Generation Capacity Expansion

Anthony Papavasiliou, National Technical University of Athens (NTUA)

Source: chapter 11, Papavasiliou [1]

Outline

- Generation capacity expansion planning
- Investment in power generation capacity
- Market design for generation capacity expansion
    - VOLL pricing
    - Capacity mechanisms
    - Operating reserve demand curves

Generation capacity expansion planning

Generation capacity expansion planning

- The long-term capacity expansion planning problem determines the technology mix that minimizes the total cost of *investing in* and *operating* the system

In its simplest form:

- Two-stage optimization
    - First stage: invest in each technology
    - Second stage: operate technologies in order to satisfy demand
- Ignores demand response

Load versus demand

Load: amount of power that would be consumed if energy were supplied at zero price

Demand: consumption at a given price

- Equal to production
- Less than or equal to load

Example: load versus demand

Consider a system with one generator (100 MW) and demand function

$$D(v) = 110 - 5v$$

- Load: 110 MW
- Demand cannot exceed 100 MW

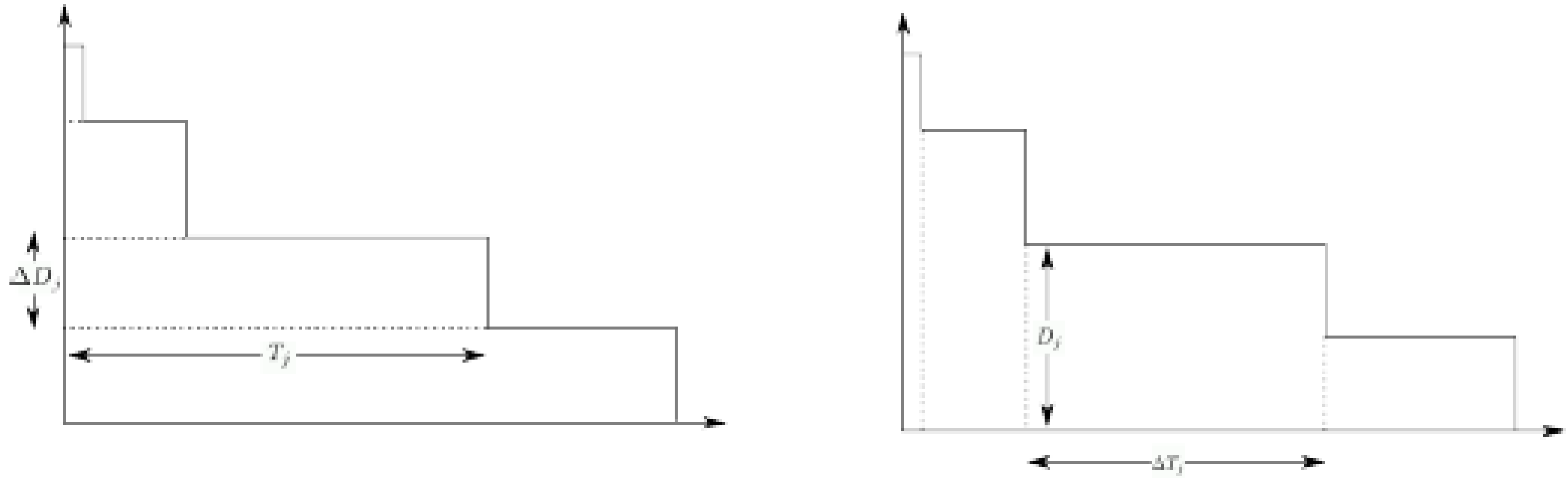
Basic ingredients of a generation capacity expansion model

- The two basic ingredients of a generation capacity expansion model is:
  - The investment cost and marginal cost of generators
  - The load profile
- The investment cost is typically converted to an hourly investment cost which is required for the construction of κατασκευή 1 MW of capacity
- Investment cost is therefore measured in $/MWh
- Marginal cost is measured in $/MWh
- In order for a technology to be an investment candidate, it must be the case that:

$$\text{if } I_1 \leq I_2 \leq \cdots \leq I_n, \text{ then } C_1 \geq C_2 \geq \cdots \geq C_n$$

Figure: Left: a horizontal partition of the load duration curve into load slices

Right: a vertical partition of the load duration curve into time slices



Generation capacity expansion planning model

Two-stage deterministic generation capacity expansion without flexible demand:

$$\max_{p,d,x} \sum_{j=1}^{m} \Delta T_j \cdot (V_j \cdot d_j - \sum_{i=1}^{n} MC_i \cdot p_{ij}) - \sum_{i=1}^{n} I_i \cdot x_i$$

$$(\rho_j \cdot \Delta T_j): d_j - \sum_{i=1}^{n} p_{ij} = 0, j = 1, \ldots, m$$

$$(\mu_{ij} \cdot \Delta T_j): p_{ij} \leq x_i, i = 1, \ldots, n, j = 1, \ldots, m$$

$$(\nu_j \cdot \Delta T_j): d_j \leq D_j, j = 1, \ldots, m$$

$$p, d, x \geq 0$$

- ΔT_j: Duration of vertical slice j
- V_j: VOLL for vertical slice j ($/MWh)
- D_j: Load of vertical slice j (MW)
- I_i: Investment cost of technology i ($/MWh)
- C_i: Marginal cost of technology i ($/MWh)

- x_i: Investment in technology i (MW)
- p_{ij}: Energy supplied to slide j from technology i (MWh)
- d_j: demand of vertical slice j (MWh)

Screening curves

- We seek a balance between operation and investment cost
- Consider a horizontal stratification of the load duration curve
- Base load (larger T_j) is better served by technologies with lower MC_i
- Peak load (smaller T_j) is better served by technologies with greater IC_i
- This logic is the basis of the graphical solution using **screening curves**

Scaling dual multipliers

- Dual multipliers are scaled by ΔT_j for every $j \; = \; 1, \dots \; m$
- In this way we avoid the propagation of the constant ΔT_j when we analyze the KKT conditions
- The scaling of a dual multiplier is essentially an advance substitution of the corresponding dual multiplier of a constraint, $\tilde{\nu}_j$, with the product of a constant ΔT_j and the new dual multiplier ν_j, where $\tilde{\nu}_j = \nu_j \cdot \Delta T_j$

Extensions of the basic model

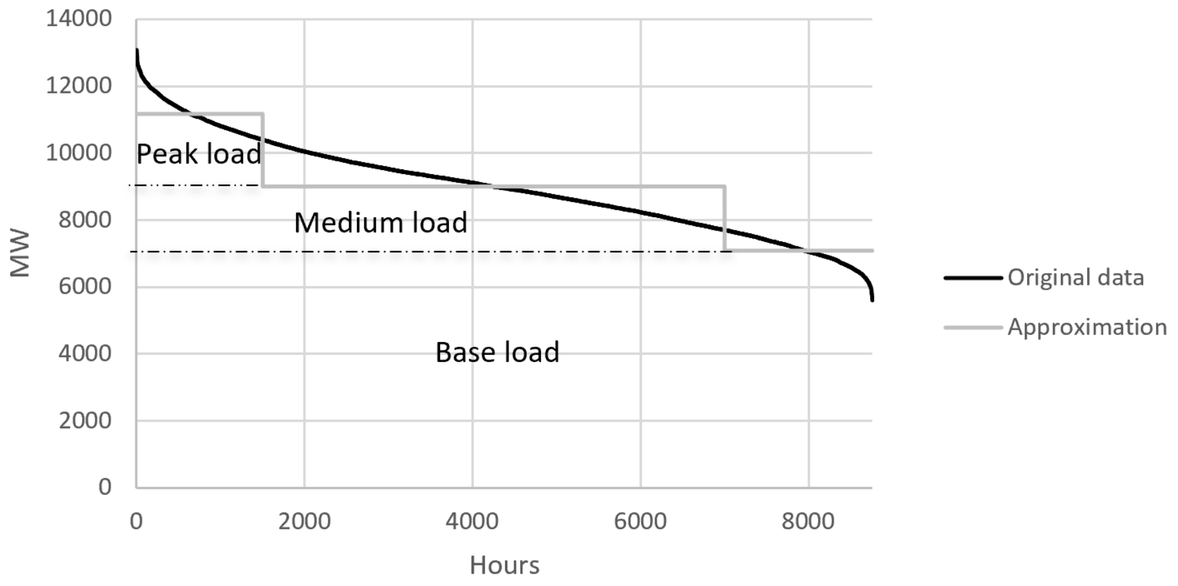
Generalizations:

- Transmission constraints
- Availability factors of different technologies
- Multiple time stages
  - Long-term evolution of equipment costs
  - Long-term evolution of load
  - Appearance of new technologies or retirement of existing equipment
- Uncertainty in evolution of equipment cost, uncertainty in the shape of the load duration curve, etc. → multi-stage stochastic programming problem

Example: candidate technologies

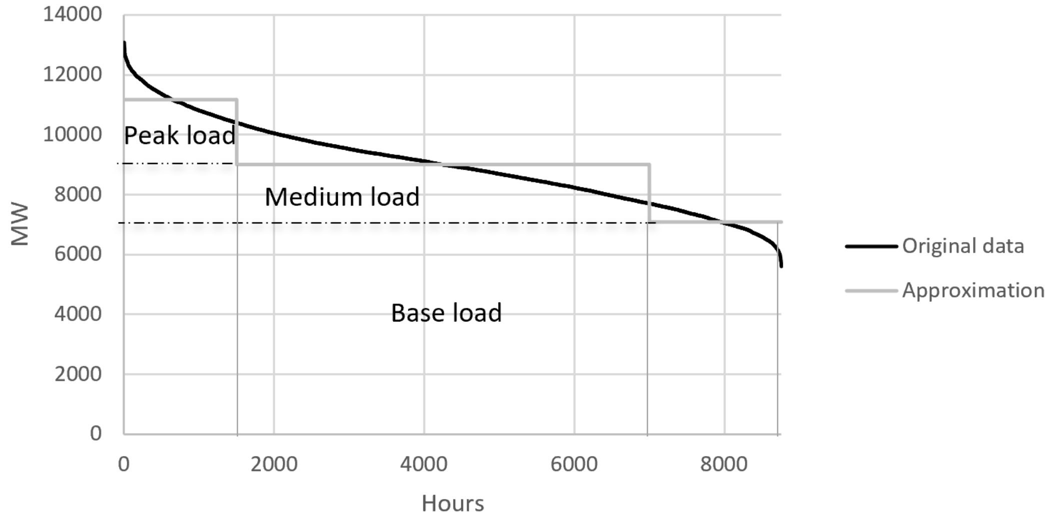
Technology	Marginal cost ($/MWh)	Investment cost ($/MWh)
Coal	25	16
Natural gas	80	5
Nuclear	6.5	32
Oil	160	2

Example: load in horizontal form



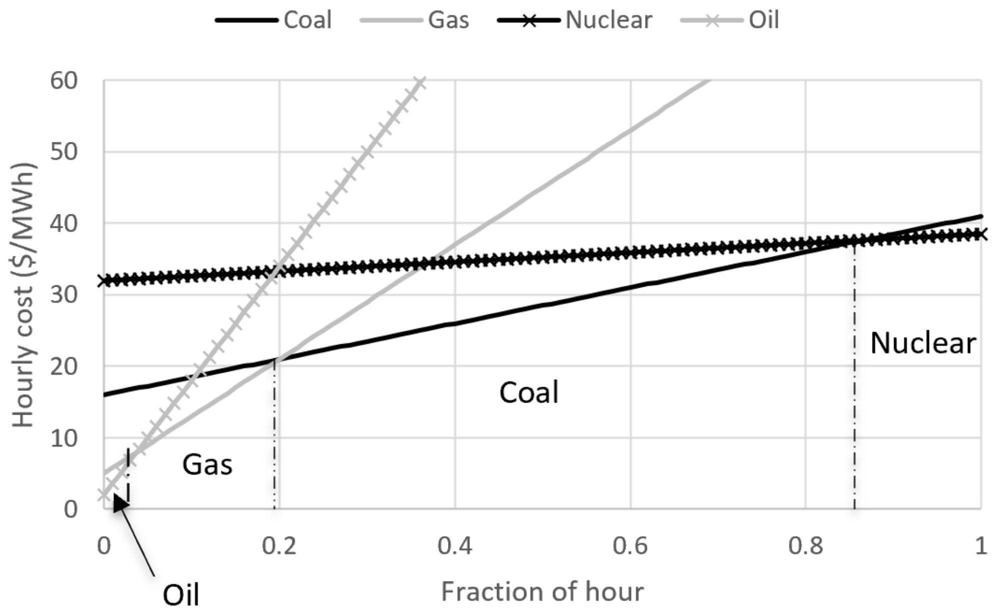
	Duration T_j (%)	Duration T_j (hours)	Load ΔD_j (MW)
Base load	100	8760	7086
Medium load	79.91	7000	1918
Peak load	17.12	1500	2165

Example: load in vertical form



	Duration ΔT_j (%)	Load D_j (MW)
Base load	20.09	7086
Medium load	62.79	9004
Peak load	17.12	11169

Screening curves

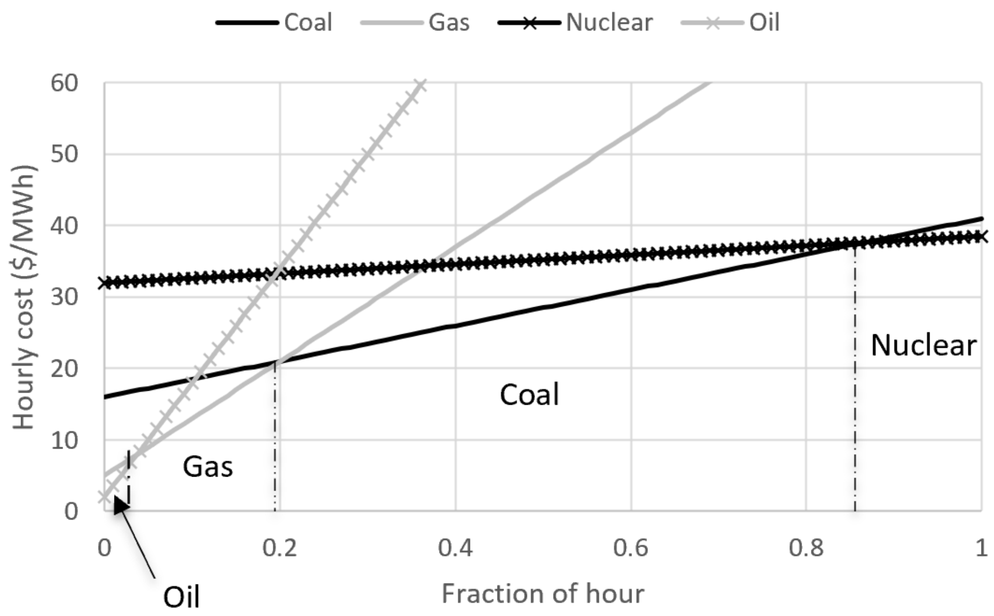


Screening curve: total hourly cost as a function of the fraction of time that a technology is used for producing energy

Βέλτιστη λύση

Fraction of time each technology should be functioning:

- Oil: $2 + 160f \leq 5 + 80f \Leftrightarrow f \leq 0.0375 \Rightarrow 0 - 328$ hours
- Natural gas: $\mathrm{f} > 0.0375$ and $5 + 80f \leq 16 + 25f \Leftrightarrow f \leq 0.2 \Rightarrow 328 - 1752$ hours
- Coal: $f > 0.2$ and $16 + 25f \leq 32 + 6.5f \Leftrightarrow f \leq 0.8649 \Rightarrow 1752 - 7576$ hours
- Nuclear energy: $0.8649 < f \leq 1 \Rightarrow 7576 - 8760$ hours



Example: optimal investments

	Duration (hours)	Load (MW)	Technology
Base load	8760	0-7086	Nuclear
Medium load	7000	7086-9004	Coal
Peak load	1500	9004-11169	Natural gas

Example: optimal production

	Base load slice (MWh)	Medium load slice (MW)	Peak load slice (MW)
Nuclear	7086	7086	7086
Coal	0	1918	1918
Natural gas	0	0	2165
Oil	0	0	0

KKT conditions of generation capacity expansion model

$$d_j - \sum_{i=1}^{n} p_{ij} = 0, j = 1, \dots, m$$

$$0 \leq \Delta T_j \cdot \mu_{ij} \perp x_i - p_{ij} \geq 0, i = 1, \dots, n, j = 1, \dots, m$$

$$0 \leq \Delta T_j \cdot \nu_j \perp D_j - d_j \geq 0, j = 1, \dots, m$$

$$0 \leq p_{ij} \perp \Delta T_j \cdot MC_i + \Delta T_j \cdot \mu_{ij} - \Delta T_j \cdot \rho_j \geq 0, i = 1, \dots, n, j = 1, \dots, m$$

$$0 \leq d_j \perp -\Delta T_j \cdot V_j + \Delta T_j \cdot \nu_j + \Delta T_j \cdot \rho_j \geq 0, j = 1, \dots, m$$

$$0 \leq x_i \perp I_i - \sum_{j=1}^{m} \Delta T_j \cdot \mu_{ij} \geq 0, i = 1, \dots, n$$

Returning to the example: computation of dual variables

- We can compute the dual variables recursively
- Since $x_{gas} > 0$, we have $\Delta T_{gas,peak} \cdot \mu_{gas,peak} = I_{gas} \Rightarrow \mu_{gas,peak} = 29.21 \frac{\$}{\text{MWh}}$
- And since $p_{gas,peak} > 0$ we have $\rho_{peak} = MC_{gas} + \mu_{gas,peak} = 109.21 \frac{\$}{\text{MWh}}$

- Since $p_{coal,peak} > 0$, we have $\mu_{coal,peak} = \rho_{peak} - MC_{coal} = 84.21 \frac{\$}{\text{MWh}}$
- Since $x_{coal} > 0$, we have $\Delta T_{coal,peak} \cdot \mu_{coal,peak} + \Delta T_{coal,medium} \cdot \mu_{coal,medium} = I_{coal} \Rightarrow \mu_{coal,medium} = 2.52 \frac{\$}{\text{MWh}}$
- And since $p_{coal,medium} > 0$, we have $\rho_{medium} = \mu_{coal,medium} + MC_{coal} = 27.53 \frac{\$}{\text{MWh}}$

- Similarly, we compute o $\mu_{nuc,medium}$, from which we can compute $\mu_{nuc,base}$, from which we can compute ρ_{base}

Example: dual variables

	Base load periods	Medium load periods	Peak load periods
Nuclear	6.06	21.02	102.71
Coal	0	2.52	84.21
Natural gas	0	0	29.21

The dual multipliers μ_{ij} (in $/MWh)

Base load periods	Medium load periods	Peak load periods
12.56	27.52	109.21

The dual multipliers ρ_j (in $/MWh)

Consumption criterion

Optimal consumption can be characterized as follows:

- If $0 < d_j < D_j$, then $V_j = \rho_j$
- If $d_j = 0$, then $V_j \leq \rho_j$
- If $d_j = D_j$, then $V_j \geq \rho_j$

Conclusion: For every j there exists a threshold ρ_j of valuation for determining consumption

Production criterion

For generators for which $x_i > 0$, optimal production is characterized as follows:

- If $0 < p_{ij} < x_i$, then $MC_i = \rho_j$
- If $p_{ij} = 0$, then $MC_i \geq \rho_j$
- If $p_{ij} = x_i$, then $MC_i \leq \rho_j$

Conclusion: For every i there is a threshold ρ_i of marginal cost for determining production

Investment criterion

Optimal investment can be characterized as follows:

- If $x_i = 0$, then $I_i \geq \sum_{j=1}^{m} \Delta T_j \cdot \mu_{ij}$
- If $x_i > 0$, then $I_i = \sum_{j=1}^{m} \Delta T_j \cdot \mu_{ij}$

Conclusion: The thresholds $\sum_{j=1}^{m} \Delta T_j \cdot \mu_{ij}$ determine if a technology is worth constructing or not

Utilization of investment

Suppose that $I_i > 0$ for all technologies, then if a technology is constructed ($x_i > 0$) this implies that it operates at its full capacity ($p_{ij} = x_i$ for some j)

Proof:

- Suppose that there is a technology for which $p_{ij} < x_i$ for all $j = 1, \ldots, m$
- Then from the KKT conditions one can show that $\mu_{ij} = 0$ for all j and $I_i = \sum_{j=1}^{m} \Delta T_j \cdot \mu_{ij}$, which is a contradiction

Investment in power generation capacity

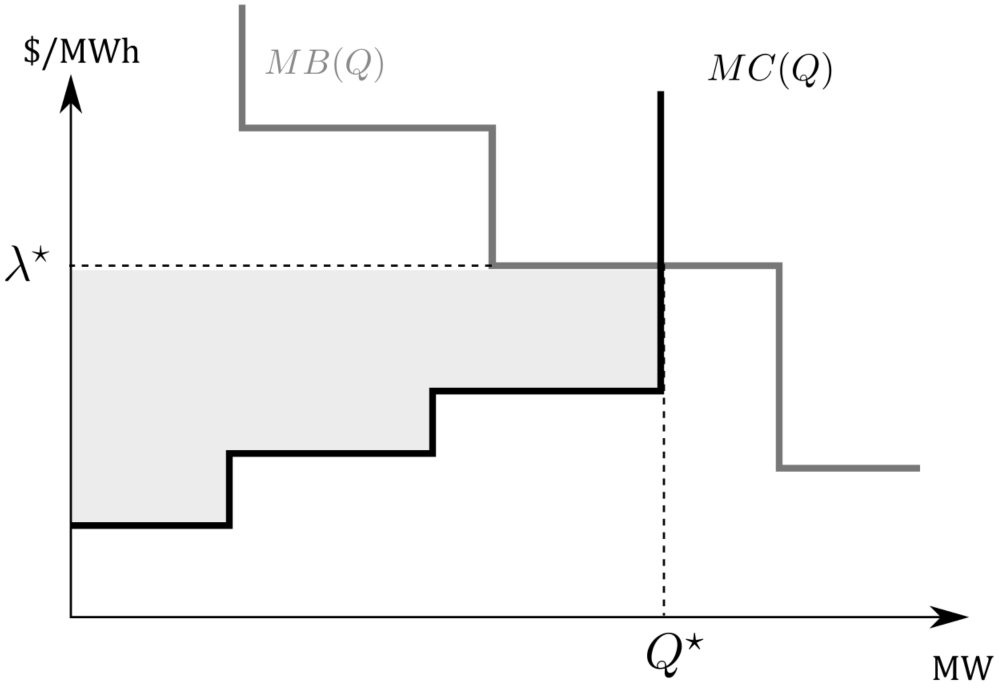
Energy-only markets

- **Energy-only markets**: energy markets that rely *exclusively* on energy price spikes in order to finance capital costs of investments though **scarcity rents**

- **Scarcity rents**: energy market revenues minus variable costs

Graphical illustration of scarcity rent

- $MC(\cdot)$: system marginal cost curve
- $MB(\cdot)$: system marginal benefit
- P^*/Q^* : market clearing price/quantity
- Shaded gray area: scarcity rent



Equilibrium model of energy-only market

- Agents:
  - Electricity producers
  - Electricity consumers
- Commodities:
  - Energy
- Markets:
  - Energy market (different price ρ_j for each time slice j)

Producer quantity adjustment

$$\max_{p,x} \sum_{j=1}^{m} \Delta T_j \cdot (\rho_j - MC_i) \cdot p_{ij} - I_i \cdot x_i$$

$$(\mu_{ij} \cdot \Delta T_j): p_{ij} \leq x_i, j = 1, \ldots, m$$

$$p, x \geq 0$$

The KKT are included in the centralized problem

Consumer quantity adjustment

$$\max_d \Delta T_j \cdot (V_j - \rho_j) \cdot d_j$$

$$(\nu_j \cdot \Delta T_j): d_j \leq D_j$$

$$d \geq 0$$

The KKT conditions are included in the centralized problem

Price adjustment

Price adjustment o the energy market for every vertical load slide j is expressed by the following condition:

$$d_j - \sum_{i=1}^{n} p_{ij} = 0$$

Observations

- Markets are efficient: KKT conditions of a competitive market equilibrium $\Leftrightarrow$ KKT conditions of centralized expansion planning
- The equivalence holds in the case of network constraints and uncertainty in consumption
- From KKT conditions, if $p_{ij} > 0$ then:

$$\mu_{ij} = \rho_j - MC_i$$

- This is the **scarcity rent** defined earlier
- Restatement of investment criterion: the investment will take place only if the scarcity rent can cover the investment cost, competition will push scarcity rents to equal investment cost:

$$0 \leq x_i \perp I_i - \sum_{j=1}^{m} \mu_{ij} \cdot \Delta T_j \geq 0$$

Example 11.3: prices and production

Market prices ρ_j are:

- Base load period: 12.56 \$/MWh
- Medium load period: 27.52 \$/MWh
- Peak load period: 109.2 \$/MWh

- The market price is not equal to the marginal cost of any unit for any period
- The decisions of all units are compatible with socially optimal

Example 11.3: profits and investments

	Profit μ_{i1} of base load period (\$/MWh)	Profit μ_{i2} of medium load period (\$/MWh)	Profit μ_{i3} of peak load period (\$/MWh)	Weighted profit $\sum_{j=1}^{m} \Delta T_j \mu_{ij}$ (\$/MWh)	Investment cost I_i (\$/MWh)	Covers investment cost? $\sum_{j=1}^{m} \Delta T_j \mu_{ij} = I_i$
Nuclear	6.06	21.02	102.7	32	32	Ναι
Coal	0	2.52	84.2	16	16	Ναι
Natural gas	0	0	29.2	5	5	Ναι
Oil	0	0	0	0	2	Όχι

- The units that are constructed cover their investment cost
- The units that cannot cover investment cost are not constructed

Energy-only markets in practice

Advantage: leads to optimal investment and operation of the system in the case of *perfect competition*

Disadvantages in practice:

- Low demand elasticity → volatile prices → uncertainty in scarcity rents → risky investment
- Load curtailment not possible in real time → markets do not clear for certain periods → regulator (not the market) must determine a price for these periods

Market design for generation capacity expansion

VOLL pricing

Capacity mechanisms

Operating reserve demand curves

Challenges of energy-only markets in practice

We have shown that energy-only markets can lead to the optimal mix in theory

Why do we not rely on energy-only markets in practice?

Some difficulties (among others) that occur in practice:

1. Market power $\Rightarrow$ price caps $\Rightarrow$ **missing money**
2. Consumers do not participate in price formation
3. Investment risk
4. Imperfect market designs (reserves, network access) and **incomplete** markets

Three designs that are encountered in practice

Energy-only markets are not the norm

In practice, the following designs occur more often (or combinations):

- VOLL pricing
- Capacity mechanisms
- Operating reserve demand curves

VOLL pricing

In **VOLL pricing**, the market model is described as follows:

- Producers maximize profit (quantity adjustment: production and investment)
- Price adjustment
- Consumers do not respond to prices
- When there is involuntary load curtailment, the market price is set equal to the **value of lost load** $VOLL$

Producer quantity adjustment

Producers decide on investment (x) and production (p) with the goal of maximizing profit:

$$\max_{p,x} \sum_{j=1}^{m} \Delta T_j \cdot (\rho_j - MC_i) \cdot p_{ij} - I_i \cdot x_i$$

$$(\Delta T_j \cdot \mu_{ij}): p_{ij} \leq x_i, i = 1, \ldots, n, j = 1, \ldots, m$$

$$p, x \geq 0$$

Price adjustment

Price is adjusted at every period $j = 1, \ldots, m$ such that demand equal production

$$D_j - ls_j - \sum_{i=1}^{n} p_{ij} = 0$$

VOLL pricing

Prices are set equal to VOLL during periods of scarcity

$$0 \leq ls_j \perp VOLL - \rho_j \geq 0$$

Market model with VOLL pricing

The market model that we describe in slides 41-44 is equivalent to the following optimization model:

$$(VOLLP): \min_{p,x,ls} \sum_{j=1}^{m} \Delta T_j \cdot (VOLL \cdot ls_j + \sum_{i=1}^{n} MC_i \cdot p_{ij}) + \sum_{i=1}^{n} I_i \cdot x_i$$

$$(\Delta T_j \cdot \rho_j): D_j - ls_j - \sum_{i=1}^{n} p_{ij} = 0, j = 1, \ldots, m$$

$$(\Delta T_j \cdot \mu_{ij}): p_{ij} \leq x_i, i = 1, \ldots, n, j = 1, \ldots, m$$

$$p, x, ls \geq 0$$

Proof: comparison of KKT conditions

Two consequences of the equivalence result

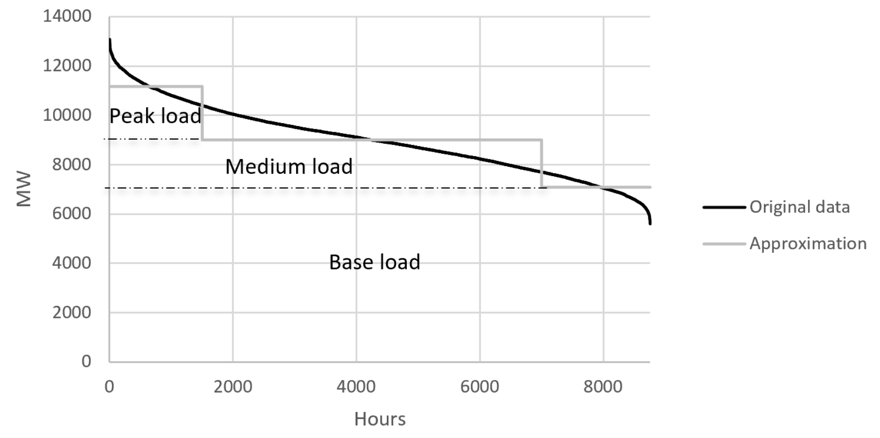
The result of the previous slide has two important consequences:

1. The VOLL pricing design can lead to the optimal mix if the estimate of $VOLL$ is precise
2. The mix can be very different from optimal if the estimate of $VOLL$ is imprecise $\Rightarrow$ important weakness of the mechanism

Example

Consider again the example of slides 13, 15

Technology	Fuel cost ($/MWh)	Investment cost ($/MWh)
Coal	25	16
Natural gas	80	5
Nuclear	6.5	32
Oil	160	2



In this example we consider the exact load duration curve (not the stepwise approximation)

Example: investments with precise and imprecise estimate of VOLL

Technology	Estimated $VOLL$: 1000 \$/MWh (precise)	Estiamted $VOLL$: 3000 \$/MWh (over-estimation)
Oil	953.3 MW	1215.7 MW
Natural gas	1417.3 MW	1417.3 MW
Coal	2852.6 MW	2852.6 MW
Nuclear	7353.8 MW	7353.8 MW

The peak technology if over-dimensioned if VOLL is over-estimated

Market design for generation capacity expansion

VOLL pricing

Capacity mechanisms

Operating reserve demand curves

Capacity mechanisms

The idea of capacity mechanisms is to conduct auctions that pay investors for building capacity <u>before</u> they actually build it

The goal is to reduce investment risk, and offer incentives for investing in new capacity

Cost of new entry (CONE)

The investment cost of the peak technology carries a special importance in capacity expansion planning, because in the optimal mix it must equal (approximately) the marginal benefit of additional capacity:

$$I_n \simeq VOLL \cdot LOLP$$

This drives the amount of capacity that needs to be installed in the system

This equality is used as a guide for how much capacity should be procured in capacity mechanisms

The investment cost of the peak technology I_n is called **cost of new entry** (CONE)

Example

Returning to the example of slide 47, in the optimal mix and for 20 hours the capacity is not enough to cover load, thus:

$$I_n = 2\ \$/\mathrm{MWh}$$

$$LOLP = \frac{20}{8760} = 0.0023$$

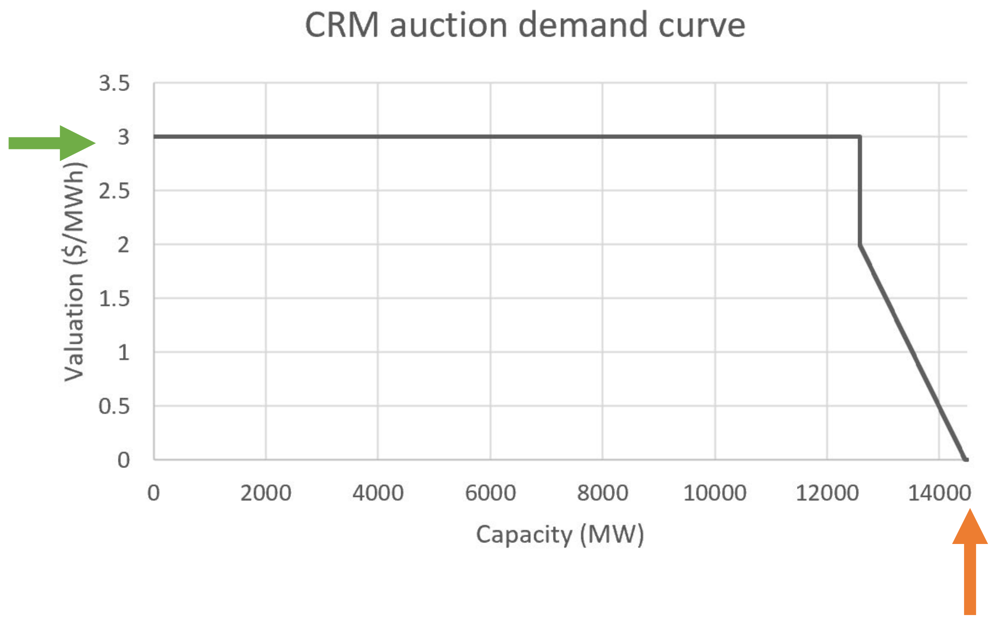
$$VOLL = 1000\ \$/\mathrm{MWh}$$

We confirm that

$$I_n = 2\,\frac{\$}{\mathrm{MWh}} \simeq VOLL \cdot LOLP = 2.3\,\frac{\$}{\mathrm{MWh}}$$

Demand curve for the capacity auction

- The optimal level of capacity in the example of slide 47 is 12577.1 MW
- In the demand curve of the figure, the demand for up to 12577.1 MW is 1.5 times CONE (to attract a minimum amount of investment), and drops to 0 $/MWh at 115% of target capacity



Market model

The market equilibrium model is expressed as the following equivalent optimization model:

$$(CRM): \max_{p,x,xd,ls} \int_{v=0}^{xd} VC(v)dv - \sum_{j=1}^{m} \Delta T_j \cdot \left(VOLL \cdot ls_j + \sum_{i=1}^{n} MC_i \cdot p_{ij} \right) - \sum_{i=1}^{n} I_i \cdot x_i$$

$$(\rho C): xd - \sum_{i=1}^{n} x_i = 0$$

$$(\Delta T_j \cdot \rho_j): D_j - ls_j - \sum_{i=1}^{n} p_{ij} = 0, j = 1, \ldots, m$$

$$(\Delta T_j \cdot \mu_{ij}): p_{ij} \leq x_i, i = 1, \ldots, n, j = 1, \ldots, m$$

$$p, x, xd, ls \geq 0$$

Model notation

$VC(\cdot)$ is the demand curve of the capacity auction (slide 53)

The dual multiplier ρC is the price of the capacity market

Capacity credit

The capacity credit is the estimated availability of a given technology during peak periods

For example, thermal units may have a capacity credit above 90%, while renewable energy sources may have a capacity credit below 50%

Generalization of model of slide 54, where CC_i is the capacity credit of technology i:

$$xd - \sum_{i=1}^{n} CC_i \cdot x_i = 0$$

Example

Returning to the example of slide 47, consider the demand curve of slide 53

Technology	Optimal mix	CRM mix
Oil	953.3 MW	1315.3 MW
Natural gas	1417.3 MW	1417.3 MW
Coal	2852.6 MW	2852.6 MW
Nuclear	7353.8 MW	7353.8 MW

Over-dimensioning of the peak technology, depends on the precise shape of the demand curve of slide 53

Market design for generation capacity expansion

VOLL pricing

Capacity mechanisms

Operating reserve demand curves

Operating reserve demand curves

Operating reserve demand curves (ORDCs) are described in section 6.4

The idea is that the system operator procures reserves with an elastic demand curve for reserves

During periods of scarcity, the reserve price carries along the energy price

Market model

Generation capacity expansion model with operating reserve demand curves:

$$(ORDC): \max_{p,r,x,dr,ls} \sum_{j=1}^{m} \Delta T_j \cdot \left(-VOLL \cdot ls_j + \int_{v=0}^{dr_j} VR_j(v)dv - \sum_{i=1}^{n} MC_i \cdot p_{ij} \right) - \sum_{i=1}^{n} I_i \cdot x_i$$

$$\left(\Delta T_j \cdot \rho R_j\right): dr_j - \sum_{i=1}^{n} r_{ij} = 0, j = 1, \dots, m$$

$$\left(\Delta T_j \cdot \rho_j\right): D_j - ls_j - \sum_{i=1}^{n} p_{ij} = 0, j = 1, \dots, m$$

$$\left(\Delta T_j \cdot \mu_{ij}\right): p_{ij} + r_{ij} \leq x_i, i = 1, \dots, n, j = 1, \dots, m$$

$$p, r, x, dr, ls \geq 0$$

Example: adaptive ORDC

ORDC curve that depends on VOLL and system imbalance distribution (equation 6.1, chapter 6):

$$VR_j(x) = \left(VOLL - \widehat{MC}_j\right) \cdot \left(1 - \Phi_{\mu(j),\sigma(j)}(x)\right)$$

- $\widehat{MC}_j$: estimate of marginal cost of the marginal unit in period j, e.g.

$$\widehat{MC}_j = \frac{D_j - \min_j D_j}{\max_j D_j - \min_j D_j} VOLL$$

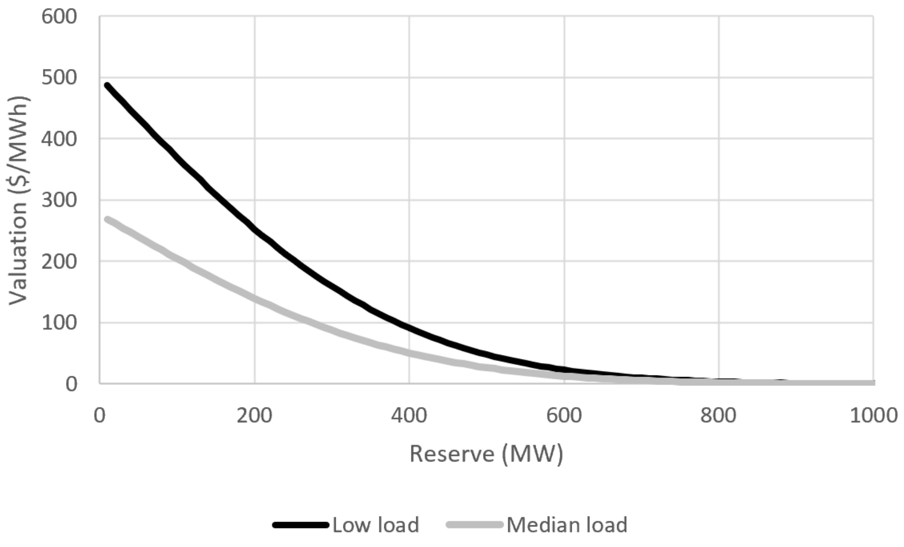
- $\Phi_{\mu(j),\sigma(j)}$: cumulative normal distribution function for imbalances with mean $\mu(j)$ and standard deviation $\sigma(j)$

Example: adaptive ORDC

Suppose that imbalances have a mean of 0 MW and standard deviation 300 MW

We present ORDCs for the central and minimum load:

- $j = 4380, D_{4380} = 8948.9$ MW, $\widehat{MC}_{4380} = 447.7$ \$/MWh
- $j = 8760, D_{8760} = 5600.8$ MW, $\widehat{MC}_{8760} = 0$ \$/MWh



Market equilibrium in an ORDC design

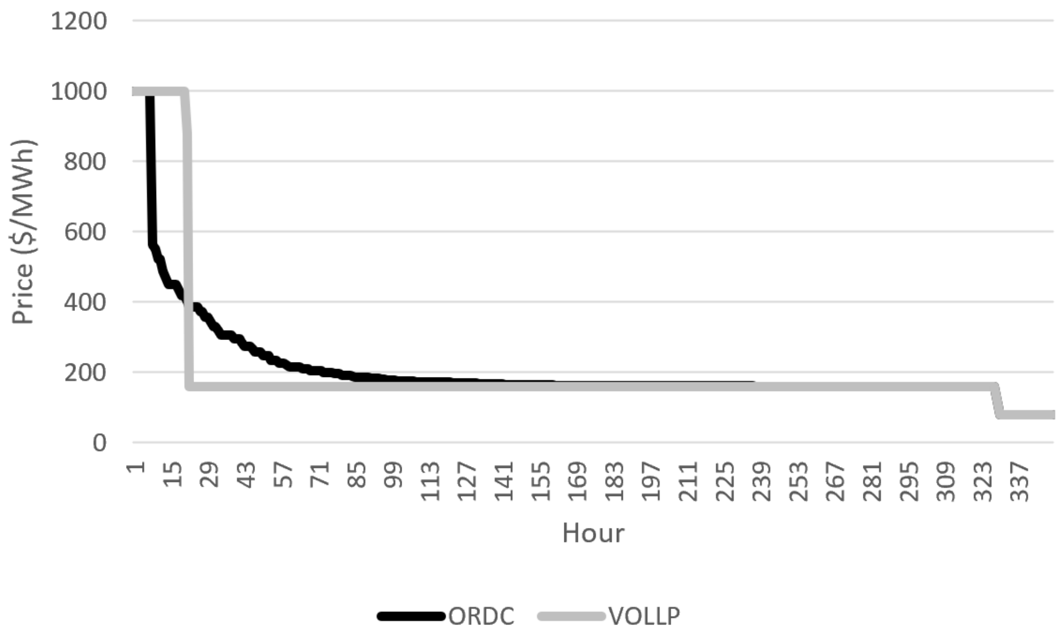
Returning to the example of slide 47, we have the capacity mix of the table below

Again more investment in the peak technology than optimal (but not as much as the CRM design)

Technology	Optimal mix	CRM mix	ORDC mix
Oil	953.3 MW	1315.3 MW	1150.8 MW
Natural gas	1417.3 MW	1417.3 MW	1417.3 MW
Coal	2852.6 MW	2852.6 MW	2852.6 MW
Nuclear	7353.8 MW	7353.8 MW	7353.8 MW

Market prices in an ORDC design

An important motivation for the ORDC design is that high prices occur with higher frequency and less intensity



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