Power System Operations

Anthony Papavasiliou, National Technical University of Athens (NTUA)

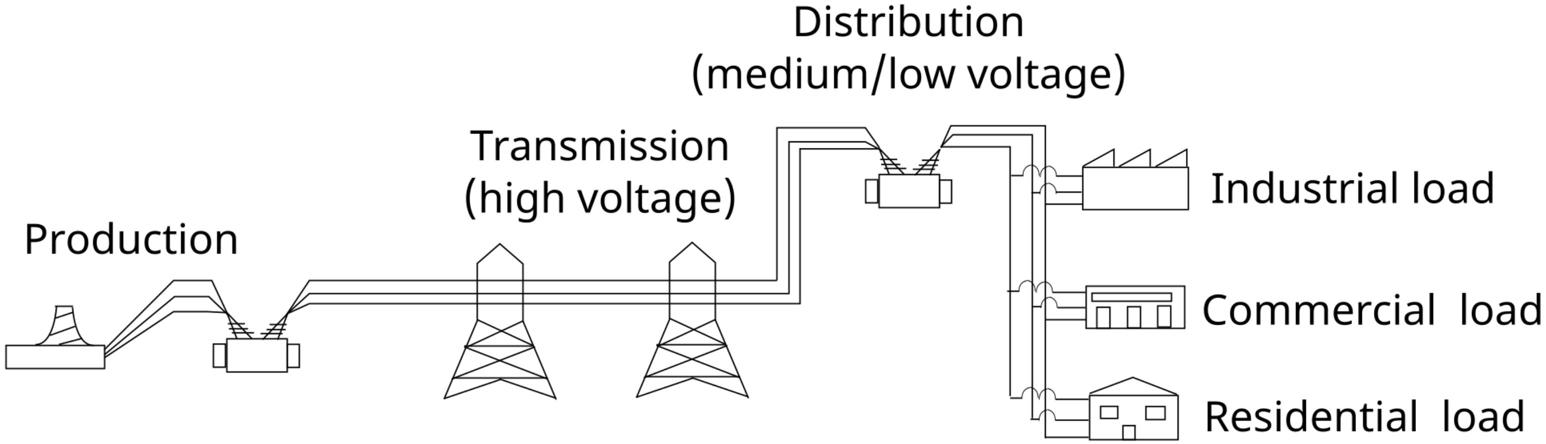
Source: chapter 3.1, Papavasiliou [1]

Outline

- Production
- Transmission and distribution
- Consumption
- Actors
- Uncertainty and reserve
- Stages of decision making

Production

Power system supply chain



- Different components of power systems:
    - Production
    - Transmission and distribution
    - Consumption

Production

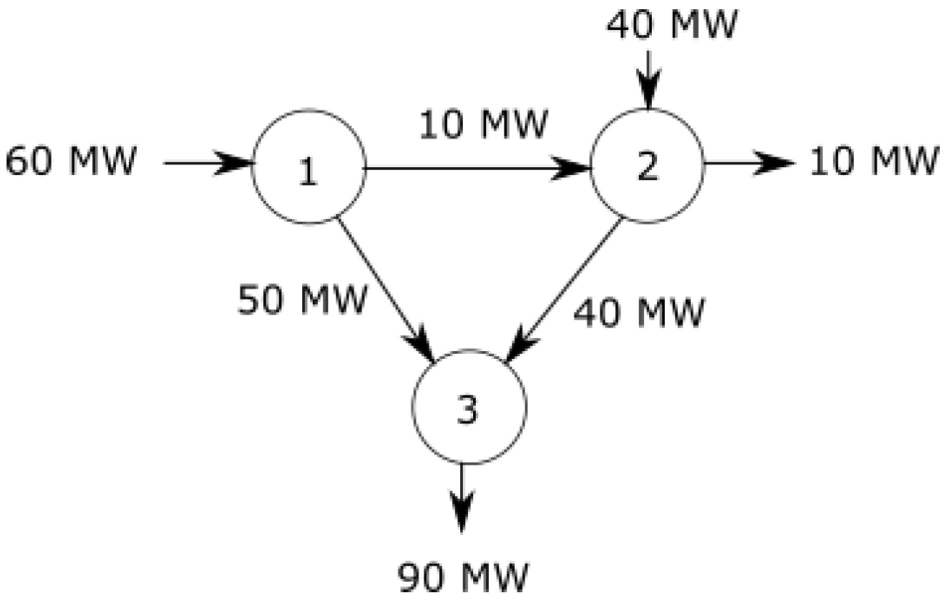
- Non-renewable energy sources:
  - Fossil fuels (coal, oil, natural gas)
  - Nuclear

- Renewable energy sources:
  - Hydroelectric (run of river, dams, pumped storage)
  - Geothermal
  - Wind
  - Solar
  - Biomass
  - Other (wave, tidal)

Units of measurement

- Energy is measured in megawatt hours (denoted MWh)
- Power is energy per unit time:
  - Rate of energy production
  - Rate of energy consumption
  - Energy flow
- Power is measured in MW

The pool analogy



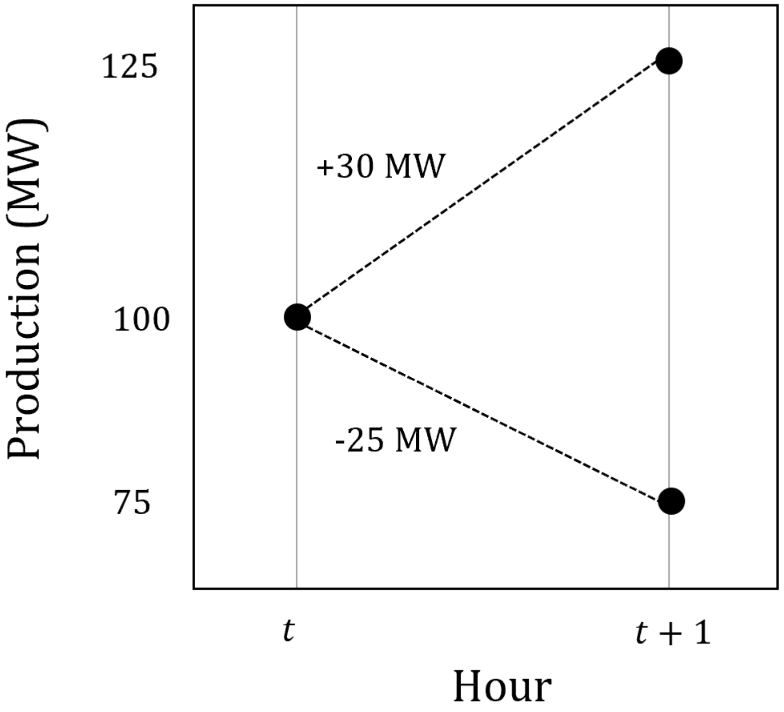
Who is supplying the load in node 3;

Production constraints

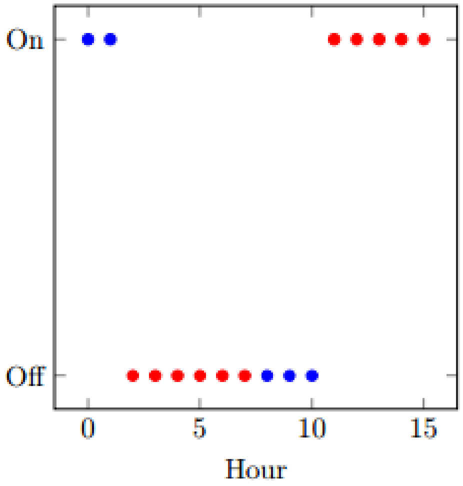
- Fossil fuel constraints:
  - Min/max production
  - Ramp constraints
  - Min up/down times

- Hydro constraints:
  - Max production
  - Max storage

Ramp constraints



Min up/down time constraints



- Min up time: 5 hours
- Min down time: 6 hours
- Red dots: constrained decisions
- Blue dots: free decisions

Variable and marginal cost

Variable/operating/fuel cost: cost that depends on amount of output

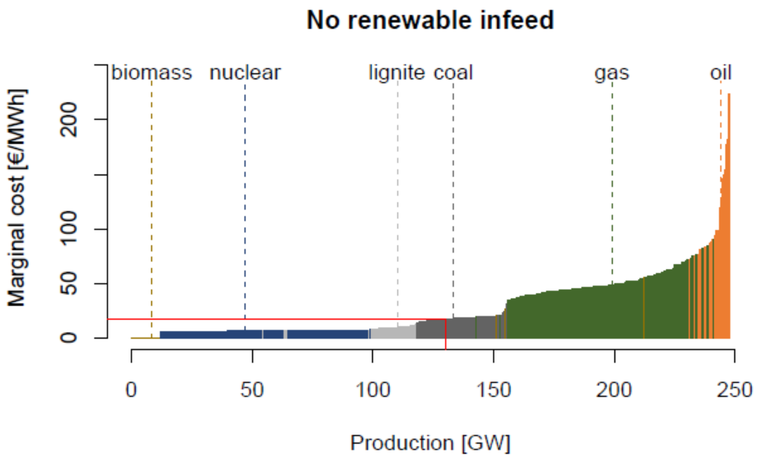
- Measured in \$/h
- Hourly cost of producing a certain amount of power

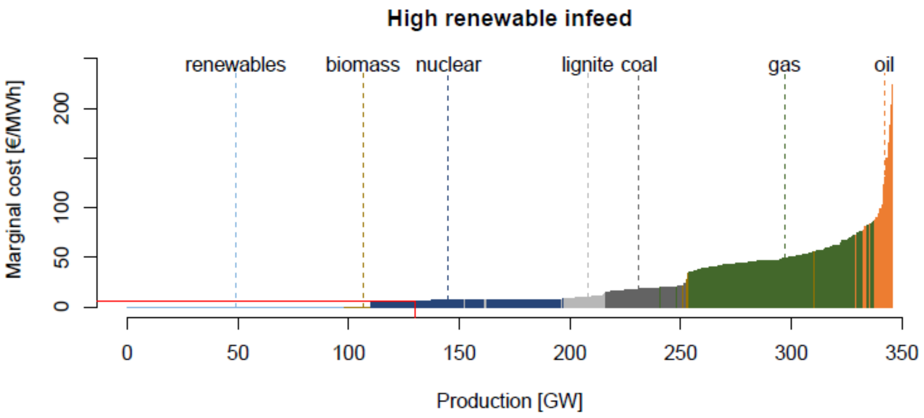
Marginal cost: derivative of fuel cost with respect to output

- Measured in \$/MWh
- Increase in fuel cost if an additional MW of power were produced/saving if one less MW is produced

Merit order curve

Merit order curve: (increasing) system marginal cost curve





What is the impact of renewable energy on the system?

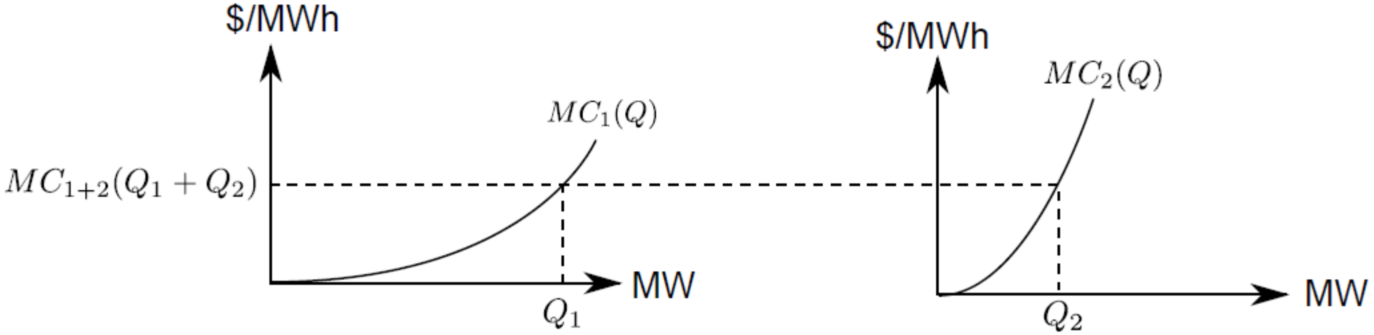
Marginal cost range

If variable cost is non-differentiable, define

- **Left-hand marginal cost**: left-hand side derivative of marginal cost
- **Right-hand marginal cost**: right-hand side derivative of marginal cost (when is it infinite?)
- **Marginal cost range**: set of values between and including left- and right-hand marginal cost

Horizontal summation of marginal costs

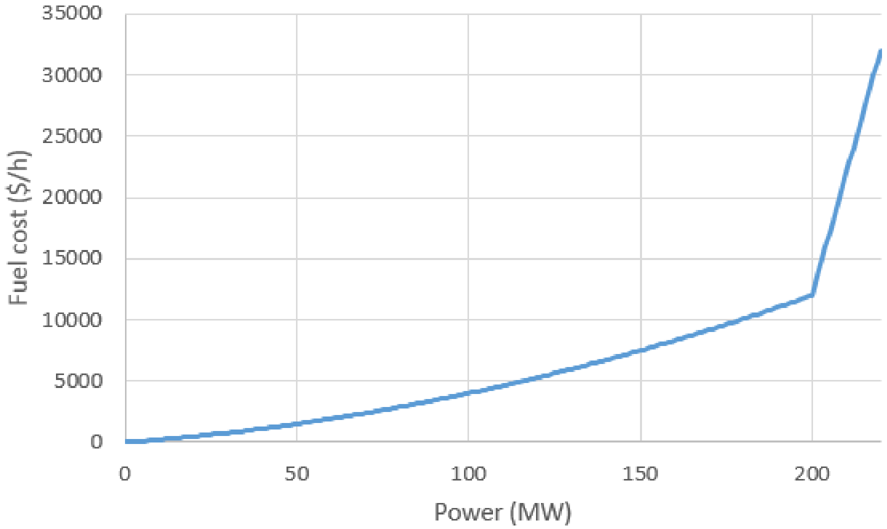
Aggregate marginal cost is obtained by horizontal summation



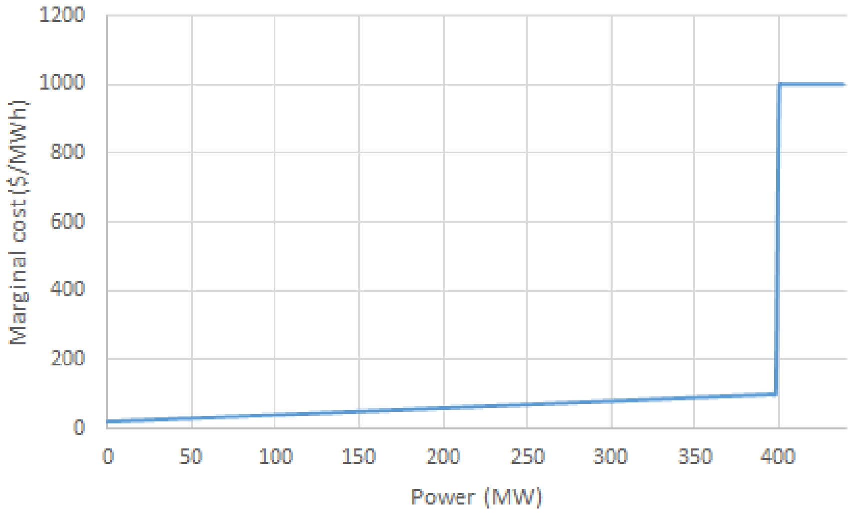
Example

Consider quadratic fuel cost with:

- MC(0 MW) = 20 \$/MWh
- MC(200 MW) = 100 \$/MWh
- MC(Q) = 1000 \$/MWh, 200 MW ≤ Q ≤ 220 MW
- VC(0 MW) = 0 \$/h



Summation of marginal cost curves



This is the marginal cost of n generators from previous slide, $n = ?$

Investment cost

- Fixed/investment cost: cost that is independent of output
  - **Overnight cost** ($/kW): cost that needs to be paid upfront per kW of investment
  - **Annualized fixed cost** ($/kWy): cost that needs to be paid per year per kW of investment
  - **Hourly fixed cost** ($/MWh): cost that needs to be paid per hour per MW of investment

Conversion of investment cost

Denote:

- T (years): investment lifetime
- r: interest rate

Annualized fixed cost FC (\$/kWy) given *annual discounting*

$$FC = \frac{r \cdot OC}{1 - 1/(1+r)^T}$$

Annualized fixed cost FC (\$/kWy) given *continuous discounting*

$$FC = \frac{r \cdot OC}{1 - e^{-rT}}$$

Hourly fixed cost (\$/MWh): divide annualized fixed cost by 8.76 (why 8.76?)

Example

- Gas turbine lifetime: 25 years
- Coal generator lifetime: 45 years
- Continuous discounting with interest rate $r = 12\%$

	OC (\$/kW)	FC (\$/kWy)	FC (\$/MWh)
Gas turbine	400	50.5	5.8
Coal	1200	144.7	16.5

Average cost

Average cost: total cost per unit of output

- Definition of average cost generalizes to the case of an *industry* that produces Q at minimum cost
- Economies of scale are realized when average cost decreases
- Average cost influences whether an industry is a **natural monopoly** or not

Intersection of average cost curve and marginal cost curve

- By definition:

$$AC(Q) = \frac{TC(Q)}{Q} = \frac{FC + VC(Q)}{Q}$$

- The minimum of the average cost curve is characterized by the following condition:

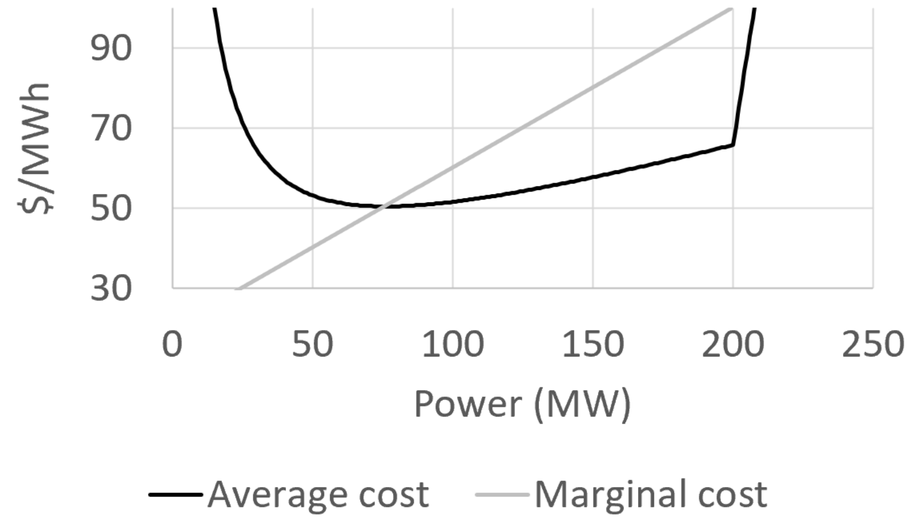
$$AC'(Q^*) = 0 \Rightarrow$$

$$\frac{MC(Q^*) \cdot Q^* - (FC + VC(Q^*))}{(Q^*)^2} = 0 \Rightarrow$$

$$MC(Q^*) = \frac{FC + VC(Q^*)}{Q^*} \Rightarrow$$

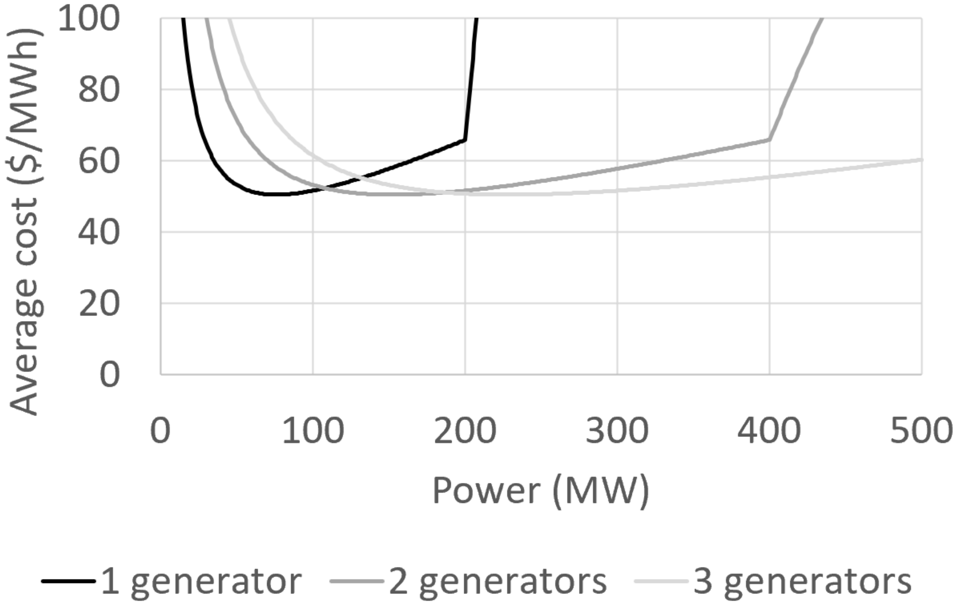
$$MC(Q^*) = AC(Q^*)$$

Average cost curve: single generator



Why is there a jump in average cost at $Q = 0$ MW?

Average cost curve: multiple generators



Average cost at unit capacity (200 – 220 MW) is lower for $n = 3$ generators

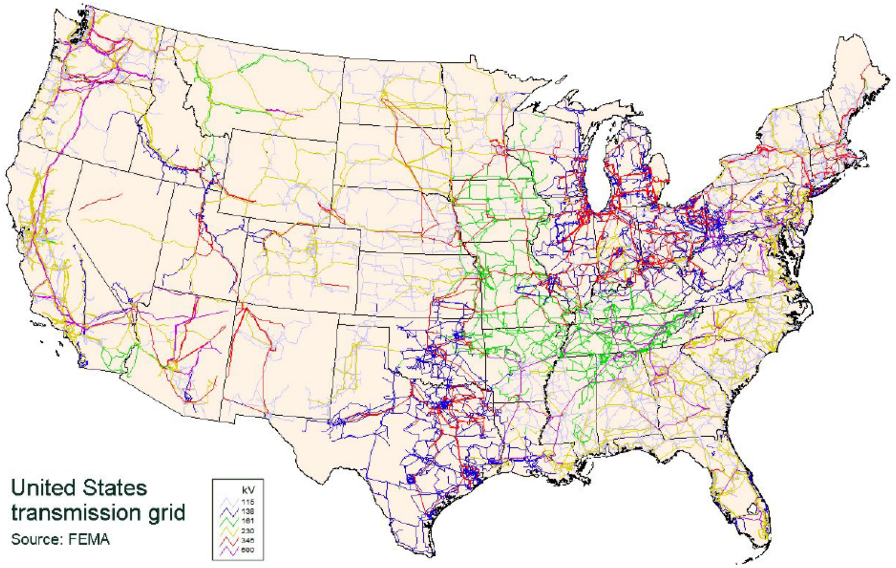
Minimum efficient scale and natural monopoly

- The point at which average cost is minimized is called **minimum efficient scale**
- If the minimum efficient scale is comparable to the level of demand in the system, this is an indication of a **natural monopoly**
- Natural monopolies require government intervention/regulation

- Natural monopolies tend to emerge in industries where fixed cost dominates variable cost
- Electric power systems exhibited natural monopoly characteristics until recently

Transmission and distribution

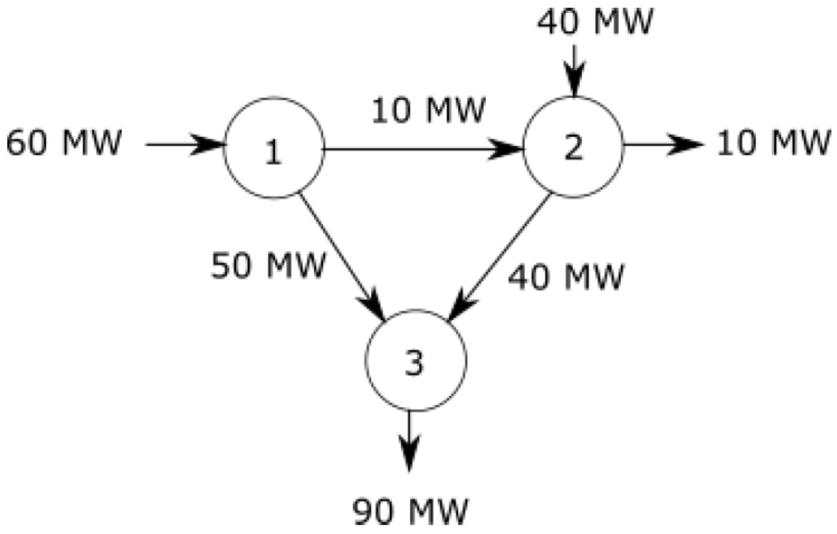
Transmission and distribution



United States
transmission grid
Source: FEMA

- Transmission: higher voltage, lower losses
- Distribution: lower voltage, higher losses
- Transformers reduce voltage at the interface

Power balance

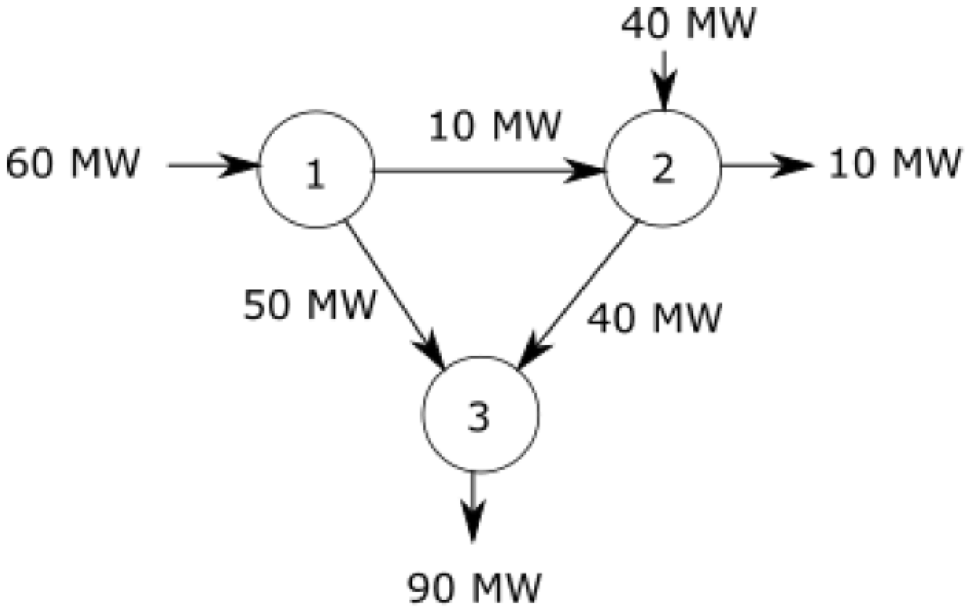


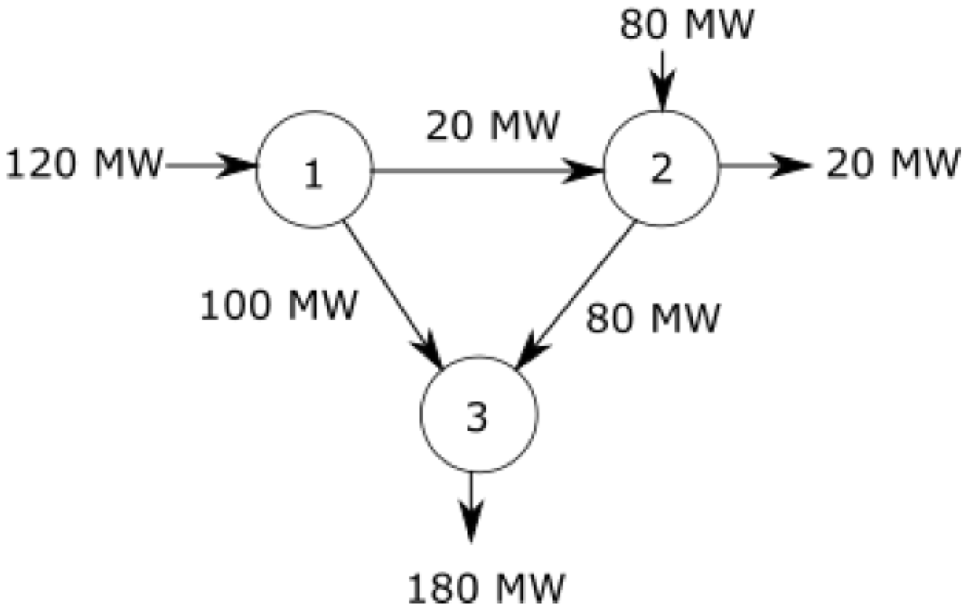
- **Buses**: nodes of the transmission network
- **Branches/lines**: edges of the transmission network
- Power balance at each bus (same as transportation models)
- Physical intuition: electricity is «lazy»

Power flow equations

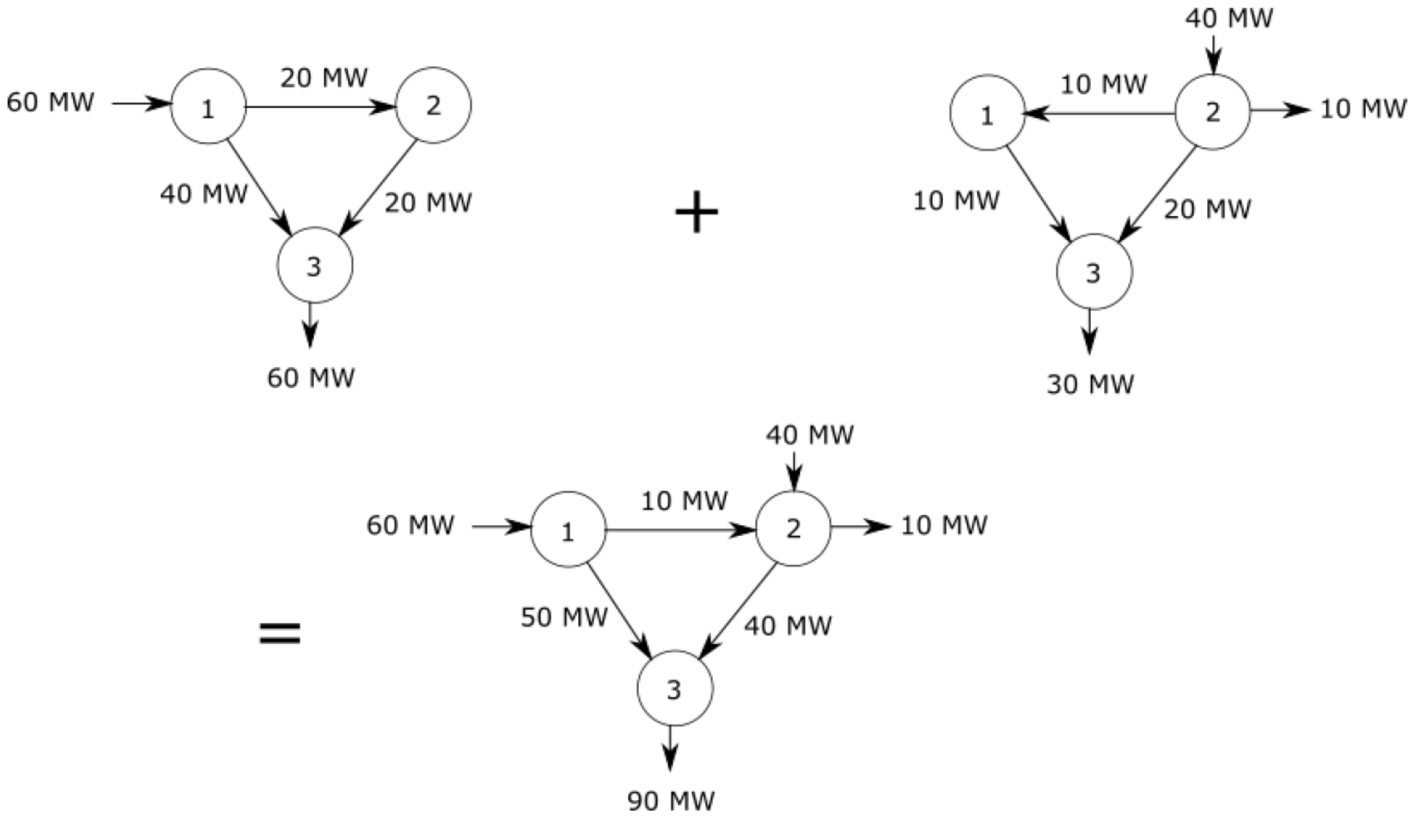
- Power networks are more complex than transportation networks
- **Kirchhoff's laws**: physical laws that govern flow of electricity in circuits, can be used to derive power flow equations
- **Power flow equations** determine a mapping $f = P(r)$ of power injections r in buses to power flows f on lines
- **Direct current (DC) power flow equations**: approximation of power flow equations by a *linear* mapping

Proportionality of power flows





Additivity of power flows



Consumption

Valuation and benefit

Consumer benefit: benefit that depends on amount of consumption

  - Measured in \$/h
  - Hourly benefit of consuming a certain amount of power

- **Marginal benefit/valuation**: derivative of benefit with respect to consumption
  - Measured in \$/MWh
  - Willingness to pay (why?)

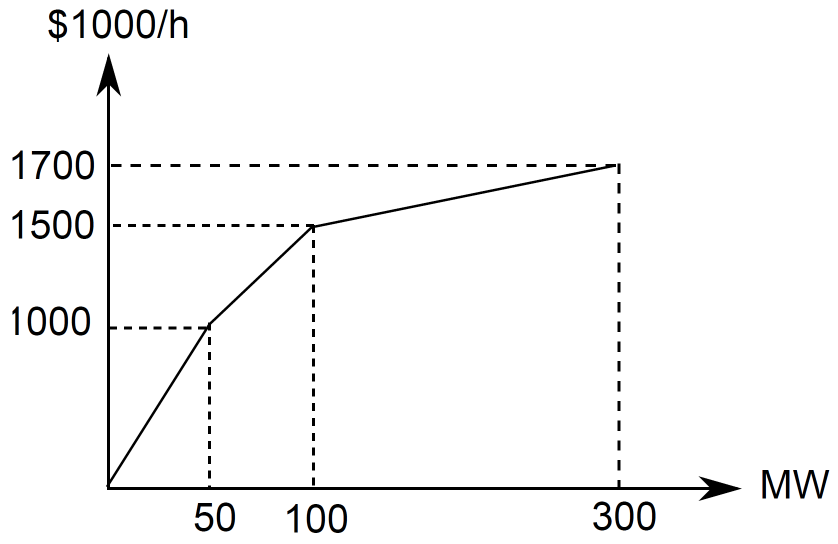
What is the supply-side analog of consumer benefit? of valuation?

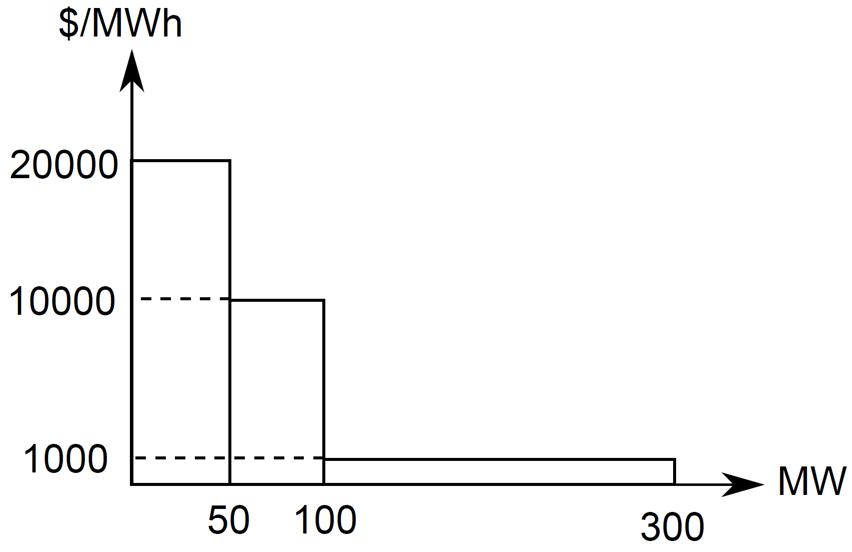
Inverse demand/marginal benefit function

Inverse demand/marginal benefit function: mapping of power consumption Q to marginal benefit $MB(Q)$

Do we expect an inverse demand function to be increasing/decreasing?

Illustration of marginal benefit function





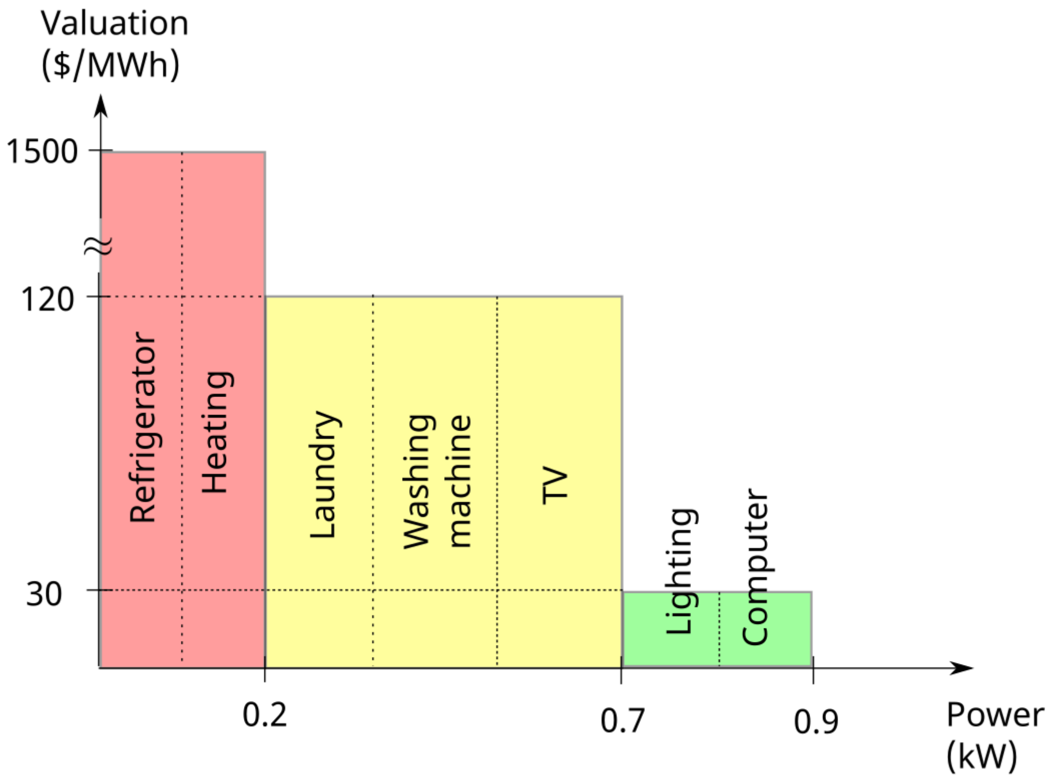
Which graph corresponds to consumer benefit? inverse demand function?

Example: household

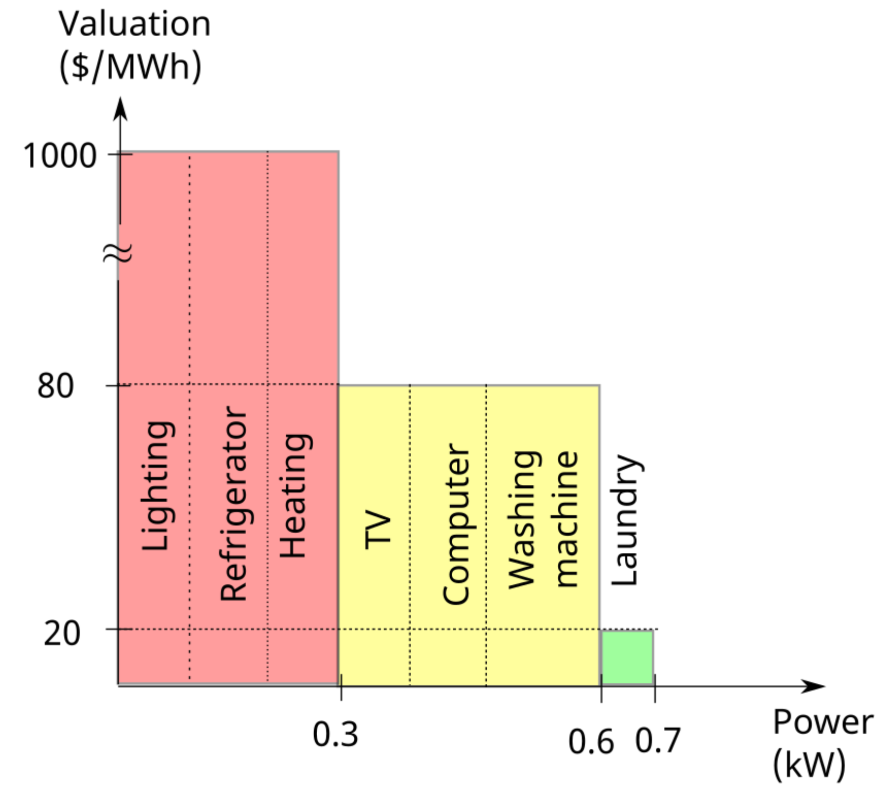
Tranche	Demand morning (kW)	Valuation morning ($/MWh)	Demand evening (kW)	Valuation evening ($/MWh)
Inflexible	0.2	1500	0.3	1000
Medium	0.5	120	0.3	80
Flexible	0.2	30	0.1	20

Devices can move from tranche to tranche
(which devices could belong to the inflexible tranche?)

Morning


Valuation ($/MWh)
1500
≈
120
30
Refrigerator
Heating
Laundry
Washing machine
TV
Lighting
Computer
0.2
0.7
0.9
Power (kW)

Evening


Valuation
($/MWh)
1000
80
20
Lighting
Refrigerator
Heating
TV
Computer
Washing machine
Laundry
0.3
0.6
0.7
Power
(kW)

Demand function

Demand function $Q(v)$: inverse mapping of inverse demand function

Maps price of power v to quantity Q that would be procured

Elasticity of demand

Elasticity: sensitivity of demand $Q(v)$ to changes in price v:

$$\varepsilon = \frac{dQ/dv}{Q/v}$$

Steep inverse demand function ⟺ flat demand function ⟺ low ε ⟺ inelastic (insensitive) demand

Average value of lost load and VOLL

- **Average value of lost load**: long-run average amount of load shed due to random disturbances (failures of generators and lines, forecast errors of renewable resources and load, etc.)

- **Value of lost load (VOLL)**: marginal change in average value of lost load due to marginal increase in system capacity, divided by marginal decrease in the amount of shed load

- VOLL useful in capacity expansion planning studies for quantifying marginal benefit of investment in generation capacity

Example: VOLL

Consider the following demand function:

$$Q(v) = 30000 - 2v$$

Lost value from 1% in service with random rationing

$$\int_{v=0}^{15000} Q(v)dv - \int_{v=0}^{15000} 0.99Q(v)dv =$$

$$= 0.01 \cdot \frac{15000 \cdot 30000}{2} = 2.25 \cdot 10^6 \text{ €}$$

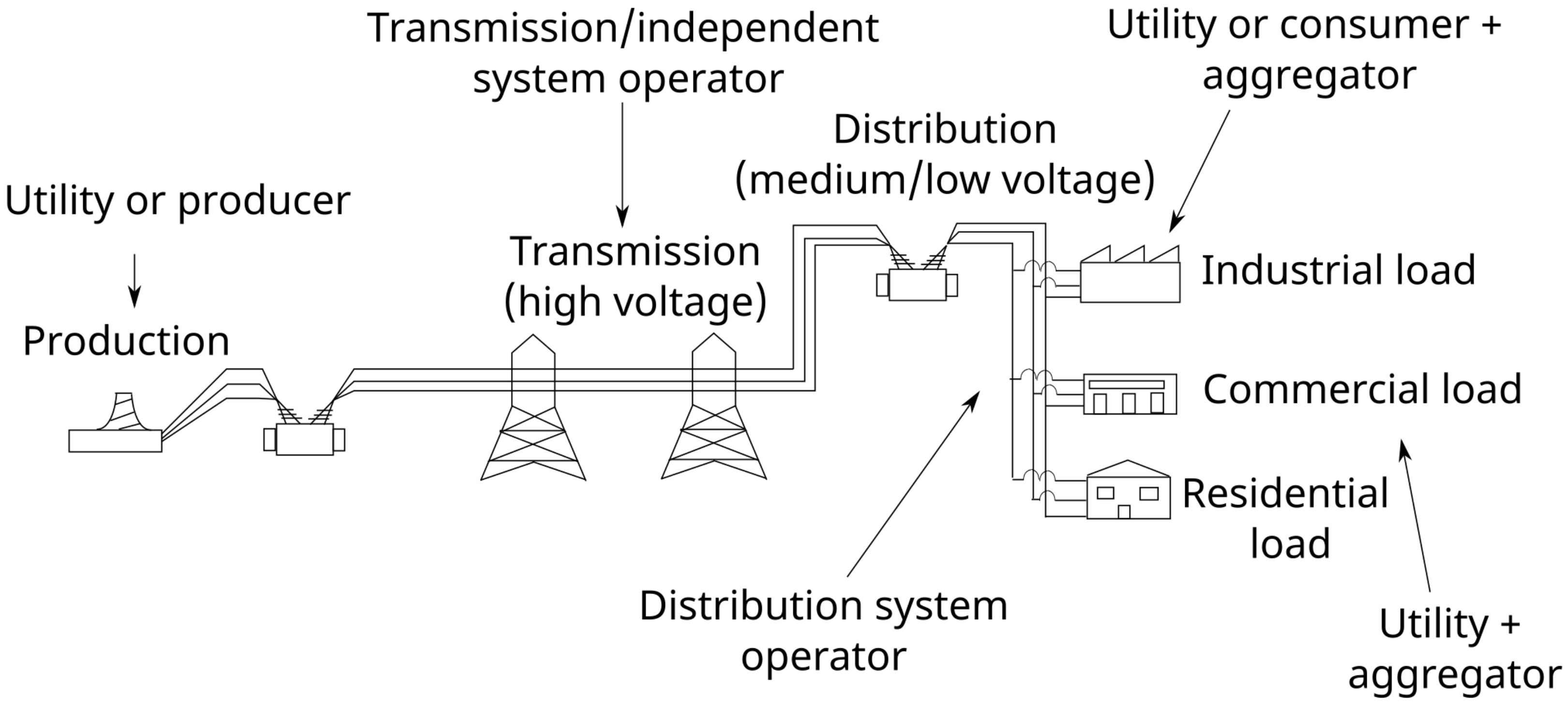
Energy shed from 1% rationing: 300 MWh

$$VOLL = \frac{2250000}{300} = 7500 \frac{\text{€}}{\text{MWh}}$$

More sophisticated computation of VOLL via simulation

Actors

Actors



Transmission/independent system operator

Utility or consumer + aggregator

Distribution (medium/low voltage)

Utility or producer

Transmission (high voltage)

Production

Industrial load

Commercial load

Residential load

Distribution system operator

Utility + aggregator

Uncertainty and reserves

Uncertainty

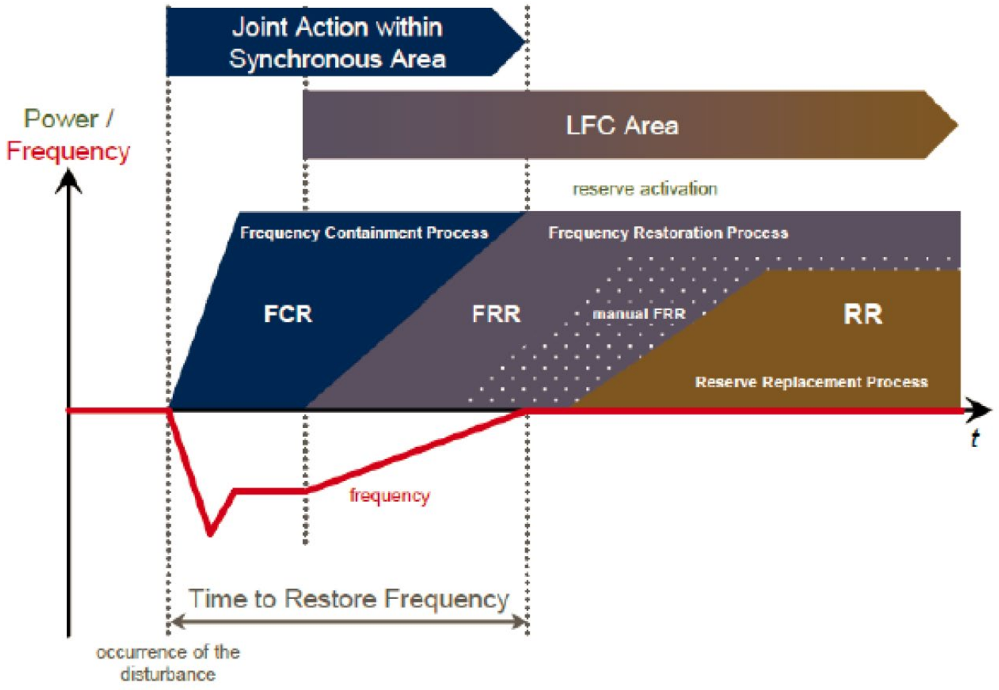
- Rainfall (affects hydro)
- Load forecast errors
- Renewable supply forecast errors
- Generator failures
- Transmission line failures
- Load failures

Contingency: failure of any system element (generator, line, transformer, load)

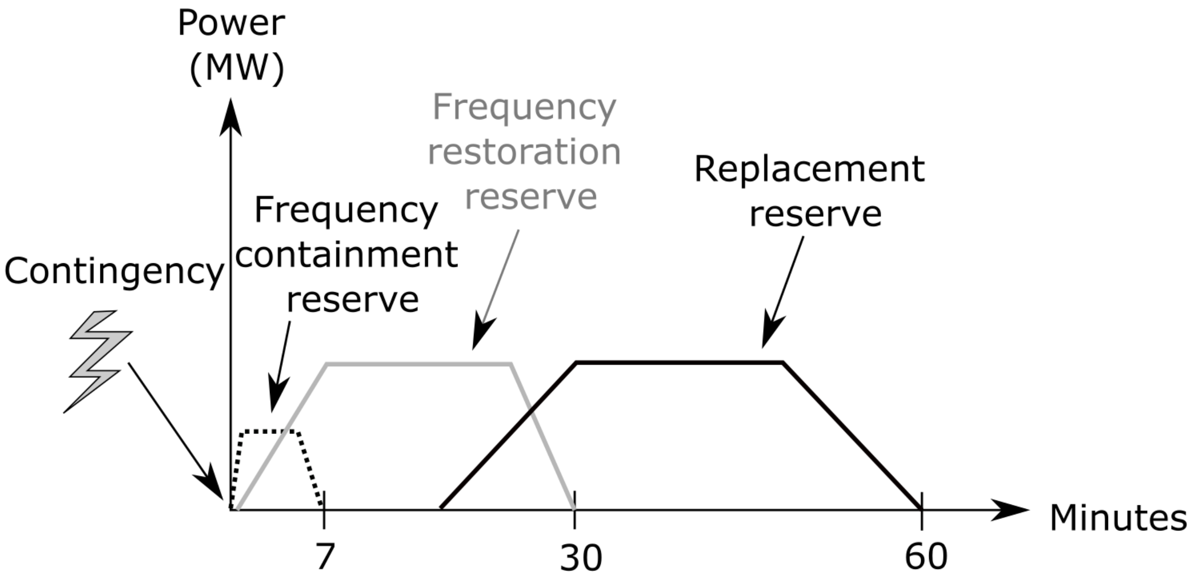
- ❖ Which of these uncertainties are short-term (hours ahead or in real time)?
- ❖ Which of these uncertainties are continuous/discrete?

Frequency control and restoration

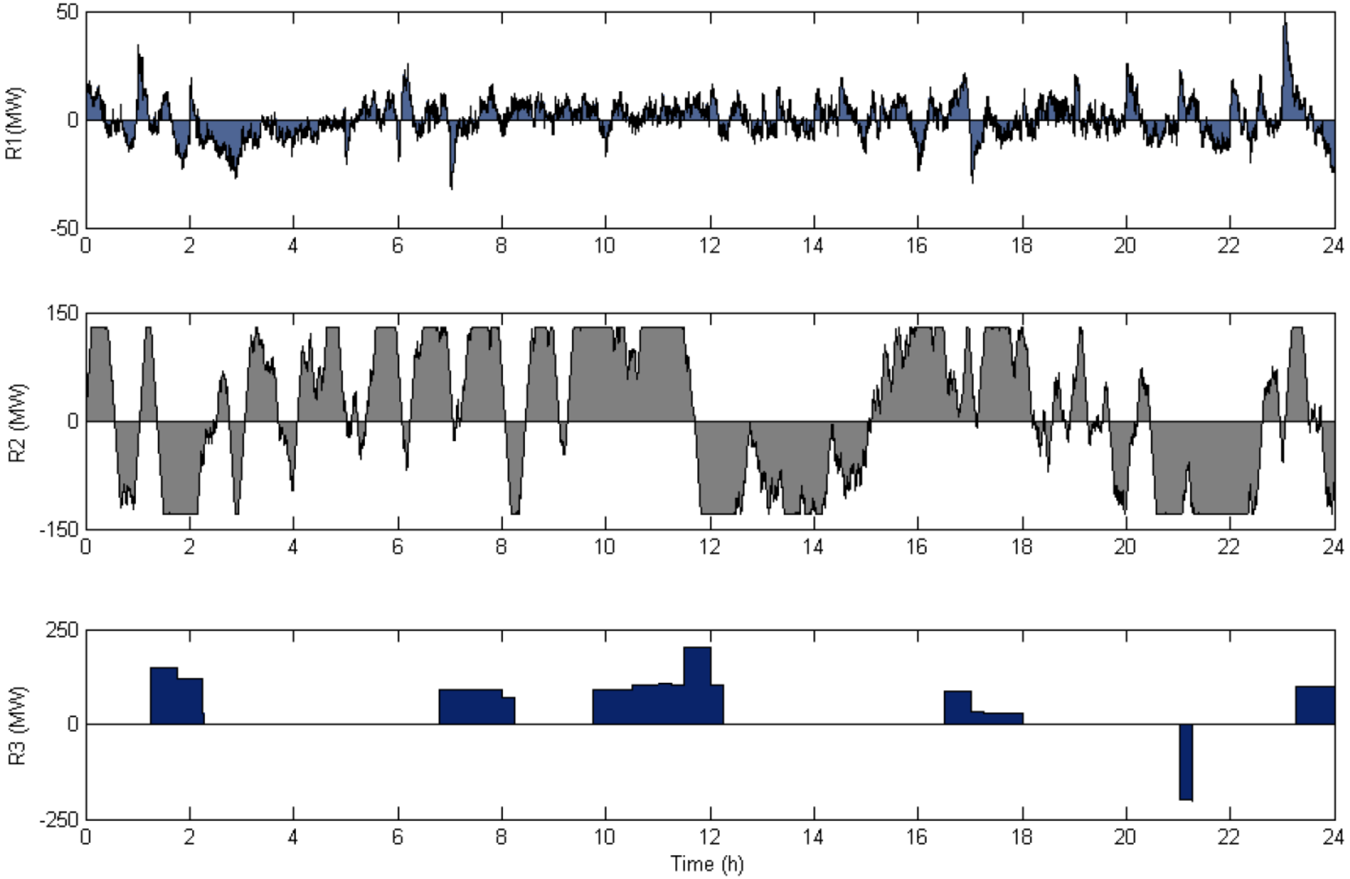
System frequency is an indicator of supply-demand balance



Sequential activation of reserves



Reserves in Belgium



Cost minimization with reserves

Consider n generators, operating cost f_i, capacity C_i, power demand D

$$\min_{p,r} \sum_{i=1}^{n} f_i\,(p_i)$$

$$\text{s.t.}\, p_i + r_i \leq C_i, i = 1, \dots, n$$

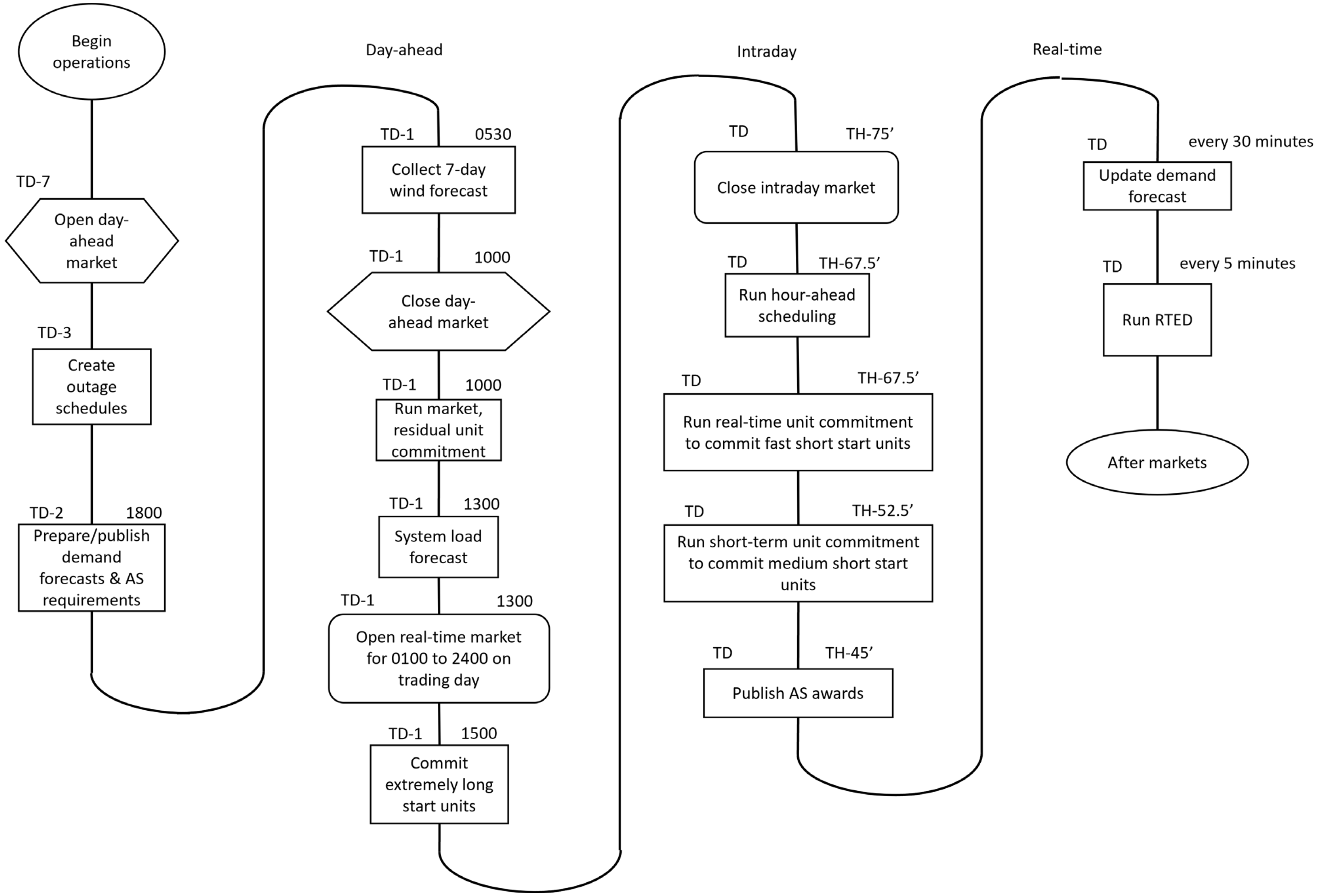
$$\sum_{i=1}^{n} p_i = D$$

$$\sum_{i=1}^{n} r_i \geq \max_{i=1,\dots,n} C_i$$

$$p_i, r_i \geq 0$$

Stages of decision-making

Flow chart of operations



Begin operations

TD-7
Open day-ahead market

TD-3
Create outage schedules

TD-2 1800
Prepare/publish demand forecasts & AS requirements

Day-ahead

TD-1 0530
Collect 7-day wind forecast

TD-1 1000
Close day-ahead market

TD-1 1000
Run market, residual unit commitment

TD-1 1300
System load forecast

TD-1 1300
Open real-time market for 0100 to 2400 on trading day

TD-1 1500
Commit extremely long start units

Intraday

TD TH-75’
Close intraday market

TD TH-67.5’
Run hour-ahead scheduling

TD TH-67.5’
Run real-time unit commitment to commit fast short start units

TD TH-52.5’
Run short-term unit commitment to commit medium short start units

TD TH-45’
Publish AS awards

Real-time

TD every 30 minutes
Update demand forecast

TD every 5 minutes
Run RTED

After markets

Analyzing the flow chart

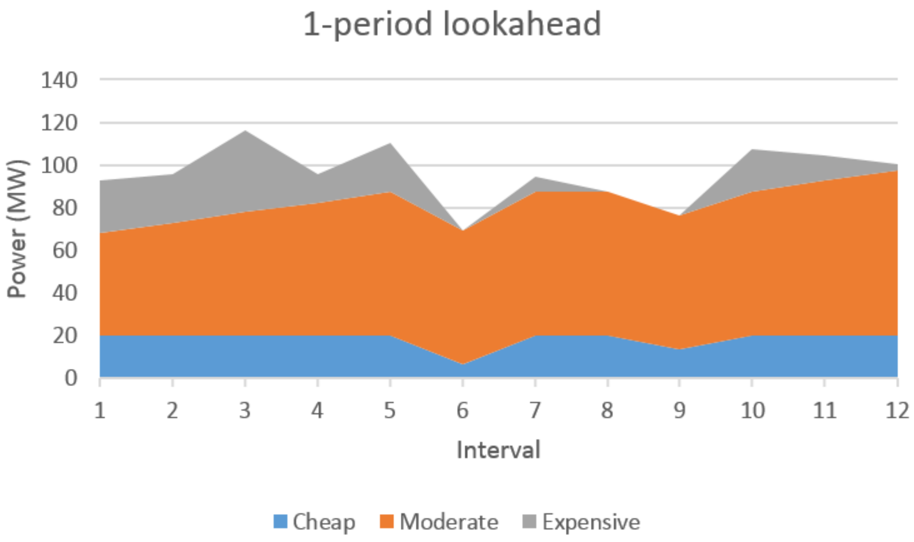
- Which decisions are binding before the day ahead/in the day ahead/in real time?
- What happens if the system operator demand forecast is much higher than traded power in day-ahead market?
- What parts of the supply chain are not actively controlled, according to the flow chart?
- Where would demand response enter in this flow chart?
- How many optimization models are shown in the flow chart?
- What would happen if each optimization model ignored future time periods?

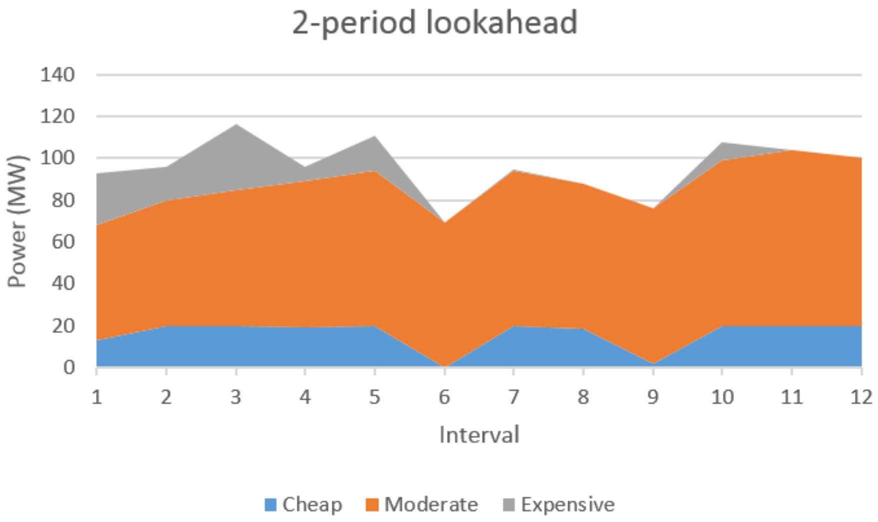
Example: looking ahead in operations

Consider the following example with three generators:

- Real-time economic dispatch: solved every 5 minutes for the next 5 minutes
- Initial conditions: 50 MW from expensive and 50 MW from moderate
- Demand: Gaussian with mean 100 MW, standard deviation 15 MW

Generator	Marginal cost ($/MWh)	Max (MW)	Ramp (MW/minute)
Cheap	0	20	$+\infty$
Moderate	10	$+\infty$	1
Expensive	80	$+\infty$	5





- Cost 5-minute lookahead: $1738
- Cost 10-minute lookahead : $1406

Why is the second policy doing better?

References

[1] A. Papavasiliou, Optimization Models in Electricity Markets, Cambridge University Press

https://www.cambridge.org/highereducation/books/optimization-models-in-electricity-markets/0D2D36891FB5EB6AAC3A4EFC78A8F1D3#overview