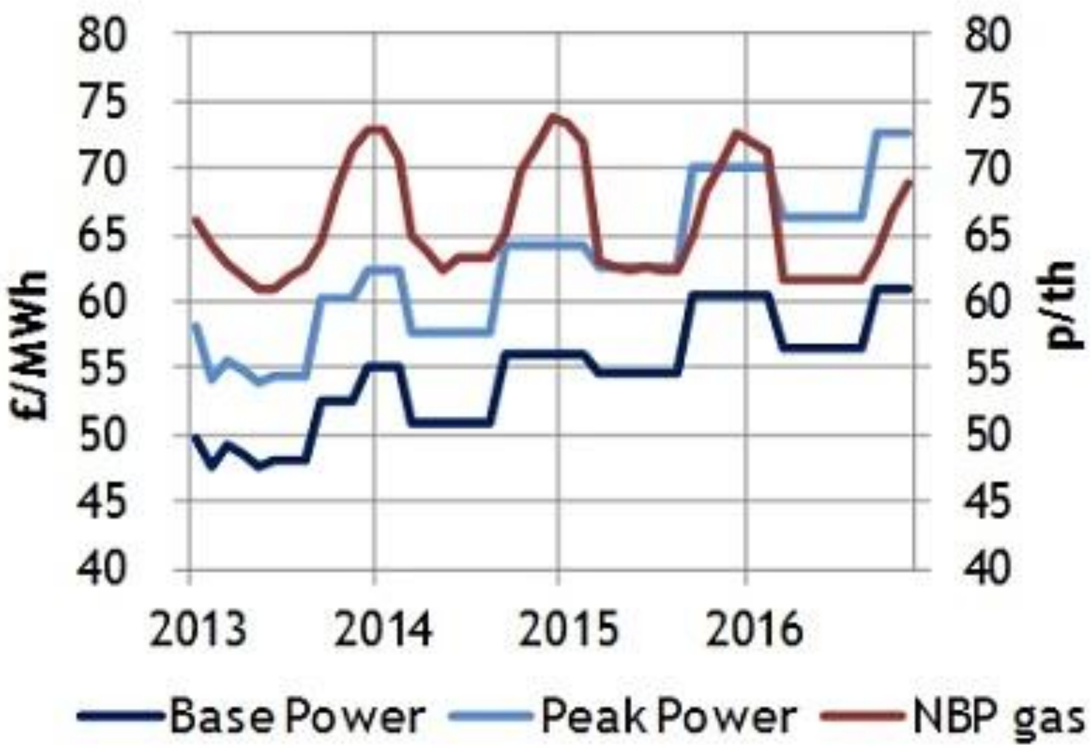
Spark spread

Spark spread is the gross margin of a gas-fired power plant from selling a unit of electricity, having bought the fuel required to produce this unit of electricity. (peak load electricity future – gas future, corrected by power plant efficiency)

Clean spark spread is the gross margin after substracting the cost of CO_2 emissions.

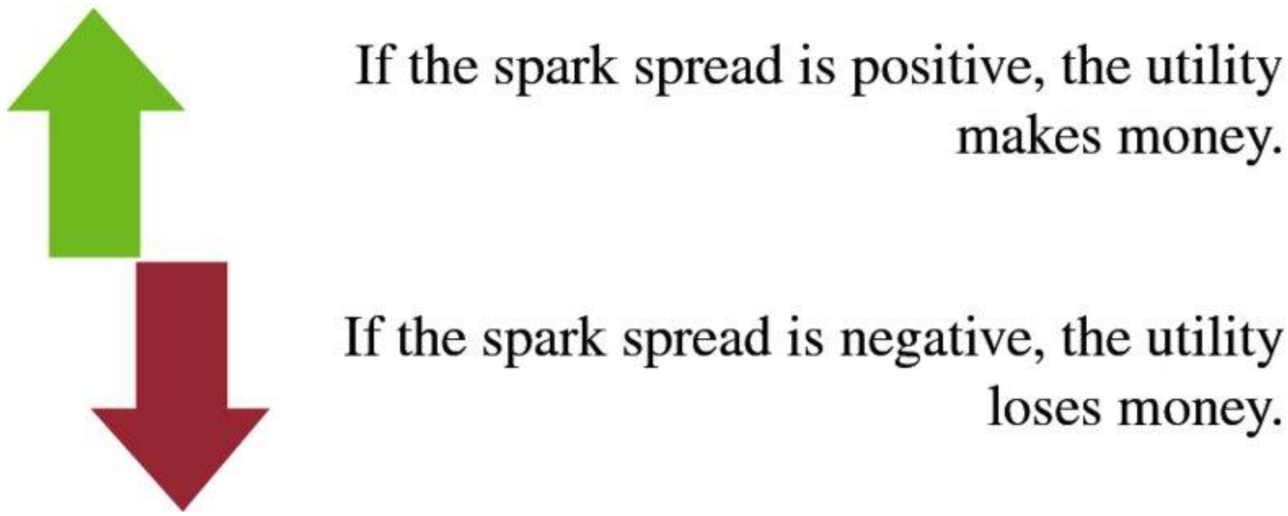
Hedging: Buying gas and emission allowances on forward markets

UK Base and Peak power and NBP gas curves



Source: ICE monthly futures

Spark spread (continued)



Source: Mack, Energy trading and risk management, 2014

Spark spread (continued)

$$\text{Spark spread} = \text{Price of electricity} - \frac{\text{Price of gas}}{\text{Efficiency factor}}$$

Spark spread > 0: It is more economical to buy gas

Spark spread < 0: It is more economical to buy power from the grid

Underlying assumptions:

- no transaction costs
- no electricity transmission costs (where relevant)
- no gas transportation costs
- no start costs (cost of starting the power plant)

Source: Mack, Energy trading and risk management, 2014

Task 2

Calculate the spark spread, given that:

Price of natural gas = 26 €/MWh
Price of electricity = 45 €/MWh
Natural gas-fired power plant with
Efficiency factor = 50%

$$\text{Spark spread} = P_e - \frac{P_{NG}}{\eta}$$

$$= 45\,€/MWh - \frac{26\,€/MWh}{0{,}5\,\frac{MWh_{el}}{MWh_{th}}} = -7\,€/MWh$$

Spark spread

Dark spread is the gross margin of a coal-fired power plant from selling a unit of electricity, having bought the fuel required to produce this unit of electricity.

Base load electricity future – coal future, corrected by the power plant efficiency factor

Clean dark spread is the gross margin after substracting cost of CO_2 emissions.

Hedging: Buying coal and emission allowances on forward markets

Spark spread (continued)

If the clean dark spread is positive, it is profitable to generate electricity on a baseload basis for the period in question.

If the clean dark spread is negative, generation would be a loss-making activity.

Source: Mack, Energy trading and risk management, 2014

Task 3

Calculate the clean dark spread, given that:

Price of coal = 10 €/MWh
Price of electricity = 40 €/MWh
Natural gas-fired power plant with
Efficiency factor = 35%
CO_2 emission factor = 0,342 tCO_2/MWh_{th}
CO_2 price = 5 €/tCO_2

Gas-fired generation is also exposed to CO_2 price but to a lesser extent.

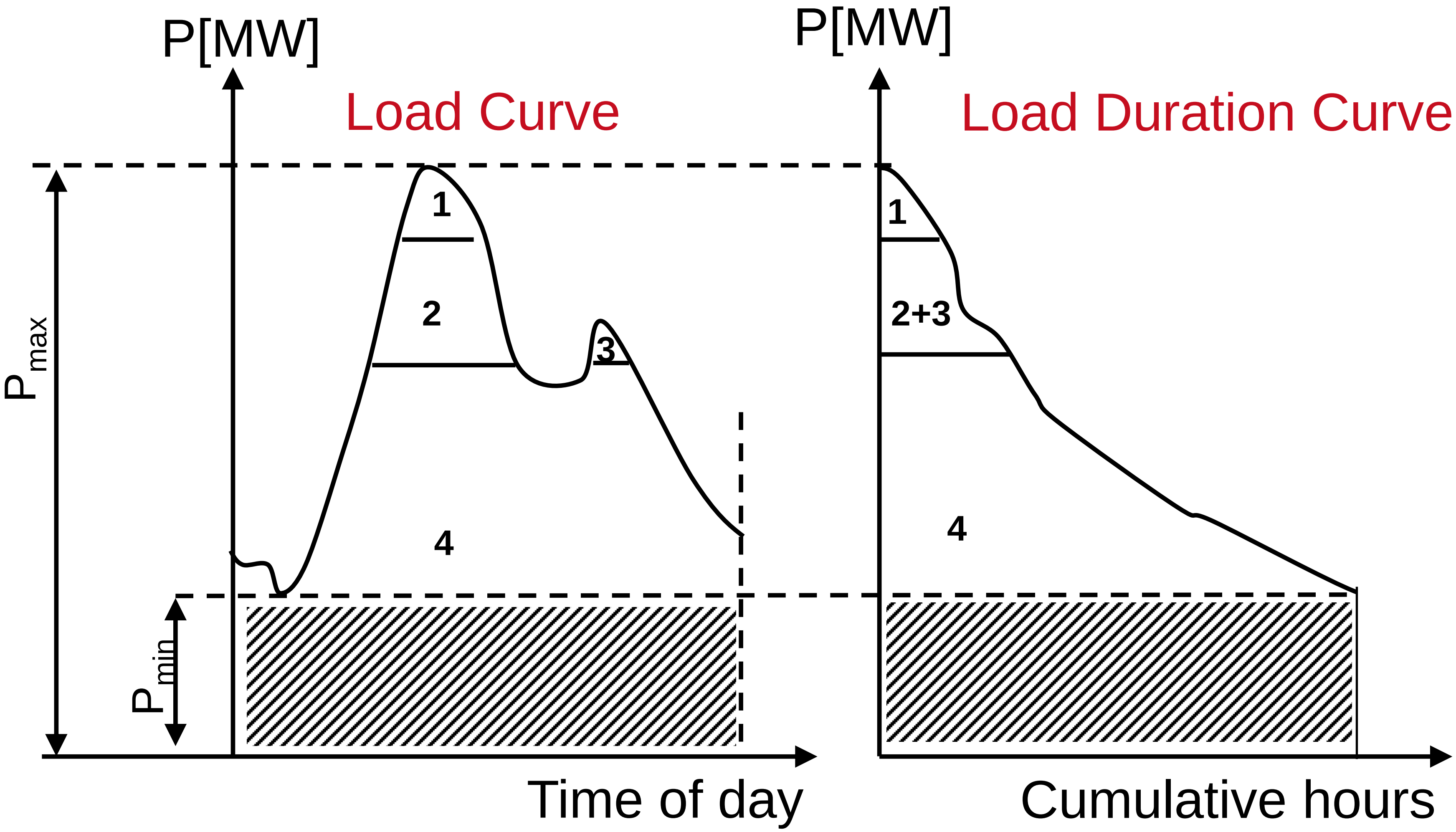
$$\text{Clean dark spread} = P_e - \frac{P_{coal}}{\eta} - \frac{P_{CO_2} \cdot EMF_{coal}}{\eta}$$

$$= 40\,€/MWh - \frac{10\,€/MWh}{0{,}35\,\frac{MWh_{el}}{MWh_{th}}} - \frac{5\,€/tCO_2 \cdot 0{,}342\,tCO_2/MWh_{th}}{0{,}35\,\frac{MWh_{el}}{MWh_{th}}} =$$

$$= 40 - 28{,}57 - 4{,}89 = 6{,}54\,€/MWh$$

for $P_{CO_2} = 25\,€/tCO_2$ (all other inputs assumed the same) for simplification:
$CDS = -13\,€/MWh$.

Load Curve and Load Duration Curve



Levelised cost of electricity (LCOE)

$$p_E = \frac{I_0}{Q \cdot AF_{i,T}} + oc$$

lifetime costs divided by lifetime electricity output

Lifetime costs: PV of total cost of building and operating

LCOE allows comparison of technologies regardless of lifetime, installed capacity, cost of capital, risk and return.

- initial capital cost*

  * *specific investment costs*: investment costs divided by capacity

- annual operating expenses
- capacity factor
- discount rate
- operational life

Levelised cost of electricity (LCOE)

How to calculate the generation costs per unit of electricity?

$$LCOE = \frac{I_0 \cdot CRF_{i,t}}{Q} + oc$$

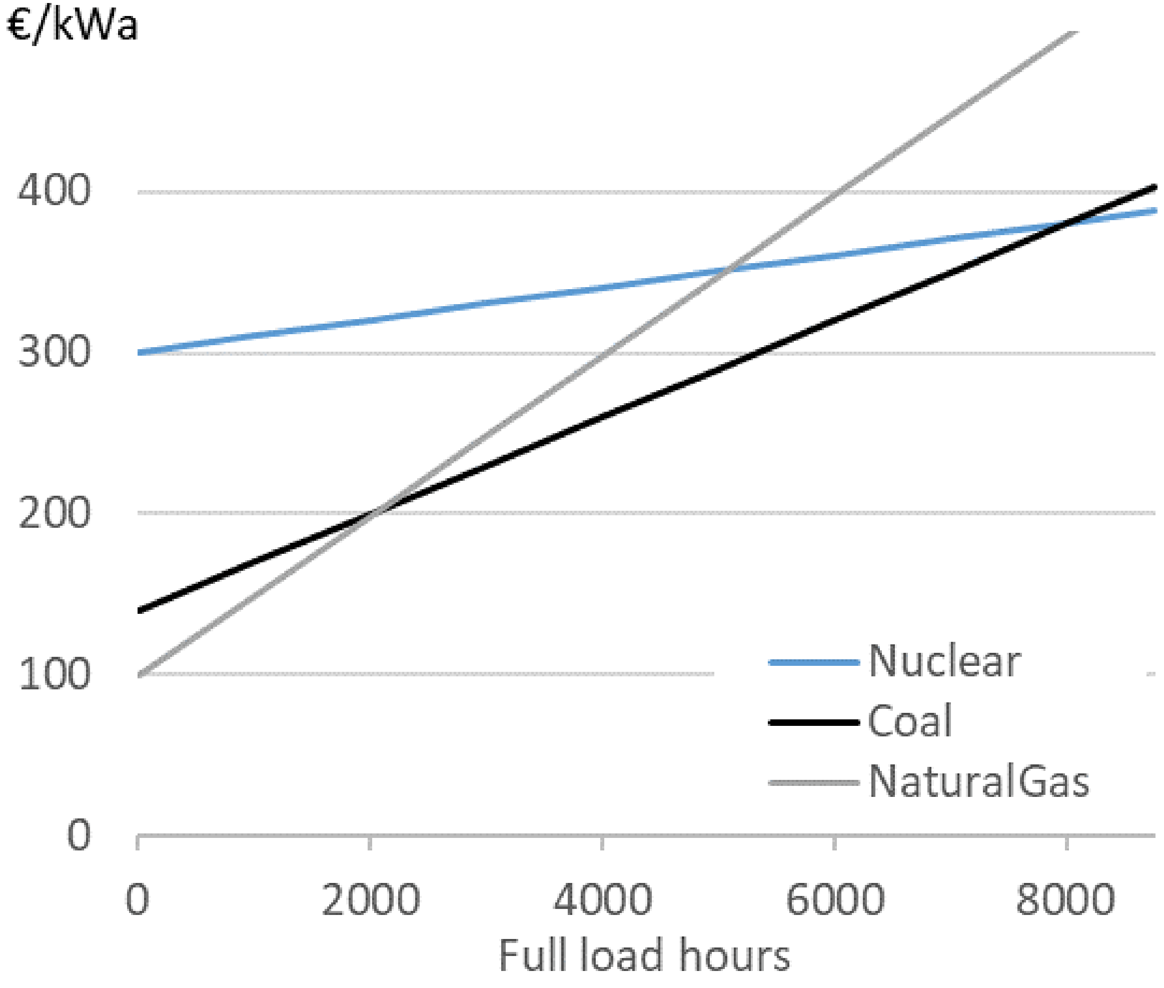
$$E_t = Cap * FLH$$

E_t	annual electricity output
Cap	installed capacity (rated power)
FLH	full load hours: annual output divided by Cap

$$\text{Capacity factor} = \frac{E_t\ [kWh]}{Cap\ [kW] * 8.760h}$$

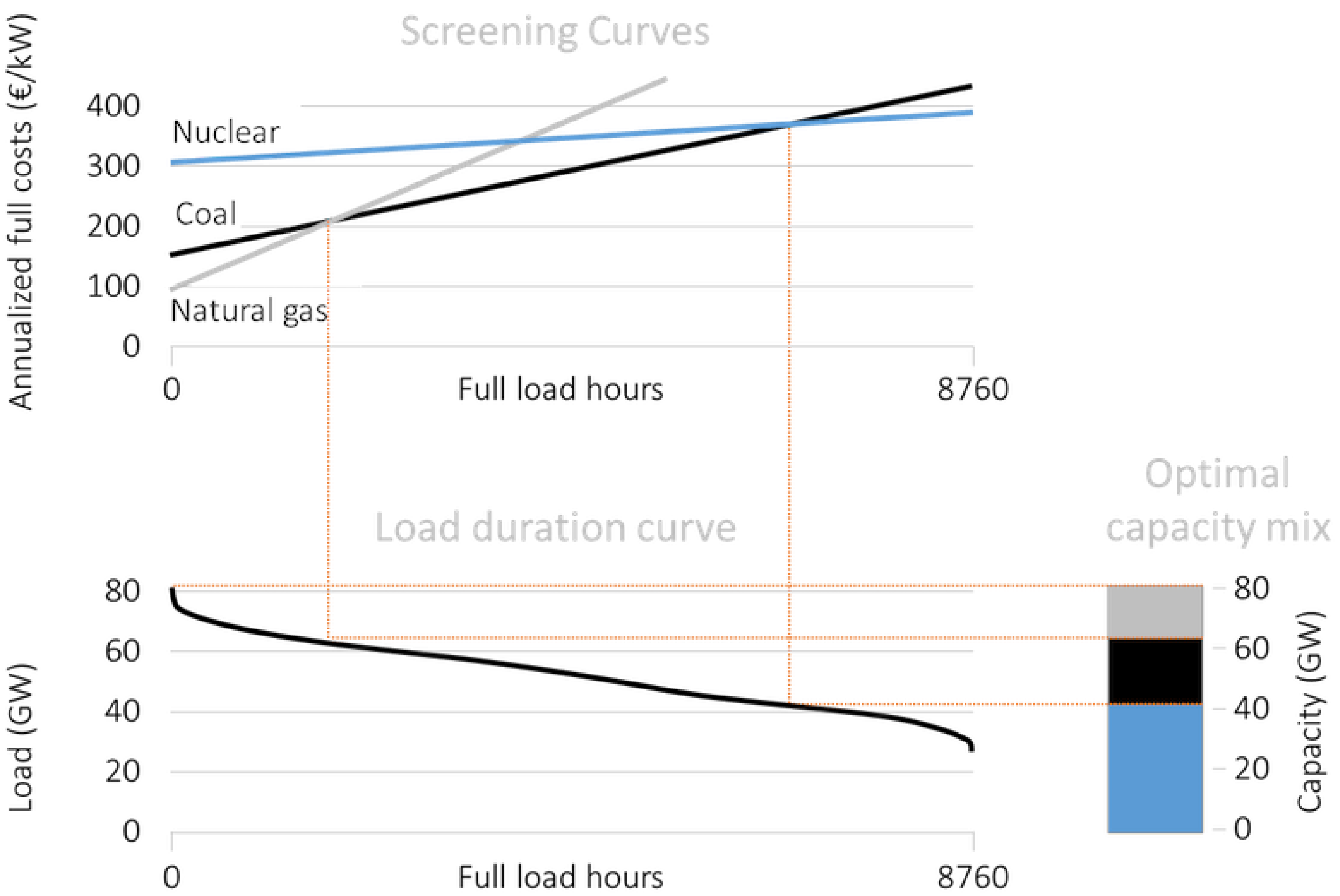
Screening Curves

Total cost p. a.
per unit of capacity



Hirth & Steckel (2016)

Cost-optimal mix of thermal technologies



Source: OEE

Power plants in the merit order

Power plant types based on their place in merit order:

Power plant type	**FLH [h/a]**	**Operation features**	**Technologies**
Baseload	> 7.000	continuous	lignite
Intermedium load	4.500 – 5.500	during peak hours (wd 8-8)	hard coal
Peak load	< 1.250	at times of peak demand	pumped-storage hydro, gas
Reserve		during power plant shut-downs	old power plants

Source: Konstantin, 2017

Merit Order: Future trends

FLH of conventional power plants will decline with increasing RES share.

This – along with higher prices of fuel and CO_2 certificates – will lead to higher LCOE.

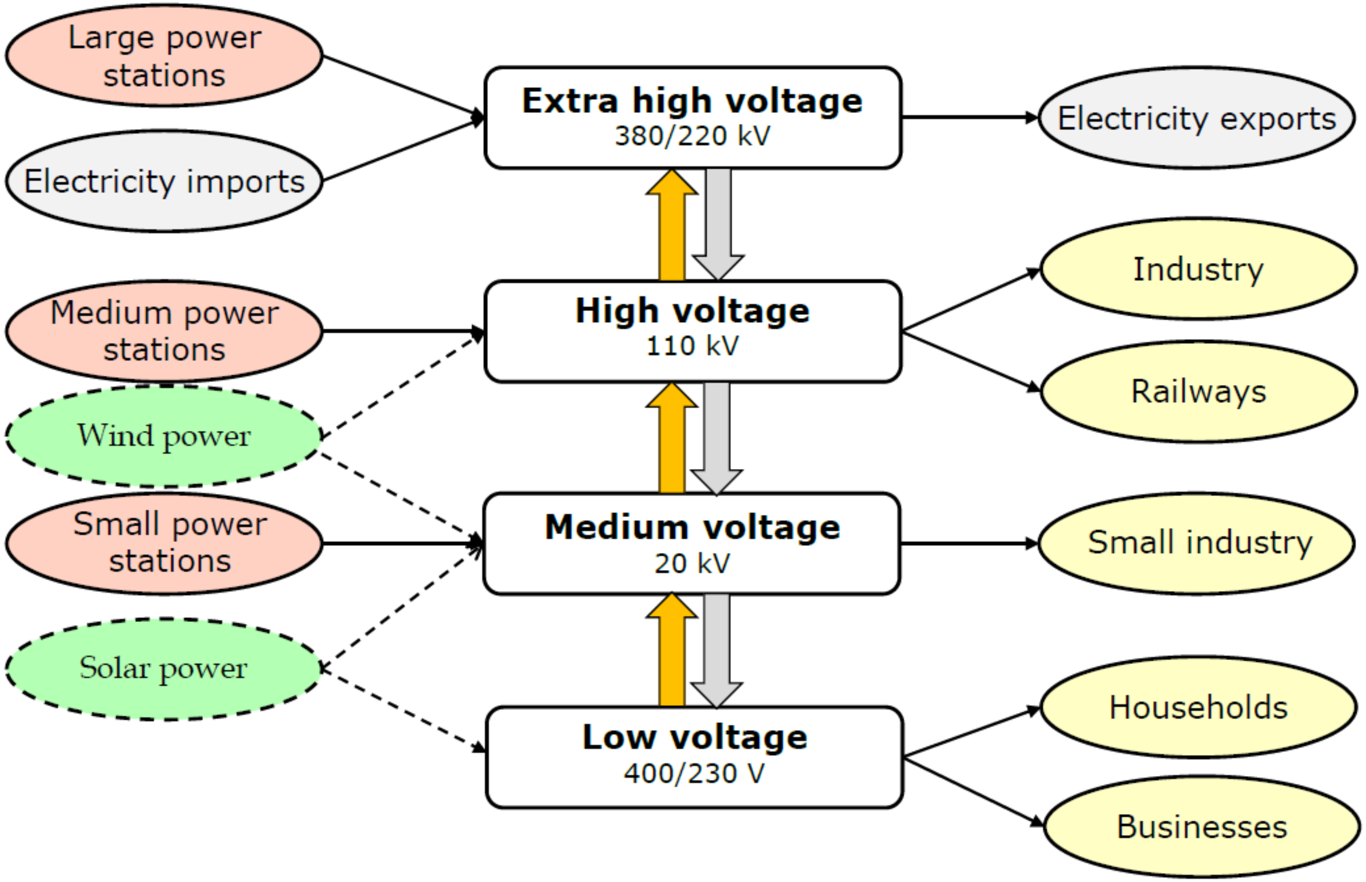
Conventional powerplants with the highest flexibility for ramping up/ramping down have the best chances to stay in the market – not necessarily the least expensive ones → gas power plants.

Source: Fraunhofer ISE, 2018

Electricity Grid: Outline

- Grid structure and system operator tasks
- Markets for control power
- Congestion management
- Grid access
- Grid tariff regulation
- Security of supply

Categories of power grids



Tasks of system operator

- Grid operation
  - system security
  - reliability
  - cost-efficiency

- Grid extension

Various organisational set-ups in different countries

Unbundling

Germany’s electrical grid

4 TSOs

approx. 900 DSOs

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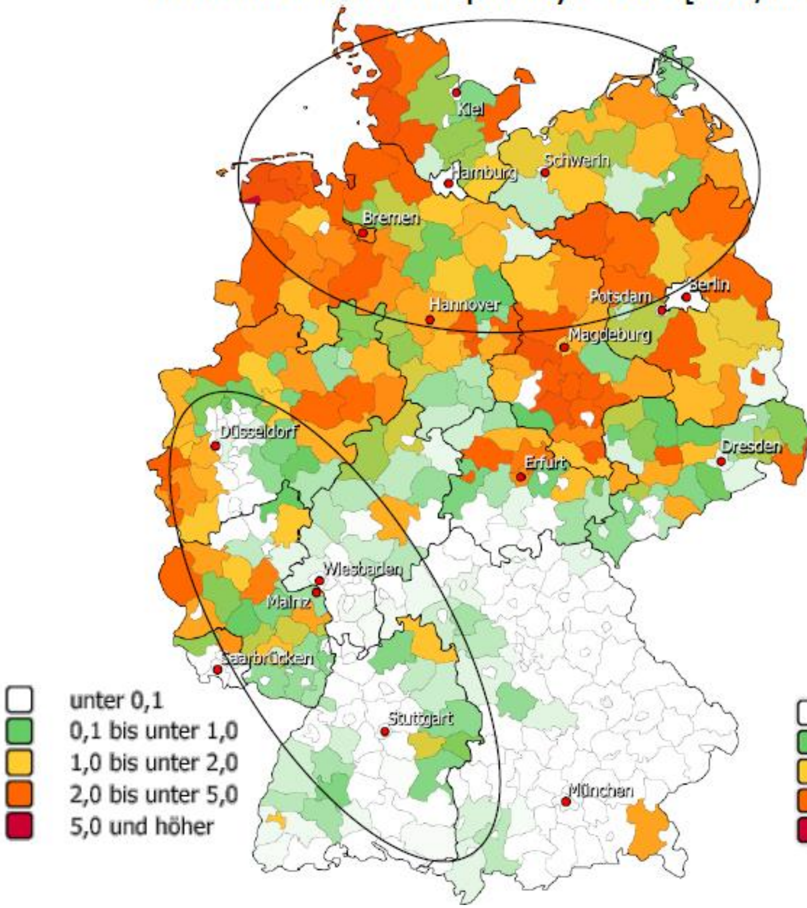
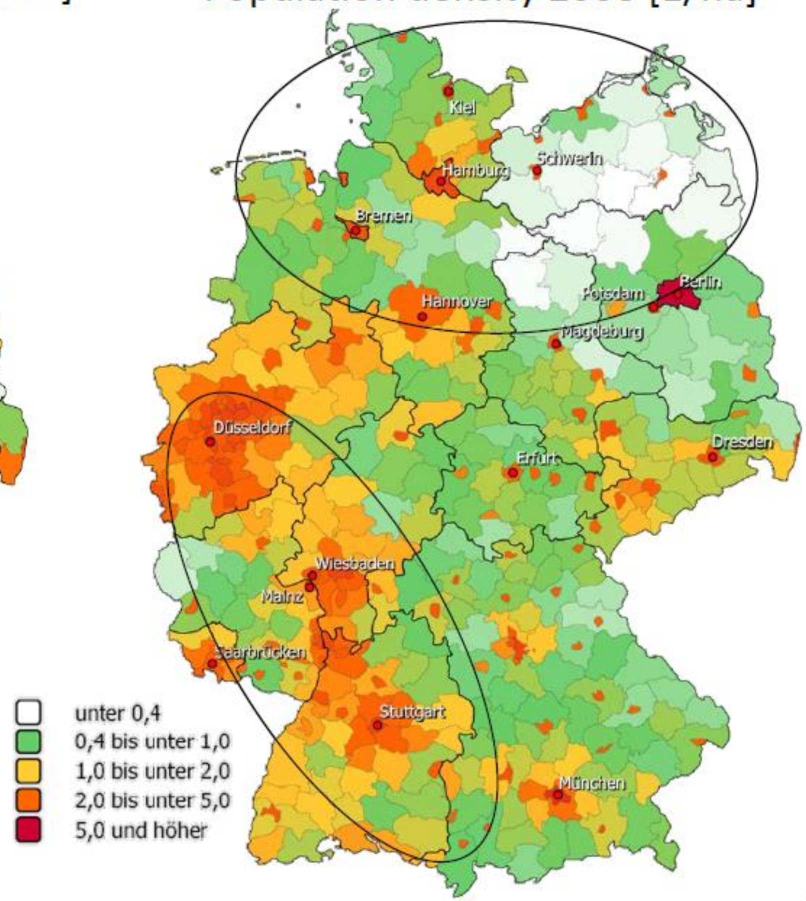
Regionalisation of generation and load

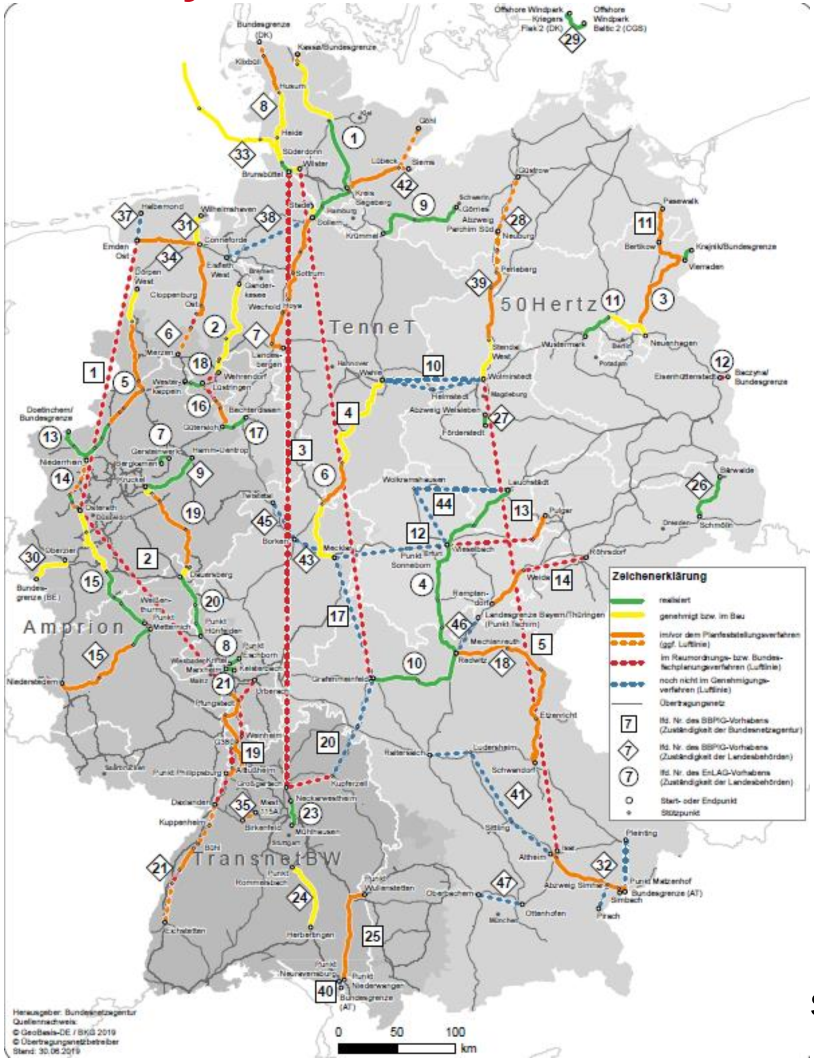
Installed Wind Capacity 2008 [kW/km²]



Population density 2008 [1/ha]

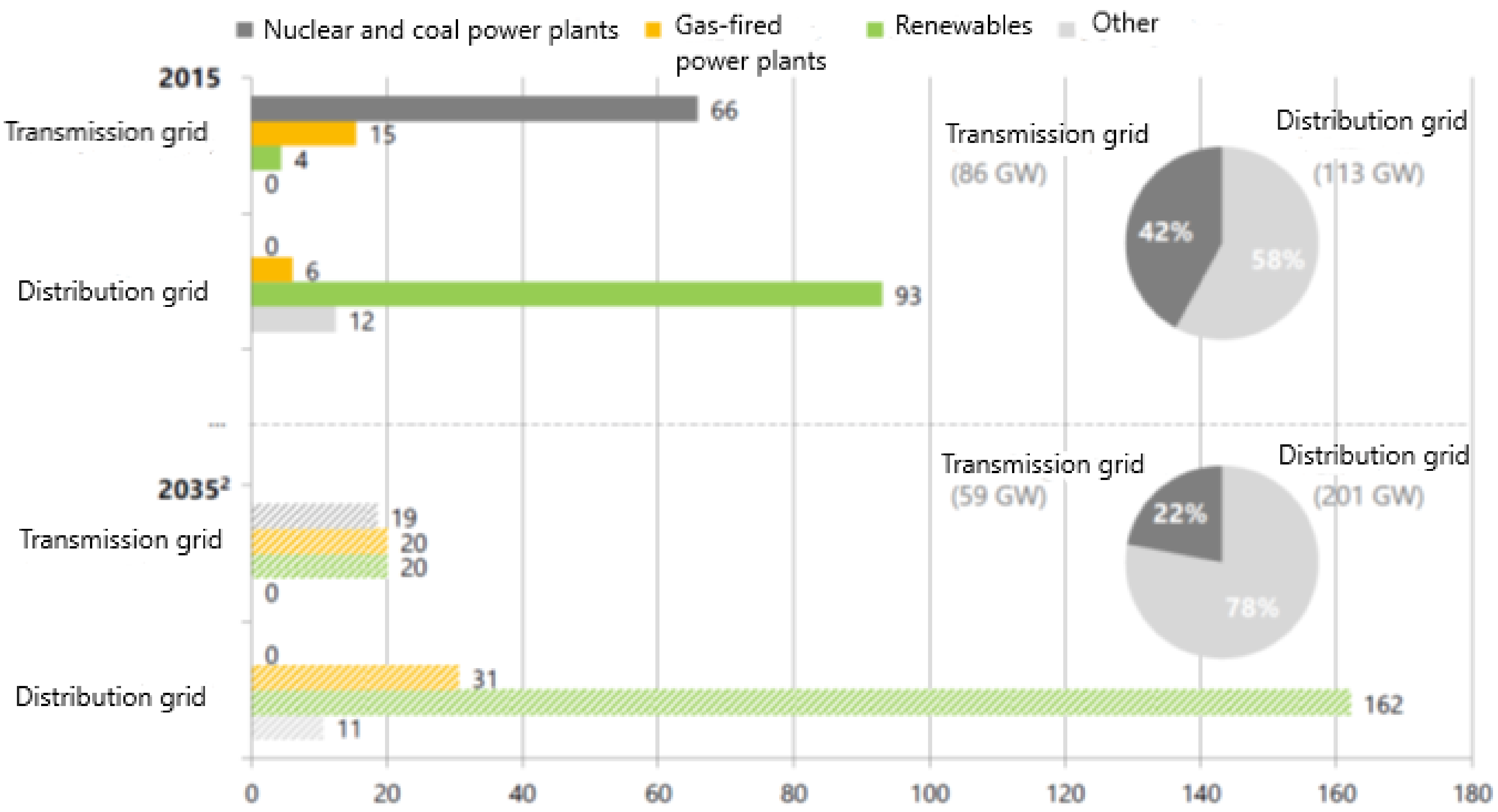


Grid extension Germany



Source: BNetzA, 2019

Energy transition in distribution grids



[2] 50Hertz, Energiewende Outlook 2035, 2016

Source: E-Bridge, MITNETZ Strom, 2016

Energy transition in distribution grids

More complexity for the DSO tasks:

- Congestion management
- Voltage control
- Grid restauration after blackout
- (Frequency control – only in isolated systems)

Nuclear phase-out in Germany

Power plant	Operating until	Installed capacity (MW)
Philippsburg 2	2019	1.402
Grohnde Gundremmingen C Brokdorf	2021	1.360 1.288 1.410
Isar 2 Emsland Neckarswestheim 2	2022	

Source: BNetzA, Monitoringbericht 2018

Fossil generation

Coal phase-out by 2038

Power plant	**Operating until**	**Installed capacity (MW)**
Jänschwalde E Neurath C	2019	757 (in total)
 Hard coal power plants Gas-fired power plant Lignite p/plant block Other technologies	 2021	852 MW in total 760 11 14 67

Source: BNetzA, Monitoringbericht 2018

European single market for electricity

Goal: Creation of a Single market for electricity in Europe

Technical constraints lead to congestion.

Adequate allocation of this scarce resouce:

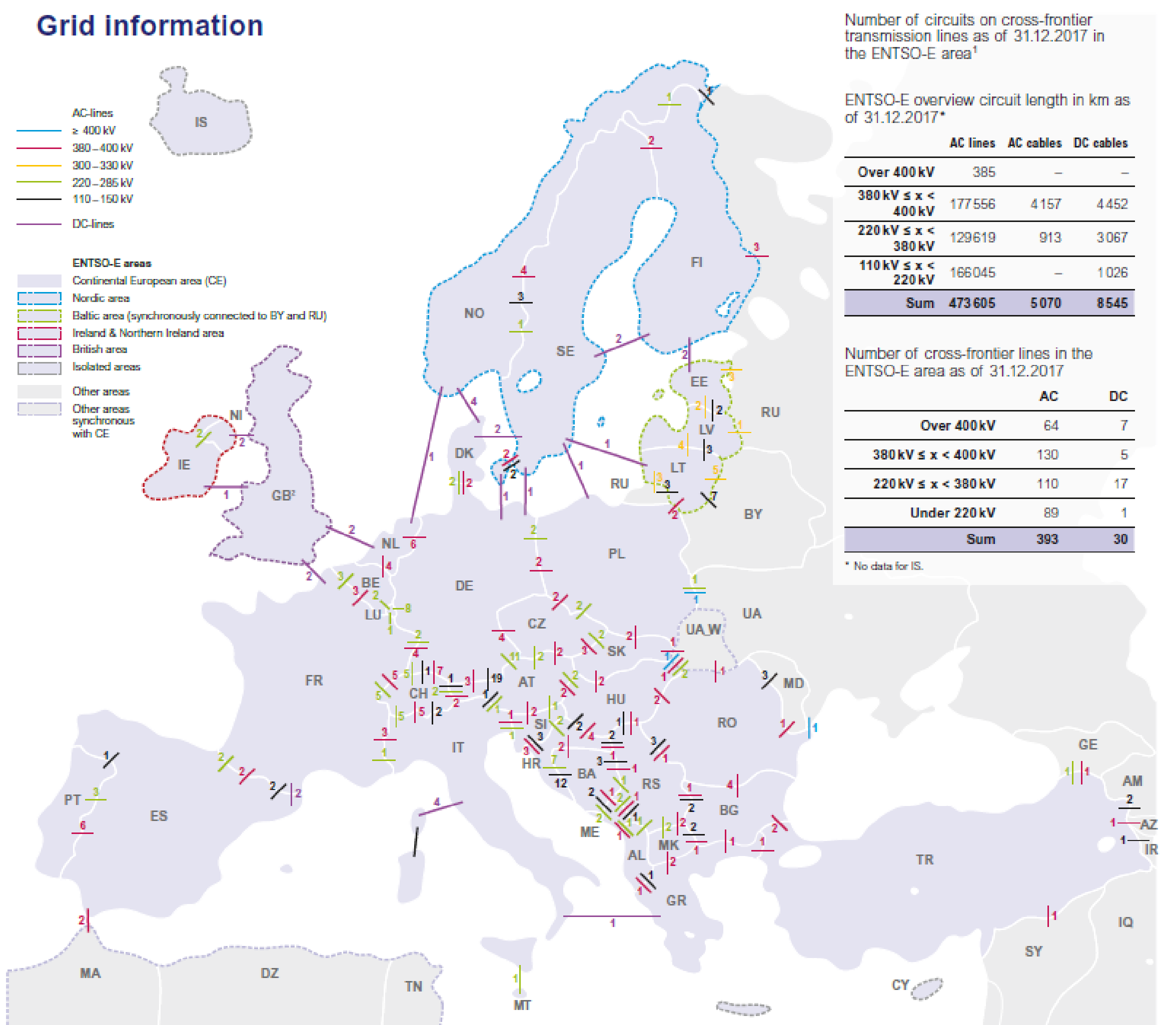
Congestion management

- Curative measure:
  - Redispatch
- Pre-emptive measure:
  - Explicit auctions
  - Implicit auctions

Benefits of market integration

- Level out price differences between bidding zones
- Strengthen competition between suppliers
- Improve system integration of volatile RES
- Improve network security

Interconnection lines Europe



Number of circuits on cross-frontier transmission lines as of 31.12.2017 in the ENTSO-E area[1]

ENTSO-E overview circuit length in km as of 31.12.2017*

	AC lines	AC cables	DC cables
Over 400 kV	385	–	–
380 kV ≤ x < 400 kV	177 556	4 157	4 452
220 kV ≤ x < 380 kV	129 619	913	3 067
110 kV ≤ x < 220 kV	166 045	–	1 026
Sum	473 605	5 070	8 545

Number of cross-frontier lines in the ENTSO-E area as of 31.12.2017

	AC	DC
Over 400 kV	64	7
380 kV ≤ x < 400 kV	130	5
220 kV ≤ x < 380 kV	110	17
Under 220 kV	89	1
Sum	393	30

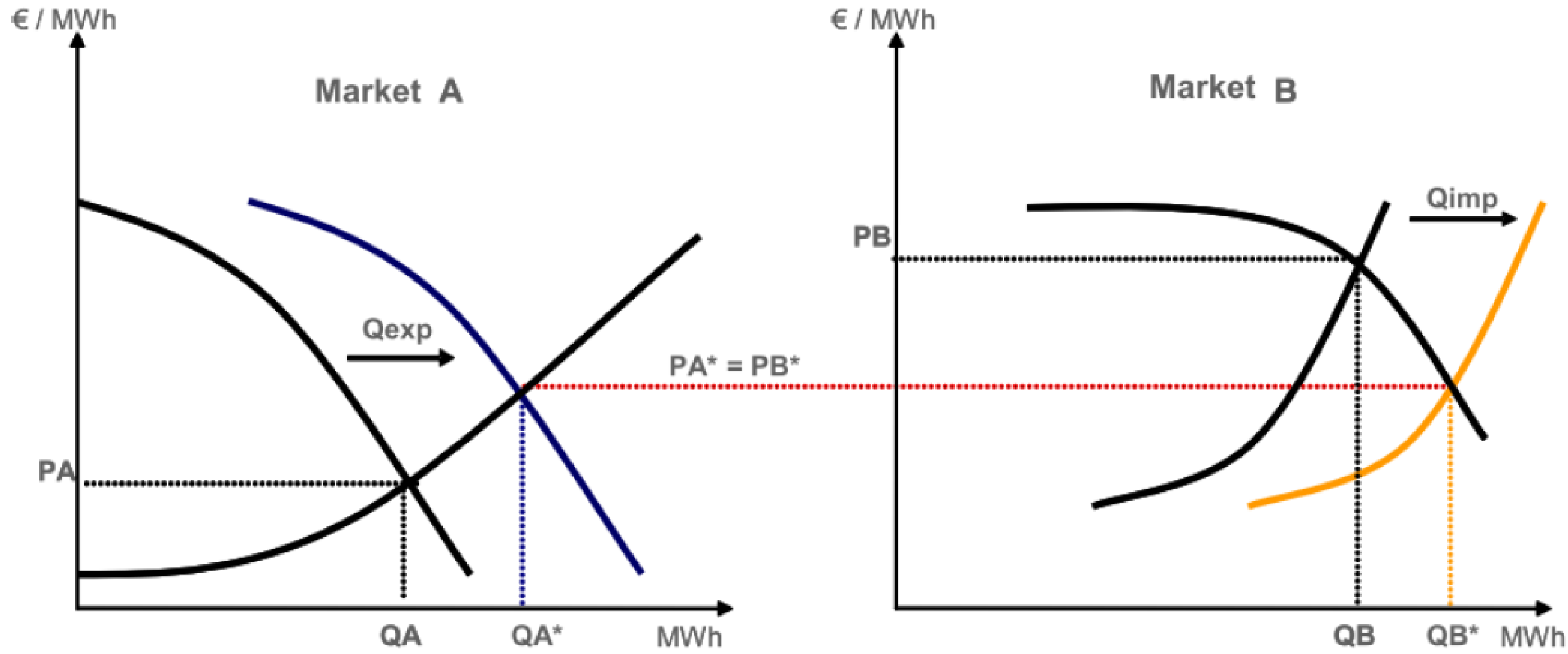
* No data for IS.

Source: ENTSO-E, 2017

Trade among different bidding zones (1)

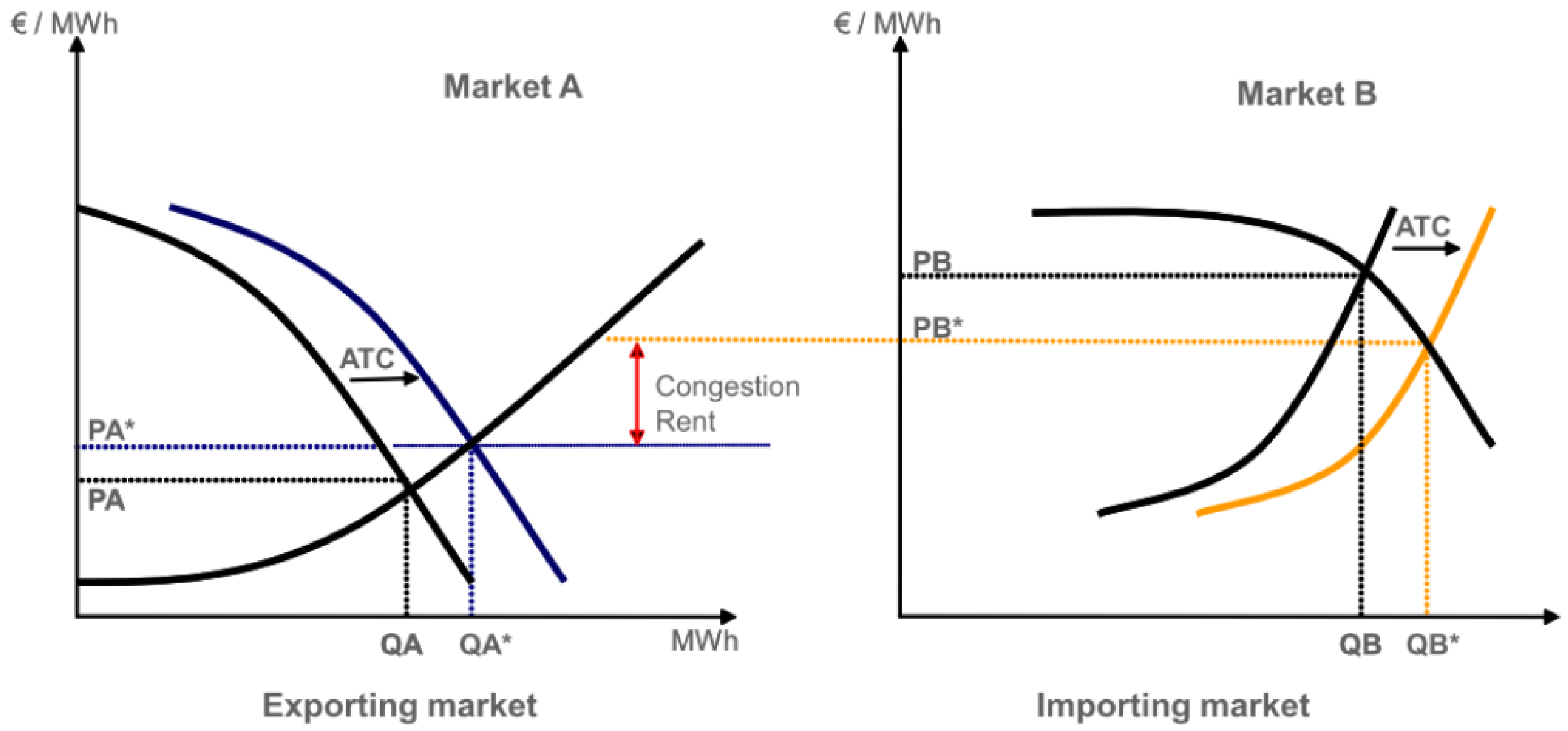
- if the price between two or more bidding zones is not the same, arbitrage is possible
- Trade is limited by interconnection capacities though
- At first price is determined individually for each zone
  - Then arbitrage opportuninities are used
  - Prices are calculated again
- If the interconnection capacity is limited, TSOs ask for a congestion rent

Trade among different bidding zones (2)



Quelle:
Epex Spot
SE

Trade among different bidding zones (3)



Source: Epex Spot SE

Crossborder transmission capacity trading

Goal: efficient allocation of cross-border transmission capacities in order to optimise social welfare.

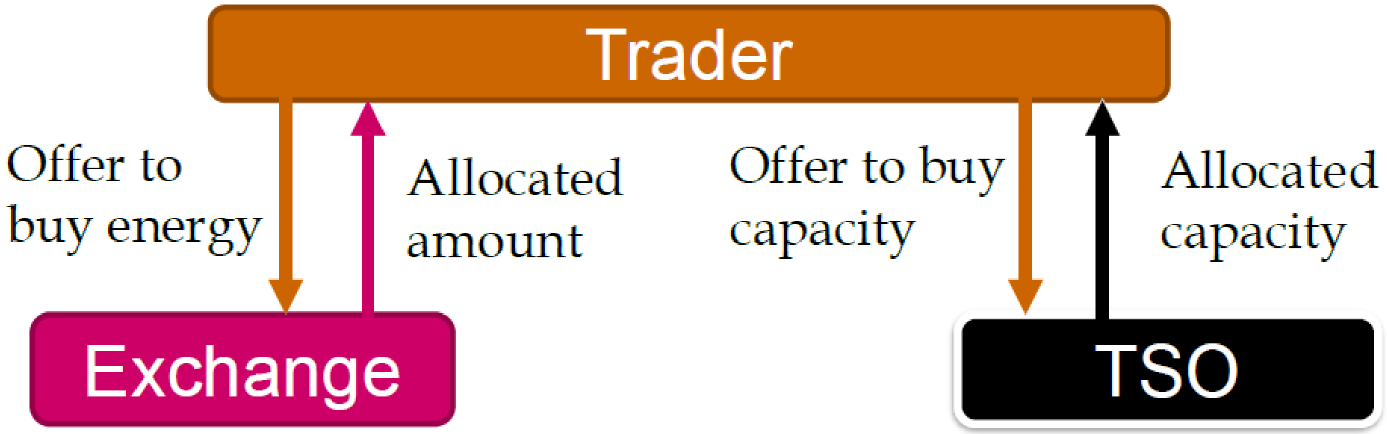
Explicit auction: transmission rights are auctioned separately and independently from the electricity market.

- annual, monthly and daily auctions
- bilaterally or via exchange

Implicit auction: transmission rights and energy are coupled and traded simultaneously (i.e. buyers bid for electricity supplied by generators from the neighbouring market area). The price per area reflects both the cost of energy and congestion.

- via exchange

Explicit auction



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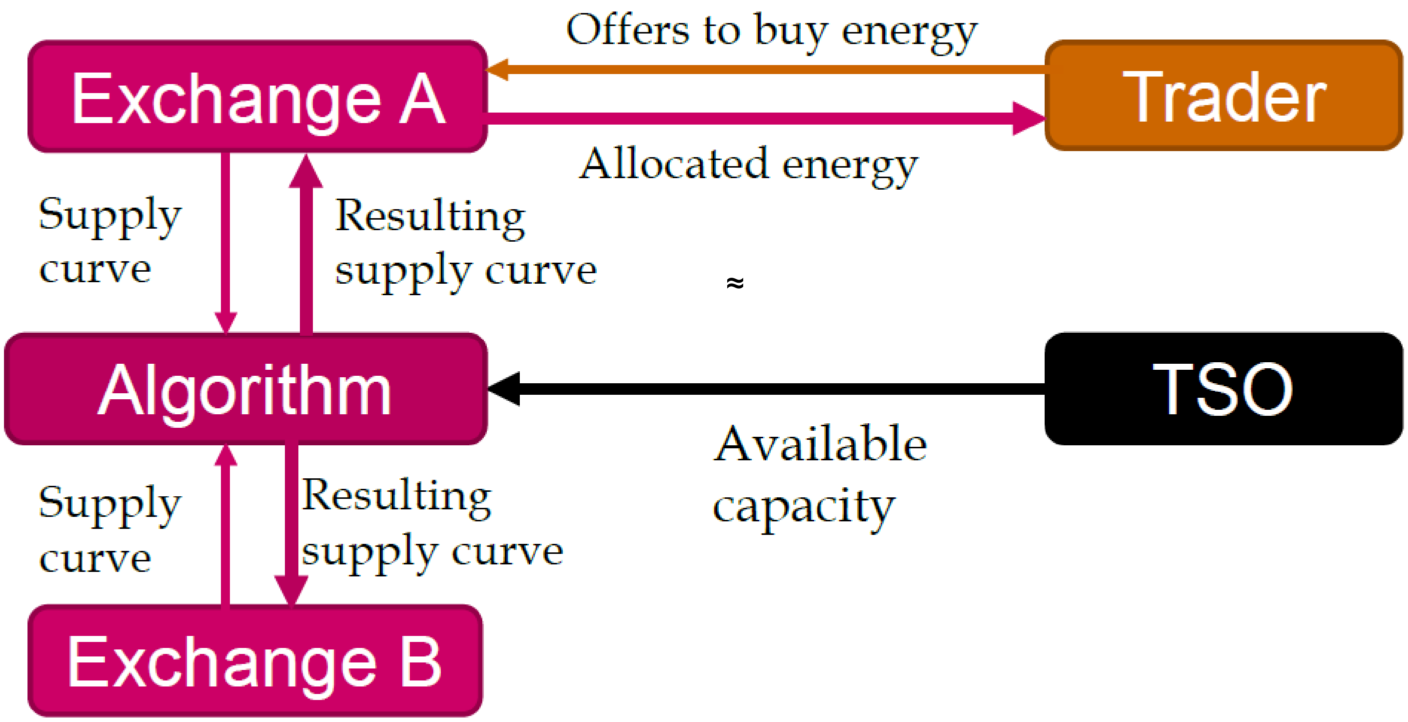
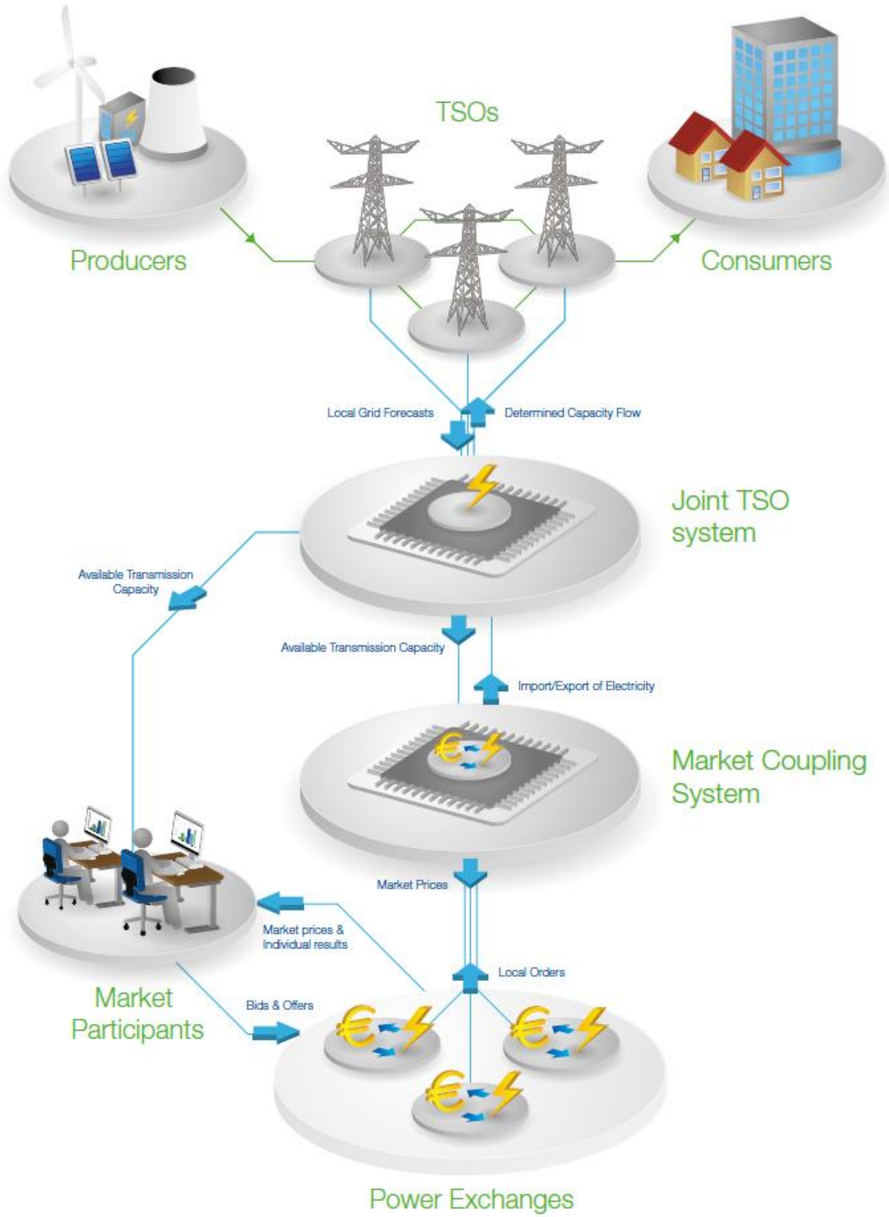
Implicit auction

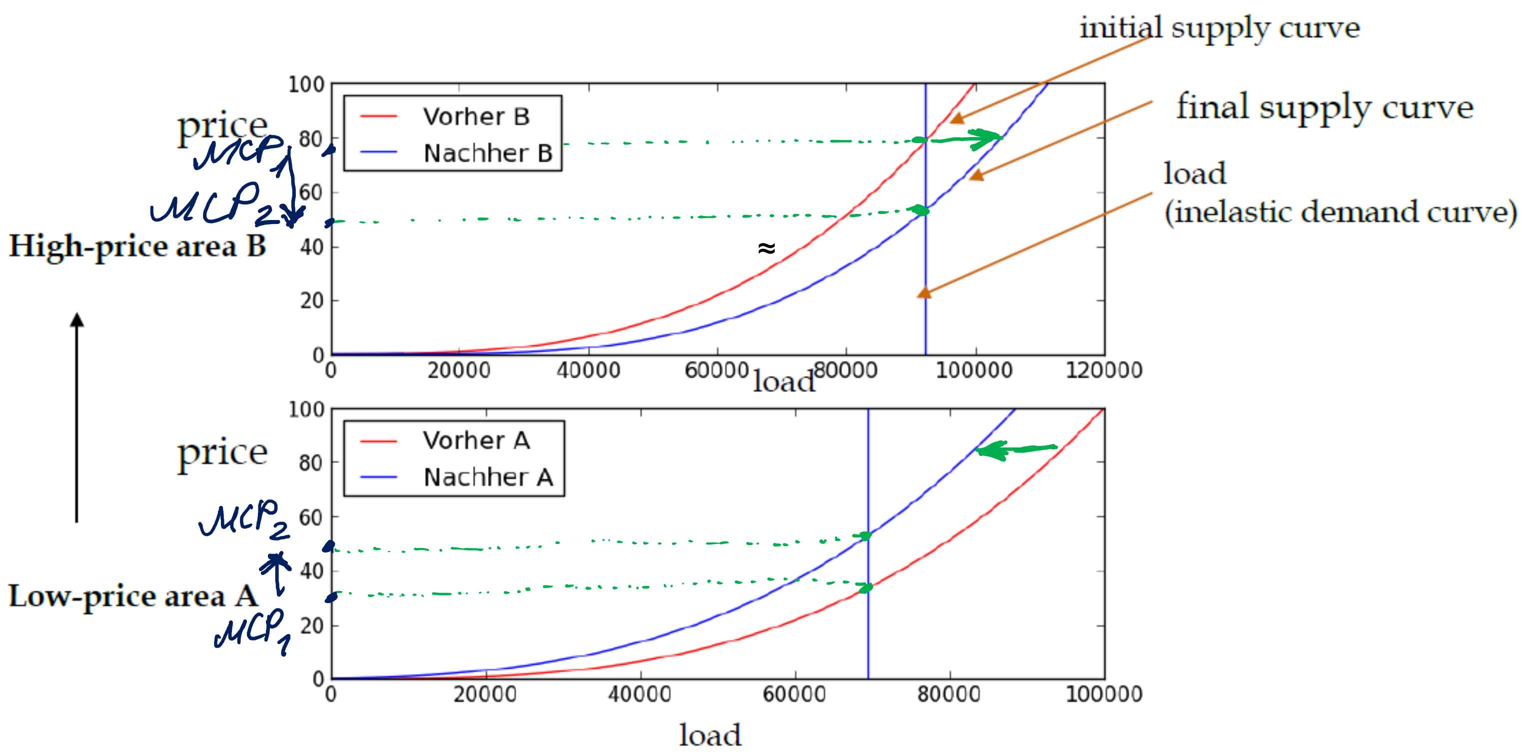


Market Coupling

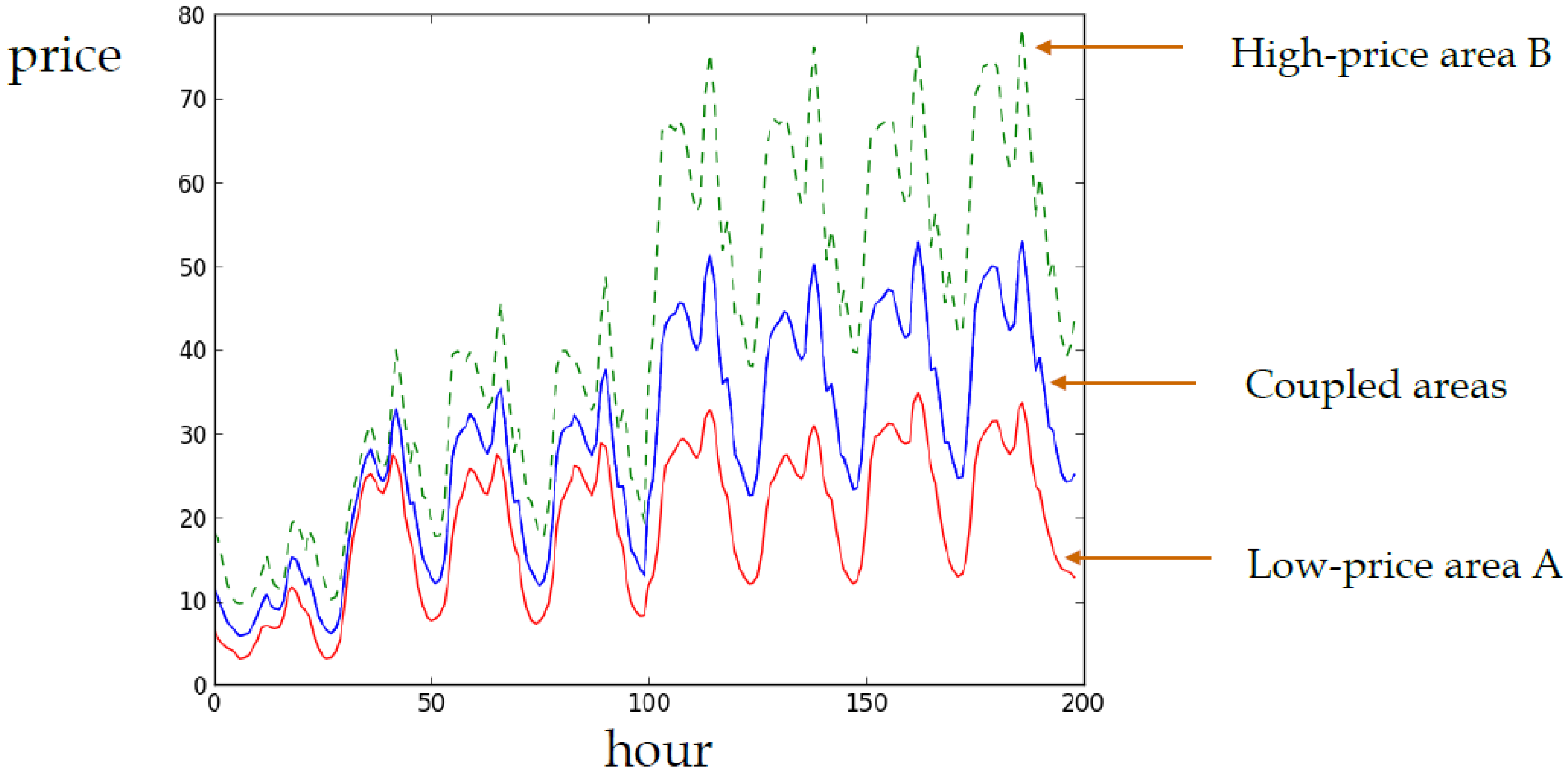


Source: TenneT (2010)

Example of trading between two markets



Example of trading between two markets (continued)



System services

- Frequency control
- Voltage control
- Black-start capacities for grid restauration after black-outs
- Compensation for transmission losses
- Cross-border interconnection management

General modes of provision:

- Compulsory
- Bilateral
- Tendering
- Wholesale market

Markets for control power

Control power markets serve for frequency control.

Frequency is determined by balance of supply and demand.

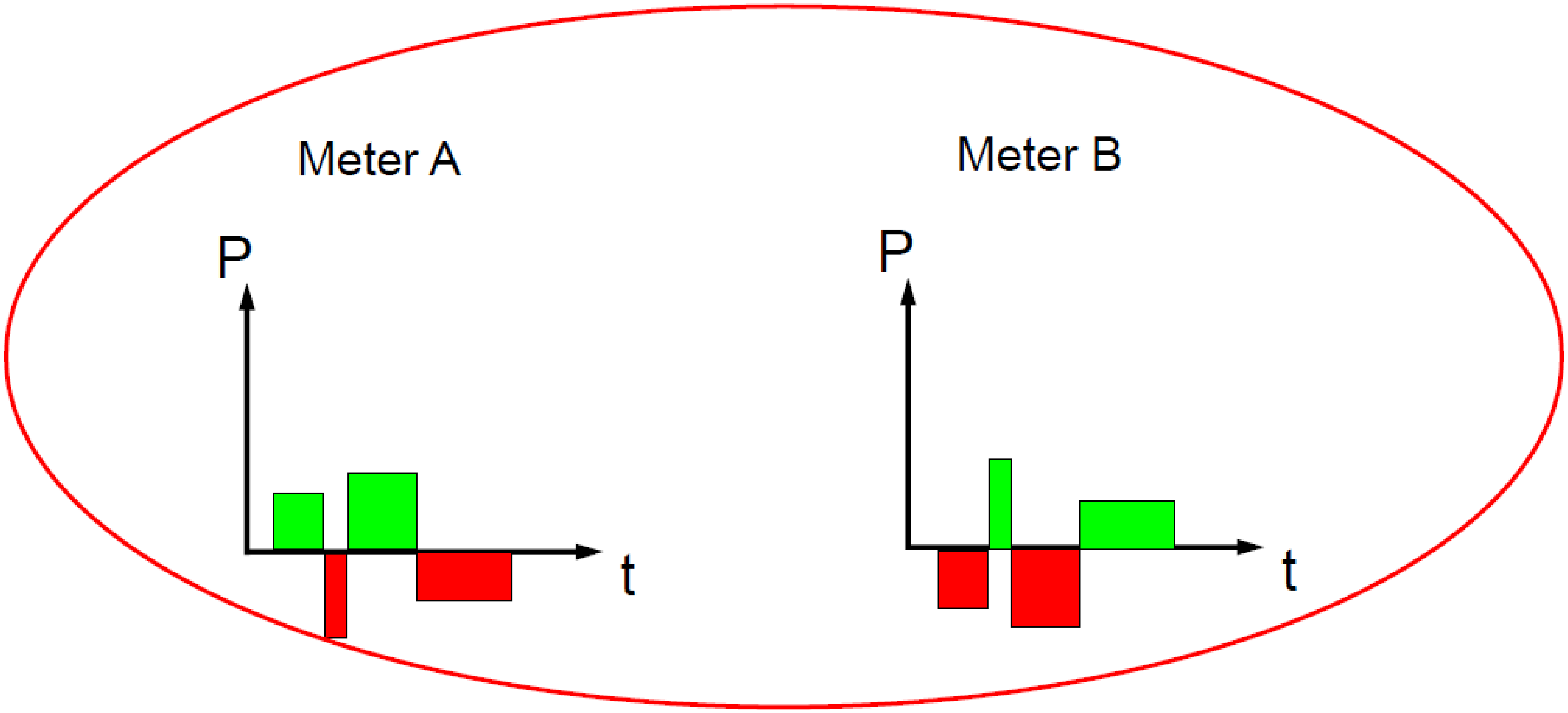
Target frequency in Europe: 50 Hz

Excessive demand → frequency drops → positive balancing energy is procured by TSO

Excessive generation → frequency rises → negative balancing energy is procured by TSO

Source: Zweifel / Praktiknjo / Erdmann, 2017

Netting of balancing power



Delivery of balancing power „long-position“

Demand of balancing power „short-position“

European balancing markets

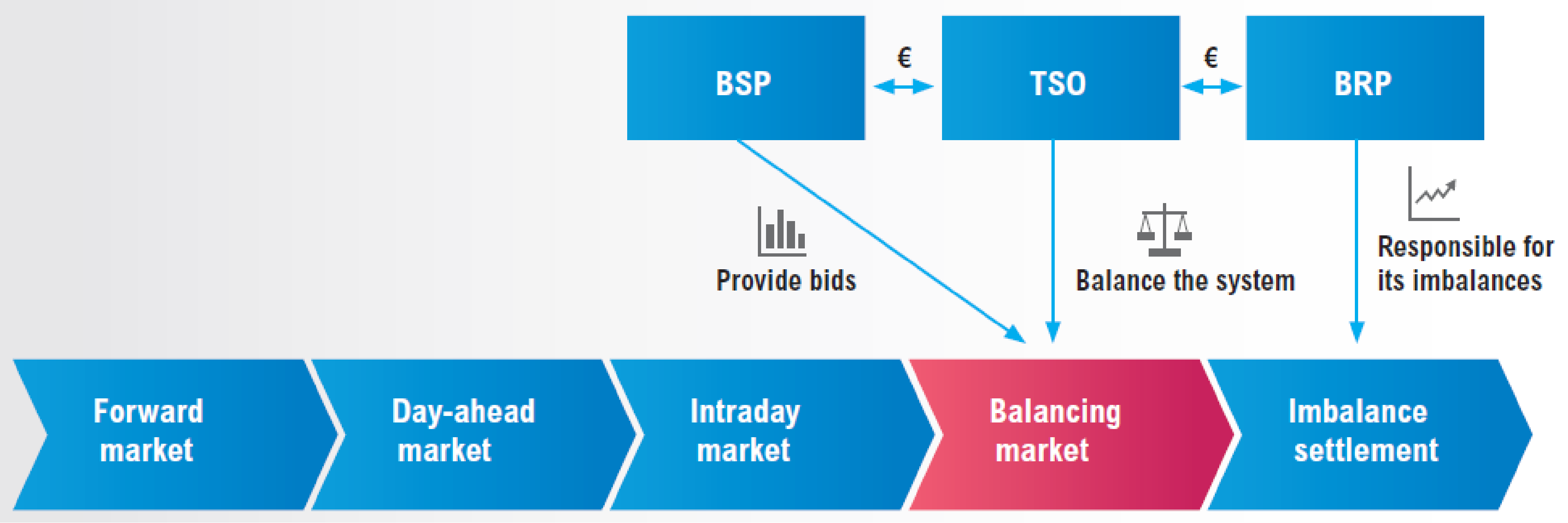
European balancing target model has following goals:

- Effective competition
- Non-discrimination
- Transparency
- Integration

European platforms and projects under development:

- IGCC, International Grid Control Cooperation – imbalance netting
- PICASSO, Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation – aFRR
- MARI, Manually Activated Reserves Initiative – mFRR
- TERRE, Trans-European Restoration Reserves Exchange – RR

Markets for control power



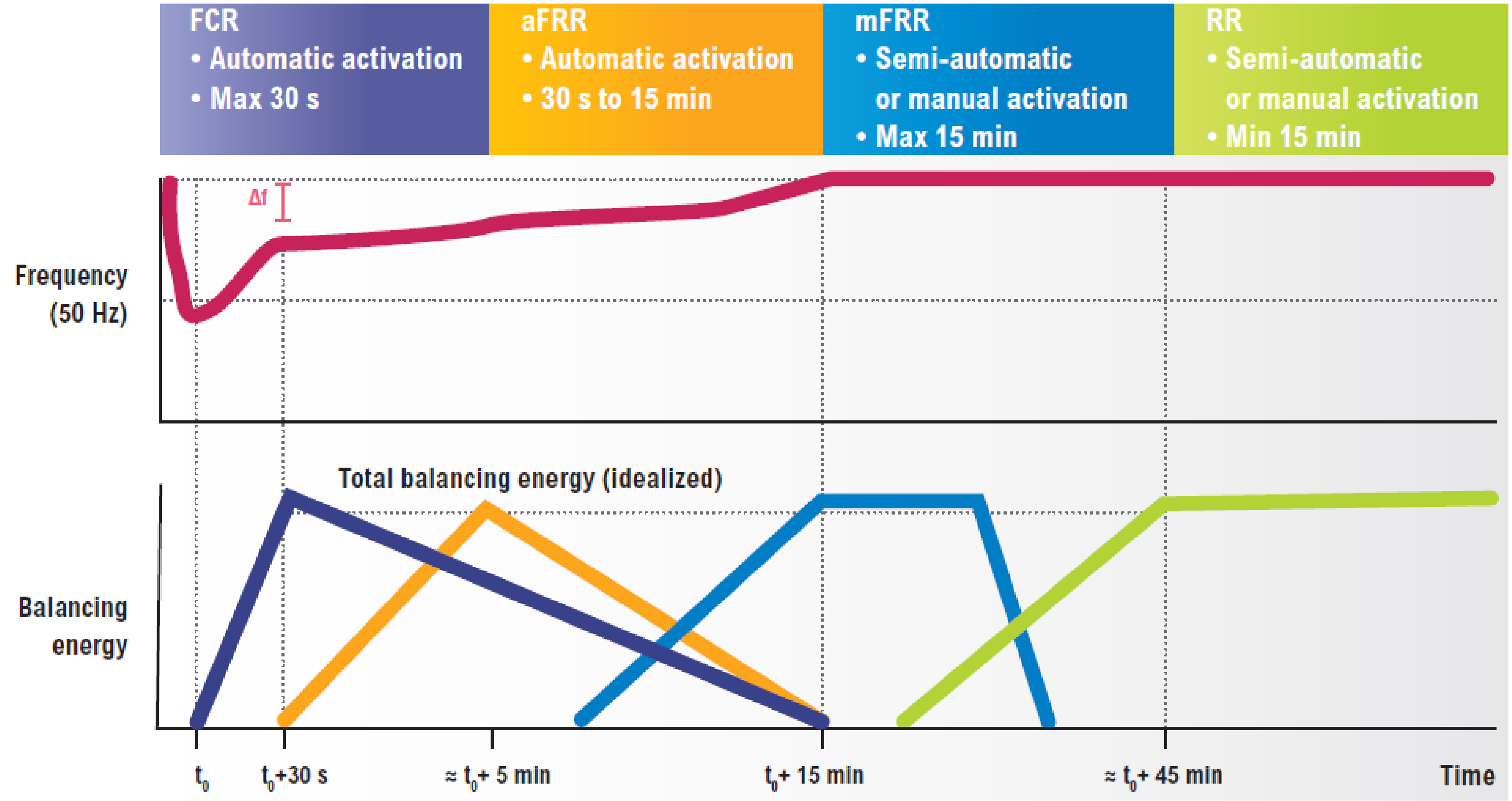
Balancing service providers:

- generators
- demand response providers
- storage facilities operators

System imbalance vs BG imbalance

Source: ENTSO-E, 2018

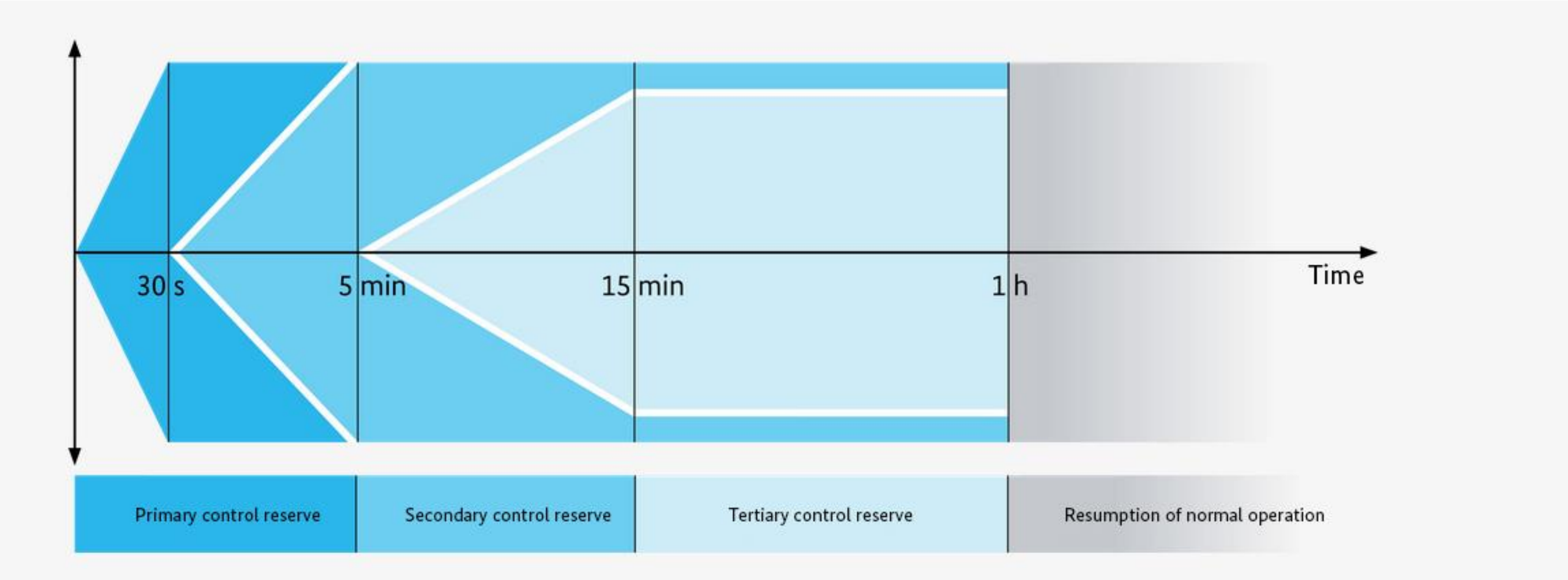
Balancing market processes



+ Imbalance netting (IN): exchange of imbalances between TSOs

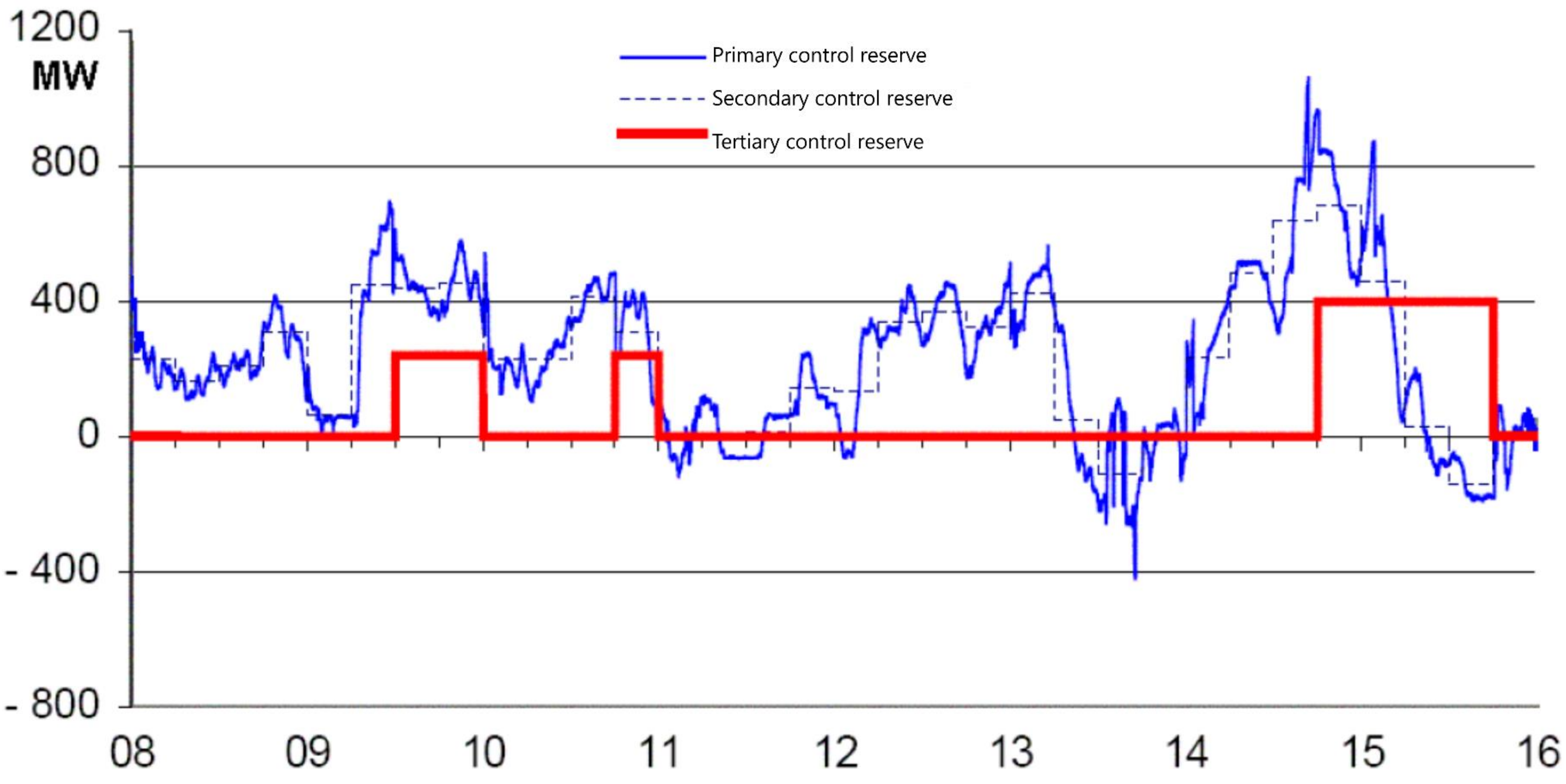
Source: ENTSO-E, 2018

Markets for control power



Source: Bundesnetzagentur

Utilisation of control power



Control power markets

Primary reserve – procured in weekly auction (Tue)

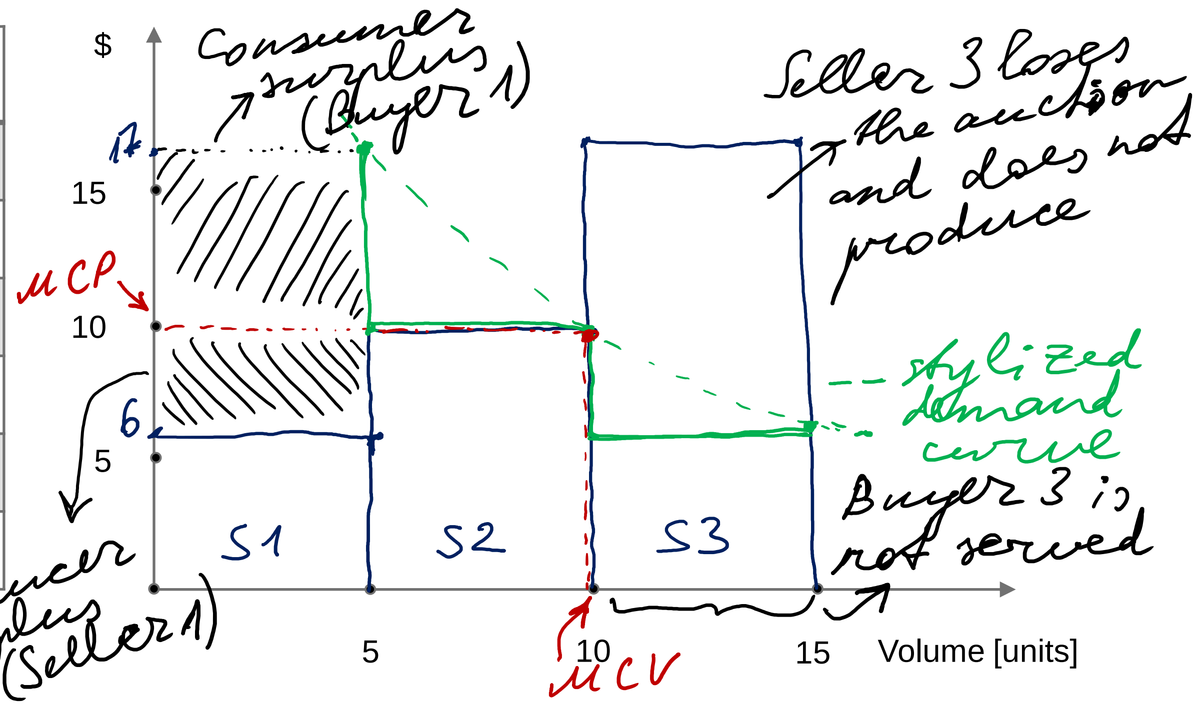
Secondary and tertiary reserves are procured in pay-as-bid auctions.

Prequalification required for participating in the control power markets.

Primary reserve	Secondary reserve	Minute reserve
until Tue 15:00 for Mo from 00:00 Time blocks: one week	daily until 8:00 for following day from 00:00 Time blocks: six 4-hour blocks	daily until 8:00 for following day from 00:00 Time blocks: six 4-hour blocks

Pay-as-bid auction: Stylised example

	No. of units	Price [$/unit]
Buyer 1	5	17
Buyer 2	5	10
Buyer 3	5	6
Seller 1	5	6
Seller 2	5	10
Seller 3	5	17

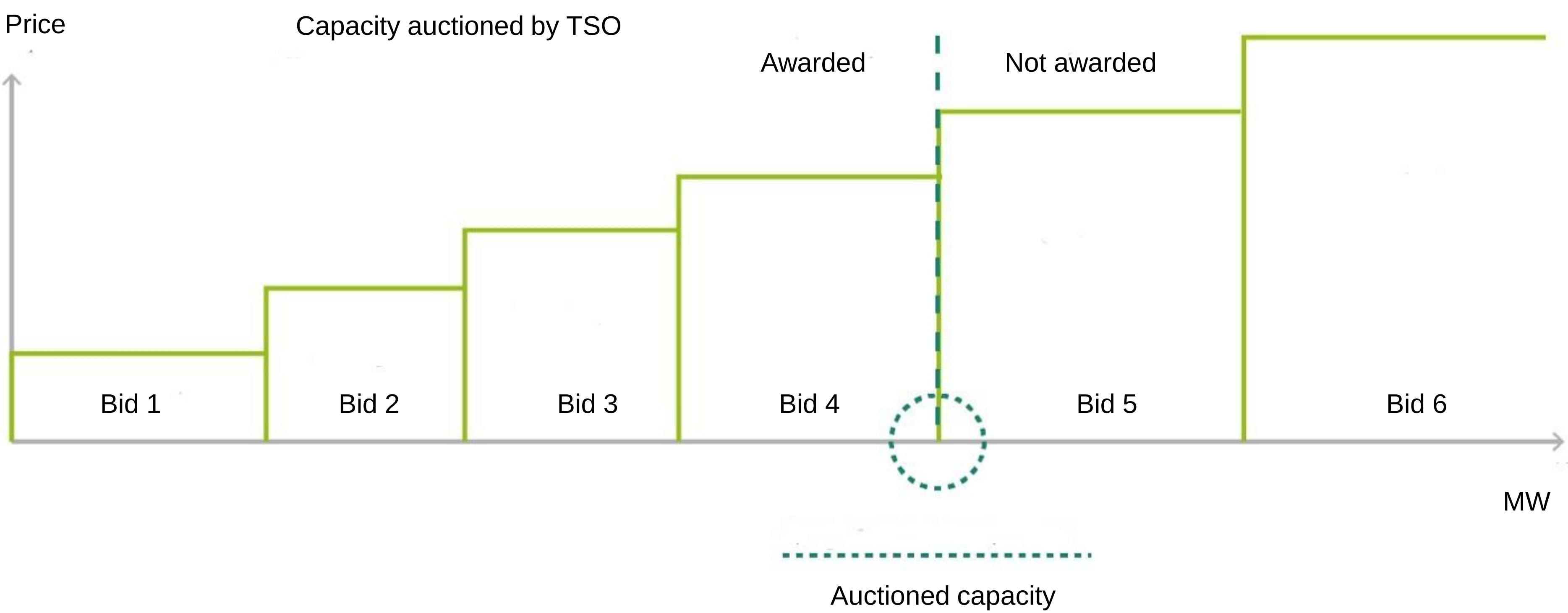


Pay-as-bid: units are sold at different prices (e.g. control power)

(vs. Uniform price: market clearing price)

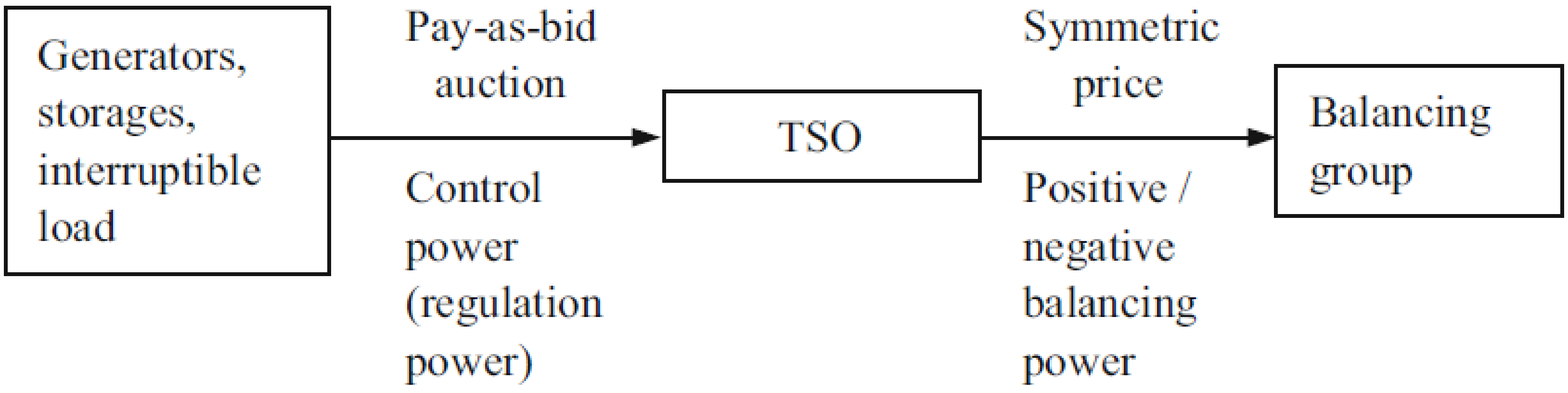
Source: Morey, EEI, 2001, p. 21-22.

Control power auction



Source: Next Kraftwerke

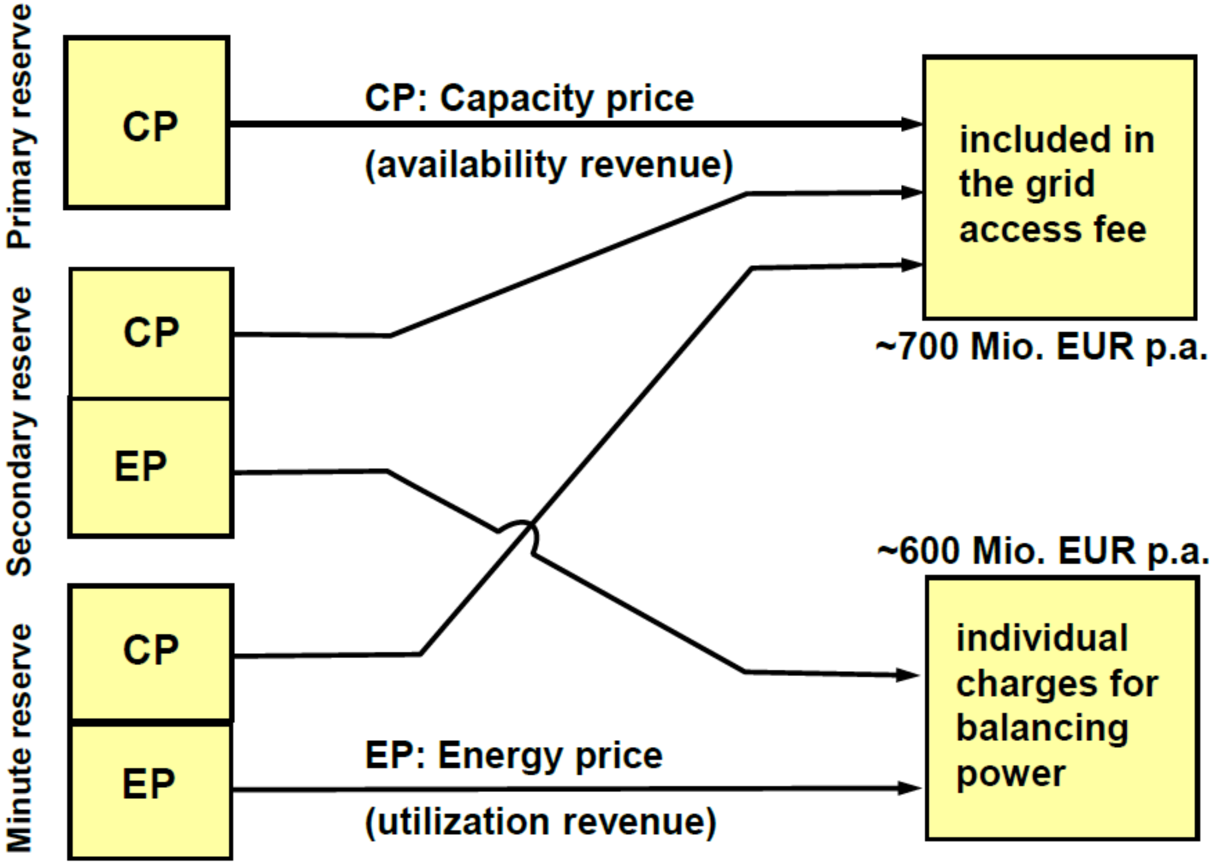
Control power markets



Source: Zweifel / Praktiknjo / Erdmann, 2017

Entry barriers are in focus of market design.

Cost allocation of control power



Control power markets

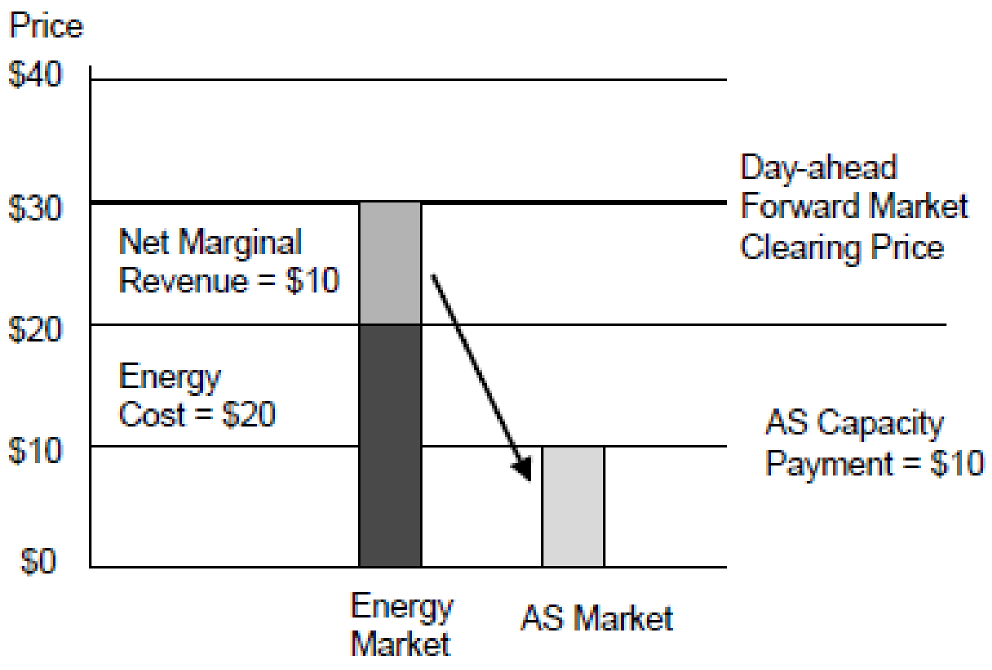
Link between energy and anciliary services:

A supplier can choose to either use a certain generation unit for supplying electricity on the wholesale market or offer its generation capacity on the control power market – not both simultaneously.

Generator’s costs:

- higher fuel consumption
- higher wear and tear
- etc.

Opportunity costs: Energy vs. Ancillary Services



Source: Morey, EEI, 2001, p. 52.

Control power markets

	Primary control	Secondary control	Tertiary control (minute reserve)
Response time	30 s, direct (continuous)	15 min or less, direct	15 min, direct or scheduled
System	UCTE	UCTE and balancing area	UCTE and balancing area
Target variable	Frequency	ACE and frequency	Current and expected level of SC activation
Activation	Based on local frequency measurement	Centralized (TSO); IT signal (AGC)	Centralized (TSO); phone/IT signal
Suppliers (typical)	Synchronized generators, (large consumers)	Synchronized generators, stand-by hydro plants, large consumers	Synchronized and fast-starting stand-by generators, large consumers
Reserved capacity	3000 MW in UCTE (600 MW in Germany)	Determined by TSO (2000 MW in Germany)	Determined by TSO (2500 MW in Germany)

Source: Hirth, Ziegenhagen / Renewable and Sustainable Energy Reviews 50 (2015), p.1039