Power System Economics: Introduction

Daniel Kirschen
Why study power system economics?

- Generation
- Transmission
- Distribution
- Customer
Why study power system economics?

- Wholesale Market and Transmission Wires
  - Retailer
  - Retailer
  - Retailer

- Retail Market and Distribution Wires
  - Customer
  - Customer
  - Customer
Why introduce competitive electricity markets?

- Monopolies are inefficient
  - No incentive to operate efficiently
    - Costs are higher than they could be
  - No penalty for mistakes
    - Unnecessary investments

- Benefits of introducing competition
  - Increase efficiency in the supply of electricity
  - Lower the cost of electricity to consumers
  - Foster economic growth
Changes that are required

• Privatisation
  ♦ Government-owned organisations become private, for-profit companies

• Competition
  ♦ Remove monopolies
  ♦ Wholesale level: generators compete to sell electrical energy
  ♦ Retail level: consumers choose from whom they buy electricity

• Unbundling
  ♦ Generation, transmission, distribution and retail functions are separated and performed by different companies
  ♦ Essential to make competition work: open access
Wholesale Competition

Wholesale Market and Transmission Wires

IPP

IPP

IPP

IPP

IPP

Disco

Disco

Disco

Disco

Customer

Customer

Customer

Customer

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Fundamental underlying assumption

• Treat electricity as a commodity
• Examples of commodities:
  ♦ A ton of wheat
  ♦ A barrel of crude oil
  ♦ A cubic meter of natural gas
How do we define the electricity commodity?

• A Volt of electricity?
• An Ampere of electricity?
• A MW of electricity?
• A MWh of electricity?
Effect of cyclical demand

- **Light load period**
  - Need only the most efficient generators
  - Marginal cost is low

- **High load period**
  - Need to run less efficient generators
  - Marginal cost is high
Effect of cyclical demand

- Electrical energy cannot be stored economically
- Electrical energy must be produced when it is consumed
- Demand for electrical energy is cyclical
- Cost of producing electrical energy changes with the load
- Value of a MWh is not constant over the course of a day
- A MWh at peak time is not the same as a MWh at off-peak time
- Commodity should be “MWh at a given time”
Effect of location

- Price of electricity at A = marginal cost at A = 50£/MWh
- Price of electricity at B = marginal cost at B = 100£/MWh
- Transmission constraint segments the market
- Commodity should be “MWh at a given time and a given location”
Effect of security of supply

- Consumers expect a continuous supply of electricity
- Commodity should be “MWh at a given time and a given location, with a given security of supply”
- Need to study how we can achieve this security of supply
Effect of the laws of physics

Power flows from high price to low price!

\[ \pi_3 = 7.50 \, \text{$/MWh} \]

\[ \pi_2 = 11.25 \, \text{$/MWh} \]

\[ \pi_3 = 10.00 \, \text{$/MWh} \]
Effect of the laws of physics

Exporting oranges from Norway to Spain?
Unbundling

• Competitive market will work only if it is fair
• One participant should not be able to prevent others from competing
• Management of the network or system should be done independently from sale of energy
  - One company should not be able to prevent others from competing using congestion in the network
  - “Open access” to the transmission network
  - Separation of “energy businesses” from “wires businesses”
• Energy businesses become part of a competitive market
• Wire businesses remain monopolies
Consequences

• Monopoly vertically-integrated utility
  ♦ One organisation controls the whole system
  ♦ Single perspective on the system
• Unbundled competitive electricity market
  ♦ Many actors, each controlling one aspect
  ♦ Different perspectives, different objectives
• How to make the system work so that all participants are satisfied (i.e. achieve their objectives)?
Generating company (GENCO)

- Produces and sells electrical energy in bulk
- Owns and operates generating plants
  - Single plant
  - Portfolio of plants with different technologies
- Often called an Independent Power Producer (IPP) when coexisting with a vertically integrated utility
- Objective:
  - Maximize the profit it makes from the sale of energy and other services

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Distribution company (DISCO)

- Owns and operates distribution network
- Traditional environment:
  - Monopoly for the sale of electricity to consumers in a given geographical area
- Competitive environment:
  - Network operation and development function separated from sale of electrical energy
  - Remains a regulated monopoly
- Objective:
  - Maximize regulated profit
Retailer (called supplier in the UK)

• Buys electrical energy on wholesale market
• Resells this energy to consumers
• All these consumers do not have to be connected to the same part of the distribution network
• Does not own large physical assets
• Occasionally a subsidiary of a DISCO
• Objective:
  ♦ Maximize profit from the difference between wholesale and retail prices
Market Operator (MO)

- Runs the computer system that matches bids and offers submitted by buyers and sellers of electrical energy
- Runs the market settlement system
  - Monitors delivery of energy
  - Forwards payments from buyers to sellers
- Market of last resort run by the System Operator
- Forward markets often run by private companies
- Objective:
  - Run an efficient market to encourage trading
Independent System Operator (ISO)

- Maintains the security of the system
- Should be independent from other participants to ensure the fairness of the market
- Usually runs the market of last resort
  - Balance the generation and load in real time
- Owns only computing and communication assets
- An *Independent Transmission Company (ITC)* is an ISO that also owns the transmission network
- Objectives:
  - Ensure the security of the system
  - Maximize the use that other participants can make of the system
Regulator

- Government body
- Determines or approves market rules
- Investigates suspected abuses of market power
- Sets the prices for products and services provided by monopolies

Objectives
- Make sure that the electricity sector operates in an economically efficient manner
- Make sure that the quality of the supply is appropriate
Small Consumer

- Buys electricity from a retailer
- Leases a connection from the local DISCO
- Participation in markets is usually limited to choice of retailer
- Objectives:
  - Pay as little as possible for electrical energy
  - Obtain a satisfactory quality of supply
Large Consumer

• Often participates actively in electricity market
• Buys electrical energy directly from wholesale market
• Sometimes connected directly to the transmission network
• May offer load control ability to the ISO to help control the system
• Objectives:
  ♦ Pay as little as possible for electrical energy
  ♦ Obtain a satisfactory quality of supply
Outline of the course (I)

• Basic concepts from microeconomics
  ♦ Fundamentals of markets
  ♦ Theory of the firm
  ♦ Perfect and imperfect competition
  ♦ Contracts
• Organisation of electricity markets
• Participating in electricity markets
Outline of the course (II)

- Security and ancillary services
  - Energy services
  - Network services
  - System perspective
  - Provider perspective

- Effect of network on prices
- Investing in transmission
- Investing in generation

Take the network into consideration
Fundamentals of Markets

Daniel Kirschen

University of Manchester
Let us go to the market...

- Opportunity for buyers and sellers to:
  - compare prices
  - estimate demand
  - estimate supply

- Achieve an equilibrium between supply and demand
How much do I value apples?

Price

One apple for my break

Quantity
How much do I value apples?

Price

One apple for my break

Take some back for lunch

Quantity
How much do I value apples?

Price

- One apple for my break
- Take some back for lunch
- Enough for every meal

Quantity
How much do I value apples?

Price

- One apple for my break
- Take some back for lunch
- Enough for every meal
- Home-made apple pie

Quantity
How much do I value apples?

Consumers spend until the price is equal to their marginal utility.
Demand curve

- Aggregation of the individual demand of all consumers
- Demand function:
  \[ q = D(\pi) \]
- Inverse demand function:
  \[ \pi = D^{-1}(q) \]
Elasticity of the demand

- Slope is an indication of the elasticity of the demand
- High elasticity
  - Non-essential good
  - Easy substitution
- Low elasticity
  - Essential good
  - No substitutes
- Electrical energy has a very low elasticity in the short term
Elasticity of the demand

- Mathematical definition:

\[ \varepsilon = \frac{dq}{q \frac{d\pi}{\pi}} = \frac{\pi}{q} \cdot \frac{dq}{d\pi} \]

- Dimensionless quantity
Supply side

• How many widgets shall I produce?
  ▪ Goal: make a profit on each widget sold
  ▪ Produce one more widget if and only if the cost of producing it is less than the market price

• Need to know the cost of producing the next widget
• Considers only the variable costs
• Ignores the fixed costs
  ▪ Investments in production plants and machines
How much does the next one cost?

Cost of producing a widget

Normal production procedure

Total Quantity
How much does the next one costs?

Cost of producing a widget

Use older machines

Total Quantity
How much does the next one costs?

Cost of producing a widget

Total

Quantity

Second shift production
How much does the next one costs?

Cost of producing a widget

Total Quantity

Third shift production
How much does the next one costs?

Cost of producing a widget

Extra maintenance costs

Total Quantity
Supply curve

- Aggregation of marginal cost curves of all suppliers
- Considers only variable operating costs
- Does not take cost of investments into account
- Supply function:
  \[ \pi = S^{-1}(q) \]
- Inverse supply function:
  \[ q = S(\pi) \]
Market equilibrium

- Price
- Supply curve: Willingness to sell
- Demand curve: Willingness to buy
- Market clearing price
- Volume transacted
- Market equilibrium

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Supply and Demand

Price

Quantity

supply

equilibrium point

demand
Market equilibrium

\[ q^* = D(\pi^*) = S(\pi^*) \]

\[ \pi^* = D^{-1}(q^*) = S^{-1}(q^*) \]

- Sellers have no incentive to sell for less
- Buyers have no incentive to buy for more!
Centralised auction

- Producers enter their bids: quantity and price
  - Bids are stacked up to construct the supply curve
- Consumers enter their offers: quantity and price
  - Offers are stacked up to construct the demand curve
- Intersection determines the market equilibrium:
  - Market clearing price
  - Transacted quantity
Centralised auction

- Everything is sold at the market clearing price
- Price is set by the “last” unit sold
- Marginal producer:
  - Sells this last unit
  - Gets exactly its bid
- Infra-marginal producers:
  - Get paid more than their bid
  - Collect economic profit
- Extra-marginal producers:
  - Sell nothing
Bilateral transactions

- Producers and consumers trade directly and independently
- Consumers “shop around” for the best deal
- Producers check the competition’s prices
- An efficient market “discovers” the equilibrium price
Efficient market

• All buyers and sellers have access to sufficient information about prices, supply and demand

• Factors favouring an efficient market
  ▪ number of participants
  ▪ Standard definition of commodities
  ▪ Good information exchange mechanisms
Examples

• Efficient markets:
  ▪ Open air food market
  ▪ Chicago mercantile exchange

• Inefficient markets:
  ▪ Used cars
Consumer’s Surplus

• Buy 5 apples at 10p
• Total cost = 50p
• At that price I am getting apples for which I would have been ready to pay more
• Surplus: 12.5p
Economic Profit of Suppliers

- Cost includes only the variable cost of production
- Economic profit covers fixed costs and shareholders’ returns
Social or Global Welfare

Consumers’ surplus + Suppliers’ profit = Social welfare
Market equilibrium and social welfare

Market equilibrium

Artificially high price:
• larger supplier profit
• smaller consumer surplus
• smaller social welfare
Market equilibrium and social welfare

Artificially low price:
- smaller supplier profit
- higher consumer surplus
- smaller social welfare

Welfare loss
Market Equilibrium: Summary

- Price = marginal revenue of supplier
  = marginal cost of supplier
  = marginal cost of consumer
  = marginal utility to consumer

- Market price varies with offer and demand
  - If demand increases
    - Price increases beyond utility for some consumers
    - Demand decreases
    - Market settles at a new equilibrium
  - If demand decreases
    - Price decreases
    - Some producers leave the market
    - Market settles at a new equilibrium

- Never a shortage
Advantages over a Tariff

- Tariff: fixed price for a commodity
- Assume tariff = average of market price
- Period of high demand
  - Tariff < marginal utility and marginal cost
  - Consumers continue buying the commodity rather than switch to another commodity
- Period of low demand
  - Tariff > than marginal utility and marginal cost
  - Consumers do not switch from other commodities
Concepts from the Theory of the Firm

Daniel Kirschen

University of Manchester
Production function

\[ y = f(x_1, x_2) \]

- \( y \): output
- \( x_1, x_2 \): factors of production

Law of diminishing marginal products
Long run and short run

- Some factors of production can be adjusted faster than others
  - Example: fertilizer vs. planting more trees
- Long run: all factors can be changed
- Short run: some factors cannot be changed
- No general rule separates long and short run
Input-output function

\[ y = f \left( x_1, \overline{x_2} \right) \quad \overline{x_2} \text{ fixed} \]

The inverse of production function is the input-output function

\[ x_1 = g \left( y \right) \text{ for } x_2 = \overline{x_2} \]

Example: amount of fuel required to produce a certain amount of power with a given plant
Short run cost function

\[ c_{SR}(y) = w_1 \cdot x_1 + w_2 \cdot x_2 = w_1 \cdot g(y) + w_2 \cdot x_2 \]

- \( w_1, w_2 \): unit cost of factors of production \( x_1, x_2 \)
Short run marginal cost function

\[ c_{SR}(y) \]

Convex due to law of marginal returns

\[ \frac{dc_{SR}(y)}{dy} \]

Non-decreasing function
Optimal production

• Production that maximizes profit:

\[
\max_y \left\{ \pi \cdot y - c_{SR} (y) \right\} \\
\frac{d\left\{ \pi \cdot y - c_{SR} (y) \right\}}{dy} = 0 \\
\pi = \frac{dc_{SR} (y)}{dy} \\
\text{Only if the price } \pi \text{ does not depend on } y \iff \text{perfect competition}
\]
Costs: Accountant’s perspective

- In the short run, some costs are variable and others are fixed
- Variable costs:
  - labour
  - materials
  - fuel
  - transportation
- Fixed costs (amortised):
  - equipments
  - land
  - Overheads
- Quasi-fixed costs
  - Startup cost of power plant
- Sunk costs vs. recoverable costs
Average cost

\[ c(y) = c_v(y) + c_f \]

\[ AC(y) = \frac{c(y)}{y} = \frac{c_v(y)}{y} + \frac{c_f}{y} = AVC(y) + AFC(y) \]
Marginal vs. average cost

Production

MC

AC

/unit
When should I stop producing?

- Marginal cost = cost of producing one more unit
- If $MC > \pi$ next unit costs more than it returns
- If $MC < \pi$ next unit returns more than it costs
- Profitable only if $Q_4 > Q_2$ because of fixed costs
Costs: Economist’s perspective

• Opportunity cost:
  ▪ What would be the best use of the money spent to make the product?
  ▪ Not taking the opportunity to sell at a higher price represents a cost

• Examples:
  ▪ Growing apples or growing kiwis?
  ▪ Use the money to grow apples or put it in the bank where it earns interests?

• Includes a “normal profit”

• Selling “at cost” does not mean no profit
Perfect competition

- The volume handled by each market participant is small compared to the overall market volume.
- No market participant can influence the market price by its actions.
- All market participants act like price takers.
Imperfect competition

- One or more competitors can influence the market price through their actions

- Strategic players
  - Participants with a large market share
  - Can influence the market price

- Competitive fringe
  - Participants with a small market share
  - Take the market price

- Cournot and Bertrand models of competition
Cournot model in a duopoly

Competition on quantity

Problem for firm 1: \[ \max_{y_1} \pi(y_1 + y_2^e) y_1 - c(y_1) \]

\[ y_1 = f_1(y_2^e) \]

Similar problem for firm 2

\[ y_2 = f_2(y_1^e) \]

Cournot equilibrium:

\[ y_1^* = f_1(y_2^*) \]
\[ y_2^* = f_2(y_1^*) \]

Neither firm has any incentive to deviate from the equilibrium.
Cournot model in an oligopoly

Total industry output: \( Y = y_1 + \cdots + y_n \)

Firm \( i \):

\[
\max_{y_i} \left\{ y_i \cdot \pi(Y) - c(y_i) \right\}
\]

\[
\frac{d}{dy_i} \left\{ y_i \cdot \pi(Y) - c(y_i) \right\} = 0
\]

\[
\pi(Y) + y_i \frac{d\pi(Y)}{dy_i} = \frac{dc(y_i)}{dy_i}
\]

\[
\pi(Y) \left\{ 1 + \frac{y_i}{Y} \frac{d\pi(Y)}{\pi(Y)} \right\} = \frac{dc(y_i)}{dy_i}
\]

\[
\pi(Y) \left\{ 1 - \frac{s_i}{|\varepsilon(Y)|} \right\} = \frac{dc(y_i)}{dy_i}
\]

Difference with perfect competition
Cournot model in an oligopoly

\[ \pi(Y) \left\{ 1 - \frac{s_i}{|\varepsilon(Y)|} \right\} = \frac{dc(y_i)}{dy_i} \]

\(< 1\)

- Strategic player operates at a marginal cost less than the market price
- Ability to manipulate prices is a function of:
  - Market share \( s_i = \frac{y_i}{Y} \)
  - Elasticity of demand \( \varepsilon \)
Bertrand model in a duopoly

• Competition on price
• Firm that sets the lowest price captures the entire market
• No firm will bid below its marginal cost of production because it would sell at a loss
• At equilibrium, both firms sell at the same price, which is the marginal cost of production
• Equivalent to competitive equilibrium!
• Not a realistic model!
Risks, Markets and Contracts

Daniel Kirschen

The University of Manchester
Concept of Risk

• Future is uncertain
• Uncertainty translates into risk
  ▪ In this case, risk of loss of income
• Risk = probability x consequences
• Doing business means accepting some risks
• Willingness to accept risk varies:
  ▪ venture capitalist vs. old-age pensioner
• Ability to control risk varies:
  ▪ Professional traders vs. novice investors
Sources of Risk

- Technical risk
  - Fail to produce or deliver because of technical problem
    - Power plant outage, congestion in the transmission system

- External risk
  - Fail to produce or deliver because of cataclysmic event
    - Weather, earthquake, war

- Price risk
  - Having to buy at a price much higher than expected
  - Having to sell at a price much lower than expected
Managing Risks

• Excessive risk hampers economic activity
  ▪ Not everybody can survive short term losses
  ▪ Society benefits if more people can take part
    • Business should not be limited to large companies with deep pockets

• How can risk be managed:
  ▪ Reduce the risk
  ▪ Share the risk
  ▪ Relocate the risk
Reducing the Risks

• Reduce frequency or consequences of technical problems
  ▪ Those who can should have an incentive to do it!
    • Owners of power plants when outages are rare
    • Owners and operators of transmission system when congestion is small

• Reduce consequences of natural catastrophes
  ▪ Design systems to be able to withstand rare events
    • Enough crews to repair the power system after a hurricane

• Avoid unnecessarily large price swings
  ▪ Develop market rules that do not create artificial spikes in the price of electrical energy

• Should only be done to a reasonable extent
Sharing the Risks

• Insurance:
  ▪ All the members of a large group each pay a small amount to compensate a few that have suffered a big loss
  ▪ The consequences of a catastrophic event are shared by a large group rather than a few

• Security margin in power system operation
  ▪ Limits the consequences of rare but unpredictable and catastrophic events
  ▪ Increases the daily cost of electrical energy
  ▪ Grid operator does not have to pay compensation in the event of a blackout
Relocating Risk

• Possible if one party is more willing or able to accept it
  ▪ Loss is not catastrophic for this party
  ▪ This party can offset this loss against gains in other activities

• Applies mostly to price risk

• How does this apply to markets?
Spot Market

- Immediate market, “On the Spot”
  - Agreement on price
  - Agreement on quantity
  - Agreement on location
  - Unconditional delivery
  - Immediate delivery
Examples of Spot Markets

- Examples
  - Food market
  - Basic shopping
  - Rotterdam spot market for oil
  - Commodities markets: corn, wheat, cocoa, coffee
- Formal or informal
Advantages and Disadvantages

- **Advantages:**
  - Simple
  - Flexible
  - Immediate

- **Disadvantages**
  - Prices can fluctuate widely based on circumstances
  - Example:
    - Effect of frost in Brazil on price of coffee beans
    - Effect of trouble in the Middle East on the price of oil
Spot Market Risks

• Problems with wide price fluctuations
  ▪ Small producer may have to sell at a low price
  ▪ Small purchaser may have to buy at a high price
  ▪ “Price risk”

• Market may not have much depth
  ▪ Not enough sellers: market is short
  ▪ Not enough buyers: market is long

• Buying or selling large quantities when the market is short or long can affect the price

• Relying on the spot market for buying or selling large quantities is a bad idea
Example: buying and selling wheat

• Farmer produces wheat
• Miller buys wheat to make flour
• Farmer carries the risk of bad weather
• Miller carries the risk of breakdown of flour mill
• Neither farmer nor miller control price of wheat
Harvest time

• If price of wheat is low:
  ▪ Possibly devastating for the farmer
  ▪ Good deal for the miller

• If the price is high:
  ▪ Good deal for the farmer
  ▪ Possibly devastating for the miller
What should they do?

- Option 1: Accept the spot price of wheat
  - Equivalent to gambling
- Option 2: Agree ahead of time on a price that is acceptable to both parties
  - Forward contract
Forward Contract

• Agreement:
  ▪ Quantity and quality
  ▪ Price
  ▪ Date of delivery (not immediate)

• Paid at time of delivery

• Unconditional delivery
Forward Contract

Contract (1 June)
1 ton of wheat at £100 on 1 September

Maturity (1 September)
Seller delivers 1 ton of wheat
Buyer pays £100
Spot Price = £90
Profit to seller = £10
How is the forward price set?

- Both parties look at their alternative: spot price
- Both forecast what the spot price is likely to be
Case 1:

- Farmer estimates that the spot price will be £100
- Miller also forecasts that the spot price will be £100
- They can agree on a forward price of £100
Case 2:

• Farmer estimates that the spot price will be £90
• Miller also forecasts that the spot price will be £110
• They can easily agree on a forward price of somewhere between £90 and £110
• Exact price will depend on negotiation ability
Case 3:

- Farmer estimates that the spot price will be £110
- Miller also forecasts that the spot price will be £90
- Agreeing on a forward price is likely to be difficult
Sharing risk

• In a forward contract, the buyer and seller share the risk that the price differs from their expectation

• Difference between contract price and spot price at time of delivery represents a “profit” for one party and a “loss” for the other

• However, in the meantime they have been able to get on with their business
  ▪ Buy new farm machinery
  ▪ Sell the flour to bakeries
Attitudes towards risk

• Suppose that both parties forecast the same value spot price at time of delivery
• Equal attitude towards risk
  ▪ Forward price is equal to expected spot price
• If buyer is less risk adverse than seller
  ▪ Buyer can negotiate a forward price lower than the expected spot price
  ▪ Seller agrees to this lower price because it reduces its risk
  ▪ Difference between expected spot price and forward price is called a premium
  ▪ Premium = price that seller is willing to pay to reduce risk
Attitudes towards risk

• If buyer is more risk adverse than seller
  ▪ Seller can negotiate a forward price higher than the expected spot price
  ▪ Buyer agrees to this lower price because it reduces its risk
  ▪ Buyer is willing to pay the premium to reduce risk
Forward Markets

• Since there are many millers and farmers, a market can be organised for forward contracts

• Forward price represents the aggregated expectation of the spot price, plus or minus a risk premium
What if...

- Suppose that millers are less risk adverse
- Premium below the expected spot price
- Spot price turns out to be much lower than forward price because of a bumper harvest
What if...

- Farmers breathe a sigh of relief...
- Millers take a big loss
- The following year the millers asks for a much bigger premium
- Is agreement between the millers and the farmers going to be possible?
Undiversified risk

- Farmers and millers deal only in wheat
- Their risk is undiversified
- Can only offset “good years” against “bad years”
- Risk remains high
- Reducing the risk further would help business
Diversification

- Diversification: deal with more than one commodity
- Average risk over different commodities
Physical participants vs. traders

• Physical participants
  ▪ Produce, consume or can store the commodity
  ▪ Face undiversified risk because they deal in only one commodity

• Traders (a.k.a. speculators)
  ▪ Cannot take physical delivery of the commodity
  ▪ Diversify their risk by dealing in many commodities
  ▪ Specialize in risk management
Trading by speculators

- Cannot take physical delivery of the commodity
- Must balance their position on date of delivery
  - Quantity bought must equal quantity sold
  - Buy or sell from spot market if necessary
- May involve many transactions
- Forward contracts limited to parties who can take physical delivery
- Need a standardised contract to reduce the cost of trading: future contract
- Future contracts (futures) allow others to participate in the market and share the risk
Futures Contract

All contracts for wheat on 1 September

2 tons at £110

1 ton at £95

1 ton at £115

2 tons at £90
Futures Contract

Shortly before 1 September

sold 2 tons at £110
sold 2 tons at £90

bought 2 tons at £110
bought 1 ton at £95
sold 1 ton at £115

Sells 2 tons at £100
Sells 1 ton at £100

bought 1 ton at £115

Spot Price £100

Delivers 4 tons
Futures Contract

bought 2 tons at £110
bought 1 ton at £95
sold 1 ton at £115
sold 2 tons at £100
net profit: £0

Spot Price = £100

bought 2 tons at £90
sold 1 ton at £95
sold 1 ton at £100
net profit: £15
Importance of information

• Speculators own some of the commodity before it is delivered
• They carry the risk of a price change during that period
• Need deep pockets
• Without additional information, this is gambling
• Information helps speculators make money
• Example:
  ▪ Global perspective on the harvest for wheat
  ▪ Long term weather forecast and its effect on the demand for gas and electricity
Options

• Spot, forward and future contracts: unconditional delivery
• Options: conditional delivery
  ▪ Call Option: right to *buy* at a certain price at a certain time
  ▪ Put Option: right to *sell* at a certain price at a certain time
• Two elements of the price:
  ▪ Exercise or strike price = price paid when option is exercised
  ▪ Premium or option fee = price paid for the option itself
Example of Call Option

• Call Option with an exercise price of £100
• About to expire
• If the spot market price is £90 the option is worth nothing
• If the spot market price is £110 the option is worth £10
• Holder makes money if value > option fee
Example of Put Option

- Put Option with an exercise price of £100
- About to expire
- If the spot market price is £90 the option is worth £10
- If the spot market price is £110 the option is worth nothing
- Holder makes money if value > option fee
Financial Contracts

• Contracts without any physical delivery
One-way contract for difference

• Example:
  ▪ buyer has call option for 50 units at £100 per unit
  ▪ spot price goes up to £110 per unit
  ▪ holder calls the option to buy 50 units at £100
  ▪ buyer owes seller £5000 (50 x £100)
  ▪ seller owes the buyer £5500 (value of 50 units)
  ▪ seller transfers £500 to the buyer to settle the contract
Two-Way Contract for Difference

• Combination of a call and a put option for the same price --> will always be used

• Example 1: CFD for 50 units at £100
  - spot price = £110
  - buyer pays £5500 on spot market
  - seller gets £5500 on spot market
  - seller pays buyer £500
  - buyer effectively pays £5000
  - seller effectively gets £5000
Two-Way Contract for Difference

• Example 2: CFD for 50 units at £100
  ▪ spot price = £90
  ▪ buyer pays £4500 on spot market
  ▪ seller gets £4500 on spot market
  ▪ buyer pays seller £500
  ▪ buyer effectively pays £5000
  ▪ seller effectively gets £5000

• Buyer and seller “insulated” from spot market
Exchanges

• “Location” where the market takes place
• Can be electronic
• Trading
  ▪ Spot
  ▪ Forwards
  ▪ Futures
  ▪ Options
• Participants must provide credit guarantee
• Needs rules, policing mechanisms
Organisation of Electricity Markets

Daniel Kirschen
Differences between electricity and other commodities

• Electricity is inextricably linked with a physical delivery system
  ♦ Physical delivery system operates much faster than any market
  ♦ Generation and load must be balanced at all times
  ♦ Failure to balance leads to collapse of system
  ♦ Economic consequences of collapse are enormous
  ♦ Balance must be maintained at almost any cost
  ♦ Physical balance cannot be left to a market
Differences between electricity and other commodities

- Electricity produced by different generators is pooled
  - Generator cannot direct its production to some consumers
  - Consumer cannot choose which generator produces its load
  - Electrical energy produced by all generators is indistinguishable
- Pooling is economically desirable
- A breakdown of the system affects everybody
Differences between electricity and other commodities

• Demand for electricity exhibits predictable daily, weekly and seasonal variations
  ♦ Similar to other commodities (e.g. coffee)
• Electricity cannot be stored in large quantities
  ♦ Must be consumed when it is produced
  ♦ “Just in Time Manufacturing”
• Production facilities must be able to meet peak demand
• Very low price elasticity of the demand
  ♦ Demand curve is almost vertical
Balancing supply and demand

• Demand side:
  - Fluctuations in the needs
  - Errors in forecast

• Supply side:
  - Disruption in the production

• Spot market:
  - Provides an easy way of bridging the gap between supply and demand
Spot market for other commodities

• Characteristics of a spot market:
  ♦ Unconditional delivery
  ♦ Immediate delivery
  ♦ Price determined through interactions of buyers and sellers
  ♦ Price tends to be volatile because market is short term

• To reduce the price risk, buyers and sellers tend to trade mostly through longer term contracts

• Spot market is used for adjustments

• Spot market is the market of last resort
Spot market for electrical energy

• Demand side:
  - Errors in load forecast

• Supply side:
  - Unpredicted generator outages

• Gaps between load and generation must be filled quickly

• Market mechanisms
  - Too slow
  - Too expensive
    - Need fast communication
    - Need to reach lots of participants
“Managed” spot market

• Balance load and generation
• Run by the system operator
• Maintains the security of the system
• Must operate on a sound economic basis
  ♦ Use competitive bids for generation adjustments
  ♦ Should ideally accept demand-side bids
  ♦ Determine a cost-reflective spot price
• Not a true market because price is not set through interactions of buyers and sellers
• Indispensable for treating electricity as a commodity
“Managed” spot market

Managed Spot Market

System operator

Generation surplus
Generation deficit

Load surplus
Load deficit

Spot price
Control actions

Bids to increase production
Bids to decrease production
Bids to decrease load
Bids to increase load
“Managed” spot market

• Also know as:
  ♦ Reserve market
  ♦ Balancing mechanism

• In North America, the day-ahead hourly market is often called the spot market
Other markets

- Well-functioning spot market is essential
  - Ensures that imbalances will be settled properly
- Makes the development of other markets possible
- Spot price is volatile
- Most participants want more certainty
- Reduce risk by trading ahead of the spot market
- Forward markets and derivative markets help reduce risks
- Forward markets must close before the managed spot market
Why is the spot price for electricity so volatile?

Time

Load

Minimum load

Peak load

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Demand curves for electricity

£/MWh

Minimum load

Peak load

Daily fluctuations
Supply curve for electricity

£/MWh

MWh

Base generation

Peaking generation

Intermediate generation
Supply and demand for electricity

Price of electricity fluctuates during the day

£/MWh

\( \pi_{\text{max}} \)

\( \pi_{\text{min}} \)

Minimum load

Peak load

MWh
Supply and demand for electricity

Small increases in peak demand cause large changes in peak prices

Normal peak

Extreme peak

\( \pi_{\text{ext}} \)

\( \pi_{\text{nor}} \)

\( \text{MWh} \)

\( \text{£/MWh} \)
Small reductions in supply cause large changes in peak prices.
PJM system (USA) for 1999
Actual peak price reached $1000/MWh for a few hours
(Source: www.pjm.com)
Forward markets

• Two approaches:
  ♦ Centralised trading (also known as “Pool Trading”)
  ♦ Bilateral trading
Pool trading

- All producers submit bids
- All consumers submit offers
- Market operator determines successful bids and offers and the market price

- In many electricity pools, the demand side is passive. A forecast of demand is used instead.
Example of pool trading

Bids and offers in the Electricity Pool of Syldavia for the period from 9:00 till 10:00 on 11 June:

<table>
<thead>
<tr>
<th>Bids</th>
<th>Company</th>
<th>Quantity [MWh]</th>
<th>Price [$/MWh]</th>
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</table>
Example of pool trading
Example of pool trading

- Accepted offers
- Market price
- Accepted bids
- Quantity traded

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<th>Price [$/MWh]</th>
<th>Quantity [MWh]</th>
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Example of pool trading

- Market price: 16.00 $/MWh
- Volume traded: 450 MWh

<table>
<thead>
<tr>
<th>Company</th>
<th>Production [MWh]</th>
<th>Consumption [MWh]</th>
<th>Revenue [$]</th>
<th>Expense [$]</th>
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Unit commitment-based pool trading

- Reasons for not treating each market period separately:
  - Operating constraints on generating units
    - Minimum up and down times, ramp rates
  - Savings achieved through scheduling
    - Start-up and no-load costs
  - Reduce risk for generators
    - Uncertainty on generation schedule leads to higher prices
Unit commitment-based pool trading

- Load Forecast
- Generators Bids
- Minimum Cost Schedule
- Market Prices
Generator Bids

• All units are bid separately
• Components:
  ✦ piecewise linear marginal price curve
  ✦ start-up price
  ✦ parameters (min MW, max MW, min up, min down,...)
• Bids do not have to reflect costs
• Bidding very low to “get in the schedule” is allowed
Load Forecast

- Load is usually treated as a passive market participant
- Assume that there is no demand response to prices
Generation Schedule
Marginal Units

- Most expensive unit needed to meet the load at each period
- Restrictions may apply
Market price

- Bid from marginal unit sets the market clearing price at each period
- System Marginal Price (SMP)
- All energy traded through the pool during that period is bought and sold at that price
Why trade all energy at the SMP?

- Why not pay the generators what they bid?
  - Cheaper generators would not want to “leave money on the table”
  - Would try to guess the SMP and bid close to it
  - Occasional mistakes ➔ get left out of the schedule
  - Increased uncertainty ➔ increase in price
Bilateral trading

- Pool trading is an unusual form of market
- Bilateral trading is the classical form of trading
- Involves only two parties:
  - Seller
  - Buyer
- Trading is a private arrangement between these parties
- Price and quantity negotiated directly between these parties
- Nobody else is involved in the decision
Bilateral trading

• Unlike pool trading, there is no “official price”
• Occasionally facilitated by brokers or electronic market operators
• Takes different forms depending on the time scale
Types of bilateral trading

• Customised long-term contracts
  ♦ Flexible terms
  ♦ Negotiated between the parties
  ♦ Duration of several months to several years
  ♦ Advantage:
    • Guarantees a fixed price over a long period
  ♦ Disadvantages:
    • Cost of negotiations is high
  ♦ Worthwhile only for large amounts of energy
Types of bilateral trading

- “Over the Counter” trading
  - Smaller amounts of energy
  - Delivery according to standardised profiles
  - Advantage:
    - Much lower transaction cost
  - Used to refine position as delivery time approaches
Types of bilateral trading

• Electronic trading
  ♦ Buyers and sellers enter bids directly into computerised marketplace
  ♦ All participants can observe the prices and quantities offered
  ♦ Automatic matching of bids and offers
  ♦ Participants remain anonymous
  ♦ Market organiser handles the settlement
  ♦ Advantages:
    • Very fast
    • Very cheap
    • Good source of information about the market
Example of bilateral trading

Generating units owned by Borduria Power:

<table>
<thead>
<tr>
<th>Unit</th>
<th>$P_{\text{min}}$ [MW]</th>
<th>$P_{\text{max}}$ [MW]</th>
<th>MC [$/\text{MWh}$]</th>
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<td>B</td>
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<tr>
<td>C</td>
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</table>
Example of bilateral trading

Trades of Borduria Power for 11 June from 2:00 pm till 3:00 pm

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<tr>
<th>Type</th>
<th>Contract Date</th>
<th>Identifier</th>
<th>Buyer</th>
<th>Seller</th>
<th>Amount [MWh]</th>
<th>Price [$/MWh]</th>
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<td>LT1</td>
<td>Cheapo Energy</td>
<td>Borduria Power</td>
<td>200</td>
<td>12.5</td>
</tr>
<tr>
<td>Long term</td>
<td>7 February</td>
<td>LT2</td>
<td>Borduria Steel</td>
<td>Borduria Power</td>
<td>250</td>
<td>12.8</td>
</tr>
<tr>
<td>Future</td>
<td>3 March</td>
<td>FT1</td>
<td>Quality Electrons</td>
<td>Borduria Power</td>
<td>100</td>
<td>14.0</td>
</tr>
<tr>
<td>Future</td>
<td>7 April</td>
<td>FT2</td>
<td>Borduria Power</td>
<td>Perfect Power</td>
<td>30</td>
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<tr>
<td>Future</td>
<td>10 May</td>
<td>FT3</td>
<td>Cheapo Energy</td>
<td>Borduria Power</td>
<td>50</td>
<td>13.8</td>
</tr>
</tbody>
</table>

Net position: Sold 570 MW
Production capacity: 750 MW
Example of bilateral trading

Pending offers and bids on Borduria Power Exchange at mid-morning on 11 June for the period from 2:00 till 3:00 pm:

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Amount [MW]</th>
<th>Price [$/MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B5</td>
<td>20</td>
<td>17.50</td>
</tr>
<tr>
<td>B4</td>
<td>25</td>
<td>16.30</td>
</tr>
<tr>
<td>B3</td>
<td>20</td>
<td>14.40</td>
</tr>
<tr>
<td>B2</td>
<td>10</td>
<td>13.90</td>
</tr>
<tr>
<td>B1</td>
<td>25</td>
<td>13.70</td>
</tr>
<tr>
<td>O1</td>
<td>20</td>
<td>13.50</td>
</tr>
<tr>
<td>O2</td>
<td>30</td>
<td>13.30</td>
</tr>
<tr>
<td>O3</td>
<td>10</td>
<td>13.25</td>
</tr>
<tr>
<td>O4</td>
<td>30</td>
<td>12.80</td>
</tr>
<tr>
<td>O5</td>
<td>50</td>
<td>12.55</td>
</tr>
</tbody>
</table>
Example of bilateral trading

Electronic trades made by Borduria Power:

<table>
<thead>
<tr>
<th>11 June 14:00-15:00</th>
<th>Identifier</th>
<th>Amount [MW]</th>
<th>Price [$/MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bids to sell energy</td>
<td>B5</td>
<td>20</td>
<td>17.50</td>
</tr>
<tr>
<td></td>
<td>B4</td>
<td>25</td>
<td>16.30</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>20</td>
<td>14.40</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>10</td>
<td>13.90</td>
</tr>
<tr>
<td></td>
<td>B1</td>
<td>25</td>
<td>13.70</td>
</tr>
<tr>
<td>Offers to buy energy</td>
<td>O1</td>
<td>20</td>
<td>12.50</td>
</tr>
<tr>
<td></td>
<td>O2</td>
<td>30</td>
<td>13.30</td>
</tr>
<tr>
<td></td>
<td>O4</td>
<td>10</td>
<td>13.25</td>
</tr>
<tr>
<td></td>
<td>O4</td>
<td>30</td>
<td>12.80</td>
</tr>
<tr>
<td></td>
<td>O5</td>
<td>50</td>
<td>12.55</td>
</tr>
</tbody>
</table>

Net position:  Sold 630 MW
Self schedule: Unit A: 500 MW

Unit B: 130 MW
Unit C: 0 MW
Example of bilateral trading

Unexpected problem: unit B can only generate 80 MW
Options: - Do nothing and pay the spot price for the missing energy
  - Make up the deficit with unit C
  - Trade on the power exchange

<table>
<thead>
<tr>
<th>11 June 14:00-15:00</th>
<th>Identifier</th>
<th>Amount [MW]</th>
<th>Price [$/MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bids to sell energy</td>
<td>B5</td>
<td>20</td>
<td>17.50</td>
</tr>
<tr>
<td></td>
<td>B4</td>
<td>25</td>
<td>16.30</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>20</td>
<td>14.40</td>
</tr>
<tr>
<td></td>
<td>B6</td>
<td>20</td>
<td>14.30</td>
</tr>
<tr>
<td></td>
<td>B8</td>
<td>10</td>
<td>14.10</td>
</tr>
<tr>
<td>Offers to buy energy</td>
<td>O4</td>
<td>30</td>
<td>12.80</td>
</tr>
<tr>
<td></td>
<td>O6</td>
<td>25</td>
<td>12.70</td>
</tr>
<tr>
<td></td>
<td>O5</td>
<td>50</td>
<td>12.55</td>
</tr>
</tbody>
</table>

Buying is cheaper than producing with C
New net position: Sold 580 MW
New schedule: A: 500 MW, B: 80 MW, C: 0 MW
Pool vs. bilateral trading

- **Pool**
  - Unusual because administered centrally
  - Price not transparent
  - Facilitates security function
  - Makes possible central optimisation
  - Historical origins in electricity industry

- **Bilateral**
  - Economically purer
  - Price set by the parties
  - Hard bargaining possible
  - Generator assumes scheduling risk
  - Must be coordinated with security function
  - More opportunities to innovate

Both forms of trading can coexist to a certain extent
Bidding in managed spot market

Borduria Power’s position:

<table>
<thead>
<tr>
<th>Unit</th>
<th>$P_{sched}$</th>
<th>$P_{min}$</th>
<th>$P_{max}$</th>
<th>MC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[MW]</td>
<td>[MW]</td>
<td>[MW]</td>
<td>[$/MWh]</td>
</tr>
<tr>
<td>A</td>
<td>500</td>
<td>100</td>
<td>500</td>
<td>10.0</td>
</tr>
<tr>
<td>B</td>
<td>80</td>
<td>50</td>
<td>80</td>
<td>13.0</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>17.0</td>
</tr>
</tbody>
</table>

Borduria Power’s spot market bids:

<table>
<thead>
<tr>
<th>Type</th>
<th>Unit</th>
<th>Price</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bid (increase)</td>
<td>C</td>
<td>17.50</td>
<td>50</td>
</tr>
<tr>
<td>Offer (decrease)</td>
<td>B</td>
<td>12.50</td>
<td>30</td>
</tr>
<tr>
<td>Offer (decrease)</td>
<td>A</td>
<td>9.50</td>
<td>400</td>
</tr>
</tbody>
</table>

Spot market assumed imperfectly competitive
Bids/offers can be higher/lower than marginal cost
Settlement process

• Pool trading:
  ◆ Market operator collects from consumers
  ◆ Market operator pays producers
  ◆ All energy traded at the pool price

• Bilateral trading:
  ◆ Bilateral trades settled directly by the parties as if they had been performed exactly

• Managed spot market:
  ◆ Produced more or consumed less ➔ receive spot price
  ◆ Produced less or consumed more ➔ pay spot price
Example of settlement

- 11 June between 2:00 pm and 3:00 pm
- Spot price: 18.25 $/MWh
- Unit B of Borduria Power could produce only 10 MWh instead of 80 MWh
- Borduria Power thus had a deficit of 70 MWh for this hour
- 40 MW of Borduria Power’s spot market bid of 50 MW at 17.50 $/MWh was called by the operator
## Borduria Power’s Settlement

<table>
<thead>
<tr>
<th>Market</th>
<th>Type</th>
<th>Amount [MWh]</th>
<th>Price [$/MWh]</th>
<th>Income [$]</th>
<th>Expense [$]</th>
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<tbody>
<tr>
<td><strong>Futures and Forwards</strong></td>
<td>Sale</td>
<td>200</td>
<td>12.50</td>
<td>2,500.00</td>
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<tr>
<td></td>
<td>Sale</td>
<td>250</td>
<td>12.80</td>
<td>3,200.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sale</td>
<td>100</td>
<td>14.00</td>
<td>1,400.00</td>
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</tr>
<tr>
<td></td>
<td>Purchase</td>
<td>-30</td>
<td>13.50</td>
<td></td>
<td>405.00</td>
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<td></td>
<td>Sale</td>
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<td>13.80</td>
<td>690.00</td>
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<td><strong>Power Exchange</strong></td>
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<td>13.30</td>
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<td>Sale</td>
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<td>13.25</td>
<td>132.50</td>
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<td>Purchase</td>
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<td>Purchase</td>
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<td>14.30</td>
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<td>286.00</td>
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<td>Purchase</td>
<td>-10</td>
<td>14.10</td>
<td></td>
<td>141.00</td>
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<tr>
<td><strong>Spot Market</strong></td>
<td>Sale</td>
<td>40</td>
<td>18.25</td>
<td>730.00</td>
<td></td>
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<tr>
<td></td>
<td>Imbalance</td>
<td>-70</td>
<td>18.25</td>
<td></td>
<td>1,277.50</td>
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<tr>
<td><strong>Total</strong></td>
<td>550</td>
<td></td>
<td></td>
<td>9,321.50</td>
<td>2,397.50</td>
</tr>
</tbody>
</table>
Example of an electricity market: NETA

- NETA = New Electricity Trading Arrangements
- Market operating in England and Wales since April 2001
- Relies on bilateral trading as much as possible
- Replaced the Electricity Pool of England and Wales, which was a centralised market
- Extended to Scotland on 1 April 2005 (BETTA)
NETA Timeline

- Forward Markets
- Electronic Power Exchange
- Balancing Mechanism
- Settlement Process

Timeline:
- T-several months
- T-1day
- T-1hr
- T
- T+1/2 hr

Processes:
- Bilateral
- Centralized

Gate Closure

Real Time
Price volatility in the balancing mechanism
Participating in Electricity Markets: The Generator’s Perspective
Market Structure

• Monopoly:
  - Monopolist sets the price at will
  - Must be regulated
• Perfect competition:
  - No participant is large enough to affect the price
  - All participants act as “price takers”
• Oligopoly:
  - Some participants are large enough to affect the price
  - Strategic bidders have market power
  - Others are price takers
Perfect competition

• All producers have a small share of the market

• All consumers have a small share of the market

• Individual actions have no effect on the market price

• All participants are “price takers”
Short run profit maximisation for a price taker

\( y \): Output of one of the generators

\[
\max_y \{\pi y - c(y)\}
\]

\[
\frac{d}{dy} \{\pi y - c(y)\} = 0
\]

\[
\pi = \frac{dc(y)}{dy}
\]

Adjust production \( y \) until the marginal cost of production is equal to the price \( \pi \).
Market structure

• No difference between centralised auction and bilateral market
• Everything is sold at the market clearing price
• Price is set by the “last” unit sold
• Marginal producer:
  ♦ Sells this last unit
  ♦ Gets exactly its bid
• Infra-marginal producers:
  ♦ Get paid more than their bid
  ♦ Collect economic profit
• Extra-marginal producers:
  ♦ Sell nothing
Bidding under perfect competition

• No incentive to bid anything else than marginal cost of production

• Lots of small producers
  - Change in bid causes a change in stacking up order

• If bid is higher than marginal cost
  - Could become extra marginal and miss an opportunity to sell at a profit
Bidding under perfect competition

• If bid is lower than marginal cost
  - Could have to produce at a loss
• If bid is equal to marginal cost
  - Get paid market price if marginal or infra-marginal producer
Oligopoly and market power

• A firm exercises market power when
  
  ♦ It reduces its output (physical withholding)

  or

  ♦ It raises its offer price (economic withholding)

in order to change the market price
Example

• A firm sells 10 units and the market price is $15

  ♦ Option 1: offer to sell only 9 units and hope that the price rises enough to compensate for the loss of volume

  ♦ Option 2: offer to sell the 10th unit for a price higher than $15 and hope that this will increase the price

• Profit increases if price rises sufficiently to compensate for possible decrease in volume
Short run profit maximisation with market power

\[
\max_{y_i} \left\{ y_i \cdot \pi (Y) - c (y_i) \right\} \\
\frac{d}{dy_i} \left\{ y_i \cdot \pi (Y) - c (y_i) \right\} = 0 \\
\pi (Y) + y_i \frac{d\pi (Y)}{dy_i} = \frac{dc (y_i)}{dy_i} \\
\pi (Y) \left\{ 1 + \frac{y_i}{Y} \frac{Y}{dy_i} \frac{d\pi (Y)}{\pi (Y)} \right\} = \frac{dc (y_i)}{dy_i}
\]

\(y_i\): Production of generator i

\(Y = y_1 + \cdots + y_n\)

is the total industry output

Not zero because of market power
Short run profit maximisation with market power

\[ \pi(Y) \left\{ 1 + \frac{y_i}{Y} \frac{d\pi(Y)}{\pi(Y)} \right\} = \frac{dc(y_i)}{dy_i} \]

\[ \varepsilon = -\frac{\frac{dy}{d\pi}}{\frac{\pi}{y}} \frac{dy}{d\pi} \]

is the price elasticity of demand

\[ s_i = \frac{y_i}{Y} \]

is the market share of generator \( i \)

\[ \pi(Y) \left\{ 1 - \frac{s_i}{|\varepsilon(Y)|} \right\} = \frac{dc(y_i)}{dy_i} \]

< 1 \( \rightarrow \) optimal price for generator \( i \) is higher than its marginal cost
When is market power more likely?

- Imperfect correlation with market share
- Demand does not have a high price elasticity
- Supply does not have a high price elasticity:
  - Highly variable demand
  - All capacity sometimes used
  - Output cannot be stored

Electricity markets are more vulnerable than others to the exercise of market power
Elasticity of the demand for electricity

- **Slope is an indication of the elasticity of the demand**
- **High elasticity**
  - Non-essential good
  - Easy substitution
- **Low elasticity**
  - Essential good
  - No substitutes
- **Electrical energy has a very low elasticity in the short term**
How Inelastic is the demand for electricity?

Price of electrical energy in England and Wales [£/MWh]

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Max</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 2001</td>
<td>0.00</td>
<td>168.49</td>
<td>21.58</td>
</tr>
<tr>
<td>February 2001</td>
<td>10.00</td>
<td>58.84</td>
<td>18.96</td>
</tr>
<tr>
<td>March 2001</td>
<td>8.00</td>
<td>96.99</td>
<td>20.00</td>
</tr>
</tbody>
</table>

Value of Lost Load (VoLL) in England and Wales: 2,768£/MWh
Price spikes because of increased demand

Small increases in peak demand cause large changes in peak prices.
Price spikes because of reduced supply

Small reductions in supply cause large changes in peak prices
Increasing the elasticity reduces price spikes and the generators’ ability to exercise market power.
Increasing the elasticity of the demand

• Obstacles
  ❖ Tariffs
  ❖ Need for communication
  ❖ Need for storage (heat, intermediate products, dirty clothes)

• Not everybody needs to respond to price signals to get substantial benefits

• Increased elasticity reduces the average price
  ❖ Not in the best interests of generating companies
  ❖ Impetus will need to come from somewhere else
Further comments on market power

• **ALL** firms benefit from the exercise of market power by one participant
• Unilaterally reducing output or increasing offer price to increase profits is legal
• Collusion between firms to achieve the same goal is not legal
• Market power interferes with the efficient dispatch of generating resources
  - Cheaper generation is replaced by more expensive generation
Modelling imperfect competition

- Bertrand model
  - Competition on prices
- Cournot model
  - Competition on quantities
Game theory and Nash equilibrium

• Each firm must consider the possible actions of others when selecting a strategy

• Classical optimisation theory is insufficient

• Two-person non-co-operative game:
  ♦ One firm against another
  ♦ One firm against all the others

• Nash equilibrium:
  ♦ given the action of its rival, no firm can increase its profit by changing its own action:

\[
\Omega^i (a^*_i, a^*_j) \geq \Omega^i (a_i, a^*_j) \quad \forall i, a_i
\]
Bertrand Competition

• Example 1
  - $C_A = 35 \cdot P_A \, \text{€/h}$
  - $C_B = 45 \cdot P_B \, \text{€/h}$

• Bid by A?
• Bid by B?
• Market price?
• Quantity traded?

\[ \pi = 100 - D \quad [\text{€/MWh}] \]

Inverse demand curve
Bertrand Competition

- Example 1
  - $C_A = 35 \cdot P_A$ €/h
  - $C_B = 45 \cdot P_B$ €/h

- Marginal cost of A: 35 €/MWh
- Marginal cost of B: 45 €/MWh
- A will bid just below 45 €/MWh
- B cannot bid below 45 €/MWh because it would lose money on every MWh
- Market price: just below 45 €/MWh
- Demand: 55 MW
- $P_A = 55$ MW
- $P_B = 0$

\[ \pi = 100 - D \quad [\text{€/MWh}] \]
Bertrand Competition

• Example 2
  - $C_A = 35 \cdot P_A \, \text{€/h}$
  - $C_B = 35 \cdot P_B \, \text{€/h}$

• Bid by A?
• Bid by B?
• Market price?
• Quantity traded?

$\pi = 100 - D \, \text{[€/MWh]}$
Bertrand Competition

• Example 2
  - $C_A = 35 \cdot P_A \, \text{€/h}$
  - $C_B = 35 \cdot P_B \, \text{€/h}$

• A cannot bid below 35 €/MWh because it would lose money on every MWh
• A cannot bid above 35 €/MWh because B would bid lower and grab the entire market
• Market price: 35 €/MWh
• Identical generators: bid at marginal cost
• Non-identical generators: cheapest gets the whole market
• Not a realistic model of imperfect competition

\[
\pi = 100 - D \quad [\, \text{€/MWh}\,]
\]
Cournot competition: Example 1

- \( C_A = 35 \cdot P_A \, \text{€/h} \)
- \( C_B = 45 \cdot P_B \, \text{€/h} \)
- \( \pi = 100 - D \quad \text{[€/MWh]} \)
- Suppose \( P_A = 15 \, \text{MW} \) and \( P_B = 10 \, \text{MW} \)
- Then \( D = P_A + P_B = 25 \, \text{MW} \)
- \( \pi = 100 - D = 75 \, \text{€/MW} \)
- \( R_A = 75 \cdot 15 = 1125 \, \text{€} \) ; \( C_A = 35 \cdot 15 = 525 \, \text{€} \)
- \( R_B = 75 \cdot 10 = 750 \, \text{€} \) ; \( C_B = 45 \cdot 10 = 450 \, \text{€} \)
- Profit of A = \( R_A - C_A = 600 \, \text{€} \)
- Profit of B = \( R_B - C_B = 300 \, \text{€} \)
Cournot competition: Example 1

Summary:

For $P_A = 15$ MW and $P_B = 10$ MW, we have:

- **Demand**: 25, 300
- **Profit of A**: 600, 75
- **Profit of B**: 25, 300
- **Price**: 600, 75
Cournot competition: Example 1

<table>
<thead>
<tr>
<th>Demand</th>
<th>Profit A</th>
<th>Profit B</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **$P_A = 15$**
  - $P_B = 10$: $25$ $600$
  - $P_B = 15$: $30$ $700$
  - $P_B = 20$: $35$ $800$
  - $P_B = 25$: $40$ $900$
- **$P_A = 20$**
  - $P_B = 10$: $30$ $75$
  - $P_B = 15$: $45$ $75$
  - $P_B = 20$: $60$ $75$
  - $P_B = 25$: $75$ $75$
- **$P_A = 25$**
  - $P_B = 10$: $40$ $625$
  - $P_B = 15$: $60$ $625$
  - $P_B = 20$: $80$ $625$
  - $P_B = 25$: $100$ $625$
- **$P_A = 30$**
  - $P_B = 10$: $50$ $500$
  - $P_B = 15$: $70$ $500$
  - $P_B = 20$: $90$ $500$
  - $P_B = 25$: $110$ $500
Cournot competition: Example 1

<table>
<thead>
<tr>
<th>Demand</th>
<th>Profit A</th>
<th>Profit B</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>600</td>
<td>30</td>
<td>700</td>
</tr>
<tr>
<td>30</td>
<td>700</td>
<td>25</td>
<td>70</td>
</tr>
<tr>
<td>35</td>
<td>750</td>
<td>20</td>
<td>65</td>
</tr>
<tr>
<td>40</td>
<td>750</td>
<td>15</td>
<td>60</td>
</tr>
</tbody>
</table>

- Price decreases as supply increases
- Profits of each affected by other
- Complex relation between production and profits
Let's play the Cournot game!

<table>
<thead>
<tr>
<th>Demand</th>
<th>Profit A</th>
<th>Profit B</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_A=15</td>
<td>25 600</td>
<td>30 700</td>
<td>35 750</td>
</tr>
<tr>
<td></td>
<td>300 75</td>
<td>250 70</td>
<td>200 65</td>
</tr>
<tr>
<td>P_B=10</td>
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<td>125 50</td>
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<td>P_B=25</td>
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</table>

Equilibrium solution!

A cannot do better without B doing worse
B cannot do better without A doing worse
Nash equilibrium
Cournot competition: Example 1

- Generators achieve price larger than their marginal costs
- The cheapest generator does not grab the whole market
- Generators balance price and quantity to maximise profits
Cournot competition: Example 2

- $C_A = 35 \cdot P_A \, \text{€/h}$
- $C_B = 45 \cdot P_B \, \text{€/h}$
- ...
- $C_N = 45 \cdot P_N \, \text{€/h}$

$\pi = 100 - D \, \text{[€/MWh]}$
Cournot competition: Example 2

- Production of firm A
- Production of another firm
- Total production of other firms

Number of Firms

Production [MWh]

© D. Kirschen 2006
Cournot competition: Example 2

Number of Firms

Price [€/MWh]

Demand

Demand [MWh]

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Cournot competition: Example 2
Other competition models

• Supply functions equilibria
  ♦ Bid price depends on quantity

• Agent-based simulation
  ♦ Represent more complex interactions

• Maximising short-term profit is not the only possible objective
  ♦ Maximising market share
  ♦ Avoiding regulatory intervention
Conclusions on imperfect competition

• Electricity markets do not deliver perfect competition

• Some factors facilitate the exercise of market power:
  ♦ Low price elasticity of the demand
  ♦ Large market shares
  ♦ Cyclical demand
  ♦ Operation close to maximum capacity

• Study of imperfect competition in electricity markets is a hot research topic
  ♦ Generator’s perspective
  ♦ Market designer’s perspective
Participating in Electricity Markets: The consumer’s perspective
Options for the consumers

- **Buy at the spot price**
  - Lowest cost, highest risk
  - Must be managed carefully
  - Requires sophisticated control of the load

- **Buy from a retailer at a tariff linked to the spot price**
  - Retailers acts as intermediary between consumer and market
  - Risk can be limited by placing cap (and collar) on the price

- **Interruptible contract**
  - Reasonable option only if cost of interruption is not too high
  - Savings can be substantial
Options for the consumers

- Buy from a retailer on a time-of-use tariff
  - Shifts some of the risk to the consumer
  - Need to control the load to save money

- Buy from a retailer at a fixed tariff
  - Lowest risk, highest cost
  - Two components to the price: average cost of energy and risk premium
Choosing a contract

• Best type of contract depends on the characteristics of the consumer:
  ♦ Cost of electricity as a proportion of total cost
  ♦ Risk aversion
  ♦ Flexibility in the use of electricity
  ♦ Potential savings big enough to justify transactions cost
Buying at the spot price

• Must forecast prices
  ♦ Much harder than load forecasting because price depends on demand and supply
  ♦ Supply factors are particularly difficult to predict (outages, maintenance, gaming, locational effects)
  ♦ Good accuracy for average price and volatility
  ♦ Predicting spikes is much harder

• Must optimize production taking cost of electricity into account
  ♦ Complex problem because of:
    • Production constraints
    • Cost of storage (losses, loss of efficiency in other steps,...)
    • Price profiles
Participating in Electricity Markets:
The retailer’s perspective
The retailer’s perspective

- Sell energy to consumers, mostly at a flat rate
- Buy energy in bulk
  - Spot market
  - Contracts
- Want to reduce risks associated with spot market
- Increase proportion of energy bought under contracts
- Must forecast the load of its customers
- Regional monopoly: traditional top-down forecasting
- Retail competition: bottom-up forecasting
  - Difficult problem: customer base changes
  - Much less accurate than traditional load forecasting
Participating in Electricity Markets: The hybrid participant’s perspective
Example: pumped storage hydro plant
Example
Example

• Energy cycle in a pumped storage plant is only about 75% efficient

• Difference between high price and low price periods must be large enough to cover the cost of the lost energy

• Profit is unlikely to be large enough to cover the cost of investments

• Pumped hydro plants can also make money by helping control the system
System Security and Ancillary Services

Daniel Kirschen
Introduction

- Electricity markets rely on the power system infrastructure
- Participants have no choice to use a different system
- Cost to consumers of outages is very high
- Consumer have expectations for continuity of service
- Cost of this security of supply must match its benefit
System security

• System must be able to operate continuously if situation does not change

• System must remain stable for common contingencies
  ♦ Fault on a transmission line or other component
  ♦ Sudden failure of a generating unit
  ♦ Rapid change in load

• Operator must consider consequences of contingencies

• Use both:
  ♦ Preventive actions
  ♦ Corrective actions
Preventive actions

• Put the system in a state such that it will remain stable if a contingency occurs
• Operate the system at less than full capacity
• Limit the commercial transactions that are allowed
Corrective actions

• Taken only if a disturbance does occur
• Limit the consequences of this disturbance
• Need resources that belong to market participants
• Ancillary services that must be purchased from the market participants by the system operator
• When called, some ancillary services will deliver some energy
• However, capacity to deliver is the important factor
• Remuneration on the basis of availability, not energy
Outline

• Describe the needs for ancillary services
  • Keeping the generation and load in balance
  • Keeping the security of the transmission network
• Obtaining ancillary services
  • How much ancillary services should be bought?
  • How should these services be obtained?
  • Who should pay for these services?
• Selling ancillary services
  • Maximize profit from the sale of energy and ancillary services
Needs for ancillary services
Balancing production and consumption

• Assume that all generators, loads and tie-lines are connected to the same bus

• Only system variables are total generation, total load and net interchange with other systems
Balancing production and consumption

• If production = consumption, frequency remains constant
• In practice:
  - Constant fluctuations in the load
  - Inaccurate control of the generation
  - Sudden outages of generators and interconnectors
• Excess load causes a drop in frequency
• Excess generation causes an increase in frequency
Balancing production and consumption

• Generators can only operate within a narrow range of frequencies
  ❖ Protection system disconnects generators when frequency is too high or too low
  ❖ Causes further imbalance between load and generation

• System operator must maintain the frequency within limits
Balancing production and consumption

• Rate of change in frequency inversely proportional to total inertia of generators and rotating loads
• Frequency changes much less in large interconnected systems than in small isolated systems
• Local imbalance in an interconnected system causes a change in tie-line flows
Balancing production and consumption

- Inadvertent flows can overload the tie-lines
- Protection system may disconnect these lines
- Could lead to further imbalance between load and generation
- Each system must remain in balance
Balancing production and consumption

• Minor frequency deviations and inadvertent flows are not an immediate threat
• However, they weaken the system
• Must be corrected quickly so the system can withstand further problems
Example: load over 5 periods
Example: energy traded

![Graph of energy traded over time]

- The x-axis represents time periods, labeled as Period 1 to 5.
- The y-axis represents load in MW, ranging from 0 to 300 MW.

The graph illustrates the energy traded over the specified periods, showing fluctuations and trends in load demand.
Example: energy produced
Example: imbalance

![Graph showing imbalance over periods]

- Imbalance [MW]
- Period
Example: imbalance with trend

- Random load fluctuations
- Slower load fluctuations
- Outages
Example (continued)

- Differences between load and energy traded:
  - Does not track rapid load fluctuations
    - Market assumes load constant over trading period
  - Error in forecast
- Differences between energy traded and energy produced
  - Minor errors in control
  - Finite ramp rate at the ends of the periods
  - Unit outage creates a large imbalance
Balancing services

• Different phenomena contribute to imbalances
• Each phenomena has a different time signature
• Different services are required to handle these phenomena
• Exact definition differ from market to market
Regulation service

• Designed to handle:
  - Rapid fluctuations in load
  - Small, unintended variations in generation

• Designed to maintain:
  - Frequency close to nominal
  - Interchanges at desired values

• Provided by generating units that:
  - Can adjust output quickly
  - Are connected to the grid
  - Are equipped with a governor and usually are on AGC
Load following service

• Designed to handle intra-period load fluctuations
• Designed to maintain:
  ♦ Frequency close to nominal
  ♦ Interchanges at desired values
• Provided by generating units that can respond at a sufficient rate
Reserve services

• Designed to handle large and unpredictable deficits caused by outages of generators and tie-lines

• Two main types:
  - Spinning reserve
    • Start immediately
    • Full amount available quickly
  - Supplemental reserve
    • Can start more slowly
    • Designed to replace the spinning reserve

• Definition and parameters depend on the market
Classification of balancing services

• Regulation and load following services:
  ♦ Almost continuous action
  ♦ Relatively small
  ♦ Quite predictable
  ♦ Preventive security actions

• Reserve services:
  ♦ Use is unpredictable
  ♦ Corrective security actions
  ♦ Provision of reserve is a form of preventive security action
Example: Outage of large generating unit

- **Primary response**
- **Secondary response**
- Gas turbines
Network issues: contingency analysis

- Operator continuously performs contingency analysis
- No credible contingency should destabilize the system
- Modes of destabilization:
  - Thermal overload
  - Transient instability
  - Voltage instability
- If a contingency could destabilize the system, the operator must take preventive action
Types of preventive actions

• Low cost preventive actions:
  ♦ Examples
    • Adjust taps of transformers
    • Adjust reference voltage of generators
    • Adjust phase shifters
  ♦ Effective but limited

• High cost preventive actions:
  ♦ Restrict flows on some branches
  ♦ Requires limiting the output of some generating units
  ♦ Affect the ability of some producers to trade on the market
Example: thermal capacity

- Each line between A and B is rated at 200 MW
- Generator at A can sell only 200 MW to load at B
- Remaining 200 MW must be kept in reserve in case of outage of one of the lines
Example: emergency thermal capacity

- Each line between A and B is rated at 200 MW
- Each line has a 10% emergency rating for 20 minutes
- If generator at B can increase its output by 20 MW in 20 minutes, the generator at A can sell 220 MW to load at B
Example: transient stability

• Assumptions:
  ♦ B is an infinite bus
  ♦ Transient reactance of A = 0.9 p.u., inertia constant H = 2 s
  ♦ Each line has a reactance of 0.3 p.u.
  ♦ Voltages are at nominal value
  ♦ Fault cleared in 100 ms by tripping affected line
• Maximum power transfer: 108 MW
Example: voltage stability

- No reactive support at B
  - 198 MW can be transferred from A to B before the voltage at B drops below 0.95 p.u.
  - However, the voltage collapses if a line is tripped when power transfer is larger than 166 MW
- The maximum power transfer is thus 166 MW
Example: voltage stability

- 25 MVAr of reactive support at B
  - 190 MW can be transferred from A to B before the outage of a line causes a voltage collapse
Voltage control and reactive support services

• Use reactive power resources to maximize active power that can be transferred through the transmission network

• Some of these resources are under the control of the system operator:
  - Mechanically-switched capacitors and reactors
  - Static VAr compensators
  - Transformer taps

• Best reactive power resources are the generators

• Need to define voltage control services to specify the conditions under which the system operator can use these resources
Voltage control and reactive support services

• Must consider both normal and abnormal conditions
  
• Normal conditions:
    ♦ $0.95 \text{ p.u.} \leq V \leq 1.05 \text{ p.u.}$

• Abnormal conditions:
    ♦ Provide enough reactive power to prevent a voltage collapse following an outage

• Requirements for abnormal conditions are much more severe than for normal conditions
• Reactive support is more important than voltage control
Example: voltage control under normal conditions

- Load at B has unity power factor
- Voltage at A maintained at nominal value
- Control voltage at B?
Example: voltage control under normal conditions

![Graph showing active power transfer on the x-axis and reactive power injection on the y-axis. The graph indicates voltage control at point B with reactive injection at B.](image-url)
Example: voltage control under normal conditions

- Controlling the voltage at B using generator at A?

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- Local voltage control is much more effective
- Severe market power issues in reactive support
Example: reactive support following line outage

Power Transfer [MW]

Post-contingency reactive power injection at bus B

[ MWAr ]

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Example: pre- and post-contingency balance

Pre-contingency:

Post-contingency:
Other ancillary services

- Stability services
  - Intertrip schemes
    - Disconnection of generators following faults
  - Power system stabilizers

- Blackstart restoration capability service
Obtaining ancillary services
Obtaining ancillary services

• How much ancillary services should be bought?
• How should these services be obtained?
• Who should pay for these services?
How much ancillary services should be bought?

- System Operator purchases the services
  - Works on behalf of the users of the system
- Services are used mostly for contingencies
  - Availability is more important than actual usage
- Not enough services
  - Can’t ensure the security of the system
  - Can’t maintain the quality of the supply
- Too much services
  - Life of the operator is easy
  - Cost passed on to system users
How much ancillary services should be bought?

• System Operator must perform a cost/benefit analysis
  - Balance value of services against their cost
• Value of services: improvement in security and service quality
• Complicated probabilistic optimization problem
• Should give a financial incentive to the operator to acquire the right amount of services at minimum cost
How should services be obtained?

• Two approaches:
  ♦ Compulsory provision
  ♦ Market for ancillary services

• Both have advantages and disadvantages

• Choice influenced by:
  ♦ Type of service
  ♦ Nature of the power system
  ♦ History of the power system
Compulsory provision

• To be allowed to connect to the system, generators may be obliged to meet some conditions

• Examples:
  - Generator must be equipped with governor with 4% droop
    • All generators contribute to frequency control
  - Generator must be able to operate from 0.85 lead to 0.9 lag
    • All generators contribute to voltage control and reactive support
Advantages of compulsory provision

• Minimum deviation from traditional practice
• Simplicity
• Usually ensures system security and quality of supply
Disadvantages of compulsory provision

- Not necessarily good economic policy
  - May provide more resources than needed and cause unnecessary investments
    - Not all generating units need to help control frequency
    - Not all generating units need to be equipped with a stabilizer
- Discourages technological innovation
  - Definition based on what generators usually provide
- Generators have to provide a costly service for free
  - Example: providing reactive power increases losses and reduces active power generation capacity
Disadvantages of compulsory provision

• Equity
  • How to deal with generators that cannot provide some services?
    • Example: nuclear units can’t participate in frequency response

• Economic efficiency
  • Not a good idea to force highly efficient units to operate part-loaded to provide reserve
  • More efficient to determine centrally how much reserve is needed and commit additional units to meet this reserve requirement

• Compulsory provision is thus not applicable to all services

• How to deal with exceptions that distort competition?
Market for ancillary services

- Different markets for different services
- Long term contracts
  - For services where quantity needed does not change and availability depends on equipment characteristics
  - Example: blackstart capability, intertrip schemes, power system stabilizer, frequency regulation
- Spot market
  - Needs change over the course of a day
  - Price changes because of interactions with energy market
  - Example: reserve
- System operator may reduce its risk by using a combination of spot market and long term contracts
Advantages of market for ancillary services

- More economically efficient than compulsory provision
- System operator buys only the amount of service needed
- Only participants that find it profitable provide services
- Helps determine the true cost of services
- Opens up opportunities for innovative solutions
Disadvantages of market for ancillary services

• More complex
• Probably not applicable to all types of services
• Potential for abuse of market power
  ♦ Example: reactive support in remote parts of the network
  ♦ Market for reactive power would need to be carefully regulated
Demand-side provision of ancillary services

• Creating a market for ancillary services opens up an opportunity for the demand-side to provide ancillary services

• Unfortunately, definition of ancillary services often still based on traditional practice

• In a truly competitive environment, the system operator should not favour any participant, either from the supply- or demand-side
Advantages of demand-side provision

• Larger number of participants increases competition and lowers cost

• Better utilization of resources
  ◆ Example:
    • Providing reserve with interruptible loads rather than partly loaded thermal generating units
    • Particularly important if proportion of generation from renewable sources increases

• Demand-side may be a more reliable provider
  ◆ Large number of small demand-side providers
Opportunities for demand-side provision

• Different types of reserve
  - Interruptible loads
• Frequency regulation
  - Variable speed pumping loads
Who should pay for ancillary services?

• Not all users value security and quality of supply equally
  ◆ Examples:
    • Producers vs. consumers
    • Semi-conductor manufacturing vs. irrigation load
  • Ideally, users who value security more should get more security and pay for it
  • With the current technology, this is not possible
    ◆ System operator provides an average level of security to all users
    ◆ The cost of ancillary services is shared by all users on the basis of their consumption
Who should pay for ancillary services?

- Sharing the cost of ancillary services on the basis of energy is not economically efficient.
- Some participants increase the need for services more than others.
- These participants should pay a larger share of the cost to encourage them to change their behaviour.
- Example: allocating the cost of reserve.
Who should pay for reserve?

- Reserve prevents collapse of the system when there is a large imbalance between load and generation.
- Large imbalances usually occur because of failure of generating units.
- Owners of large generating units that fail frequently should pay a larger proportion of the cost of reserve.
- Encourage them to improve the reliability of their units.
- In the long term:
  - Reduce need for reserve.
  - Reduce overall cost of reserve.
Selling ancillary services
Selling ancillary services

• Ancillary services are another business opportunity for generators

• Limitations:
  - Technical characteristics of the generating units
    • Maximum ramp rate
    • Reactive capability curve
  - Opportunity cost
    • Can’t sell as much energy when selling reserve
    • Need to optimize jointly the sale of energy and reserve
Example: selling both energy and reserve

• Generator tries to maximize the profit it makes from the sale of energy and reserve

• Assumptions:
  ♦ Consider only one type of reserve service
  ♦ Perfectly competitive energy and reserve markets
    • Generator is a price-taker in both markets
    • Generator can sell any quantity it decides on either market
  ♦ Consider one generating unit over one hour
    • Don’t need to consider start-up cost, min up time, min down time
  ♦ No special payments for exercising reserve
Notations

$\pi_1$ : Market price for electrical energy (£/MWh)

$\pi_2$ : Market price for reserve (£/MW/h)

$x_1$ : Quantity of energy bid and sold

$x_2$ : Quantity of reserve bid and sold

$P^{\text{min}}$ : Minimum power output

$P^{\text{max}}$ : Maximum power output

$R^{\text{max}}$ : Upper limit on the reserve (ramp rate x delivery time)

$C_1(x_1)$ : Cost of producing energy

$C_2(x_2)$ : Cost of providing reserve (not opportunity cost)
Formulation

Objective function:

\[ f(x_1, x_2) = \pi_1 x_1 + \pi_2 x_2 - C_1(x_1) - C_2(x_2) \]

Constraints:

\[ x_1 + x_2 \leq P^{\text{max}} \]

\[ x_1 \geq P^{\text{min}} \]

\[ x_2 \leq R^{\text{max}} \quad (\text{We assume that } R^{\text{max}} < P^{\text{max}} - P^{\text{min}}) \]

Lagrangian function:

\[ \ell(x_1, x_2, \mu_1, \mu_2, \mu_3) = \pi_1 x_1 + \pi_2 x_2 - C_1(x_1) - C_2(x_2) \]

\[ + \mu_1 (P^{\text{max}} - x_1 - x_2) + \mu_2 (x_1 - P^{\text{min}}) + \mu_3 (R^{\text{max}} - x_2) \]
Optimality conditions

\[
\frac{\partial \ell}{\partial x_1} \equiv \pi_1 - \frac{dC_1}{dx_1} - \mu_1 + \mu_2 = 0
\]

\[
\frac{\partial \ell}{\partial x_2} \equiv \pi_2 - \frac{dC_2}{dx_2} - \mu_1 - \mu_3 = 0
\]

\[
\frac{\partial \ell}{\partial \mu_1} \equiv P^{max} - x_1 - x_2 \geq 0
\]

\[
\frac{\partial \ell}{\partial \mu_2} \equiv x_1 - P^{min} \geq 0
\]

\[
\frac{\partial \ell}{\partial \mu_3} \equiv R^{max} - x_2 \geq 0
\]
Complementary slackness conditions

\[ \mu_1 \cdot (P_{\text{max}} - x_1 - x_2) = 0 \]

\[ \mu_2 \cdot (x_1 - P_{\text{min}}) = 0 \]

\[ \mu_3 \cdot (R_{\text{max}} - x_2) = 0 \]

\[ \mu_1 \geq 0; \mu_2 \geq 0; \mu_3 \geq 0 \]
Case 1: $\mu_1 = 0; \mu_2 = 0; \mu_3 = 0$

- No binding constraints

$$\frac{\partial \ell}{\partial x_1} \equiv \pi_1 - \frac{dC_1}{dx_1} - \mu_1 + \mu_2 = 0 \Rightarrow \frac{dC_1}{dx_1} = \pi_1$$

$$\frac{\partial \ell}{\partial x_2} \equiv \pi_2 - \frac{dC_2}{dx_2} - \mu_1 - \mu_3 = 0 \Rightarrow \frac{dC_2}{dx_2} = \pi_2$$

- Provide energy and reserve up to the point where marginal cost is equal to price

- No interactions between energy and reserve
Case 2: \( \mu_1 > 0; \mu_2 = 0; \mu_3 = 0 \)

- Generation capacity fully utilized by energy and reserve:

\[
x_1 + x_2 = P_{\text{max}}
\]

\[
\frac{\partial \ell}{\partial x_1} \equiv \pi_1 - \frac{dC_1}{dx_1} - \mu_1 + \mu_2 = 0
\]

\[
\frac{\partial \ell}{\partial x_2} \equiv \pi_2 - \frac{dC_2}{dx_2} - \mu_1 - \mu_3 = 0
\]

- Marginal profit on energy equal to marginal profit on reserve

\[
\pi_1 - \frac{dC_1}{dx_1} = \pi_2 - \frac{dC_2}{dx_2} = \mu_1 \geq 0
\]
Case 3: \( \mu_1 = 0; \mu_2 > 0; \mu_3 = 0 \)

- Unit operates at minimum stable generation

\[
x_1 = P^{\text{min}}
\]

\[
\frac{\partial \ell}{\partial x_1} \equiv \pi_1 - \frac{dC_1}{dx_1} - \mu_1 + \mu_2 = 0 \quad \Rightarrow \quad \frac{dC_1}{dx_1} - \pi_1 = \mu_2
\]

\[
\frac{\partial \ell}{\partial x_2} \equiv \pi_2 - \frac{dC_2}{dx_2} - \mu_1 - \mu_3 = 0 \quad \Rightarrow \quad \frac{dC_2}{dx_2} = \pi_2
\]

- Marginal profit on reserve
- Marginal loss on energy minimized by operating at minimum
- KKT conditions guarantee only marginal profitability, not actual profit
Cases 4 & 5: $\mu_1 > 0; \mu_2 > 0; \mu_3 = 0$ $\mu_1 > 0; \mu_2 > 0; \mu_3 > 0$

$\mu_1 : x_1 + x_2 \leq P^{max}$

$\mu_2 : x_1 \geq P^{min}$

$\mu_3 : x_2 \leq R^{max}$

Since we assume that $R^{max} < P^{max} - P^{min}$ these cases are not interesting because the upper and lower limits cannot be binding at the same time.
Case 6: $\mu_1 = 0; \mu_2 = 0; \mu_3 > 0$

- Reserve limited by ramp rate

\[ x_2 \leq R^{\text{max}} \]

\[
\frac{\partial \ell}{\partial x_1} \equiv \pi_1 - \frac{dC_1}{dx_1} - \mu_1 + \mu_2 = 0 \quad \Rightarrow \quad \frac{dC_1}{dx_1} = \pi_1
\]

\[
\frac{\partial \ell}{\partial x_2} \equiv \pi_2 - \frac{dC_2}{dx_2} - \mu_1 - \mu_3 = 0 \quad \Rightarrow \quad \pi_2 - \frac{dC_2}{dx_2} = \mu_3
\]

- Maximum profit on energy
- Profit on reserve could be increased if ramp rate constraint could be relaxed
Case 7: $\mu_1 > 0; \mu_2 = 0; \mu_3 > 0$

- Maximum capacity and ramp rate constraints are binding

$$
\begin{align*}
x_1 + x_2 &= P_{max} \\
x_2 &= R_{max}
\end{align*}
$$

$$
\begin{align*}
\frac{\partial \ell}{\partial x_1} &\equiv \pi_1 - \frac{dC_1}{dx_1} - \mu_1 + \mu_2 = 0 &\Rightarrow \quad \pi_1 - \frac{dC_1}{dx_1} = \mu_1 \\
\frac{\partial \ell}{\partial x_2} &\equiv \pi_2 - \frac{dC_2}{dx_2} - \mu_1 - \mu_3 = 0 &\Rightarrow \quad \pi_2 - \frac{dC_2}{dx_2} = \mu_1 + \mu_3
\end{align*}
$$

- Sale of energy and sale of reserve are both profitable
- Sale of reserve is more profitable but limited by the ramp rate constraint
Case 8: $\mu_1 = 0; \mu_2 > 0; \mu_3 > 0$

- Generator at minimum output and reserve limited by ramp rate

$x_1 = P^{\text{min}}$

$x_2 = R^{\text{max}}$

\[
\frac{\partial \ell}{\partial x_1} \equiv \pi_1 - \frac{dC_1}{dx_1} - \mu_1 + \mu_2 = 0 \quad \Rightarrow \quad \pi_1 - \frac{dC_1}{dx_1} = -\mu_2
\]

\[
\frac{\partial \ell}{\partial x_2} \equiv \pi_2 - \frac{dC_2}{dx_2} - \mu_1 - \mu_3 = 0 \quad \Rightarrow \quad \pi_2 - \frac{dC_2}{dx_2} = \mu_3
\]

- Sale of reserve is profitable but limited by ramp rate constraint
- Sale of energy is unprofitable
- Overall profitability needs to be checked
Effect of the Transmission Network on Electricity Prices

Daniel Kirschen
Introduction

• No longer assume that all generators and loads are connected to the same bus

• Need to consider:
  ♦ Congestion, constraints on flows
  ♦ Losses

• Two forms of trading
  ♦ Bilateral or decentralised trading
  ♦ Pool or centralised trading
Bilateral or decentralised trading

• Transactions involves only buyer and seller
• Agree on price, quantity and other conditions
• System operator
  ♦ Does not get involved directly in trading
  ♦ Maintains balance and security of the system
    • Buys or sells limited amounts of energy to keep load and generation in balance
    • Limits the amount of power that generators can inject at some nodes if security cannot be ensured by other means
Example of bilateral trading

- $G_1$ sold 300 MW to $L_1$
- $G_2$ sold 200 MW to $L_2$
- Prices are a private matter
- Quantities must be reported to system operator so it can check security
Example of bilateral trading

- \( G_1 \) sold 300 MW to \( L_1 \)
- \( G_2 \) sold 200 MW to \( L_2 \)
- If capacity of corridor \( \geq 500 \) MW \( \Rightarrow \) No problem
- If capacity of corridor \( < 500 \) MW \( \Rightarrow \) some of these transactions may have to be curtailed
But curtail which one?

• Could use administrative procedures
  - These procedures consider:
    - Firm vs. non-firm transactions
    - Order in which they were registered
    - Historical considerations
  - Do not consider relative economic benefits
  - Economically inefficient
  - Let the participants themselves decide

• Participants should purchase right to use the network when arranging a trade in energy
  - Physical transmission rights
  - Support actual transmission of power over a given link
Physical transmission rights

- $G_1$ sold 300 MW to $L_1$ at 30 €/MWh
- $G_2$ sold 200 MW to $L_2$ at 32 €/MWh
- $G_3$ selling energy at 35 €/MWh
- $L_2$ should not pay more than 3 €/MWh for transmission rights
- $L_1$ should not pay more than 5 €/MWh for transmission rights
Problems with physical rights

- Parallel paths
- Market power
Parallel paths

\[ F^A = \frac{x_B}{x_A + x_B} P \]

\[ F^B = \frac{x_A}{x_A + x_B} P \]
Parallel paths

<table>
<thead>
<tr>
<th>Branch</th>
<th>Reactance [p.u.]</th>
<th>Capacity [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
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</tr>
<tr>
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<td>0.2</td>
<td>250</td>
</tr>
<tr>
<td>2-3</td>
<td>0.1</td>
<td>130</td>
</tr>
</tbody>
</table>
Parallel paths

400 MW transaction between B and Y
Need to buy transmission rights on all lines
Parallel paths

<table>
<thead>
<tr>
<th>Branch</th>
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</tr>
<tr>
<td>2-3</td>
<td>0.1</td>
<td>130</td>
</tr>
</tbody>
</table>

400 MW transaction between B and Y

\[ F^I = \frac{0.2}{0.2 + 0.3} \times 400 = 160 \text{ MW} \]

\[ F^{II} = \frac{0.3}{0.2 + 0.3} \times 400 = 240 \text{ MW} \]

Not possible because exceeds capacities of lines 1-2 and 2-3
Counter-flows

200 MW transaction between D and Z

\[ F_{III} = \frac{0.2}{0.2 + 0.3} \times 200 = 80 \text{ MW} \]

\[ F_{IV} = \frac{0.3}{0.2 + 0.3} \times 200 = 120 \text{ MW} \]
The resultant flows are within the limits.

\[ F_{12} = F_{23} = F^I - F^{III} = 160 - 80 = 80 \text{ MW} \]

\[ F_{13} = F^II - F^{IV} = 240 - 120 = 120 \text{ MW} \]
Physical rights and parallel paths

- Counter-flows create additional physical transmission rights
- Economic efficiency requires that these rights be considered
- Decentralised trading:
  - System operator only checks overall feasibility
  - Participants trade physical rights bilaterally
  - Theory:
    - Enough participants ⇒ market discovers optimum
  - Practice:
    - Complexity and amount of information involved are such that it is unlikely that this optimum can be found in time
Physical rights and market power

- $G_3$ only generator at bus B
- $G_3$ purchases transmission rights from A to B
- $G_3$ does not use or resell these rights
- Effectively reduces capacity from A to B
- Allows $G_3$ to increase price at B
- “Use them or loose them” provision for transmission rights: difficult to enforce in a timely manner
Centralised or Pool Trading

• Producers and consumers submit bids and offers to a central market
• Independent system operator selects the winning bids and offers in a way that:
  - Optimally clears the market
  - Respects security constraints imposed by the network
• No congestion and no losses: uniform price
• Congestion or losses: price depend on location where generator or load is connected
Borduria-Syldavia Interconnection

- Perfect competition within each country
- No congestion or losses within each country
  - Single price for electrical energy for each country
  - Price = marginal cost of production
Borduria-Syldavia Interconnection

\[ \pi_B = MC_B = 10 + 0.01 P_B \text{ [$/MWh]} \]

\[ \pi_S = MC_S = 13 + 0.02 P_S \text{ [$/MWh]} \]

\[ \pi_B = MC_B = 10 + 0.01 \times 500 = 15 \text{ $ / MWh} \]

\[ \pi_S = MC_S = 13 + 0.02 \times 1500 = 43 \text{ $ / MWh} \]
Borduria-Syldavia Interconnection

Economic effect of an interconnection?
Can Borduria supply all the demand?

- Generators in Syldavia can sell at a lower price than generators in Borduria
- Situation is not tenable
- Not a market equilibrium

\[
P_B = 2000 \text{MW} \quad MC_B = 30\$/\text{MWh}
\]
\[
P_S = 0 \text{MW} \quad MC_S = 13\$/\text{MWh}
\]
Market equilibrium

\[ \pi = \pi_B = \pi_S \]

\[ P_B + P_S = D_B + D_S = 500 + 1500 = 2000 \text{ MW} \]

\[ \pi_B = MC_B = 10 + 0.01 P_B \ ($/\text{MWh}) \]

\[ \pi_S = MC_S = 13 + 0.02 P_S \ ($/\text{MWh}) \]

\[ \pi = \pi_B = \pi_S = 24.30$ / MWh \]

\[ P_B = 1433 \text{ MW} \]

\[ P_S = 567 \text{ MW} \]
Flow at the market equilibrium

\[ P_B = 1433 \text{MW} \]

\[ P_S = 567 \text{MW} \]

\[ F_{BS} = P_B - D_B = D_S - P_S = 933 \text{MW} \]
Graphical representation

\[ \pi_B = MC_B \]

Supply curve for Syldavia

\[ \pi_S = MC_S \]

Supply curve for Borduria

24.3 $/MWh

\[ P_B = 1433 \text{ MW} \]

\[ P_S = 567 \text{ MW} \]

\[ F_{BS} = 933 \text{ MW} \]

\[ D_B = 500 \text{ MW} \]

\[ D_S = 1500 \text{ MW} \]

\[ D_B + D_S = 2000 \text{ MW} \]
Constrained transmission

• What if the interconnection can carry only 400 MW?
• $P_B = 500 \text{ MW} + 400 \text{ MW} = 900 \text{ MW}$
• $P_S = 1500 \text{ MW} - 400 \text{ MW} = 1100 \text{ MW}$

\[
\pi_B = MC_B = 10 + 0.01 \times 900 = 19 \text{ $/MWh}$
\]

\[
\pi_S = MC_S = 13 + 0.02 \times 1100 = 35 \text{ $/MWh}$
\]

• Price difference between the two locations
• Locational marginal pricing or nodal pricing
Graphical representation

\[ \pi_B = MC_B \]

\[ \pi_S = MC_S \]

\[ P_B = 900 \text{ MW} \]

\[ P_S = 1100 \text{ MW} \]

\[ F_{BS} = 400 \text{ MW} \]

\[ D_B = 500 \text{ MW} \]

\[ D_S = 1500 \text{ MW} \]

\[ D_B + D_S = 2000 \text{ MW} \]

35 $/\text{MWh}

16 $/\text{MWh}
## Summary

<table>
<thead>
<tr>
<th></th>
<th>Separate markets</th>
<th>Single market</th>
<th>Single market with congestion</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_B$ [MW]</td>
<td>500</td>
<td>1,433</td>
<td>900</td>
</tr>
<tr>
<td>$\pi_B$ [$/\text{MWh}$]</td>
<td>15</td>
<td>24.33</td>
<td>19</td>
</tr>
<tr>
<td>$R_B$ [$/\text{h}$]</td>
<td>7,500</td>
<td>34,865</td>
<td>17,100</td>
</tr>
<tr>
<td>$E_B$ [$/\text{h}$]</td>
<td>7,500</td>
<td>12,165</td>
<td>9,500</td>
</tr>
<tr>
<td>$P_S$ [MW]</td>
<td>1500</td>
<td>567</td>
<td>1100</td>
</tr>
<tr>
<td>$\pi_S$ [$/\text{MWh}$]</td>
<td>43</td>
<td>24.33</td>
<td>35</td>
</tr>
<tr>
<td>$R_S$ [$/\text{h}$]</td>
<td>64,500</td>
<td>13,795</td>
<td>38,500</td>
</tr>
<tr>
<td>$E_S$ [$/\text{h}$]</td>
<td>64,500</td>
<td>36,495</td>
<td>52,500</td>
</tr>
<tr>
<td>$F_{BS}$ [MW]</td>
<td>0</td>
<td>933</td>
<td>400</td>
</tr>
<tr>
<td>$R_{TOTAL} = R_B + R_S$</td>
<td>72,000</td>
<td>48,660</td>
<td>55,600</td>
</tr>
<tr>
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<td>48,660</td>
<td>62,000</td>
</tr>
</tbody>
</table>
Winners and Losers

• Winners:
  ♦ Economies of both countries
  ♦ Bordurian generators
  ♦ Syldavian consumers

• Losers
  ♦ Bordurian consumers
  ♦ Syldavian generators

• Congestion in the interconnection reduces these benefits
Congestion surplus

Consumer payments:

\[ E_{\text{TOTAL}} = \pi_B \cdot D_B + \pi_S \cdot D_S \]

Producers revenues:

\[ R_{\text{TOTAL}} = \pi_B \cdot P_B + \pi_S \cdot P_S = \pi_B \cdot (D_B + F_{BS}) + \pi_S \cdot (D_S - F_{BS}) \]

Congestion or merchandising surplus:

\[ E_{\text{TOTAL}} - R_{\text{TOTAL}} = \pi_S \cdot D_S + \pi_B \cdot D_B - \pi_S \cdot P_S - \pi_B \cdot P_B \]
\[ = \pi_S \cdot (D_S - P_S) + \pi_B \cdot (D_B - P_B) \]
\[ = \pi_S \cdot F_{BS} + \pi_B \cdot (-F_{BS}) \]
\[ = (\pi_S - \pi_B) \cdot F_{BS} \]
Congestion surplus

![Graph showing flow on the interconnection in MW on the x-axis and payments and revenues in $/h on the y-axis. The graph indicates the relationship between flow and payments/revenues, with a point of intersection indicating the congestion surplus.](image)
Congestion surplus

• Collected by the market operator in pool trading
• Should not be kept by market operator in pool trading because it gives a perverse incentive
• Should not be returned directly to network users because that would blunt the economic incentive provided by nodal pricing
Pool trading in a three-bus example

<table>
<thead>
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<td>2-3</td>
<td>0.1</td>
<td>130</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Generator</th>
<th>Capacity [MW]</th>
<th>Marginal Cost [$/MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>140</td>
<td>7.5</td>
</tr>
<tr>
<td>B</td>
<td>285</td>
<td>6</td>
</tr>
<tr>
<td>C</td>
<td>90</td>
<td>14</td>
</tr>
<tr>
<td>D</td>
<td>85</td>
<td>10</td>
</tr>
</tbody>
</table>
Economic dispatch

Diagram showing the economic dispatch with nodes A, B, C, and D connected by lines and flows.

- Node A: 125 MW to Node B
- Node B: 285 MW to Node C
- Node C: 0 MW to Node D
- Node D: 300 MW to Node 1

Flows labeled:
- $F_{12}$
- $F_{13}$
- $F_{23}$

Nodes labeled:
- Node 1
- Node 2
- Node 3
- Node D
Superposition

360 MW
1
60 MW
2
300 MW
3

300 MW
1
60 MW
2
300 MW
3

300 MW
1
60 MW
2
300 MW
3

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Flow with economic dispatch

A 125 MW
B 285 MW

1 156 MW

D 300 MW

C 0 MW

50 MW
204 MW 96 MW 60 MW

© 2005 D. Kirschen
Correcting the economic dispatch

Additional generation at bus 2

0.6 MW

0.4 MW

© 2005 D. Kirschen
Superposition

360 MW

1

300 MW

2

60 MW

204 MW

96 MW

156 MW

3

50 MW

1

2

50 MW

20 MW

30 MW

310 MW

1

126 MW

2

10 MW

184 MW

116 MW

3

300 MW

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Correcting the economic dispatch

Additional generation at bus 3

1 MW

0.4 MW

0.6 MW

1 MW

© 2005 D. Kirschen
Superposition

1. 360 MW
   - 156 MW
   - 204 MW
   - 300 MW

2. 300 MW

3. 300 MW
   - 96 MW

4. 60 MW

5. 60 MW

6. 285 MW
   - 126 MW

7. 159 MW
   - 66 MW
   - 225 MW

8. 60 MW
Cost of the dispatches

- Economic dispatch: 2,647.50 $/h
- Redispatch generator 2: 2,972.50 $/h
- Redispatch generator 3: 2,835.00 $/h
- Cost of security: 187.50 $/h
Security constrained dispatch

A

50 MW

B

285 MW

0 MW

1

126 MW

2

60 MW

159 MW

66 MW

3

75 MW

D

300 MW

50 MW
Nodal prices

- Cost of supplying an additional MW of load without violating the security constraints
- Start from the security constrained dispatch
Nodal prices

- Node 1:
- A is cheapest
- $\pi_1 = MC_A = 7.50 \text{ $/MWh}$
Nodal prices

- Node 3
- A is cheaper than D
- Increasing A would overload line 1-2
- Increase D by 1 MW

{\pi_3} = MC_D = 10 \ $ / \text{MWh}
Nodal prices

- Node 2
- C is very expensive
- Increasing A or D would overload line 1-2
- ?
Nodal price at node 2
Nodal price at node 2

- Increase generation at node 3 AND decrease generation at node 1
Nodal price using superposition

\[ \Delta P_1 + \Delta P_3 = \Delta P_2 = 1 \text{ MW} \]

\[ 0.6 \Delta P_1 + 0.2 \Delta P_3 = \Delta F_{12} = 0 \text{ MW} \]

\[ \Delta P_1 = -0.5 \text{ MW} \]

\[ \Delta P_3 = 1.5 \text{ MW} \]

\[ \pi_2 = 1.5 \cdot MC_D - 0.5 \cdot MC_A = 11.25 \text{ }\$/\text{MWh} \]
Observations

- Generators A and D are marginal generators because they supply the next MW of load at the bus where they are located.
- Generators B and C are not marginal.
- Unconstrained system: 1 marginal generator.
- m constraints: m+1 marginal generators.
- Prices at nodes where there is no marginal generator are set by a linear combination of the prices at the other nodes.
Summary for three-bus system

<table>
<thead>
<tr>
<th></th>
<th>Bus 1</th>
<th>Bus 2</th>
<th>Bus 3</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumption [MW]</td>
<td>50</td>
<td>60</td>
<td>300</td>
<td>410</td>
</tr>
<tr>
<td>Production [MW]</td>
<td>335</td>
<td>0</td>
<td>75</td>
<td>410</td>
</tr>
<tr>
<td>Nodal marginal price [$/MWh]</td>
<td>7.50</td>
<td>11.25</td>
<td>10.00</td>
<td>-</td>
</tr>
<tr>
<td>Consumer payments [$/h]</td>
<td>375.00</td>
<td>675.00</td>
<td>3,000.00</td>
<td>4,050.00</td>
</tr>
<tr>
<td>Producer revenues [$/h]</td>
<td>2,512.50</td>
<td>0.00</td>
<td>750.00</td>
<td>3,262.50</td>
</tr>
<tr>
<td>Merchandising surplus [$/h]</td>
<td></td>
<td></td>
<td></td>
<td>787.50</td>
</tr>
</tbody>
</table>
Counter-intuitive flows

Power flows from high price to low price!

\[ \pi_3 = 7.50 \text{ \$/MWh} \]

\[ \pi_2 = 11.25 \text{ \$/MWh} \]

\[ \pi_3 = 10.00 \text{ \$/MWh} \]

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Counter-intuitive prices

- Prices at nodes without a marginal generator can be higher or lower than prices at the other nodes
- Nodal prices can even be negative!
- Predicting nodal prices requires calculations
- Strategically placed generators can control prices
- Network congestion helps generators exert market power
Method for computing prices

• Optimisation problem:
  ♦ Objective: maximisation of welfare
  ♦ Constraints: power flow equations
  ♦ Lagrange multipliers give the nodal prices
  ♦ Usually dc power flow approximation

• Optimisation carried out ex-post on the basis of the actual operation of the system
Effect of losses on prices

\[ L_{\text{variable}} = I^2 R \approx \left( \frac{S}{V} \right)^2 \]

\[ R = \frac{P^2 + Q^2}{V^2} \cdot R \approx \frac{R}{V^2} \cdot P^2 = K \cdot P^2 \]

\[ G(D) = D + L = D + K \cdot D^2 \]

\[ G = G(D + \Delta D) - G(D) = \Delta D + 2 \Delta D \cdot D \cdot K = (1 + 2D \cdot K) \Delta D \]

\[ C = c \left( 1 + 2D \cdot K \right) \Delta D \]

\[ \frac{\Delta C}{\Delta D} = c \left( 1 + 2D \cdot K \right) \]

\[ \pi_1 = c \]

\[ \pi_2 = \pi_1 \left( 1 + 2D \cdot K \right) \]
Losses between Borduria & Syldavia

\[ P_S = D_S - F_{BS} \]

\[ P_B = D_B + F_{BS} + K \cdot F_{BS}^2 \]

Minimisation of the total cost
Financial Transmission Rights

Prof. Daniel Kirschen

The University of Manchester
Managing transmission risks

• Congestion and losses affect nodal prices
• Additional source of uncertainty and risk
• Market participants seek ways of avoiding risks
• Need financial instruments to deal with nodal price risk
Contracts for difference

• Centralised market
  ♦ Producers must sell at their nodal price
  ♦ Consumers must buy at their nodal price

• Producers and consumers are allowed to enter into bilateral financial contracts
  ♦ Contracts for difference
Example of contract for difference

- Contract between Borduria Power and Syldavia Steel
  - Quantity: 400 MW
  - Strike price: 30 $/MWh
- Other participants also trade across the interconnection
No congestion $\Rightarrow$ market price is uniform

- Borduria Power sells 400 at 24.30 $/\text{MWh} \Rightarrow$ gets $9,720
- Syldavia Steel buys 400 at 24.30 $/\text{MWh} \Rightarrow$ pays $9,720
- Syldavia Steel pays 400 (30 - 24.30) = $2,280 to Borduria Power
- Syldavia Steel net cost is $12,000
- Borduria power net revenue is $12,000
- They have effectively traded 400 MW at 30 $/\text{MWh}$
Congestion ⇒ Locational price differences

- Borduria Power sells 400 at 19.00 ⇒ gets $7,600
- Syldavia Steel buys 400 at 35.00 ⇒ pays $14,000
- Borduria Power expects 400 (30 - 19) = $4,400 from Syldavia Steel
- Syldavia Steel expects 400 (35 - 30) = $2,000 from Borduria Power
- Shortfall of $6,400
- Basic contracts for difference break down with nodal pricing!
Financial Transmission Rights (FTR)

• Observations:
  ♦ shortfall in contracts for difference is equal to congestion surplus
  ♦ Congestion surplus is collected by the system operator

• Concept:
  ♦ System operator sells financial transmission rights to users
  ♦ FTR contract for F MW between Borduria and Syldavia entitles the owner to receive:
    \[ F \cdot (\pi_S - \pi_B) \]
  ♦ Holders of FTRs are indifferent about where they trade energy
  ♦ System operator collects exactly enough money in congestion surplus to cover the payments to holders of FTRs
Example of Financial Transmission Rights

- Contract between Borduria Power and Syldavia Steel
  - Quantity: 400 MW
  - For delivery in Syldavia
  - Strike price: 30 $/MWh
- To cover itself against location price risk, Borduria Power purchases 400 MW of financial transmission rights from the System Operator
Example of Financial Transmission Rights

- Borduria Power sells 400 at 19.00 ⇒ gets $7,600
- Syldavia Steel buys 400 at 35.00 ⇒ pays $14,000
- The system operator collects 400 (35 -19) = $ 6,400 in congestion surplus
- Borduria Power collects 400 (35 -19) = $6,400 from the system operator
- Borduria Power pays Syldavia Steel 400 (35 -30) = $2,000
- Syldavia Steel net cost is $12,000
- Borduria power net revenue is $12,000

The books balance!
Financial transmission rights (FTR)

- FTRs provide a perfect hedge against variations in nodal prices
- Auction transmission rights for the maximum transmission capacity of the network
  - The system operator cannot sell more transmission rights than the amount of power that it can deliver
  - If it does, it will loose money!
- Proceeds of the auction help cover the investment costs of the transmission network
- Users of FTRs must estimate the value of the rights they buy at auction
Financial transmission rights

• FTRs are defined from point-to-point
• No need for a direct branch connecting directly the points between which the FTRs are defined
• FTRs automatically factor in the effect of Kirchoff’s voltage law
• Problem:
  - There are many possible point-to-point transmission rights
  - Difficult to assess the value of all possible rights
  - Difficult to set up a market for point-to-point transmission rights
Flowgate rights

• Observation:
  - Typically, only a small number of branches are congested

• Concept:
  - Buy transmission rights only on those lines that are congested
  - Theoretically equivalent to point-to-point rights

• Advantage:
  - Fewer rights need to be traded
  - More liquid market

• Difficulty:
  - Identify the branches that are likely to be congested
Generation Expansion

Daniel Kirschen
Perspectives

• The investor’s perspective
  ✷ Will a new plant generate enough profit from the sale of energy to justify the investment?

• The consumer’s perspective
  ✷ Will there be enough generation capacity to meet the demand from all the consumers?
  ✷ Do investors need an extra incentive to build enough generation capacity?
The investor’s perspective
Example: Investing in a new plant

Data for a coal plant

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment cost</td>
<td>1021 $/kW</td>
</tr>
<tr>
<td>Expected plant life</td>
<td>30 years</td>
</tr>
<tr>
<td>Heat rate at rated output</td>
<td>9,419 Btu/kWh</td>
</tr>
<tr>
<td>Expected fuel cost</td>
<td>1.25 $/MBtu</td>
</tr>
</tbody>
</table>

- Is it worth building a 500MW plant?
- Assume a utilization factor of 80%
- Assume average price of electrical energy is 32 $/MWh
Example (continued)

Investment cost:

\[
1021 \$/kW \times 500 \text{ MW} = 510,500,000
\]

Estimated annual production:

\[
0.8 \times 500 \text{ MW} \times 8760 \text{ h/year} = 3,504,000 \text{ MWh}
\]

Estimated annual production cost:

\[
3,504,000 \text{ MWh} \times 9419 \text{ Btu/kWh} \times 1.25 \$/\text{MBtu} = 41,255,220
\]

Estimated annual revenue:

\[
3,504,000 \text{ MWh} \times 32 \$/\text{MWh} = 112,128,000
\]
### Example (continued)

<table>
<thead>
<tr>
<th>Year</th>
<th>Investment</th>
<th>Production</th>
<th>Production cost</th>
<th>Revenue</th>
<th>Net Cash Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$510,500,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>- $510,500,000</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
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<td>$41,255,220</td>
<td>$112,128,000</td>
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</tr>
</tbody>
</table>

**Total net cash flow over 30 years:**

\[-$510,500,000 + 30 \times $70,872,780 = $1,615,683,400\]

Is this plant profitable enough?
Example (continued)

• Time value of money
  ◆ A dollar now is worth more to me than a dollar next year or
  ◆ How much interest should I be paid to invest my dollar for one year rather than spend it now?
  ◆ This has nothing to do with inflation

• Apply this concept to investments
  ◆ Calculate Internal Rate of Return (IRR) of net cash flow stream
    • Standard accounting formula (use a spreadsheet)
    • Gives more weight to profit in the early years than in the later years
  ◆ Example: IRR = 13.58%
Example (continued)

• Is an IRR of 13.58% good enough?
  ✷ Compare it to the Minimum Acceptable Rate of Return (MARR) of the investor
  ✷ If IRR ≥ MARR ➔ investment is OK
  ✷ If IRR < MARR ➔ investment is not worth making

• How do firms set their MARR?
  ✷ Specializes in high risk investments ➔ set MARR high
  ✷ Specializes in low risk investments ➔ set MARR lower but check carefully the risks associated with each investment
Example (continued)

• What are the risks?
  ♦ Average price of electricity may be less than 32 $/MWh
  ♦ Utilization factor may be less than 80%

• Recalculate the IRR for various conditions

![Graph showing IRR (%) against Price of Electrical Energy ($/MWh) with MARR and Utilization factor indicated.]
Retiring generation capacity

- Once a plant has been built:
  - Most of the investment cost becomes a sunk cost
  - Sunk costs are irrelevant in further decisions
- A plant will be retired if it no longer recovers its operating cost and is not likely to do so in the future
- Examples:
  - Operating cost increases because fuel cost increases
  - Plant utilization and/or energy price decrease because cheaper plants become available
- Decision based only on prediction of future revenues and costs
- Technical fitness and lifetime are irrelevant
Effect of a cyclical demand

• Basic microeconomics:
  - If demand increases or supply decreases (because plants are retired) prices will increase
  - If prices increase, investment projects become more profitable
  - New generating plants are built

• Difficulties
  - Demand for electricity is cyclical
  - Electrical energy cannot be stored economically
  - Must forecast utilization factor for each plant
Load Duration Curve

Number of hours per year during which the demand exceeds a certain level

PJM (Pennsylvania Jersey Maryland) system in 1999
Effect of cyclical demand

- Peak load is much higher than average load
- Total installed capacity must be much higher than average load
- Cheap generators operate most of the time
- More expensive generators operate during only a fraction of the time
- Prices will be higher during periods of high demand
- Competition will be limited during periods of high demand because most generators are already fully loaded
Price duration curve

Actual peak price reached $1000/MWh for a few hours

PJM system, 1999
What about the most expensive unit?

- In a competitive market
  - Market price set by marginal cost of marginal generator
  - Infra marginal generators collect an economic profit because their marginal cost is less than the market price
  - Economic profit pays the fixed costs
  - Marginal generator does not collect any economic profit
  - Marginal generator does not pay its fixed costs
What about the most expensive unit?

• Because of the cyclical demand, most units will be infra-marginal during part of the year

• Most unit will therefore have an opportunity to recover their fixed costs

• The unit that only runs a few hours a year to meet the peak demand is never infra-marginal

• It must recover its costs by incorporating them in its price
  ♦ Must be recovered over a few hours only
  ♦ Prices are very high during these periods (price spikes)
  ♦ Possible because market is not competitive during these periods
  ♦ What if the yearly peak demand is lower than expected?
The consumer’s perspective
Meeting the peak demand

• In a competitive environment, there is no obligation on generating companies to build enough capacity to meet the peak demand

• Rely on price signals to encourage investments

• What if no generation company wants to own the most expensive unit that runs only a few hours a year?
  ✗ Owning that plant is not very profitable

• Will there be enough generation capacity available to meet the reliability expectations?
Consequences of not meeting the peak demand

• Load must be shed (i.e. customers temporarily disconnected)
• Cost of these interruptions: Value of Lost Load (VOLL)
• VOLL is about 100 times larger than the average cost of electricity
• Customers have a much stronger interest in having enough generation capacity than generators
• Customers may be willing to pay extra to guarantee that there will be enough capacity available
Capacity incentives

• Advantages
  ❖ Capacity insurance policy: pay a little bit regularly to avoid a major problem

• Disadvantages
  ❖ Less economically efficient behaviour
  ❖ How much should generators be paid per MW?
    Or
  ❖ How much capacity should be available?
Capacity incentives

• Capacity payments
  ♦ Pay generators a fixed rate per MW of capacity available
  ♦ Encourages them to keep available plants that don’t generate many MWh

• Capacity market
  ♦ Regulator determines the generation capacity required to meet a reliability target
  ♦ Consumers must all “buy” their share of this capacity
  ♦ Generators bid to provide this capacity
  ♦ Price paid depends on how much capacity is offered