

Models for the Electricity Sector and Electricity Market Reforms

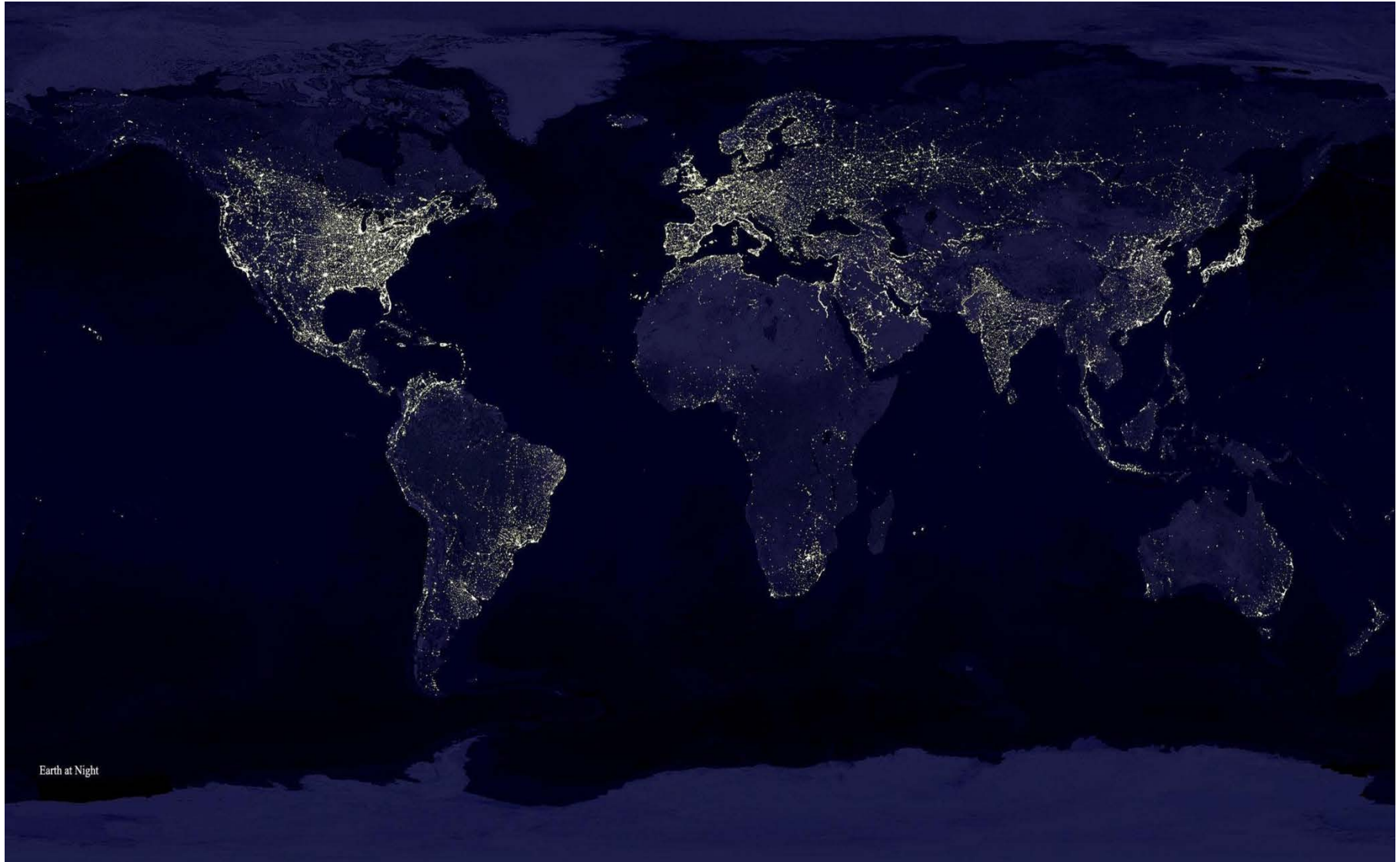
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Nanyang Technological University

18 February 2015

The 8th Capacity Building for
Officers of Electricity Regulatory Commissions

18 – 20 February 2015, Singapore

World at Night from Satellite

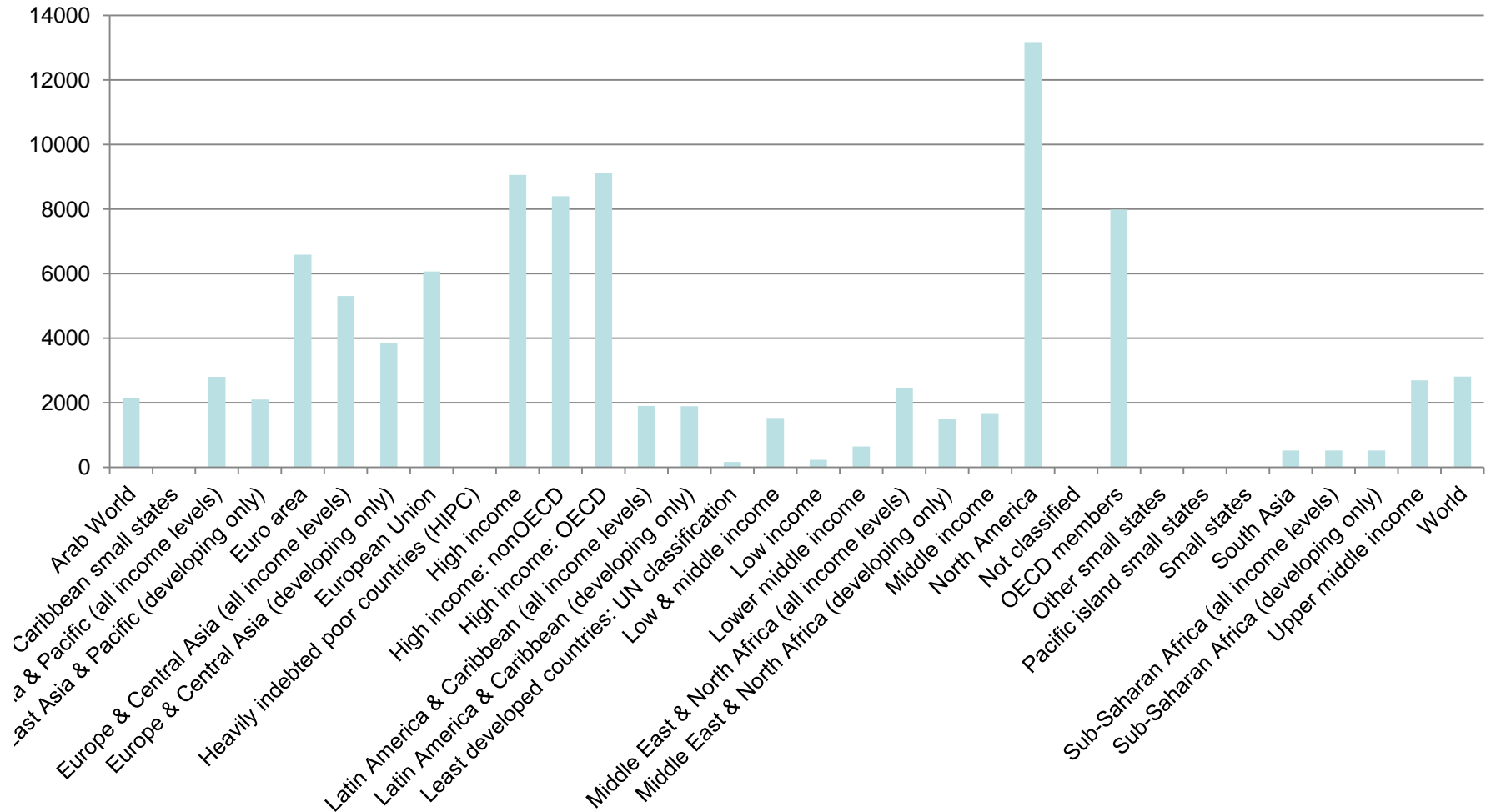


Earth at Night

Models for the Electricity Sector and Electricity Market Reforms

- Descriptive statistics
- Modeling natural monopoly
 - Social optimum in a natural monopoly market
- Government policy for a natural monopoly
 - Rate of return regulation
 - Utility base
- Various load structures, load and load duration curve
- Peak Load Pricing
- Models for restructuring the electricity sector
 - System marginal price and capacity charge
 - Market power and measures

Electricity Consumption per Capita (kWh) in 2009



Source: World Bank (2012)

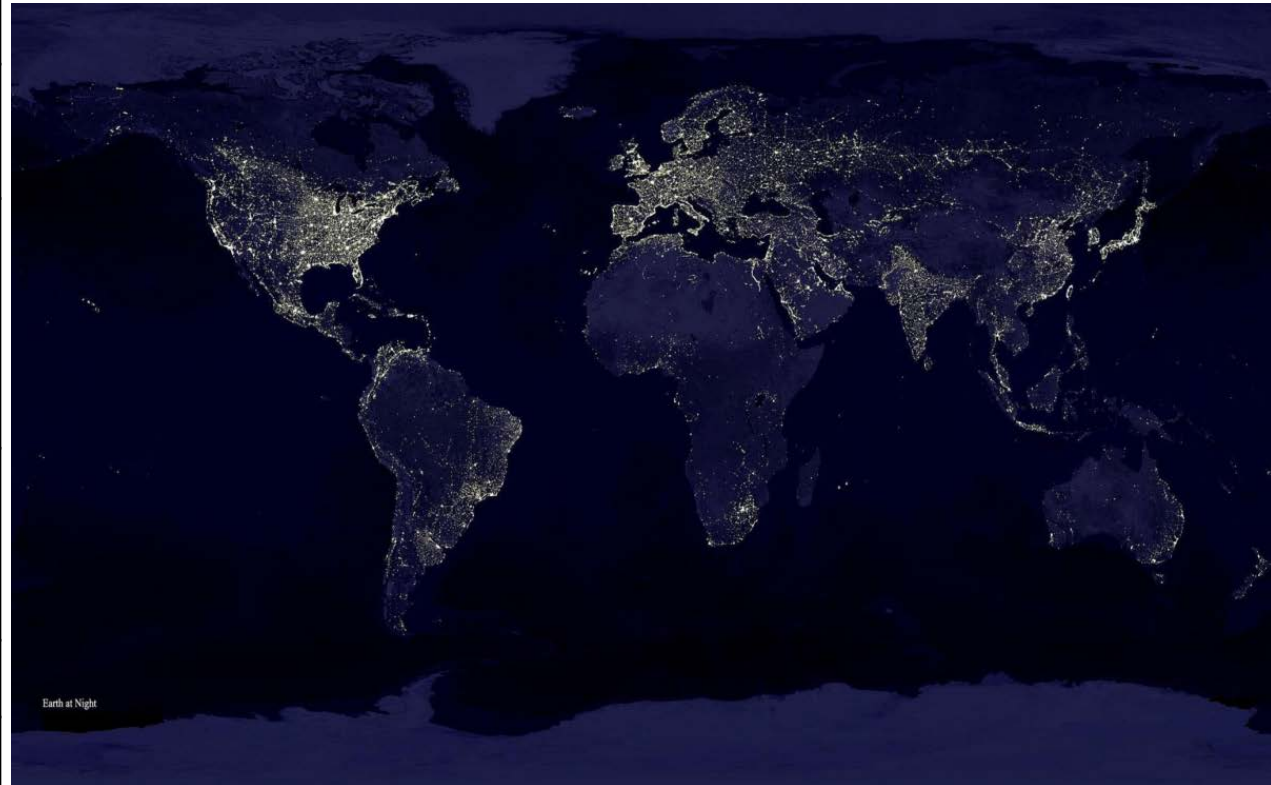
Electricity Consumption per Capita by Region in 2009 (kWh)

Region	Consumption
Arab World	2,154.8
East Asia and Pacific	2,797.4
Euro Area	6,588.7
European Union	6,063.6
Latin America and Caribbean	1,901.2
Middle East and North Africa	2,445.2
North America	13,167.1
OECD	7,981.8
South Asia	516.9
Sub Saharan Africa	517.4
World	2,806.9

Source: World Bank (2012)

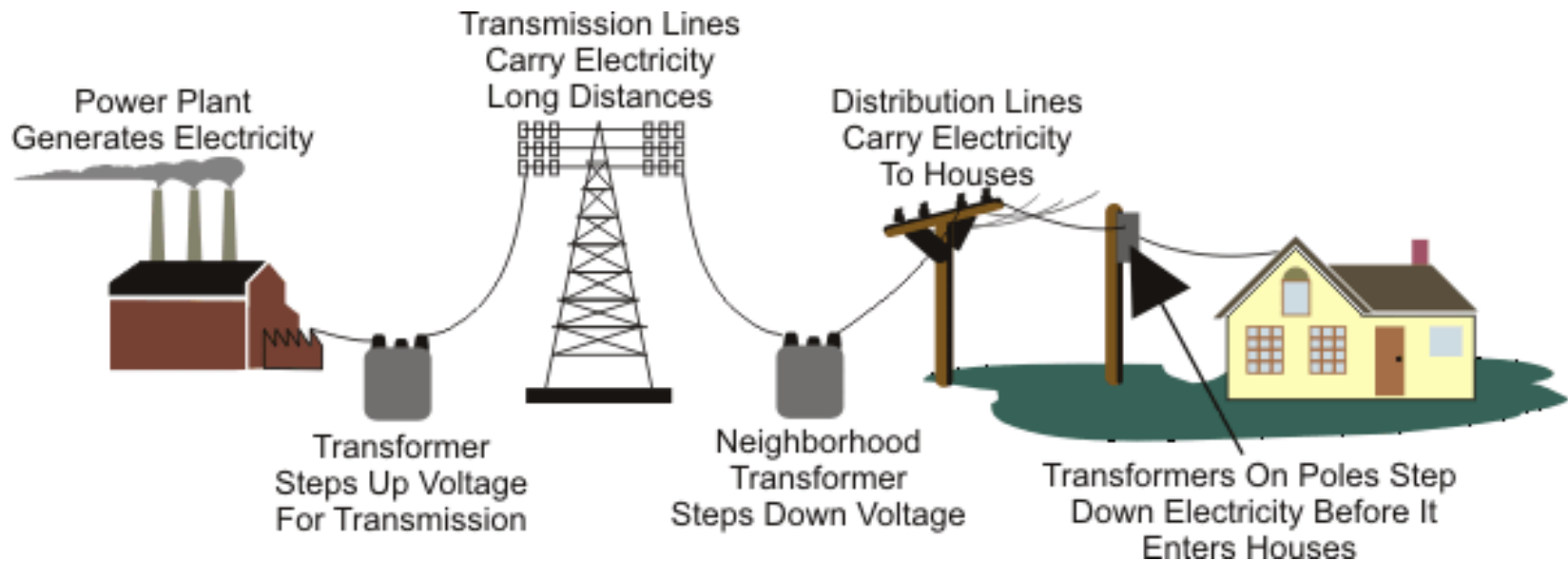
World Population Without Electricity (Millions of People)

	Rural	Urban
S. America	38	7
North Africa-Middle East	30	17
Sub-Saharan Africa	438	109
S. Asia	580	126
S.E. Asia	182	41
Total	1,268	300

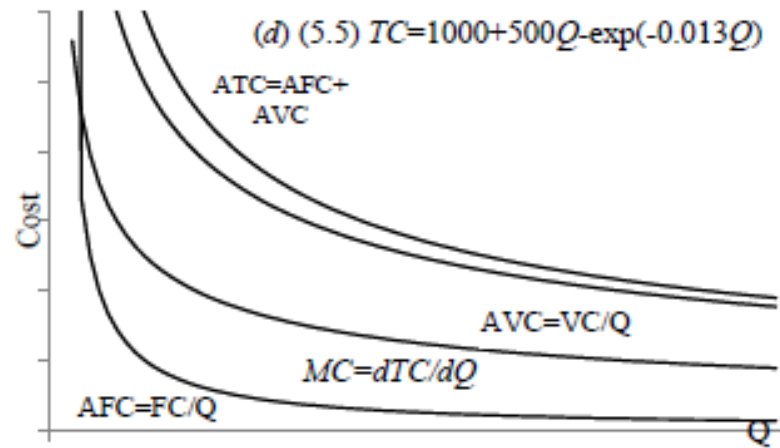
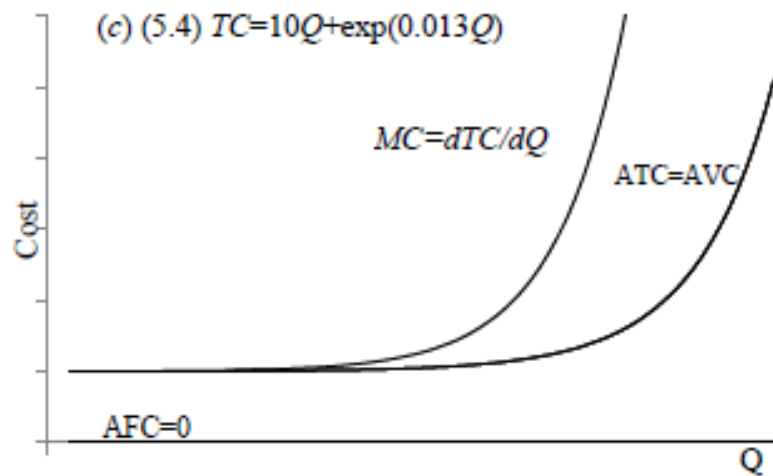
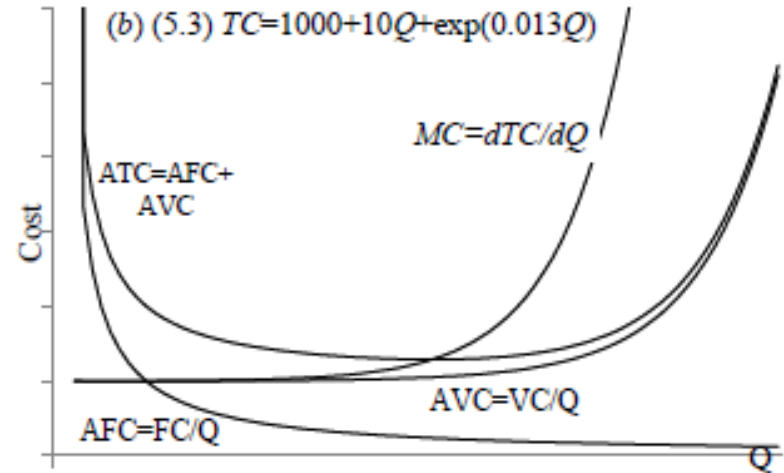
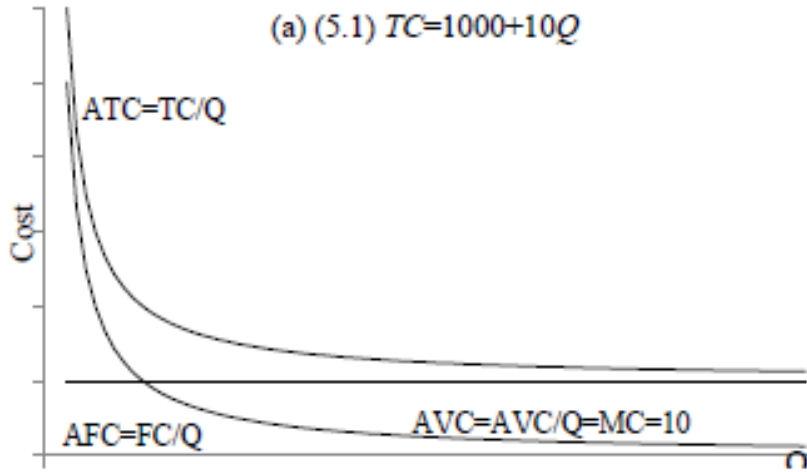


Source: World Energy Outlook 2006 (IEA)

Electricity Generation, Transmission and Distribution: A Schematic Diagram

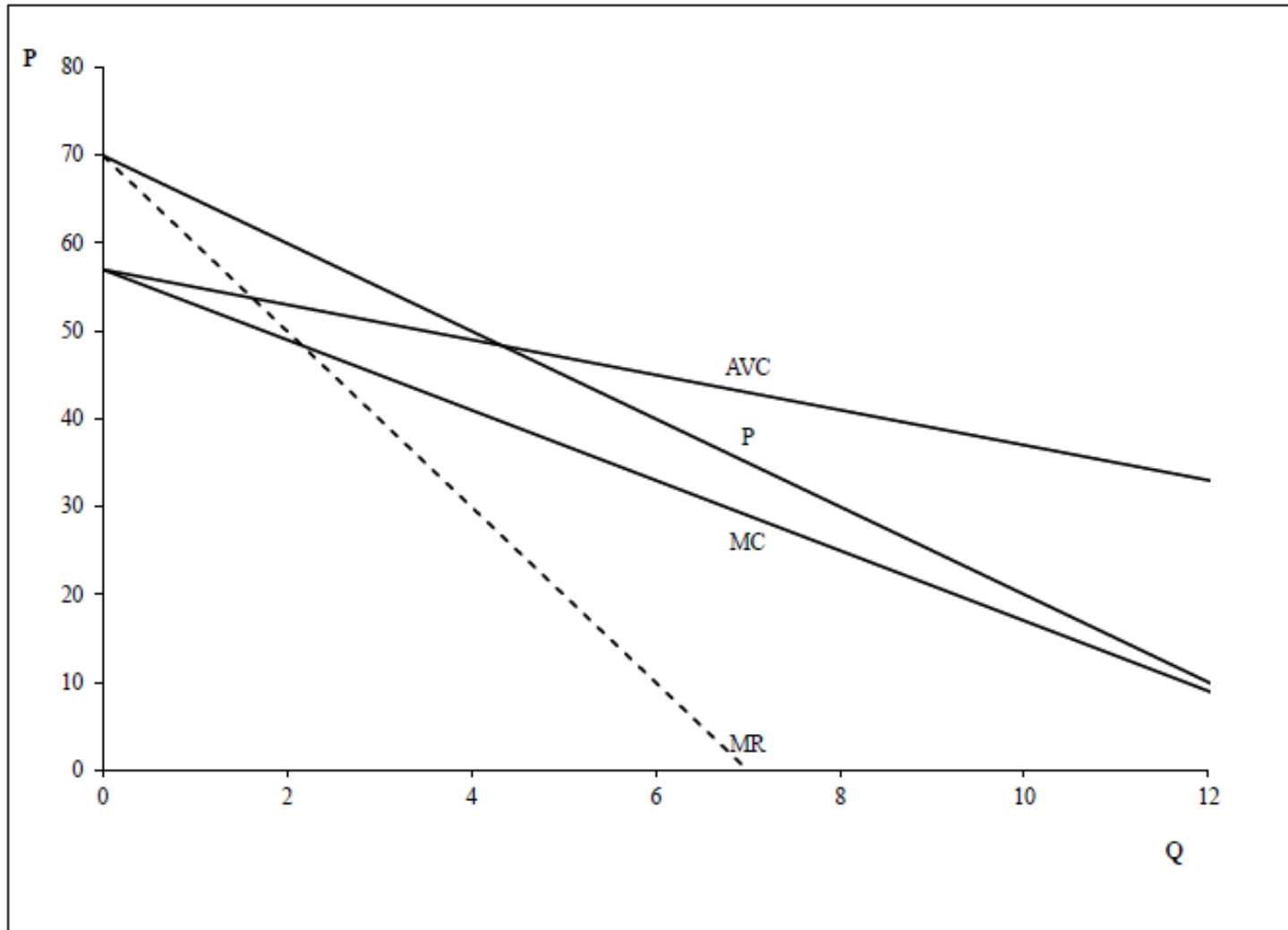


Various Cost Structure

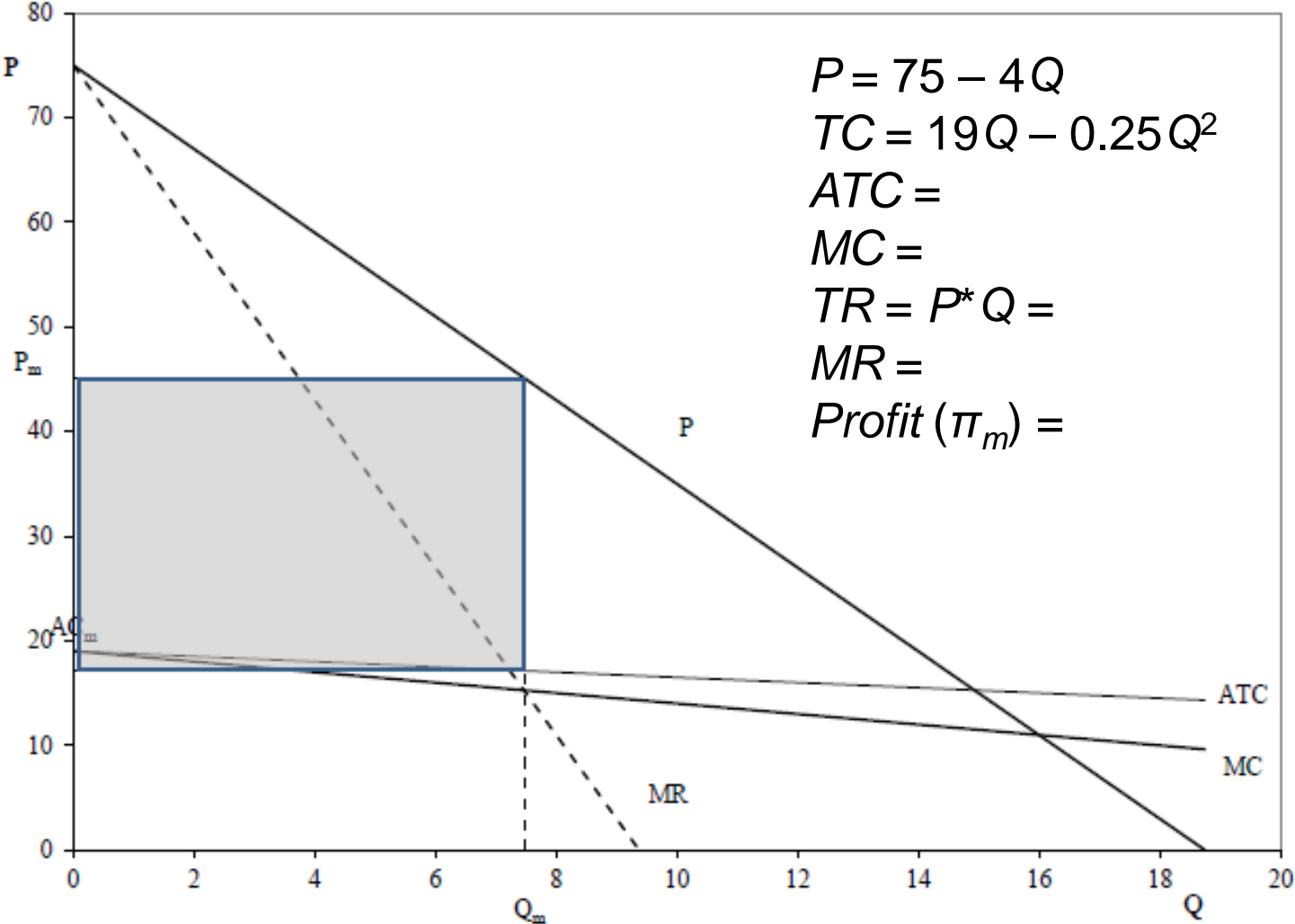


$$TC = FC + VC(Q)$$

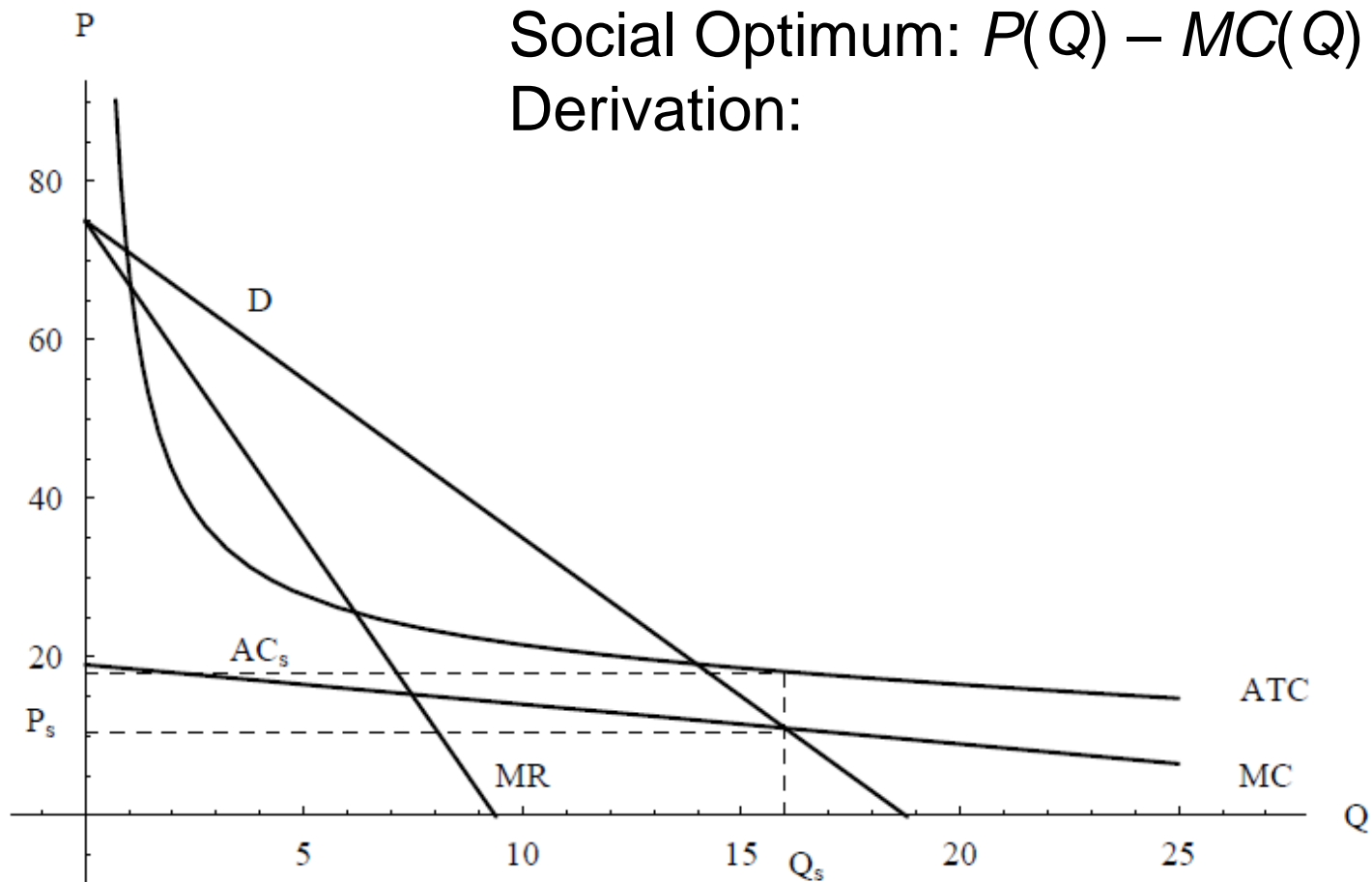
Inverse Demand and Cost Curves in a Decreasing Cost Industry



Monopoly Production, Price and Profit



Social Optimum in a Natural Monopoly Market



Government Policy for a Natural Monopoly

- Rate of Return Regulation

- The utility is allowed to earn a normal rate of return on their capital stock or their rate base (RB)
- The accounting equation

$$\sum_{i=1}^n P_i Q_i = \text{expenses} + s(RB)$$

where P_i = the price of the i - th service class

Q_i = the quantity of the i - th service class

n = the number of service classes

s = the allowable of "fair" rate of return

RB = the rate base of the regulated firm's investment

A Case of Rate Increase: An Illustration

- Suppose that a utility has a rate base of \$2,000
 - It expects to sell 4,000 kWh to industrial customers and 2,500 kWh to residential customers
 - Its operating costs are \$200
 - The regulator believes that 10% is a normal rate of return for the utility
 - The utility has asked the public utility commission for a rate increase to \$0.05 per kWh for industrial customers and to \$0.10 per kWh for residential customers.
- Should the commission approve the rate increase?

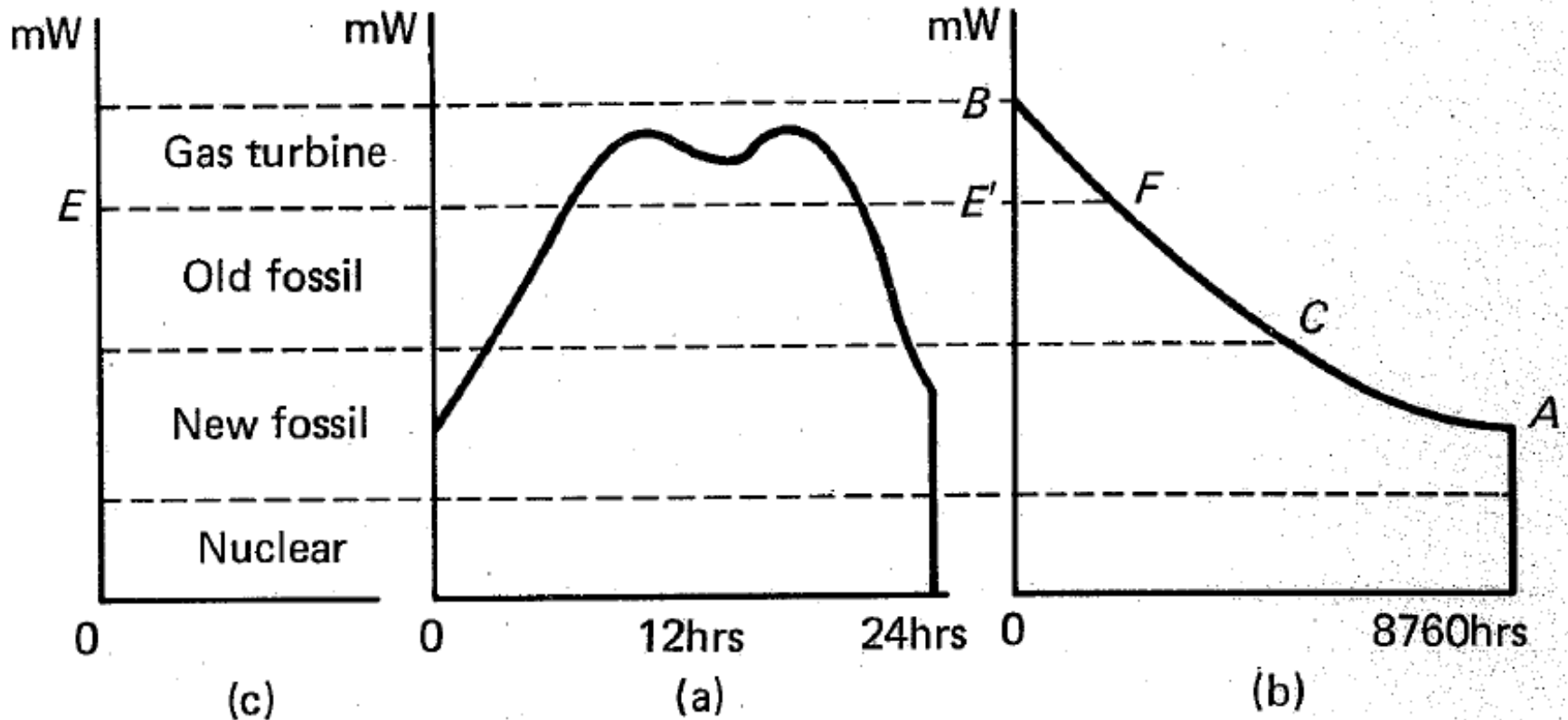
Utility Rate Base

- Rate Base (RB) is usually original capital cost minus depreciation
 - Suppose a plant was bought in 1980 for 500 million 1980 dollars and it is depreciated over 40 years. So annual depreciation is $500/40 = 12.5$.
 - The rate base in 2000
 - $RB(2000) = 500 - 20 * 12.5 = 250$ million
 - This value could understate actual investment if inflation has occurred
 - If prices have doubled from 1980 to 2000, the rate base related to 2000 dollars would be $2 * 250 = 500$ million
 - The rate base can be adjusted with an appropriate index

Load Structure

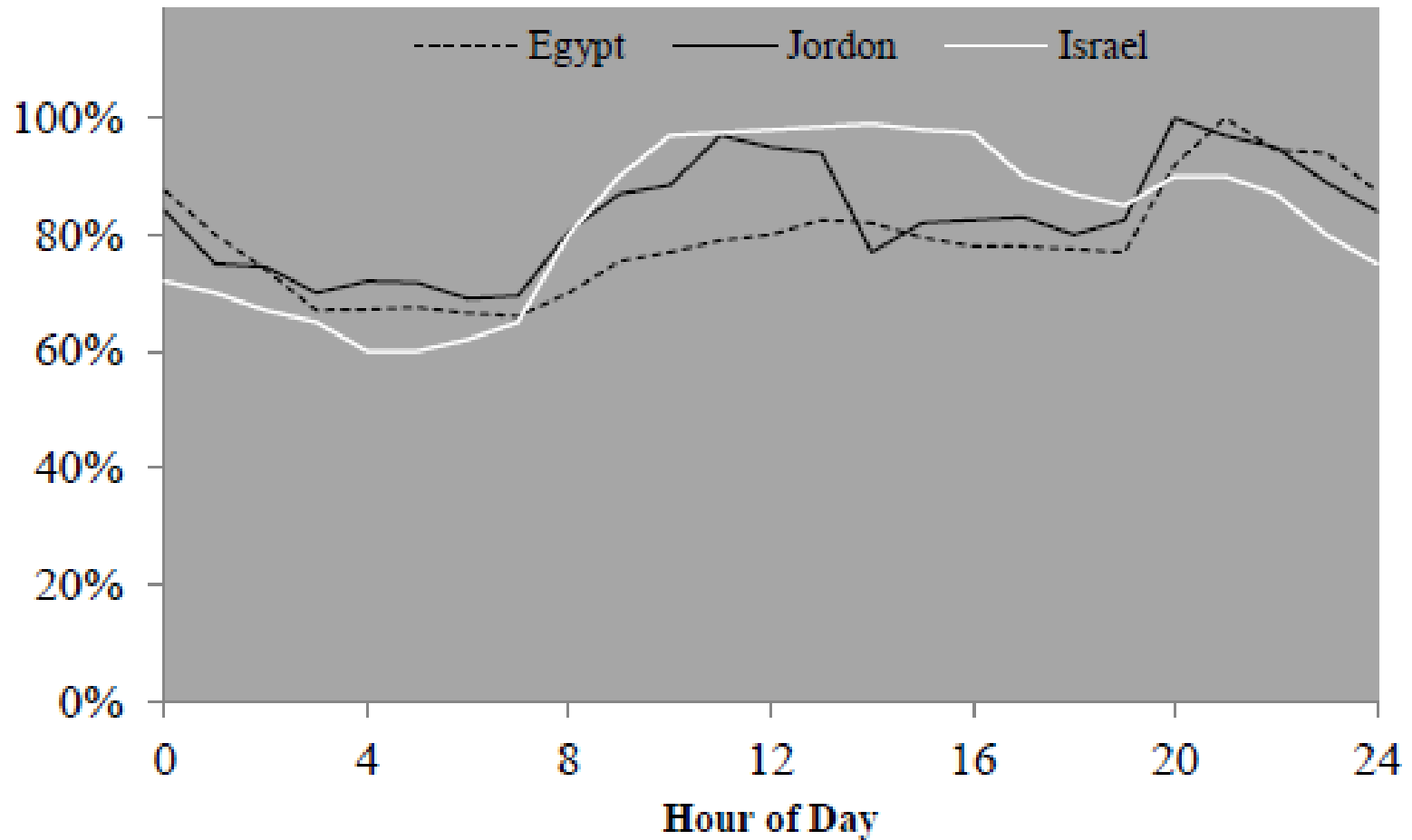
- Load curve
 - Plots demands over a 24-hour period
 - Variation of the electricity demand on a national grid and a day
- Load-duration curve
 - Measures how long a level of demand lasts over a year
- A typical peak load
 - Egypt, Jordan and Israel
 - UK
 - U.S. and Canada
 - Shopping Malls in Hong Kong
 - Singapore

Load and Load Duration Curve

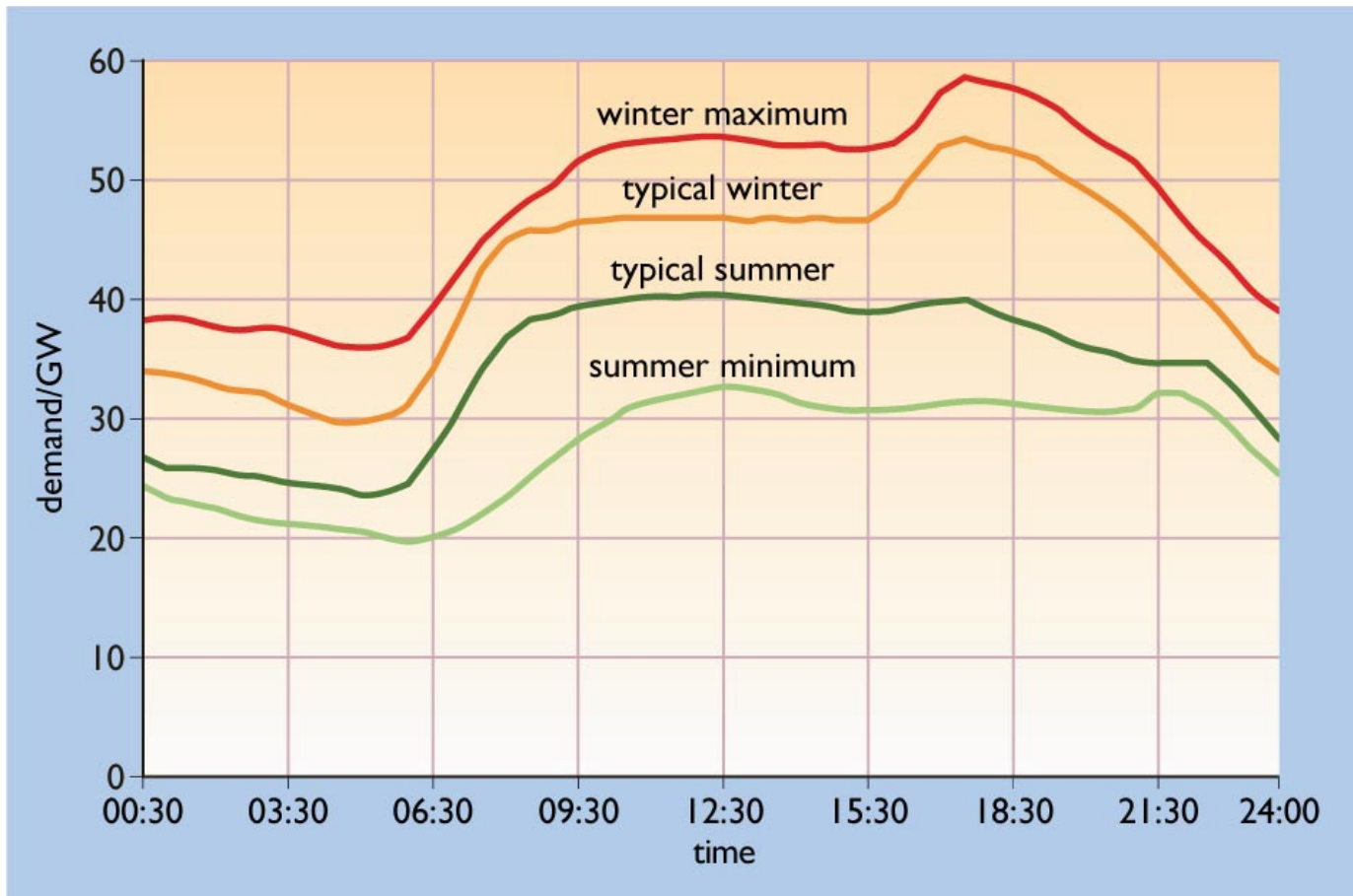


Source: Crew and Kleindorfer (1986)

Typical Daily Electric Load Curve



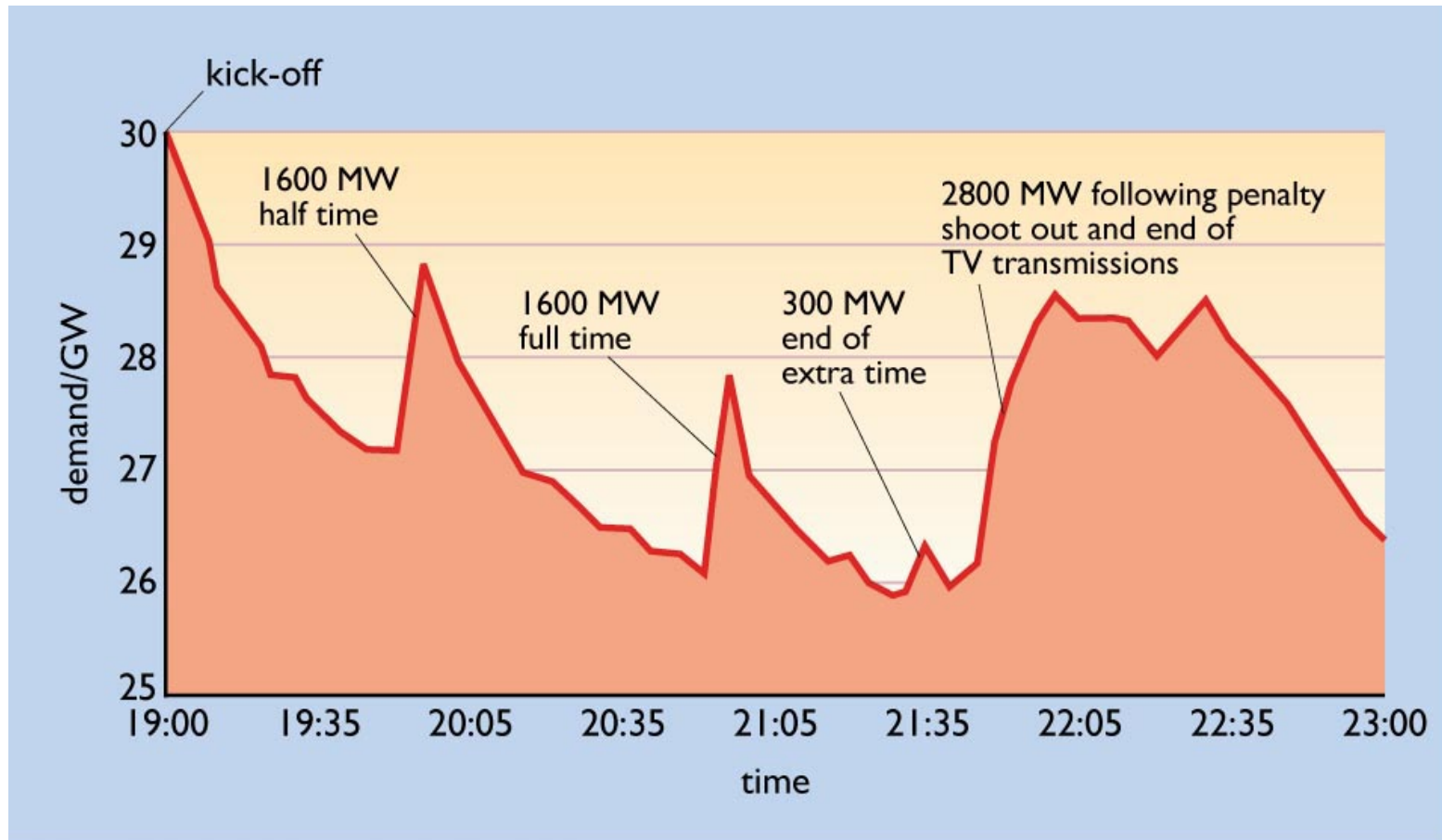
Variation of the Electricity Demand on the National Grid, 2009-10



Copyright © 2010 National Grid Plc

Source: National Grid (2010)

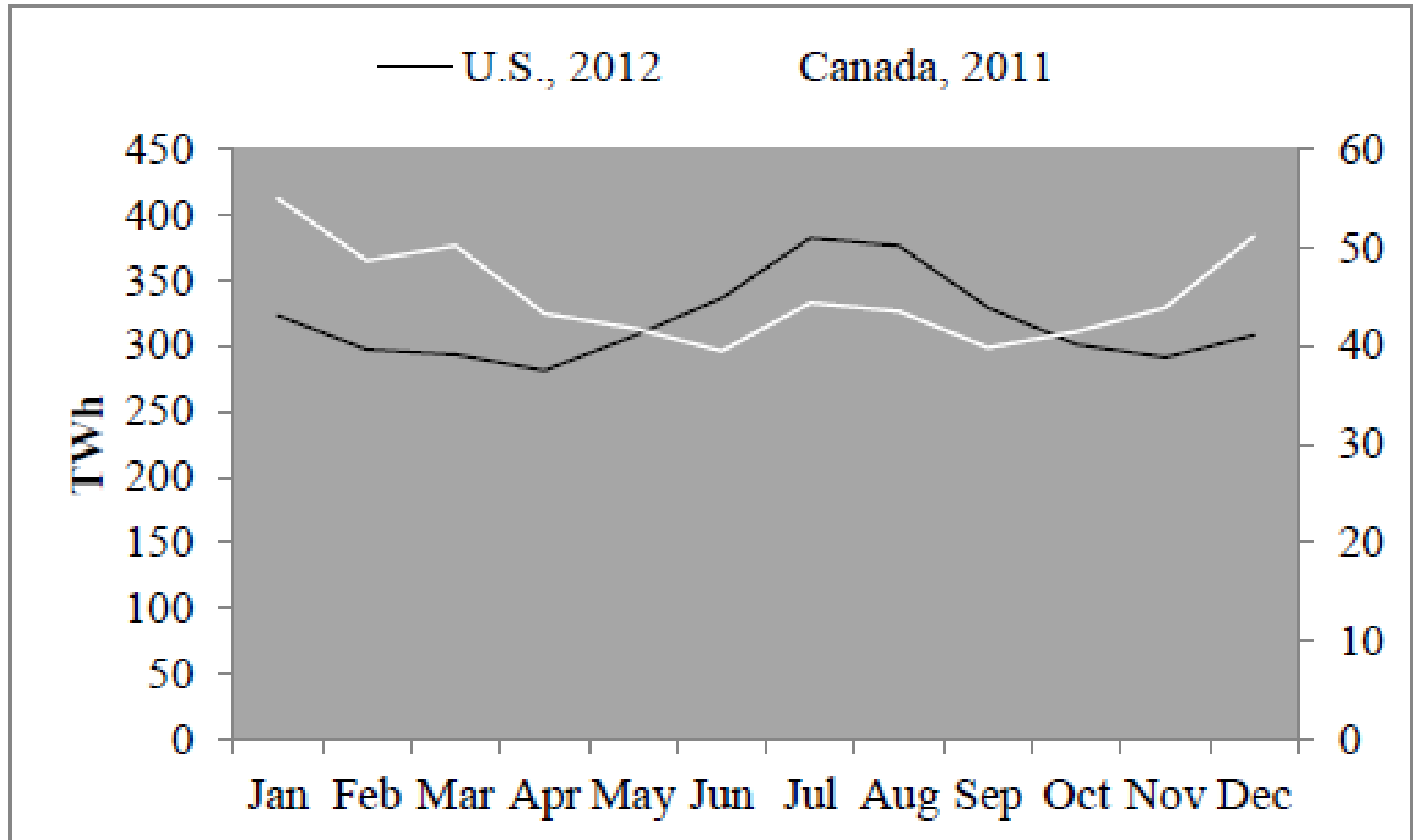
Variation in UK Electricity Demand during the 1990 World Cup Semi-Final



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Source: National Grid (2010)

Electricity End Use by Month



Monthly Electricity Consumption Profiles for Four Shopping Malls in Hong Kong



Electricity consumption varies seasonally and the load curve depends on the climate, how much electricity is used for heating and cooling, and whether commercial and industrial activity follow a seasonal pattern or not.

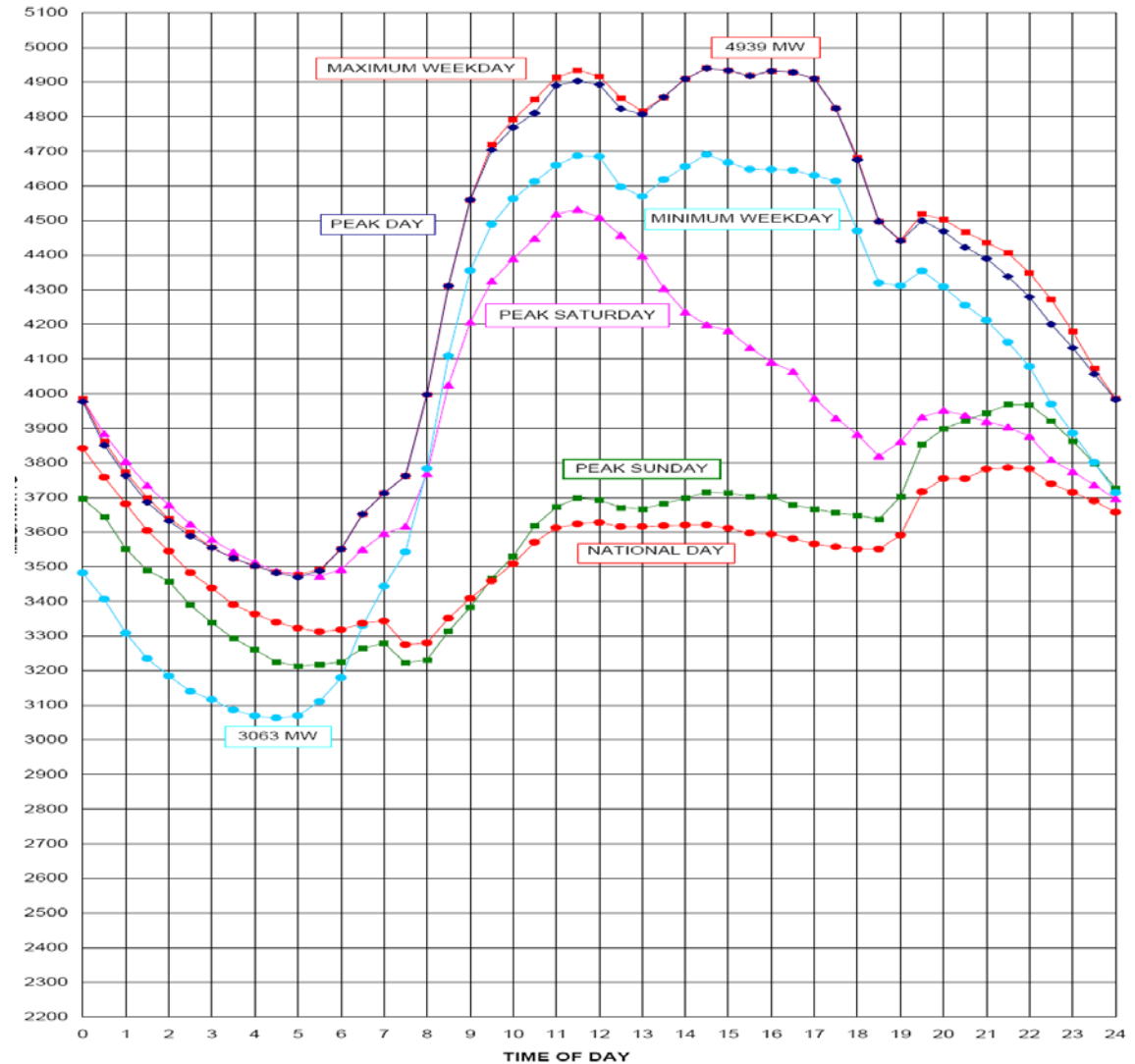
Source: Lam and Li (2003)

Singapore Load Curve

Daily peak production tends to occur during the day,

Shoulder production early in the morning and later in the evening,

Off-peak during the night



Source: Energy Market Authority (EMA) Singapore

Peak-Load Pricing

- Charging different prices for electricity depending on the load factor
 - Storing electricity is expensive
 - So, capacity is usually made large enough to satisfy the on-peak demand
 - Hence, during much of the time (i.e., off-peak time) some capital is sitting idle

Capacity Requirement: Illustration

- A utility produces 55 billion kWh per year
 - Its average single-customer demand is 6,300 MW
 - Peak demand is 11,145 MW
 - Installed capacity is 13,234 MW, with the extra needed as a mandated reliability margin
- What would happen if the utility can move some of the on-peak demand to off-peak?
 - Can it decrease the amount of total capital needed and cost by using existing capital more intensely?

Peak-Load Pricing: Setting

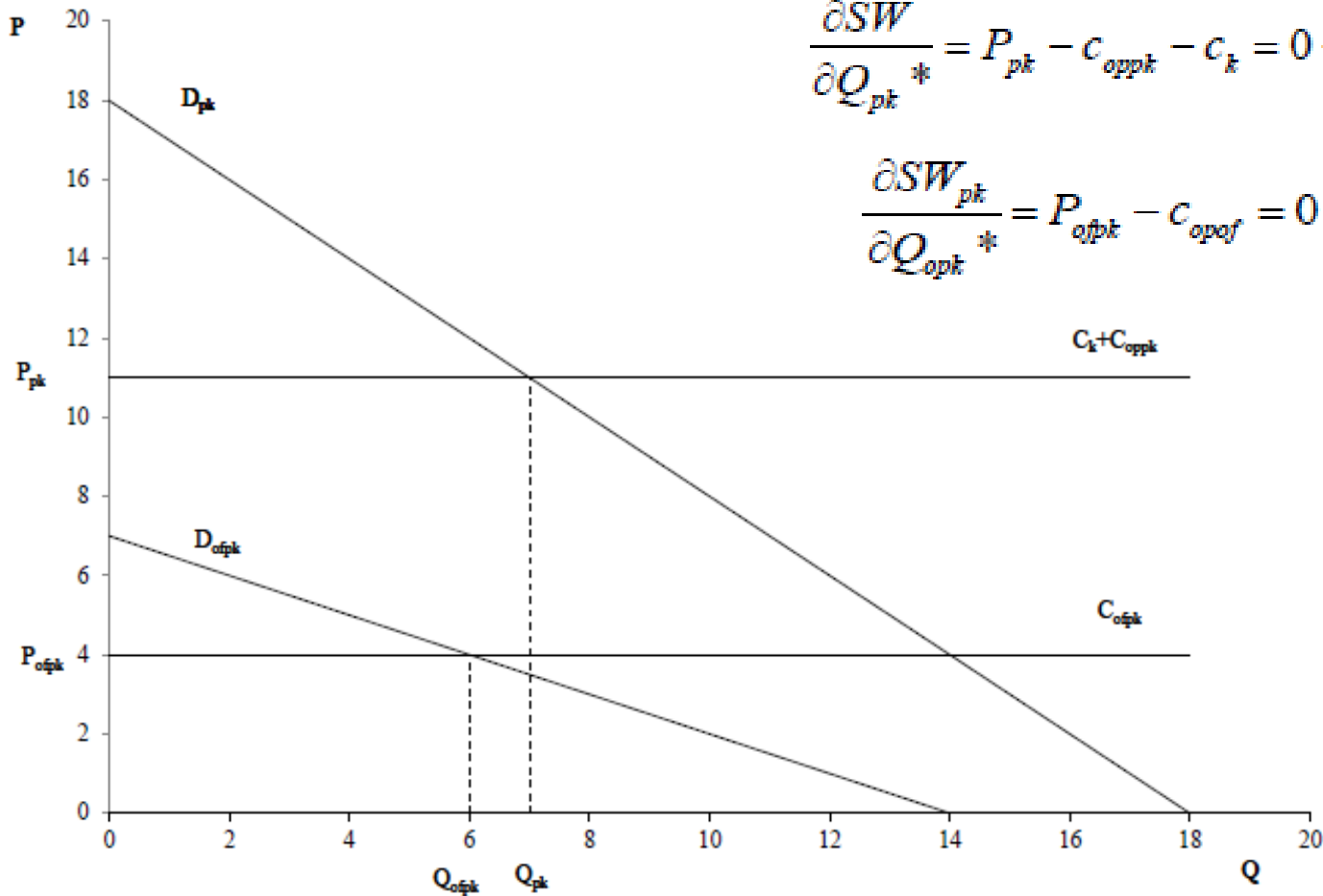
- Suppose daily demand
 - D_{pk} for on-peak and D_{ofpk} for off-peak
 - Demands are independent
 - The price in the on-peak period does not affect the quantity demanded in the off-peak period and vice versa
- Operating costs
 - C_{oppk} for on-peak and C_{opof} for off-peak
- Capital costs per unit are constant at C_k
 - Assume capital can be added in small increments
- To pick prices in the two markets (on-peak and off-peak) to maximize social welfare

Peak-Load Model

$$SW = \int_0^{Q_{pk}^*} P_{pk}(Q_{pk})dQ_{pk} + \int_0^{Q_{ofpk}^*} P_{ofpk}(Q_{ofpk})dQ_{ofpk} - c_{oppk}Q_{pk}^* - c_{opof}Q_{ofpk}^* - c_kQ_{pk}$$

$$\frac{\partial SW}{\partial Q_{pk}^*} = P_{pk} - c_{oppk} - c_k = 0 \rightarrow P_{pk} = c_{oppk} + c_k$$

$$\frac{\partial SW_{pk}}{\partial Q_{ofpk}^*} = P_{ofpk} - c_{opof} = 0 \rightarrow P_{ofpk} = c_{opof}$$



Peak-Load Pricing: Implications

- The first-order conditions require
 - On-peak load pays its operating plus capital costs
 - Off-peak load only pays its operating costs
- Implications:

Generating Costs

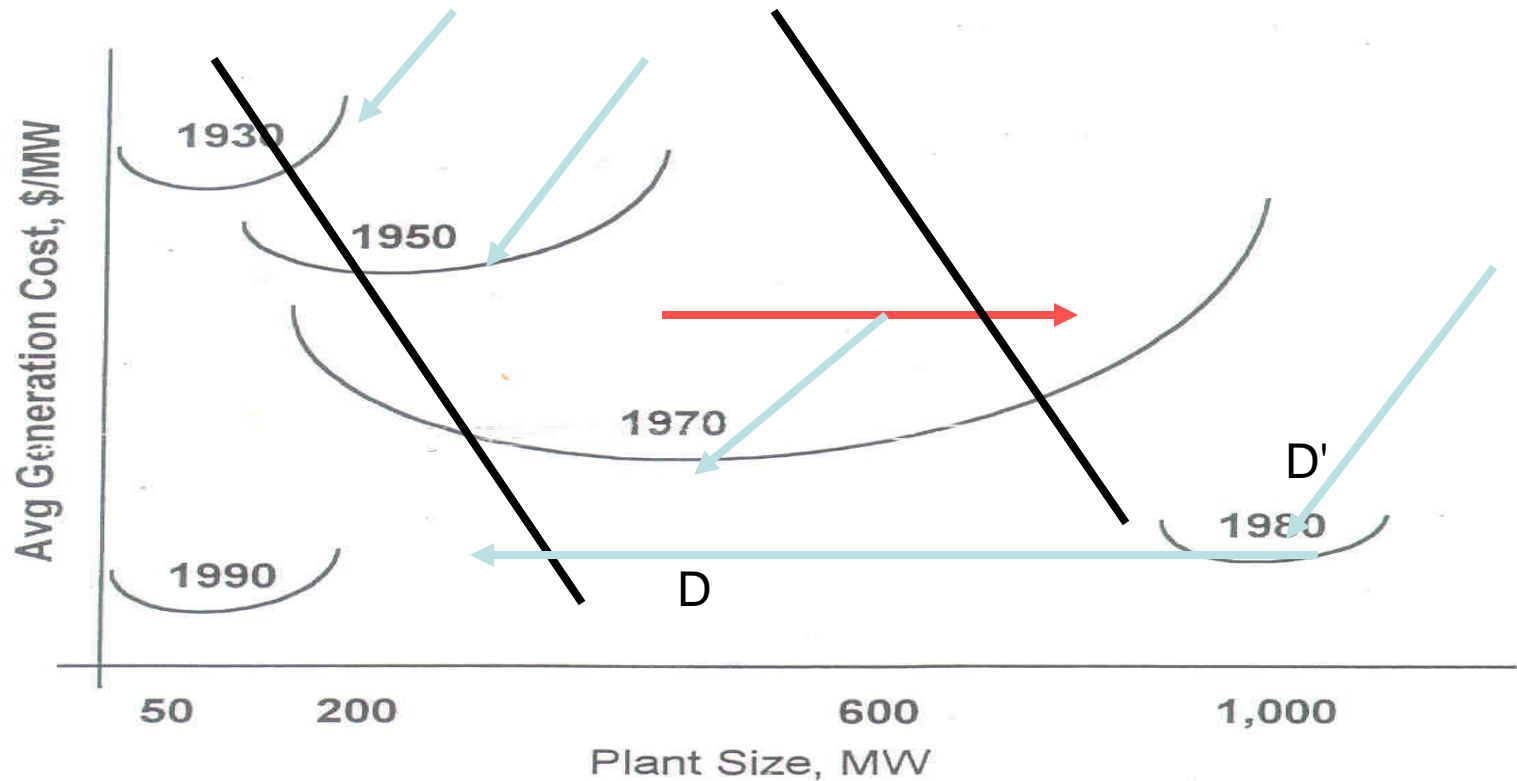


Figure 2. Optimal generation plant size for a single plant based on cost per megawatt (MW), 1930-1990.

Source: Bayless 1994, 21.

Structures of Electricity Market

- Under regulation
 - Vertically integrated, mostly government owned, natural monopoly
 - Instruments for regulation
 - Price and quantity
- Under deregulation
 - Separation of industry by ownership
 - Horizontally unbundled
 - Full competition in generation and wholesale/retail
 - Still monopoly in transmission and distribution (T&D)
- Motivations for unbundling?

In a Deregulated Electricity Market

- Market becomes competitive
 - Non-existence (or little abuse) of market power
 - Easy entry and exit of players
 - Efficiency of allocation and lower and/or stable prices
- Market functions properly
 - Informed decisions
 - Allocation of risk
 - Transactions at minimal cost and lower production costs
- Market leads close to marginal-cost pricing
 - Prices would be close to the marginal cost under workable competition and a reasonably well-functioning market environment
- What do we expect?
 - Right and Stable Prices
 - Competition and Reliability

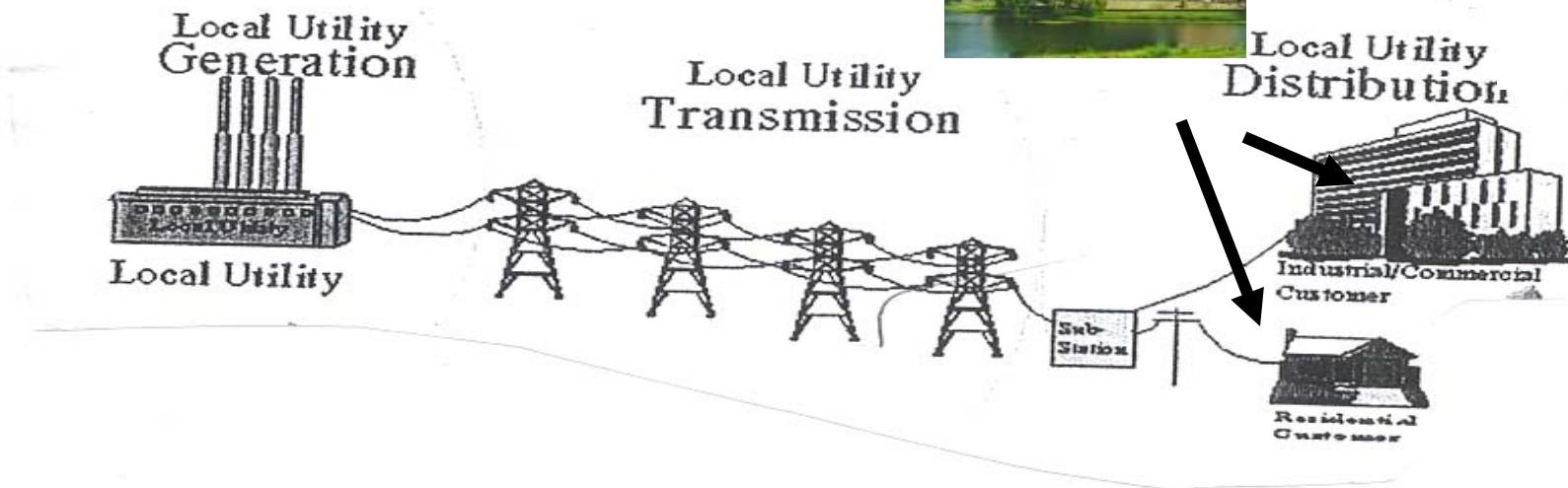
Models for the Electricity Sector

- Model 1
 - No competition, vertically integrated, publicly or privately owned
- Model 2
 - Model 1 but with competition in generation. A single buyer (a distribution company) may buy from a number of different producers
- Model 3
 - Model 2 but with common or contract carriage of high voltage transmission lines offered to all wholesale sellers and buyers
- Model 4
 - Model 3 but retail customers also choose their suppliers in full retail competition

4 Electricity Restructuring Models – Model 1

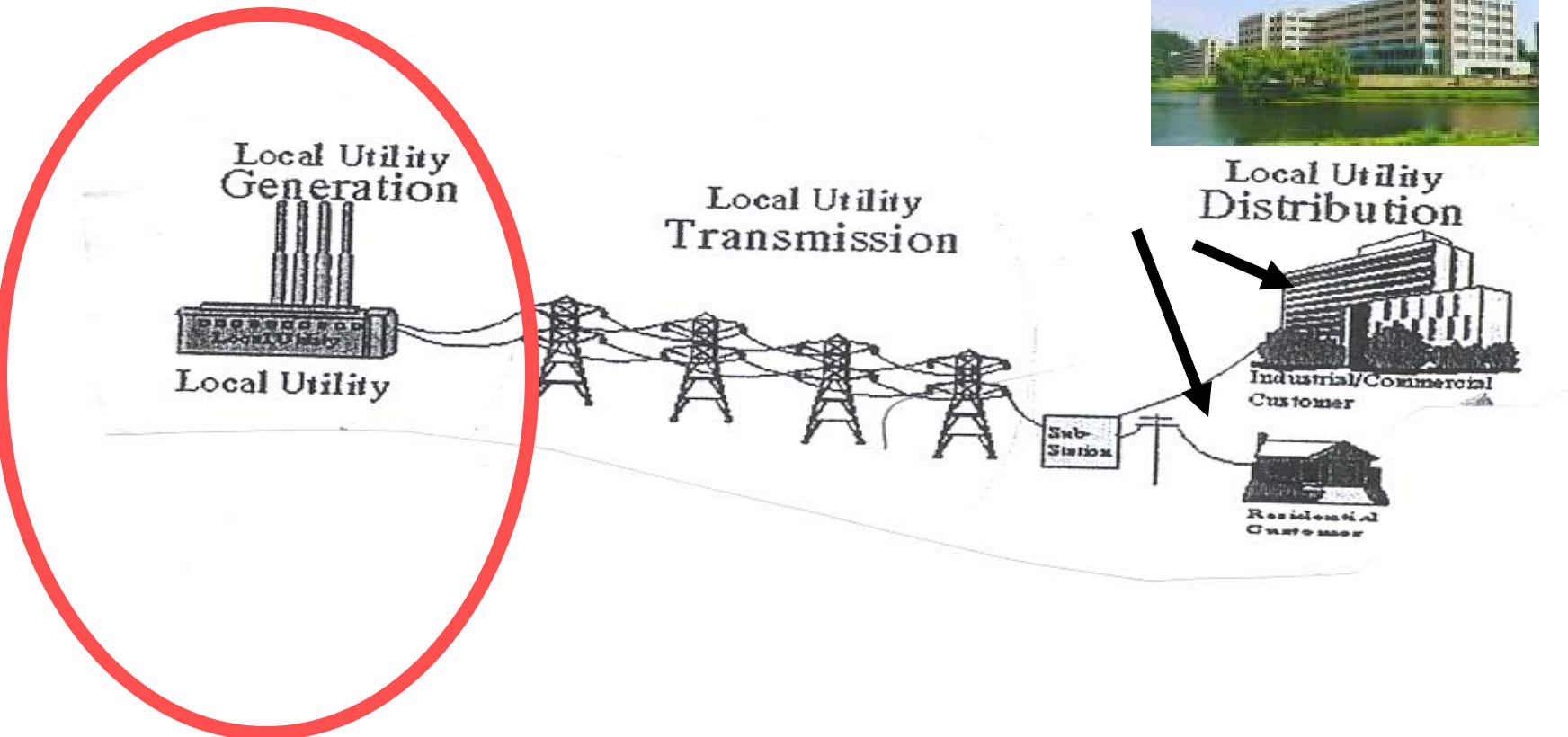
- Hunt and Shuttleworth (1996) – 4 models
- depend on competition at each stage
- Model 1: no competition - vertical integration

Local Distribution



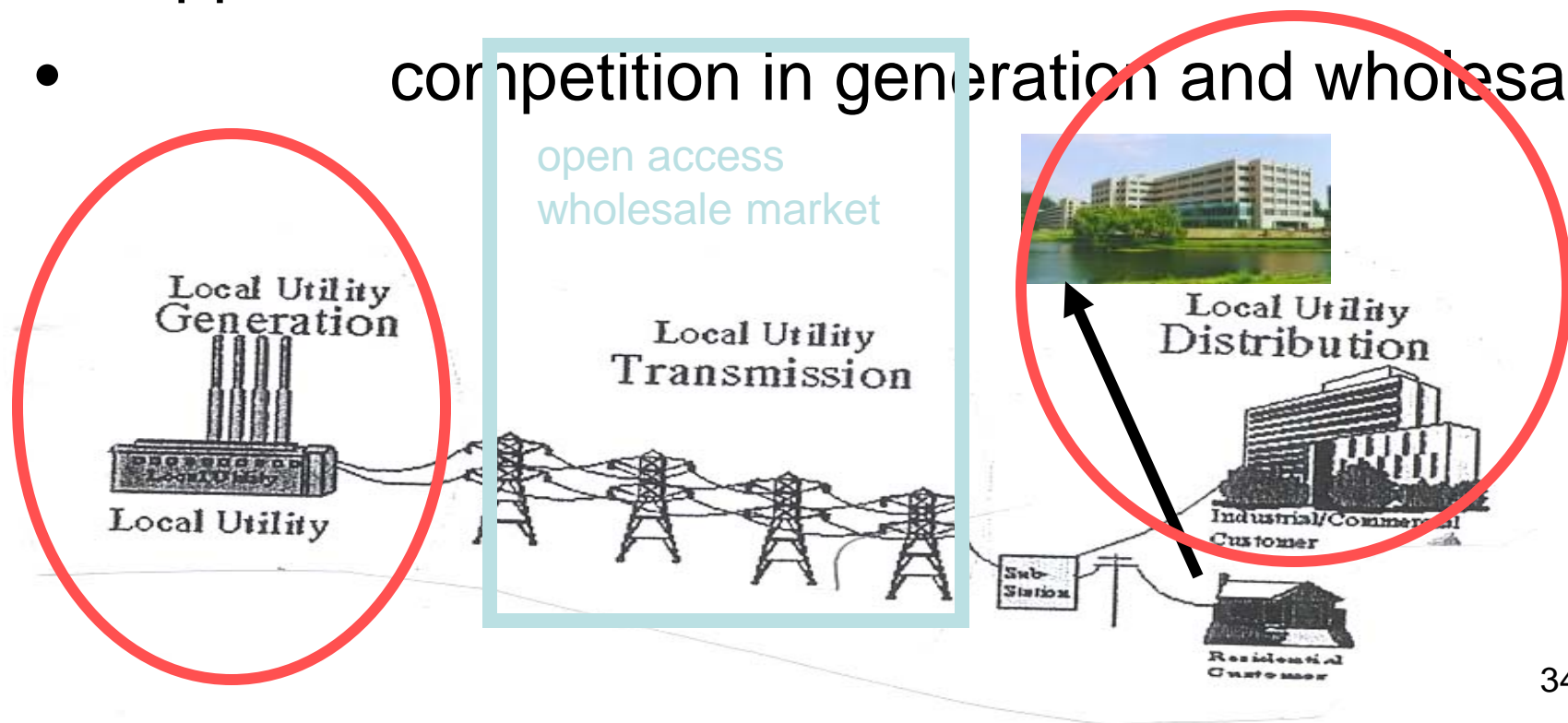
Electricity Restructuring Models – Model 2

- Model 2: competition generation (gencos)



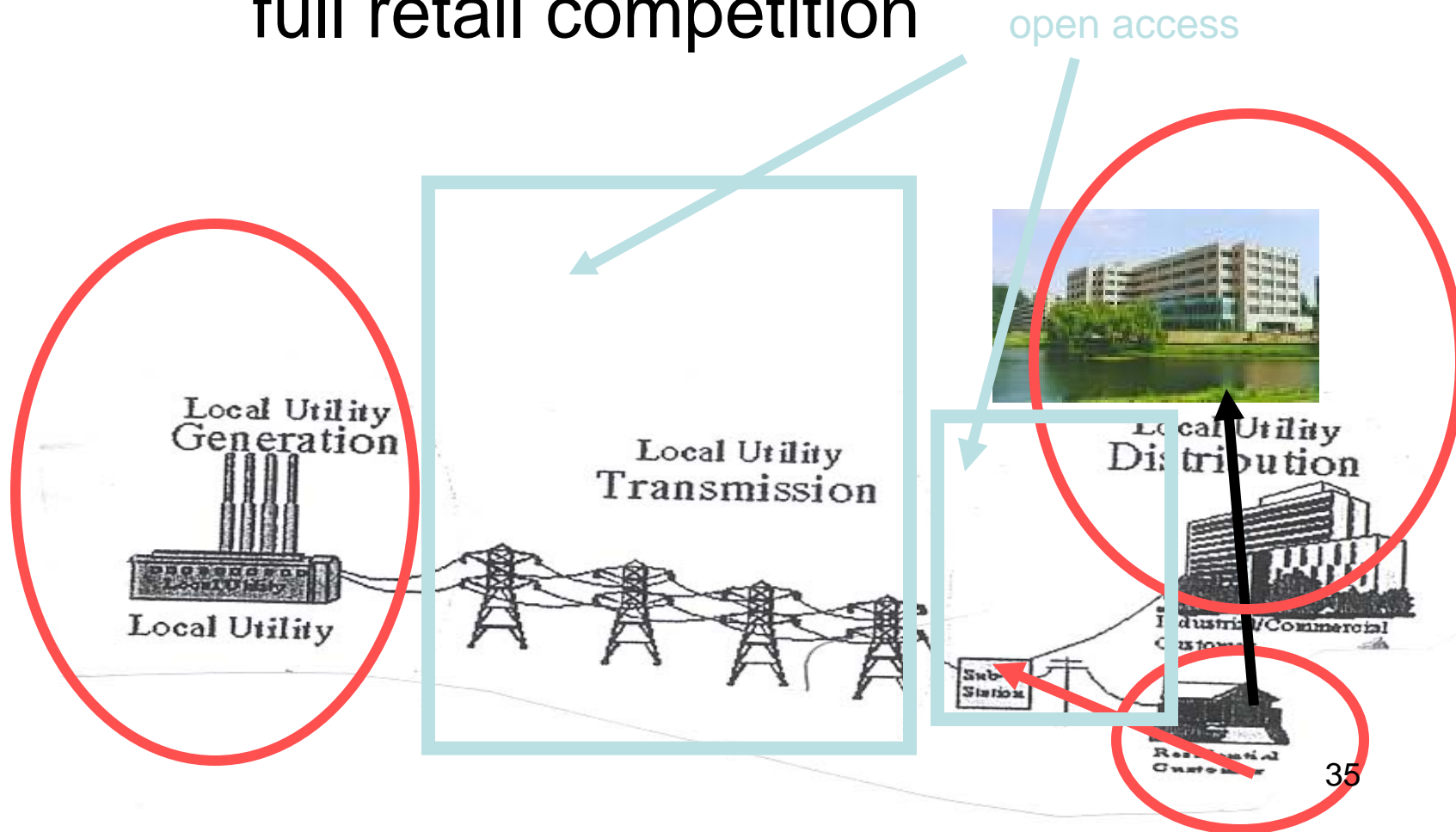
Electricity Restructuring Models – Model 3

- Model 3: distribution companies (distcos)
- own the distribution wires
- distcos and large buyers choose their supplier
- competition in generation and wholesale



4 Electricity Restructuring Models – Model 4

- Model 4: all customers choose suppliers
- full retail competition
-



Model 4 is the Most Economically Efficient

- If there are
 - A well-established electricity retailing system
 - Mature market institutions
 - Constant vigilance against market power
 - Appropriate methods of dispatch

Electricity Prices and Taxes, \$/kWh, 2011

	Chile	U.K.	New Zealand	Norway	Sweden	U.S
	Price (Tax)	Price (Tax)	Price (Tax)	Price (Tax)	Price (Tax)	Price (Tax)
Industrial	0.18 (N/A)	0.12 (0.00)	0.06 (N/A)	0.04 (0.01)	0.08 (0.00)	0.07 (N/A)
Households	0.25 (0.04)	0.19 (0.01)	0.18 (0.02)	0.10 (0.03)	0.18 (0.05)	0.12 (N/A)

Observations:

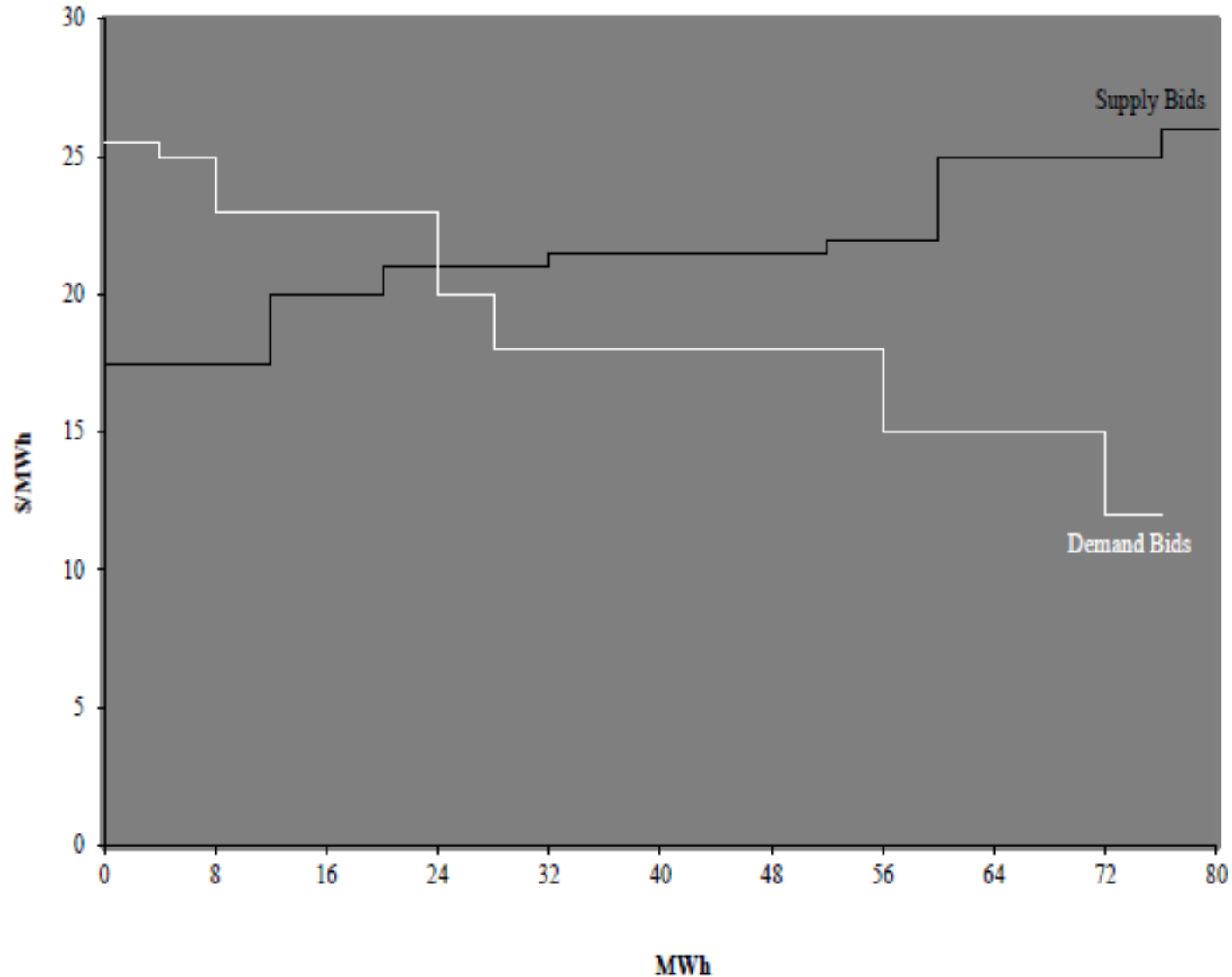
Electricity Restructuring: U.K.

- United Kingdom
 - A first country that reforms electricity market
 - The market reform (in England and Wales) was considered a success
 - In 2001, New Electricity Trading Arrangements (NETA) replaced the power pool; bilateral contracts and self power dispatch
 - Climate change levee (CCL) replaced non-fossil fuel obligation (NFFO) in 2001; Feed-in-Tariffs for renewables (2008 and 2010)

Electricity Restructuring: New Zealand

- New Zealand
 - A third early reformer
 - A role model for electricity market deregulation in Singapore
 - The SMP is determined where the supply and demand bids intersect (next slide)
 - No price caps

Double Sided Bidding Market



Electricity Restructuring: Norway

- Norway
 - Only second in Europe
 - Unique in power generation – hydropower (more than 90%)
 - Long experiences in electricity pool operation
 - Third-party access for all networks
 - Generation: largely government owned (90%)
 - Network services or distribution companies: natural monopolies

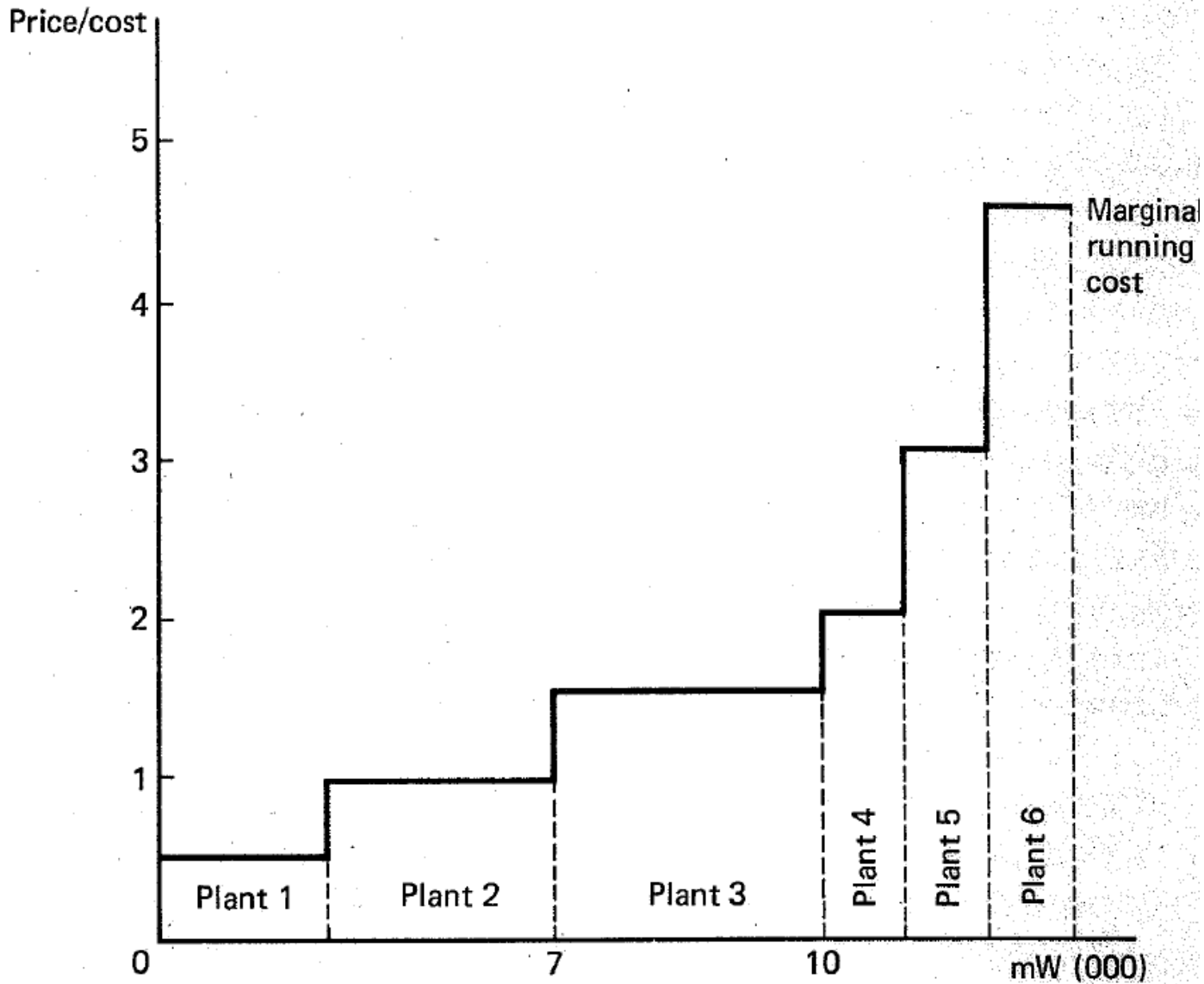
Electricity Restructuring: Sweden

- Sweden
 - High energy intensity and per capita consumption
 - Liberalization was resumed in 1996 with third-party access to the network
 - Joined Nord Pool in 1996
 - Nord Pool is considered one of the most successful wholesale markets

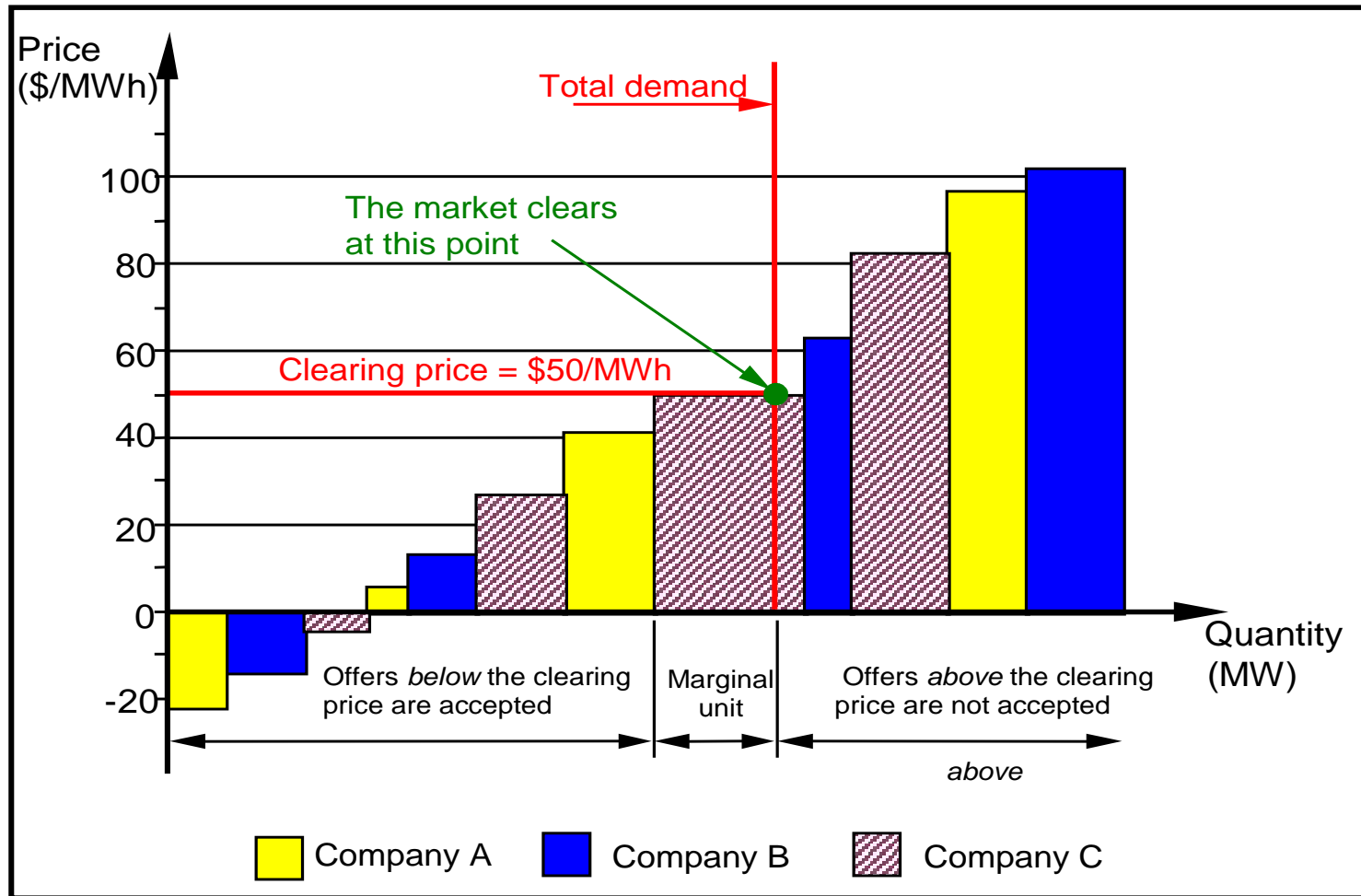
Why Does Economics Concern Power Supply?

- Motivations
 - Cost structure is rather unique
 - Continuity requirement in power supply
 - Efficiency
- Generation technologies and cost structures
 - Long-Run Marginal Cost (LRMC)
 - Fixed and variable costs
 - Short-Run Marginal Cost (SRMC)
 - Variable costs or avoidable costs

Merit Order by Marginal Running Cost



Market Clearing Price



Source: EMA (2012)

A System Marginal Price (SMP)

- Suppose that the forecast demand is **100 kW** for the next hour
 - National Power bids \$0.05 per kWh for 75 kW of capacity (with a transmission capacity of 65 kW)
 - Power Gen bids \$0.06 kWh for 25kW of capacity
 - Scottish Power bids \$0.07 per kWh for 50 kW of capacity
 - EdF bids \$0.075 per kWh for 10 kW of capacity
 - National Grid bids \$0.08 per kWh for 50 kW of capacity
 - The SMP for this case is _____

Pool Purchase Price (PPP)

- All generators who bids SMP or lower will be paid the pool purchase price (PPP) equal to this SMP plus a capacity charge (CC)
 - $PPP = SMP + CC$
 - CC signals how much need there for new generation capacity

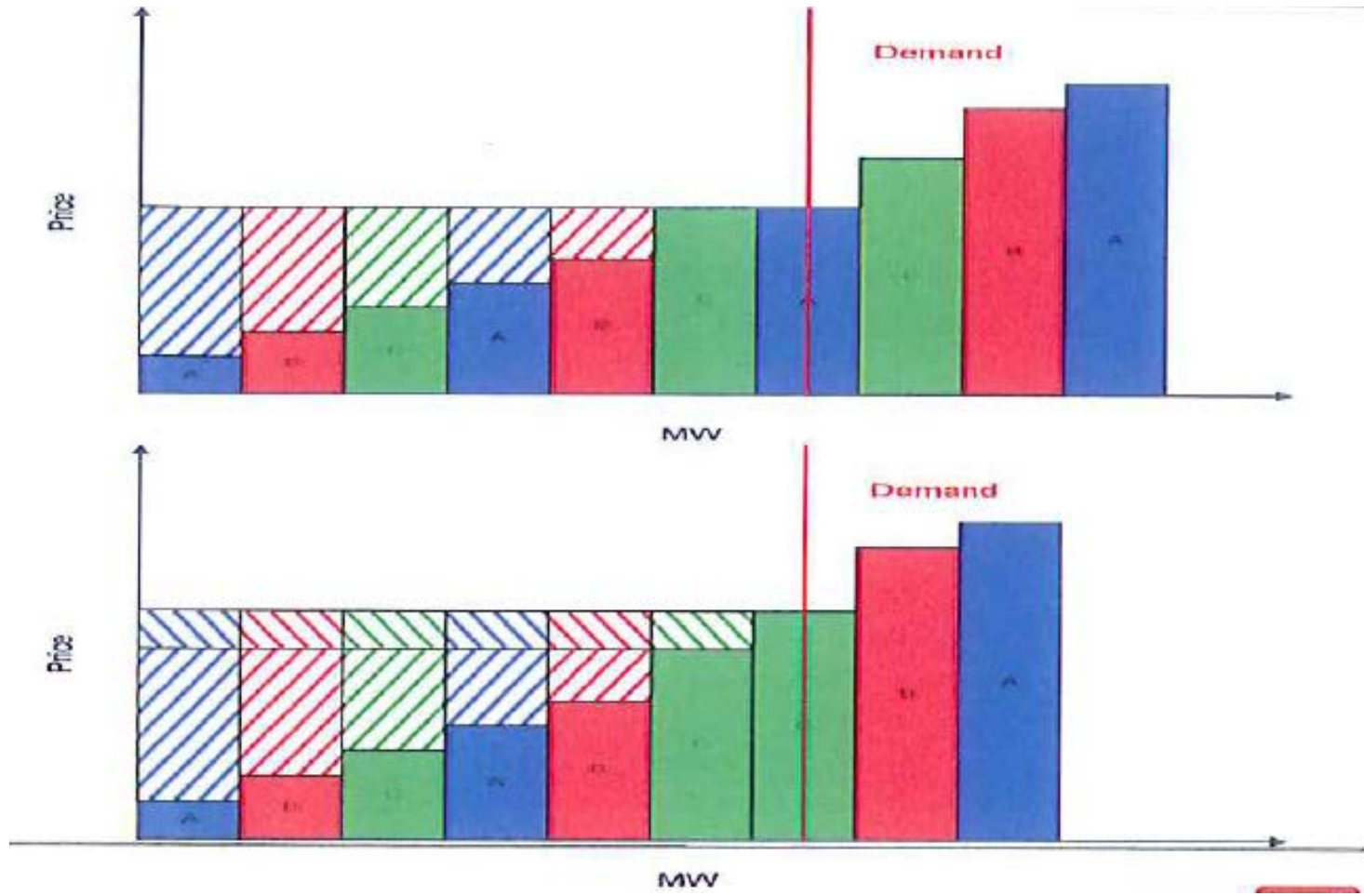
Capacity Charge (CC)

- It is computed as follows:
 - $CC = LOLP * VOLL$ distributed over all producers
 - LOLP: The Loss of Load Probability
 - The likelihood of a load interruption because of capacity constraints
 - VOLL: The Value of Lost Load (estimated)
- Suppose there is a 5% probability of a 10 kWh shortfall. The loss of output from a 10 kWh shortfall is estimated at \$15
 - $LOLP * VOLL = 0.05 * 15 = \0.75
 - $CC = \$0.75 / 100 = \0.0075
- $PPP = SMP + CC = \$0.07 + \$0.0075 = \$0.0775$

Pool-Selling Price (PSP)

- PPP plus an uplift charge (U)
- The uplift charge
 - To recover costs from extra electricity or spinning reserve dispatched to cover transmission constraints and demand forecast errors
 - If a plant is dispatched to provide 10kWh of spinning reserve at \$0.06 per kWh, but there is no market for the power, the producer must still be paid for being ready
 - The payment is divided over all power users
 - $U = 0.06 * 10 / 100 = \$0.006$
- PSP is total charge to cover energy, capacity and uncertainty
 - $PSP = SMP + CC + U = \$0.07 + \$0.0075 + \$0.006 = \0.0835

Physical and Economic Withholding



Source: EMC (2012)

Market Power and Measures

- Concentration Ratio
 - CS4 ($\sum_{i=1}^4 s_i$)
 - CS8 ($\sum_{i=1}^8 s_i$)
- Herfindahl-Hirschman Index (HHI)
 - The sum of the squares of the market shares of firms in the industry ($\sum_{i=1}^n s_i^2$)
- Supply Margin Assessment (SMA)
 - Tests if a day's peak demand is met by the total capacity without the capacity of the generator in question
 - $(D_{peak} - \sum_i s_{-i})$
- Residual Supply Index (RSI)
 - Evaluates how much excess capacity the total capacity without the capacity of the generator in question is in a given hour
 - $\frac{\sum_i s_{-i}}{D_{peak}}$

Lerner Index

- The relative mark-up over marginal cost
 - The difference between price and marginal cost as a fraction of the price
 - A ratio of price less marginal cost of supply to price
 - Price-cost margin
 - Zero (0): no market power
 - One (1): infinite market power
- It measures a firm's ability to maintain prices above competitive level at its profit-maximizing level of output

Test Results of Market Power: An Example

Measures	Values and Remarks
CS4	96%
CS8	Close to 100%
HHI	0.2662
SMA	Negative for all gencos
RSI	Larger than 1 for all gencos
Lerner Index	0.188 – 0.250

Source: Compiled from Chang (2007) *Energy Policy*, 35: 403 – 412

Key Points

- Modeling natural monopoly
 - Social optimum in a natural monopoly market
- Government policy for a natural monopoly
 - Rate of return regulation
 - Utility base
- Various load structures, load and load duration curve
- Peak Load Pricing
- A Schematic Diagram of Electricity Market
- Models for the Electricity Sector
- Market Power: Definitions and Measures
 - CS, HHI, SMA, RSI, and Lerner Index