Engineering, Economics & Regulation of the Electric Power Sector

ESD.934, 6.974

Session 9 & 10. Spring 2010
Module D.2

Principles of microeconomics
Application to power systems

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What do we want to know?

- How basic microeconomic principles translate into electricity markets?
- How is the price of electricity determined in a competitive market context?
- Are all the generation costs completely recovered in a competitive electricity market? Identify reasons for mismatches in cost recovery
- Study relationships between short and long term marginal costs and optimal wholesale electricity prices

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Study material

- Florence School of Regulation (FSR), "The economics of regulation: Competitive activities"
- P. Joskow, "The difficult transition to competitive electricity markets in the US", 2003 *(see page 58 and following of this document, which belongs to the study material of module B)*

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Readings

The rigorous mathematical formulation of the theory corresponding to the case study that is presented in the slides of this module

- "Wholesale marginal prices in competitive generation markets", I.J. Pérez-Arriaga & C. Meseguer, IEEE Transactions on Power Systems, vol. 12, No. 2, May 1997

Information for the Homework

- "Fixed Cost of a Best New Entrant Peaking Plant", Single Electricity Market Committee of Ireland, 2009, http://www.allislandproject.org/

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A simple example

(which is backed by sound theoretical analysis *)

(*) See "Wholesale marginal prices in competitive generation markets", Pérez-Arriaga, I.J., Meseguer, C., IEEE Transactions on Power Systems, vol. 12, no. 2, May 1997.

Example
Description of a power system

- Assume just 3 generation technologies *(conceptually):*
  - N (nuclear; baseload), C (coal; intermediate), F (fuel-oil; peaker)
- Under a traditional regulatory framework
  - Centralized investment planning & economic generation dispatch
  - Short & long-term average & marginal costs
- Under a market-based regulatory framework
  - Investment at risk & competitive rules for determination of market prices

Example
Description of a power system

- The data
  - 3 generation technologies:
    - Base-loaded, e.g. N (nuclear)
    - Mid-range, e.g. C (coal)
    - Peaker, e.g. F (fuel-oil)
  - per unit ($/kW) fixed costs: FN, FC, FF
  - per unit ($/kWh) variable costs: VN, VC, VF
  - cost of non-served energy: VP
- The unknowns
  - installed capacities: KN, KC, KF
  - energy generated: EN, EC, EF
  - non-served energy: EP

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Example
The strategy to be followed

- Start with an ideal **welfare maximization model** for electricity supply & consumption
  - Then analyze a **Traditional electricity company model** that is regulated so that welfare maximization is achieved
    - Centralized decisions of the company to meet demand
  - Then analyze a **Market model**
    - Decentralized decisions by all market agents

→**Compare** the expected outcome of the **traditional** & **market** models against the benchmark welfare maximization model & draw conclusions

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Centralized investment & operation
The optimization model

- Maximize social welfare:

surplus of consumers + surplus of suppliers =
= (utility to consumers – electricity acquisition cost) +
+ (sales revenues - supply cost) =
= utility to consumers - supply cost

- Pragmatic proxy *(given low elasticity of demand to price)*:

minimize an "extended" supply cost =
= supply cost + cost of any non-served energy
(therefore explicitly including estimated costs of non-supplied load, which is the negative component of the utility to consumers)

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Centralized investment & operation
The optimization model

- Assumptions:
  - Static planning model (just one future horizon year)
  - Continuous variables (investment costs, connection costs, no technical minima)
  - Deterministic production cost model
  - Constant fixed & variable costs (do not depend on volume of investments or production level)

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Centralized investment & operation
The optimization model

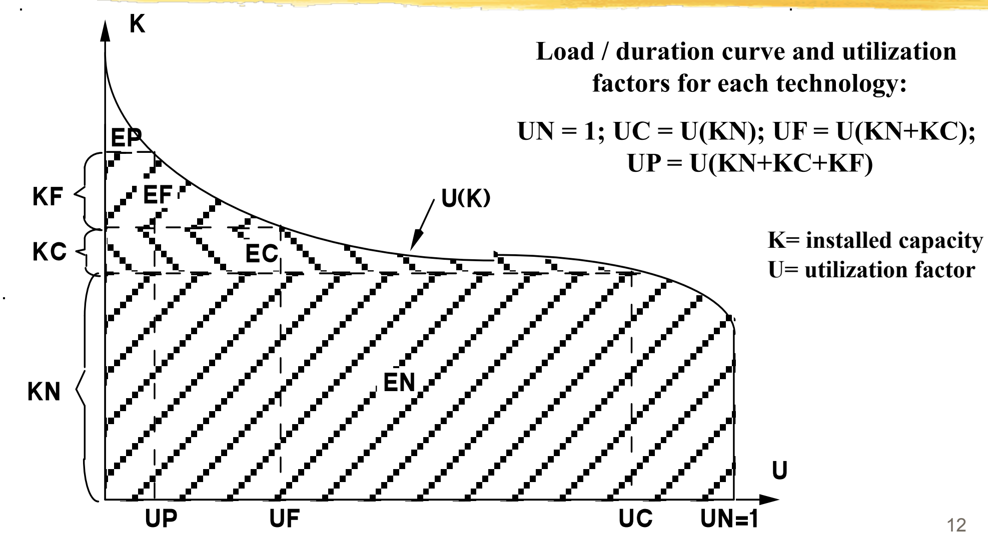
- Supply cost minimization problem:

$$\underset{KN,KC,KF,EN,EC,EF,EP}{\text{Minimize TC}} = KN*FN + KC*FC + KF*FF + VN*EN$$
$$+VC*EC + VF*EF + VP*EP$$

where the variables are: KN, KC, KF, EN, EC, EF, EP

- The production cost problem can be solved by inspection of the figure in next page: EN, EC, EF & EP are trivially obtained from the figure once KN, KC & KF are known
- If there are economies of scale, fixed costs are a function of the installed capacity: CFN(KN), CFC(KC), CFF(KF)

Centralized investment & operation
The solution *(graphically)*



Centralized investment & operation
The solution *(analytically)*

Optimality conditions for each technology:

$$\frac{\partial TC}{\partial KN} = 0 = \frac{\partial CFN(KN)}{\partial KN} + \frac{\partial}{\partial KN}(VN.EN + VC.EC + VF.EF + VP.EP) =$$
$$= FN(KN) + UC(VN - VC) + UF(VC - VF) + UP(VF - VP);$$
$$FN(KN) - UC(VC - VN) - UF(VF - VC) - UP(VP - VF) = 0$$

$$\frac{\partial TC}{\partial KC} = 0 = \frac{\partial CFC(FC)}{\partial KC} + \frac{\partial}{\partial KC}(VN.EN + VC.EC + VF.EF + VP.EP) =$$
$$= FC(KC) + \quad UF(VC - VF) + UP(VF - VP);$$
$$FC(KC) - UF(VF - VC) - UP(VP - VF) = 0$$
$$\frac{\partial TC}{\partial KF} = 0 = \frac{\partial CFF(KF)}{\partial KF} + \frac{\partial}{\partial KF}(VN.EN + VC.EC + VF.EF + VP.EP) = FF(KF) +$$
$$+UP(VF.VP);$$
$$FF(KF) - UP(VP - VF) = 0$$

If no economies of scale, then all CF functions are linear, with constant derivatives

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Centralized investment & operation
The solution *(analytically)*

- Optimality conditions in terms of competition between pairs of technologies:
  - Nuclear vs. Coal:
    FN + VN*UC = FC + VC * UC
  - Coal vs. Fuel-oil:
    FC + VC*UF = FF + VF*UF
  - Fuel-oil vs. unserved energy:
    FF + VF*UP = VP*UP

  which have a direct graphical interpretation

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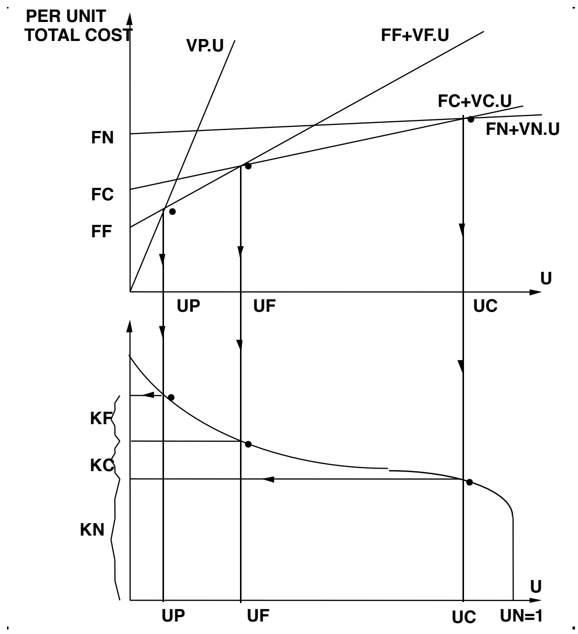

Graphical solution to the centralized optimal investment problem for generation

Centralized investment & operation
The short-term & the long-term

- Decisions are made with different time scales
  - Long-term: investments in **new** facilities
  - Short-term: operation of the **existing** facilities. Multiple time scales exist within operation
    - fuel purchase (or reservoir management)
    - maintenance scheduling
    - unit commitment
    - operating reserves
    - energy production

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Centralized investment & operation
The short-term & the long-term

For a given demand D

INVESTMENT MODEL:

Min total cost TC = F C (K) + V C* (K, D)
Investment K

WHERE:

GIVEN D — GIVEN K*

OPERATION MODEL

V C (K*, D) = min V C (K*, F)
Fuel F

SUBJECT TO MEETING DEMAND:
D = f (K*, F)

D: demand; K: installed capacity; F: fuel supply

K*(Q): optimal investment; VC*(K,Q): optimal operation

Centralized investment & operation
Short & long-term marginal costs

- Within the traditional framework of centralized planning & operation
- Long-term marginal cost
  - Additional total cost of supplying one more unit of demand, when evaluated in the long-term (includes investment & operation costs)
- Short-term marginal cost
  - Additional total cost of supplying one more unit of demand, when evaluated in the short-term (includes only operation costs of existing facilities)

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Centralized investment & operation
Short & long-term marginal costs

- Assume
  - optimal investments ➔ capacity is *perfectly adapted* to demand
  - optimal operation ➔ minimum costs of meeting demand (including costs of non-served energy) with the existing capacity

then

long-term marginal cost =

= short-term marginal cost

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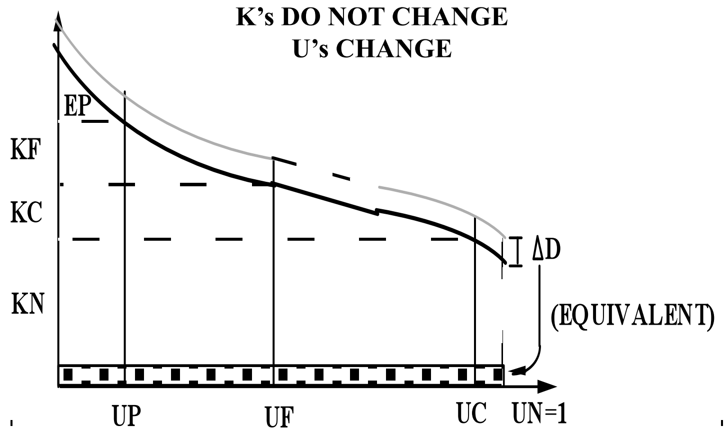
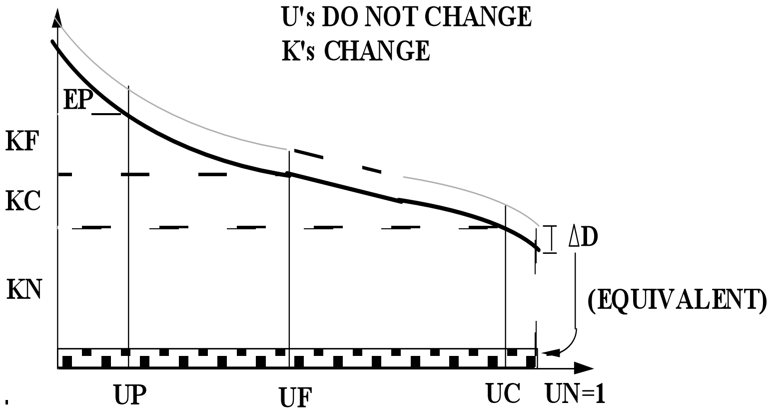
EXAMPLE (continuation)



Short-term marginal cost

$$SMC = \frac{\partial CV}{\partial D} = UP.VP + (UF-UP).VF + (UC-UF).VC + (1-UC).VN$$

EXAMPLE (continuation)



Long-term marginal cost

$$LMC = \frac{\partial TC}{\partial D} = FN + 1.VN$$

Centralized investment & operation
Short & long-term marginal costs

- Proof of the equality of SMC & LMC
- The conditions of optimality of investments and operation are required for the proof

LMC = FN + VN =

= FC + (VC - VN).UC + VN =

= FF + (VF - VC).UF + (VC - VN).UC + VN =

= (VP -VF).UP + (VF -VC).UF * (VC -VN).UC + VN =

=UP.VP+(UF-UP).VF+(UC-UF).VC+(1-UC).VN =

= SMC

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Market-based regulatory framework
The individual supply firm

- At a given time, there are two decision variables (interdependent) of firm i with a total production cost $TC_i(Q_i)$:
  - produced quantity Q_i
  - selling price P_i (may be an exogenous input)

- Goal of firm i: profit maximization

$$\max P_i.Q_i - TC_i(Q_i)$$

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Market-based regulatory framework
Supply characterization

- Generation firms
- When many units (optimally sized) of each technology are needed & much new investment is needed to meet demand growth ➔ no economies of scale ➔
  - per unit fixed supply costs do not depend on the volume of new investment (when it is much larger than the optimal unit size)
  - marginal & average long-term supply costs are equal

  and at every level *(e.g. peak, shoulder, off-peak)* of demand competition can exist

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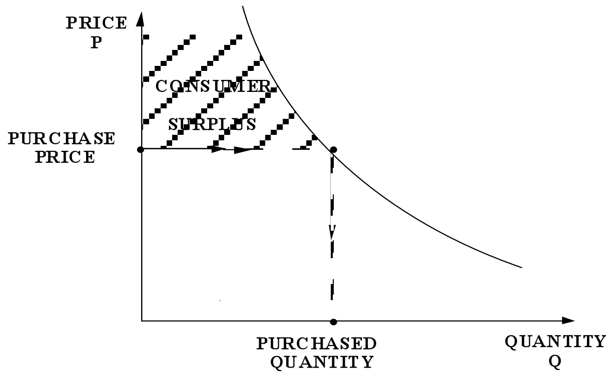
Market-based regulatory framework
Demand characterization



D(P): Response of demand D to price P as external input

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Market-based regulatory framework
Perfectly competitive market

- **Characterization**
  - Many small (compared to market size) supply firms that provide the same product ➔ none can control market price P
  - No entry cost or barriers to entry
- **Strategy of firm:** max profit ➔ produce Q_i while marginal cost $MC_i(Q_i) \le P$ ➔
  - At a given time, P results from the intersection of the demand curve P(Q) and the aggregated supply curve $\Sigma Q_i(P)=Q(P)$
  - Firms who loose, exit the market; if firms make extra profits there will be new entrants ➔ all remaining firms just recover costs (including reasonable return on investment)

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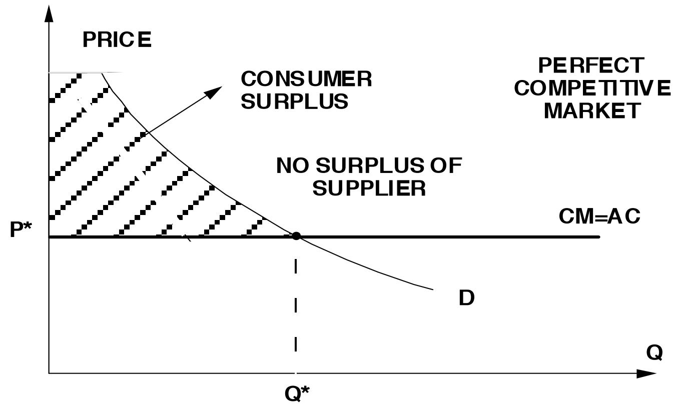
The classical static representation of a perfectly competitive market *(without economies of scale in supply)*, where no distinction is made between the long & short terms *(not of much use in electricity markets)*



No economies of scale in supply ➔ uniform supply cost

Example (cont.)
Perfectly competitive market (1)

- Under perfect competition fuel-oil generators bid their marginal costs & are paid the market marginal price & must have zero net profits

  revenues: VP.UP.KF

  costs: FF.KF+VF.UP.KF

  Since, under perfect competition, there is no margin for extra profit

  net profit = (VP - VF).UP.KF - FF.KF = 0

  Note that this is the same optimality condition of the centralized traditional approach ➔ under the assumed idealized conditions, both regulatory approaches (centralized & competitive) result in the same investment for each technology)

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Example (cont.)
Perfectly competitive market (2)

- Implications:
  - Under perfect competition in technology F the volume of investment in F coincides with the result under central planning
  - Under perfect competition the fixed & variable costs of technology F are exactly recovered *(zero extra profit)* if volume of investment in F is optimal
  - The above result holds irrespective whether investments in N or C are optimal or not *(but, in general, the optimal investment for a technology k depends on the actual investments of other technologies)*

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Market models
Non regulated monopoly

- **Characterization**
  - Single supplier for the entire market
    - exclusive franchise or a natural monopoly
  - No competitors may enter the market
  - Freedom to set the selling price (not a given input now)
- **Strategy of firm:** max profit ➔ produce Q while marginal revenue MR(Q) > marginal cost MC(Q), but charge the maximum price P(Q) that the demand can accept ➔ monopoly withholds demand to increase price

Note: marginal revenue MR=d/d(Q) [P(Q).Q]=P+Q.dP/dQ<P where P(Q) is given by the demand curve

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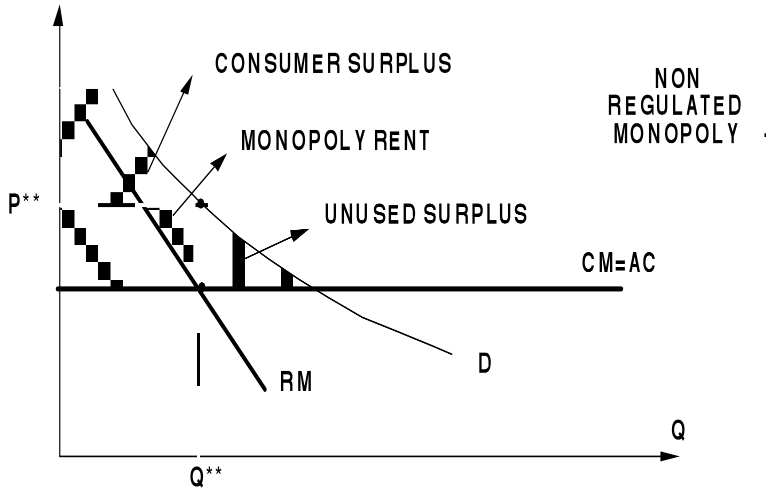
The classical static representation of a perfectly competitive market *(without economies of scale in supply)*, where no distinction is made between the long & short terms *(not of much use in electricity markets)*



No economies of scale in supply ➔ uniform supply cost

Example (cont.)
Non regulated monopoly

- Strategy of a monopoly of the fuel-oil technology:

  maximize net benefit NBF= (VP -VF).UP.KF - FF.KF

  ➔ $\frac{\partial NBF}{\partial KF}$ = 0 = (VP-VF).UP_{new}+(VP-VF).KF.$\frac{\partial UP}{\partial KF}$ -FF

  ➔ FF = (VP-VF).UP_{new}+(VP-VF).KF.$\frac{\partial UP}{\partial KF}$

- Comparison with the condition characterizing the competitive market (& centralized planning):

  FF = (VP-VF).UP

  Since $\frac{\partial UP}{\partial KF}$ <0 ➔ UP_{new}>UP ➔ the monopoly withholds production (investment)

Another possible strategy of the monopolist would be to raise prices up to VP

Market models
Oligopoly

- In an oligopolistic market
  - some firms have market power ➔ the *price setters*, who have some control on market price
  - remaining firms are *price takers*
- Price setter i decides price P_i & quantity Q_i based on the assessment of
  - its own impact
  - the expected behavior of competitors
- Diverse available alternative models to understand & to evaluate oligopolies ➔ results are intermediate between competition & non regulated monopoly

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Market power

- Market power: the ability of a firm or a group of firms to modify prices from the competitive level for its own benefit
  - the standard for the normal price is the competitive equilibrium price
  - market power depends on the structure, not on the rules in a competitive market

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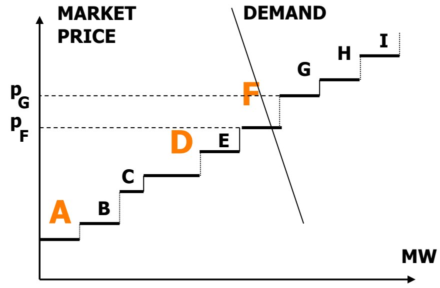
How can market power be exercised?



If plants A, D & F belong to the same generation company, removal of plant F (by bidding higher) increases the system price from P_F to P_G and the benefits to the company may increase

Always remember that …

"When structure is not conducive to competition, the regulator and pool operator will find themselves unsuccessfully chasing after conduct. The solution is not a better rule, but a change in structure"(*)

(*) From "Governance & regulation of power pools & system operators", Barker, J., Tenenbaum, B. & Woolf, F., World Bank, 1997.

Forms of market power

- Vertical market power: when a firm, having a monopoly position in a regulated segment (e.g. transmission or distribution), is able to favour itself, or its affiliate, in a potentially competitive segment
- Horizontal market power: when exercised within a potentially competitive segment (i.e. generation or supply), through the control of a substantial share of supply in the relevant market
- Distinguish between the existence and the (ab)use of market power
- Detection – more difficult than the definition
- Remedies – more effective if structural

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Detection of market power (1)

- Analysis of market concentration
  - Herfindhal-Hirschman Index

$$HHI = \Sigma_i (s_i)^2$$

$i = 1, \ldots, N$ firms in the "relevant market"

s_i = market share of firm i

- If N = 1 (monopoly) HHI = 10,000
- If N tends to ∞ (atomistic competition) HHI tends to 0
- Generally HHI < 1,000 indicates adequate competition
  HHI > 1,800 indicates inadequate competition

- However
  - in highly contestable markets, large firms may not have significant (horizontal) market power
- What is the relevant market?
  - Geographical dimension: grid constraints
  - Product dimension: capabilities of technologies, times of day

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Detection of market power (2)

- Analysis of market prices
  - Lerner Index measures the mark-up of prices over marginal costs, as a percentage of prices (on the assumption that, in competition, prices equal marginal costs)

$$\text{Lerner} = (P - MC)/P$$

- However:
  - difficulties in estimating costs and marginal costs accurately
  - prices higher than marginal costs may just signal scarcity (and may persist until new capacity enters in operation)

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Market power
Mitigation measures

- **Elasticity of demand**
- **Avoidance of situations with scarcity of supply**
- **Divestiture &/or virtual sales**
- **Volume of forward contracts / bid caps**
  - voluntary (not a real limitation factor)
  - mandatory (load to be supplied at a regulated price, mandatory volume of contracted capacity)
  - Recovery of stranded costs "by differences" have a similar effect
- **Uncertainty in demand**
- **Long-term consequences**
  - Contestability of new entrants
  - Demand elasticity (in the long-run)
  - Regulator response

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Detail *(mitigation of market power)*

Long-term contracts

- Margin of oligopolist if plant F **is not** removed: $Q_A.(P_F\text{-}CV_A)+Q_D.(P_F\text{-}CV_D)$
- Margin of oligopolist if plant F **is** removed:
  $Q_A.(P_G\text{-}CV_A)+Q_D.(P_G\text{-}CV_D)$
- Margin of oligopolist if Q_A is contracted at P_{con} & plant F **is not** removed:
  $Q_A.(P_{con}\text{-}CV_A)+Q_D.(P_F\text{-}CV_D)$
- Margin of oligopolist if Q_A is contracted at P_{con} & plant F **is** removed:
  $Q_A.(P_{con}\text{-}CV_A)+Q_D.(P_G\text{-}CV_D)$

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Detail *(mitigation of market power)*

Virtual power sales

- Measure to mitigate market power when there is excessive horizontal concentration (e.g. Alberta, France, Spain)
- Ownership of physical assets remains with the original owner
- But the commercialization of the output of the plants is offered in a competitive open auction. Possibilities
  - The energy that is produced by some prescribed plants
  - An option to buy energy from the company up to a prescribed capacity & for a prescribed time

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A conceptual model for the analysis of marginal remuneration

(to account for some of the numerous complexities of actual electricity markets)

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A conceptual model
The strategy *(same as in the example)*

- Compare an ideal **welfare maximization model** for electricity supply & consumption with two practical models
  - **Traditional utility model**
    Centralized utility decisions to meet demand
  - **Market model**
    Decentralized decisions by all market agents

  ➔Find the correct regulation of the two practical models so that each one exactly reproduces the results of the ideal model

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The models to be compared (1)

Welfare maximization model
(centralized)

Max { Social Net Benefit }

= Max {consumers' utility function-

- consumption investment cost-
- supply investment cost-
- supply variable cost }

Traditional utility model
(centralized)

Max {Electricity company Net Benefit }

subject to some regulatory restrictions (to be found)

The models to be compared (2)

Welfare maximization model
(centralized)

Max { Social Net Benefit }

= Max {consumers' utility function-

- consumption investment cost-
- supply investment cost-
- supply variable cost }

Market model
(decentralized)

Max {Net Benefit of each individual agent *(producer or consumer)*}

where both generators & consumers relate through market prices

➔ find economic efficient prices

Modeling assumptions

- Network aspects are ignored
- Continuous decision variables
- Uncertainty is represented by N scenarios
- Variable costs include the cost of non served energy
- Three time ranges for decision making

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Constraint classification

- **Common** (appear in all models)
  Examples: Technical minima, exhausted resources
- **Internal** (only in decentralized market model)
  Example: take or pay fuel supply contract
- **External** (only at system level)
  Examples: Network constraints, global environmental constraints ➔ need for economic incentives or ad hoc restraining rules in a decentralized environment

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Welfare maximization model (1)

MAX { Global net social benefit }
subject to

- Expansion constraints
  - reliability constraint (if any)
  - technology constraints
- Operation constraints
  - energy balance
  - security constraints
  - fuel constraints

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Welfare maximization model (2)

- **Objective function**

  Global net social benefit = Utility of consumers
  -- investment cost of consumers -
  - supply investment & operation costs
- **Decision variables**
  - consumers' installed capacity
  - demand
  - generators' installed capacity
  - connected generation capacity
  - generation output

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Competitive market model (1)

- For each generator:

MAX { Generator net benefit }

where

Generator net benefit =

= market price x generator output -

- generator investment & operation costs

subject to

- generator operation constraints

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Competitive market model (2)

- For each consumer:

MAX { Consumer net benefit }

where

Consumer net benefit =utility of consumption -

- market price x consumption - consumer investment costs

subject to

- Operation constraints

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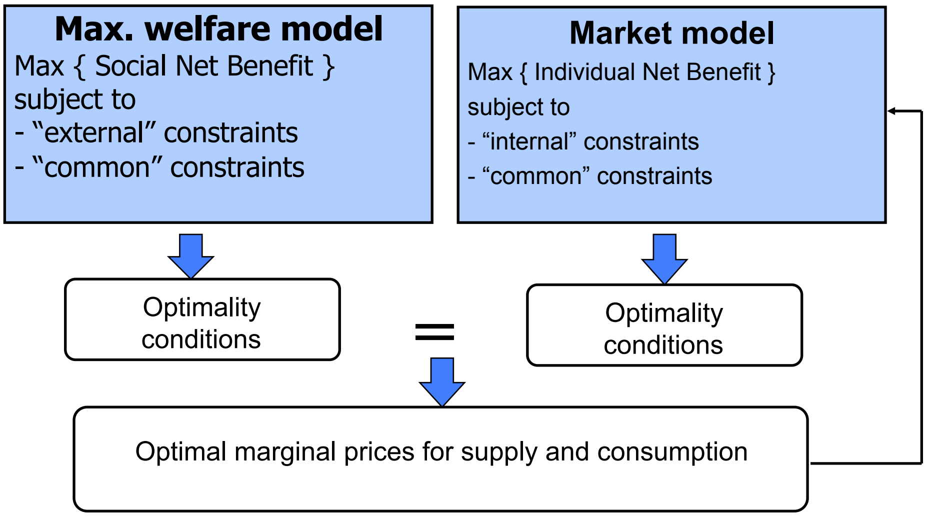
Competitive market model
Optimal marginal prices



Competitive market model
Optimal marginal prices (cont. 1)

Methodology:

- Formulate the Lagrangian function & the corresponding optimality conditions for each optimization problem
- Find (by observation) the market prices that result in identical optimality conditions → same results for the optimization problems

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Competitive market model
Optimal marginal prices (cont. 2)

- Optimality requires the use of different market **prices for the generation services** provided at each time range
  - Price of generated energy
    - This is the marginal price of "the last unit in the merit order" of energy production
  - Price of operating reserves
    - Only if some security target (minimum requirement) is set by the System Operator
  - Price of available installed capacity
    - Only if some reliability target is set somehow

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Capacity payment
Detail

- Payment per MW of installed capacity Kg of any generation technology g

$$\left(\frac{d\,\mathrm{Re}liability}{dKg} \Big/ \frac{d\,\mathrm{Re}liability}{dKpeak}\right).\left(\frac{dICpeak}{dKpeak} + \frac{dOPex}{dKpeak}\right)$$

Kpeak is the peak technology (lowest investment cost per MW)

ICpeak is the investment cost per MW of Kpeak

Opex are the operation costs of the power system *(note that* $\frac{dOPex}{dKpeak}$ *is negative)*

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Competitive market model
Optimal marginal prices (cont. 3)

- Optimality requires the use of the following market **price for consumption:**

  marginal price of generated energy +

  + marginal price of operating reserves +

  + marginal price of available installed capacity

  The last two terms only exist if security &/or reliability targets have been set by regulator &/or system operator

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The traditional utility model

The welfare maximization model can be reformulated in a format suitable for traditional utility regulation

MIN { Total utility supply cost }

subject to

- Expansion constraints
- Operation constraints

where the cost of non-supplied energy must be included in the utility supply costs

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The traditional utility model
Short & long term marginal costs

STMC = Increment of total cost for a per unit increment in demand, with the existing installed capacity

LTMC = Increment of total cost for a per unit increment in demand, with no restrictions on the existing installed capacity

- LTMC is equal to STMC only if:
  - Installed capacity is optimal
  - There is no active reliability constraint
  - The same scenarios of uncertainty are considered

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Cost recovery analysis

If a technology (or power plant) is perfectly adapted:

Marginal revenues + adjustment term
= total generation supply cost

Mismatches:

- common constraints on installed capacity (e.g. exhausted technology)
- internal constraints on installed capacity (e.g. Must build plant to burn waste)
- economies of scale in production

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Marginal pricing of generation services
The practice

- STMC must be obtained
  - ex ante from an operation model
  - ex post from actual data of operation
- Without inter-period couplings ➔ STMC is the variable cost (bid price) of the last dispatched unit in economic merit order
- Inter-period coupling requires accounting for
  - technical minima / start-up costs / unit commitment constraints (e.g. ramps) / hydro-thermal coordination

THANK YOU FOR YOUR ATTENTION

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