UNIVERSIDAD PONTIFICIA ICAI ICADE COMILLAS MADRID

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA

INSTITUTO DE INVESTIGACIÓN TECNOLÓGICA (IIT)

Long Term Operation Models for Deregulated Electricity Markets

Andrés Ramos

Mariano Ventosa   Michel Rivier

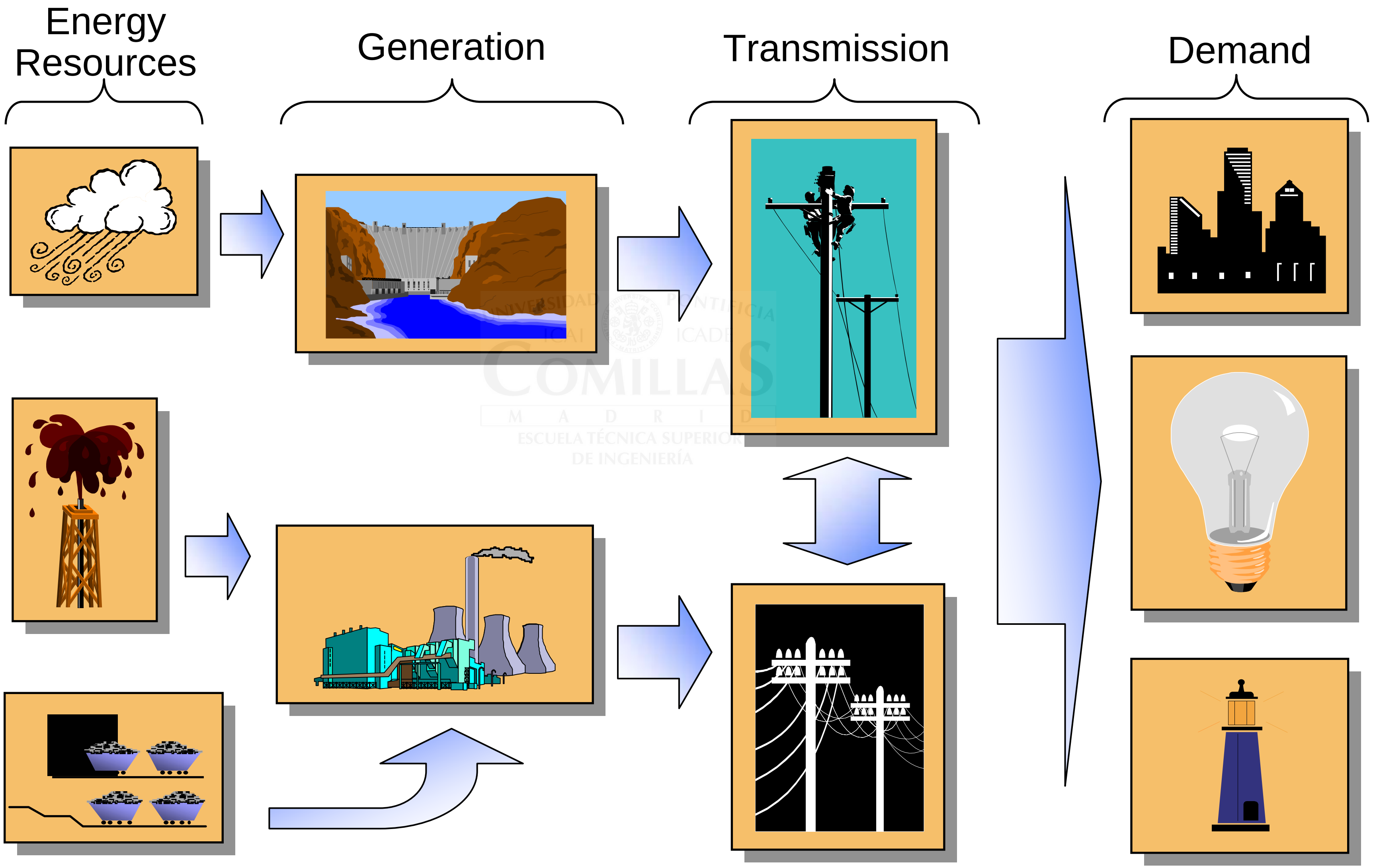
EES-UETP

Madrid, April 2000

Outline

- Introduction
- Market Equilibrium in Microeconomic Theory: Perfect Competition, Monopoly, Oligopoly
- Thermal and Hydrothermal Theoretical Equilibrium Model
- Generation Operation Planning Models based on:
  - Mixed Complementarity Problem (MCP)
  - Market Equilibrium Constraints

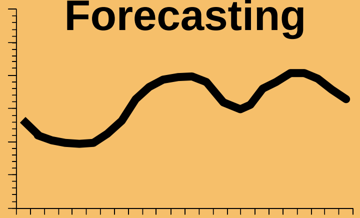
Electric Energy Systems

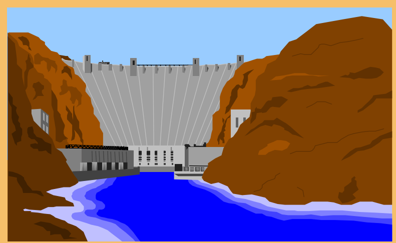


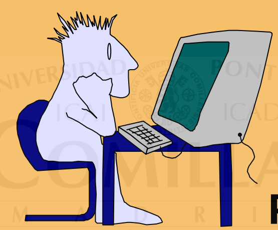
Generating System Planning

Minimum generation cost that satisfies the electricity demand subject to operation constraints

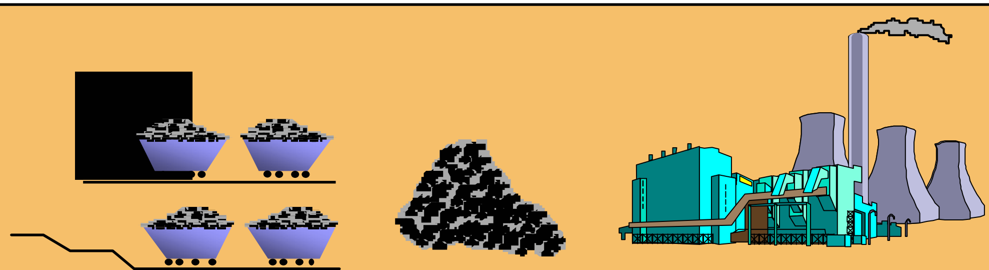
Electricity Demand Forecasting







Planer



Technical Studies

- System Operation
- Hydro scheduling
- Fuel scheduling
- Maintenance scheduling
- New Plants

Economic Studies

- Cash flow
- Costs estimation
- Tariffs determination
- Investments

Traditional Generation Operation Planning Models

Minimisation of:

Objective Function →

Total Generation Variable Costs +
+ Unserved Demand Costs

Subject to:

Operation Constraints →

- Interperiod Constraints
  - Hydro management
  - Operation of seasonal pumped-hydro units
  - Fuel management
  - Maintenance scheduling
- Intraperiod Constraints
  - Balance between generation and demand
  - Generation Limits
  - Daily/Weekly pumped-storage units
  - Reserve Margin

Toward competition (I)

- Power systems restructuring toward deregulation and competition
- Generation of electricity becomes a market based activity
- Utilities managerial decisions become risky and market price oriented
- Companies require new tools and models to support their decisions
- Regulators require new tools to supervise the market behavior

Toward competition (II)

- Increased **opportunities** and increased **risks**
- New **responsibilities**
    - Self-Hydrothermal coordination
    - Self-Unit commitment
    - Biding prices and quantities
- New original models that consider:
    - The technical operation constraints
    - The new **competitive framework** (objective function):
        - each firm looks forward to maximizing its own profit
        - profit = market revenues - operational costs

Electricity Market Equilibrium Model

Behavior of Firm *1*

- Objectives
- Production Structure
- Market Influence

…

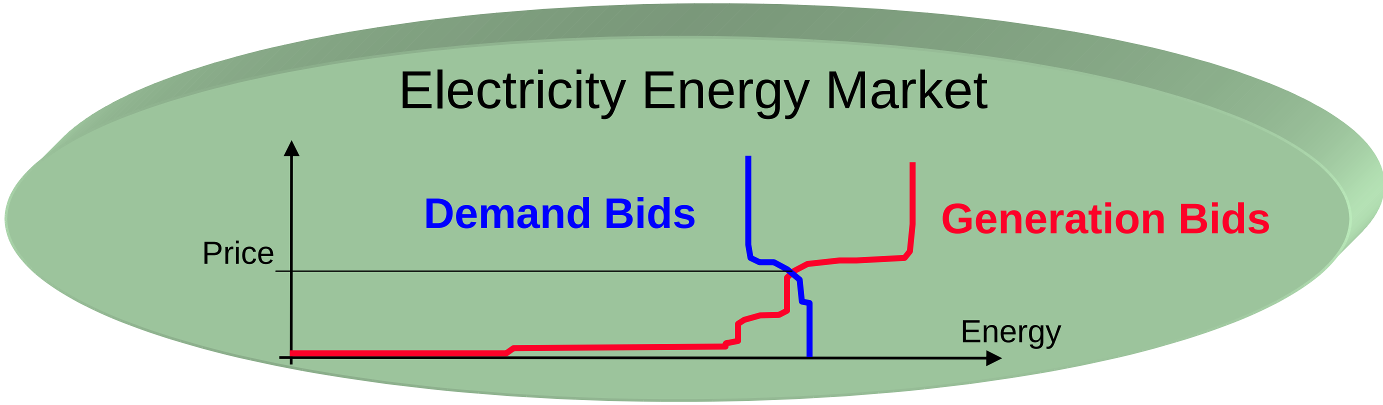
Behavior of Firm *e*

- Objectives
- Production Structure
- Market Influence

…

Behavior of Firm *E*

- Objectives
- Production Structure
- Market Influence



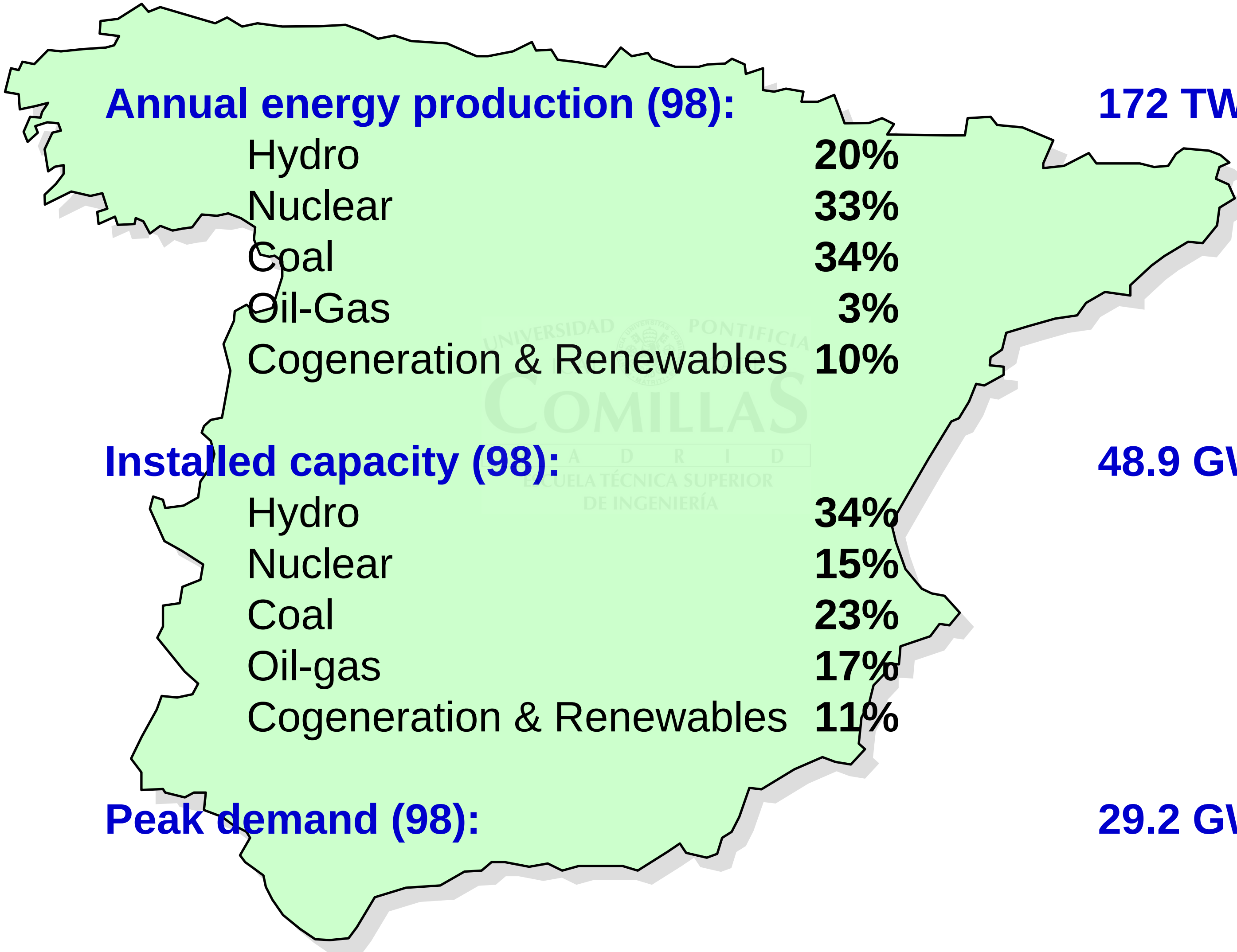
Generation planning functions reformulated

- Long term (up to several years)
  - fuel purchase and energy contracts
  - market share objectives, annual budget
- Medium and short term (1 week to several months)
  - hydrothermal operation planning
- Very short term (1 day)
  - energy market bidding process
- On line
  - complementary services bidding process

Spanish context

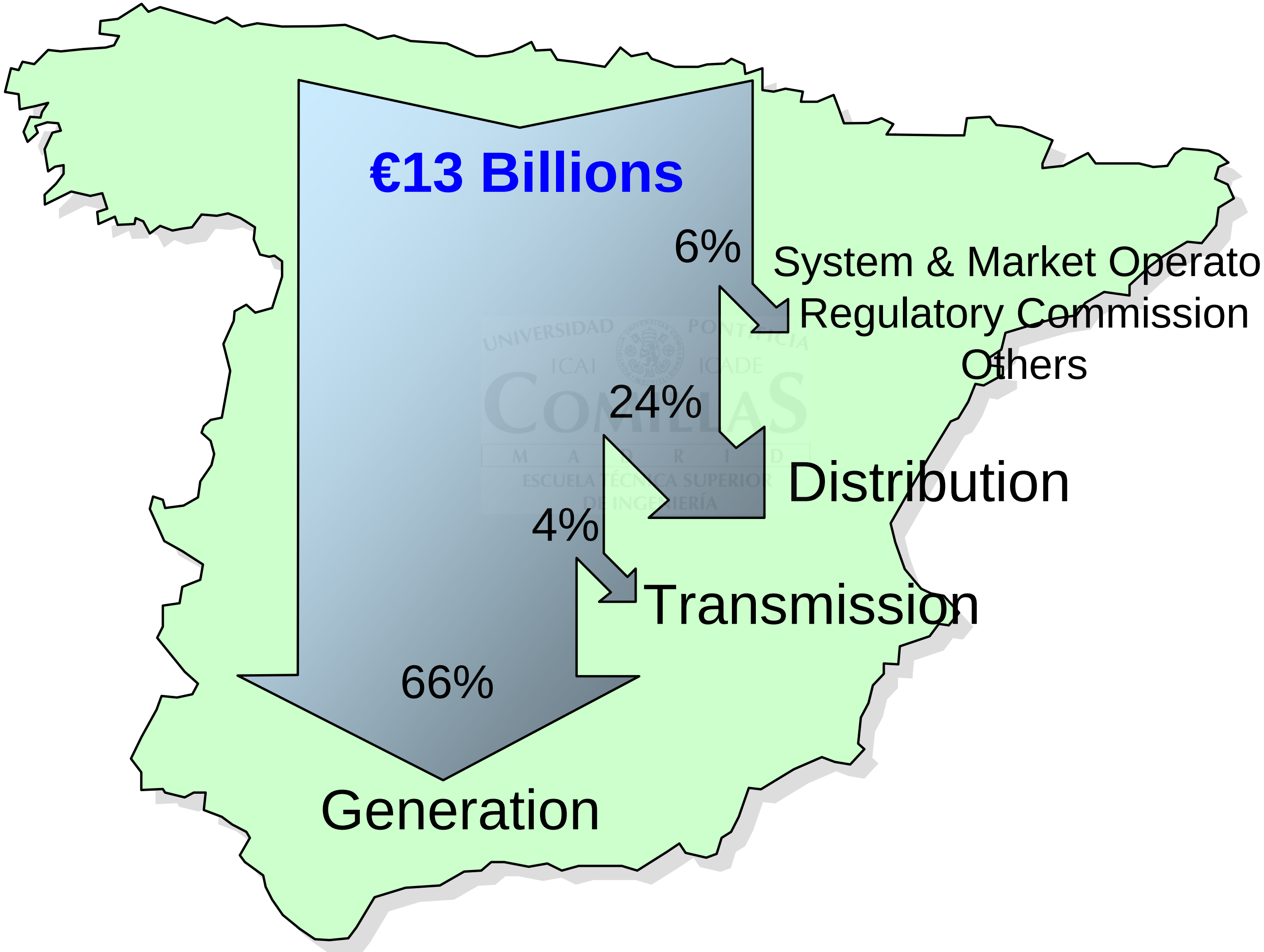
- Wholesale energy market running since January 1, 1998
- Based on a simple merit order of the bids
- Market clearing price is the highest accepted bid
- Characteristics
  - relevant hydro component:
    - Intertemporal links
  - four big companies:
    - Oligopoly
  - well developed and meshed network:
    - Absence of important network constraints

The Spanish Electric System

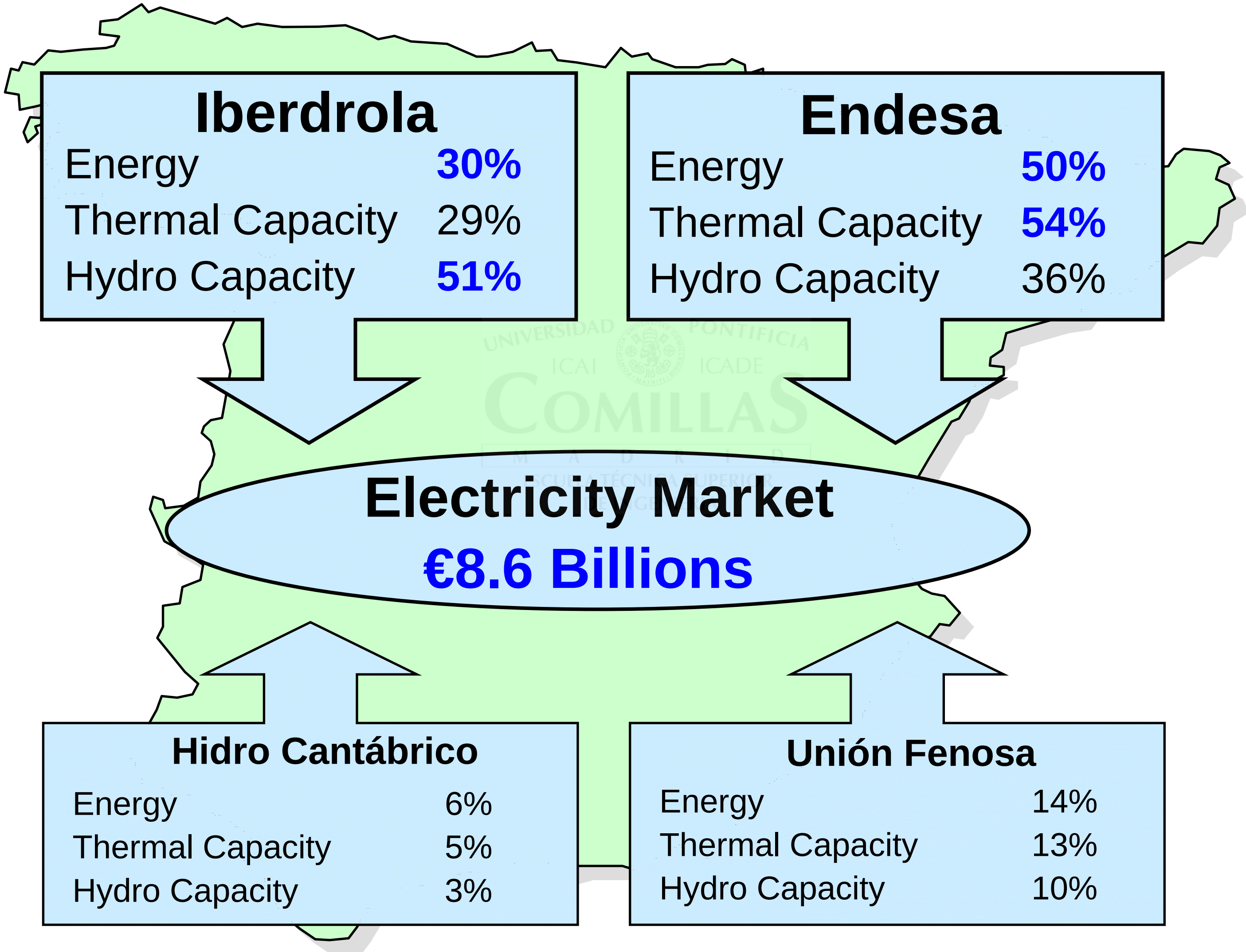


Annual energy production (98):		**172 TWh**
Hydro	**20%**	
Nuclear	**33%**	
Coal	**34%**	
Oil-Gas	**3%**	
Cogeneration & Renewables	**10%**	
Installed capacity (98):		**48.9 GW**
Hydro	**34%**	
Nuclear	**15%**	
Coal	**23%**	
Oil-gas	**17%**	
Cogeneration & Renewables	**11%**	
Peak demand (98):		**29.2 GW**

The Spanish Electric Business



The Spanish Electric Market



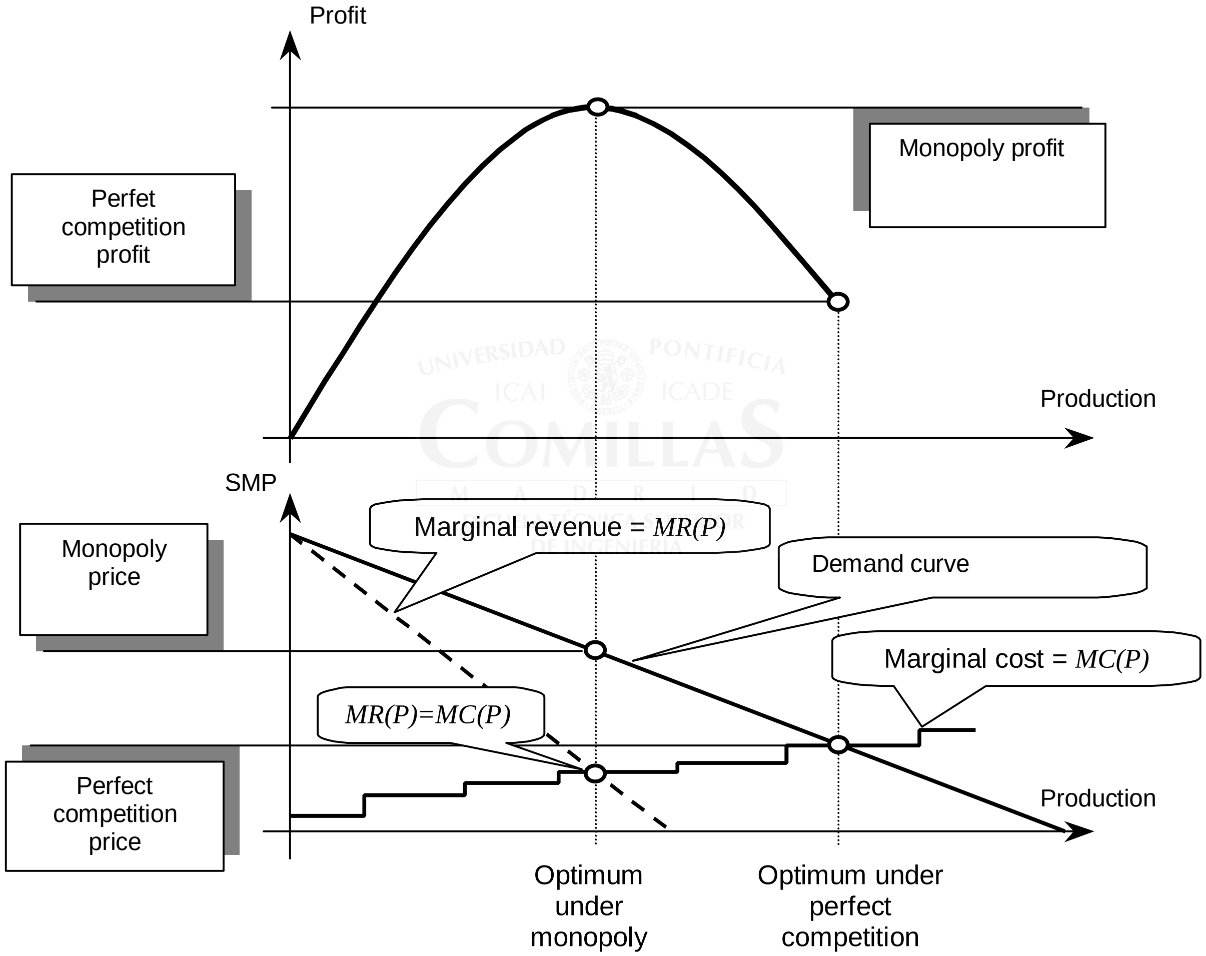
Microeconomic Theory

- Price influence and market shares
- Electricity market equilibrium models
  - Perfect competition
  - Monopoly
  - Oligopoly
    - Cournot
    - Bertrand
    - Edgeworth
    - Leader in quantity (Stackelberg)
    - Leader in price

Perfect competition market

- Many production companies with a small market share
- No company can influence the market price (all of them are price takers)
- The demand curve is horizontal from firm's point of view
- Each company can only play with its own bid curve (as the marginal price is given)
- Bidding price must be the marginal cost for each unit

Profit and market equilibrium



Monopoly market

- Only one company can set the price (price setter)
- Maximum profit is reached where the marginal revenue equals the marginal cost
- Price is greater than marginal cost and production is lower than in perfect competition market

Oligopoly market

- Some companies can affect the price (price setters)
- It is the most frequent state at the beginning of the deregulation process
- Modeling the oligopoly:
  - Competition in prices (Bertrand's model)
  - Competition in quantities (Cournot's model)
  - Edgeworth's model
  - Leader in quantity (Stackelberg's model)
  - Leader in price

Bertrand's model (competition in price)

- *Price* is the strategic variable. All the production is offered at this price
- The lower price bid gets all the demand
- It can not include the production limit of each unit
- The companies behave as competitive

Cournot's model (competition in quantity)

- *Production* is the strategic variable. A certain production is offered at zero price
- $\text{Benefit}_e = \text{SMP} * \text{Production}_e - \text{Total\_Cost}_e$

$$\frac{\partial B_e}{\partial P_e} = 0 \Rightarrow SMP + P_e \cdot \frac{\partial SMP}{\partial P_e} - MC_e = 0$$

$$MR_e\left(P_e\right) = SMP + P_e \cdot \frac{\partial SMP}{\partial P} = MC_e\left(P_e\right)$$

- System marginal price increases as the production is reduced
- SMP greater than in perfect competition and lower supply of demand

Edgeworth's model

- Introduces capacity constraints in Bertrand's model
- In the first stage the firms chose a quantity to bid and in the second stage the bid price subject to a capacity constraint
- The result of the two stages is equal to Cournot's model

Leader in quantity (Stackelberg's model)

- Firstly, the leader chooses its optimal production and then the competitors choose their optimum level. Market seen by competitors is lower than those seen by the leader
- It can be used to the generation expansion planning problem. The leader builds optimally and the competitors take their decision knowing the leader's decision
- The leader get more benefits than the competitors

Leader in price

- Firstly, the leader chooses its optimal price and then the competitors choose their optimum production level once known the price
- The competitors behave as competitive firms
- The leader knows that the competitors are going to bid their marginal costs
- The leader is a monopolist against the residual demand left by the competitors
- To be competitor is the best option

Thermal Equilibrium Model (Cournot's approach)

- No interperiod constraints
- For each strategic firm

$$B_e = SMP \cdot P_e - C_e \qquad SMP = f\left(\sum_e P_e\right)$$

$$\frac{\partial B_e}{\partial P_e} = 0 \Rightarrow SMP + P_e \cdot \frac{\partial SMP}{\partial P_e} - MC_e = 0$$

$$MR_e\left(P_e\right) = SMP + P_e \cdot \frac{\partial SMP}{\partial P} = MC_e\left(P_e\right)$$

$$P_e = \frac{SMP - MC_e\left(P_e\right)}{-\partial SMP / \partial P} \qquad P_e \frac{\partial SMP}{\partial P} = SMP - MC_e\left(P_e\right) = \text{mark up}$$

- Lerner's index $P_e \dfrac{\partial SMP}{\partial P}$ measures the firm's power market

Hydrothermal Equilibrium Model (I)

- Hydro generation is included and therefore interperiod constraints

$$\max B_{\mathrm{e}} = \sum_{p} \left[SMP_p \cdot (P_{\mathrm{pe}}^{T} + P_{\mathrm{pe}}^{H}) - C_{\mathrm{pe}} \right]$$

$$\sum_{p} P_{pe}^{H} = I_e \quad : \lambda_e$$

$$SMP_p = f\left(\sum_{e} (P_{pe}^{T} + P_{pe}^{H}) \right)$$

- Lagrangian function and KKT first order conditions

$$\frac{\partial L^e}{\partial P_{pe}^{T}} = SMP_p + \left(P_{pe}^{T} + P_{pe}^{H} \right) \cdot \frac{\partial SMP}{\partial P} - MC_{pe}^{T}(P_{pe}^{T}) = 0$$

$$\frac{\partial L^e}{\partial P_{pe}^{H}} = SMP_p + \left(P_{pe}^{T} + P_{pe}^{H} \right) \cdot \frac{\partial SMP}{\partial P} - \lambda_e = 0$$

Hydrothermal Equilibrium Model (II)

- Marginal revenue = marginal cost

$$MR_{pe} = SMP_p + \left(P_{pe}^T + P_{pe}^H\right) \cdot \frac{\partial SMP}{\partial P} = MC_{pe}^T(P_{pe}^T)$$

- Optimum production for each firm

$$\left(P_{pe}^T + P_{pe}^H\right) = \frac{SMP_p - MC_{pe}^T(P_{pe}^T)}{-\partial SMP / \partial P} =$$

- Water value = marginal cost for each firm. Water is used to replace the own thermal generation

$$MC_{pe}^T(P_{pe}^T) = \lambda_e$$

- Water value is different for each firm

MCP and Market Equilibrium Constratints Approaches

- **Detailed modeling operation** of thermal, hydro and pumped units
- **Single shot** optimization procedure
- Poolco-based market model
- Work and give coherent results
- Able to solve realistic sized systems in reasonable computer times

Firm's optimization program

maximize

$f^e(y)$

subject to:

$h_j^e(y) = 0 \quad : \lambda_j^e$

$g_k^e(y) \leq 0 \quad : \mu_k^e$

Lagrange Function

$$\mathcal{L}^e(y,\lambda,\mu) = f^e + \sum_j \lambda_j^e \cdot h_j^e + \sum_k \mu_k^e \cdot g_k^e$$

Optimality Conditions
=
Mixed Complementarity Problem

$$\nabla_y \mathcal{L}^e(y,\lambda,\mu) = \frac{\partial \mathcal{L}^e}{\partial y^e} = 0$$

$$\nabla_\lambda \mathcal{L}^e(y,\lambda,\mu) = \frac{\partial \mathcal{L}^e}{\partial \lambda_j^e} = h_j^e = 0$$

$$\mu_k^e \cdot g_k^e = 0 \qquad g_k^e \leq 0 \qquad \mu_k^e \leq 0$$

Generation Model based on MCP

Optimality Conditions of Firm *1*

Optimality Conditions of Firm *e*

Optimality Conditions of Firm *E*

$$\nabla_y \mathcal{L}^1(y,\lambda,\mu) = \frac{\partial \mathcal{L}^1}{\partial y^1} = 0 \qquad \nabla_y \mathcal{L}^e(y,\lambda,\mu) = \frac{\partial \mathcal{L}^e}{\partial y^e} = 0 \qquad \nabla_y \mathcal{L}^E(y,\lambda,\mu) = \frac{\partial \mathcal{L}^E}{\partial y^E} = 0$$

$$\nabla_\lambda \mathcal{L}^1(y,\lambda,\mu) = \frac{\partial \mathcal{L}^1}{\partial \lambda_j^1} = h_j^1 = 0 \quad \cdots \quad \nabla_\lambda \mathcal{L}^e(y,\lambda,\mu) = \frac{\partial \mathcal{L}^e}{\partial \lambda_j^e} = h_j^e = 0 \quad \cdots \quad \nabla_\lambda \mathcal{L}^E(y,\lambda,\mu) = \frac{\partial \mathcal{L}^E}{\partial \lambda_j^E} = h_j^E = 0$$

$$\mu_k^1 \cdot g_k^1 = 0 \quad g_k^1 \le 0 \quad \mu_k^1 \le 0 \qquad \mu_k^e \cdot g_k^e = 0 \quad g_k^e \le 0 \quad \mu_k^e \le 0 \qquad \mu_k^E \cdot g_k^E = 0 \quad g_k^E \le 0 \quad \mu_k^E \le 0$$

Price-m(y)=0

Electricity Energy Market

Meaning of Optimality Conditions

- Optimality Conditions provide useful information for each firm about:
  - Thermal generation:

    Marginal Revenue = Marginal Cost

  - Hydro management (peak hours):

    tries to equalize firm´s Marginal Cost

  - Pumped-Hydro (off-peak hours):

    tries to equalize firm´s Marginal Cost

Sample Case

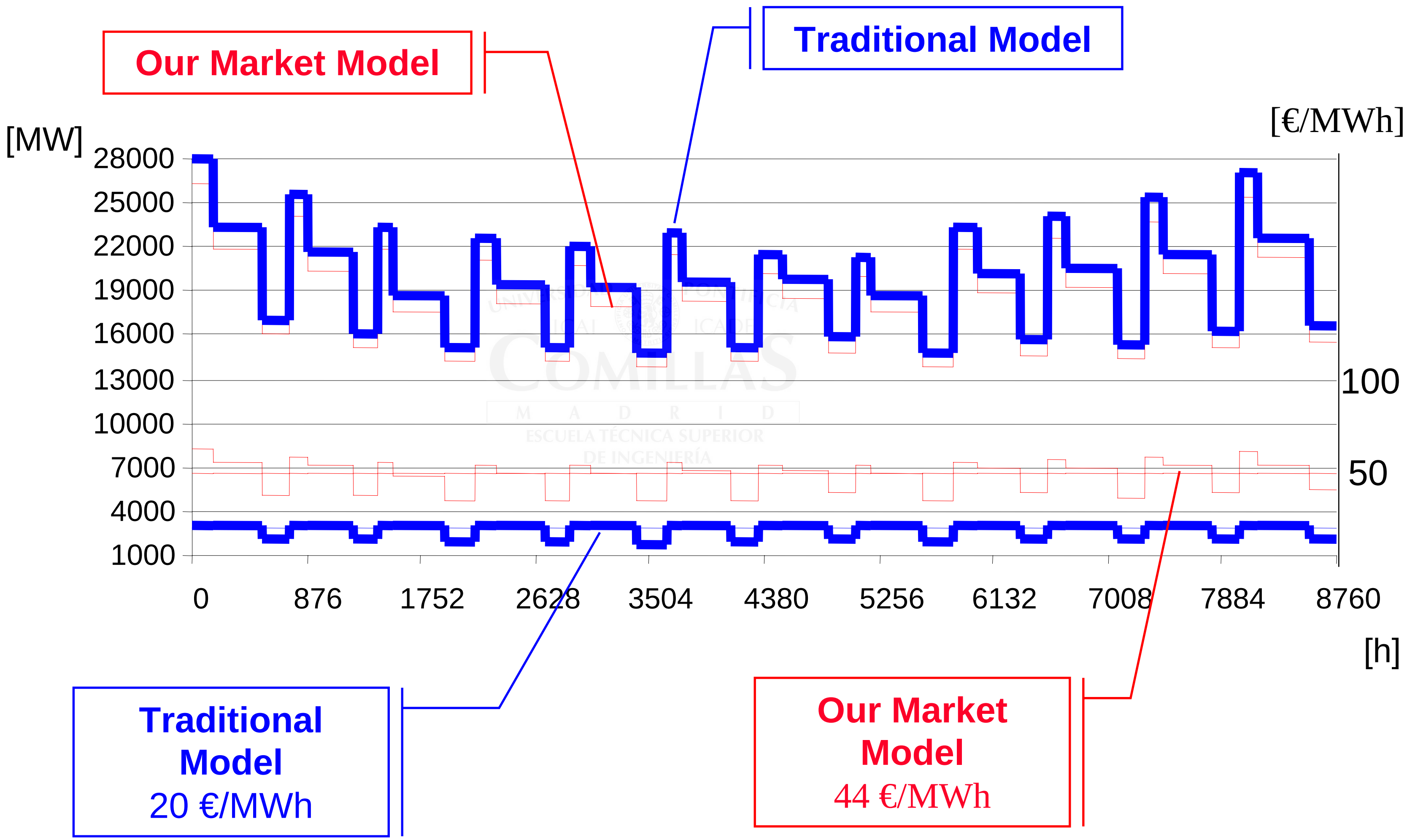
- It has been applied to the Spanish power market:
  - 73 thermal units and 30 equivalent hydro units
  - Scope of one year, divided into 12 periods with 3 load levels
- The size of the MCP is around 5,000 equations
- A Pentium II 233 MHz spends 2÷8 minutes to solve this problem with MILES

Sample Case

- Heuristic algorithm based on Linear Programming obtains a “good” starting point in 5 seconds

- It is established that the equilibrium of a multi-period Cournot model exists and is unique if:
  - Linear demand function
  - Monotone stepped marginal cost function

Sample Case: Results



MCP Summary

- A Generation Operation Planning approach based on Mixed Complementarity Problem
- Obtain the market equilibrium while taking into account operation constraints
- Meaningful optimality conditions
- Open issues:
  - Binary commitment variables
  - Large-scale stochastic problems

Generation Model based on Market Equilibrium Constraints (I): Traditional Production Cost Models

- Traditional Production Cost Models:
  - Long term operation planning studies
  - Minimum generation cost subject to operation constraints
- Two relevant characteristics of these models:
  - A **detailed representation** of the electric system operation
  - Their **main** decision **variables** are the generation **output levels** offered to the market

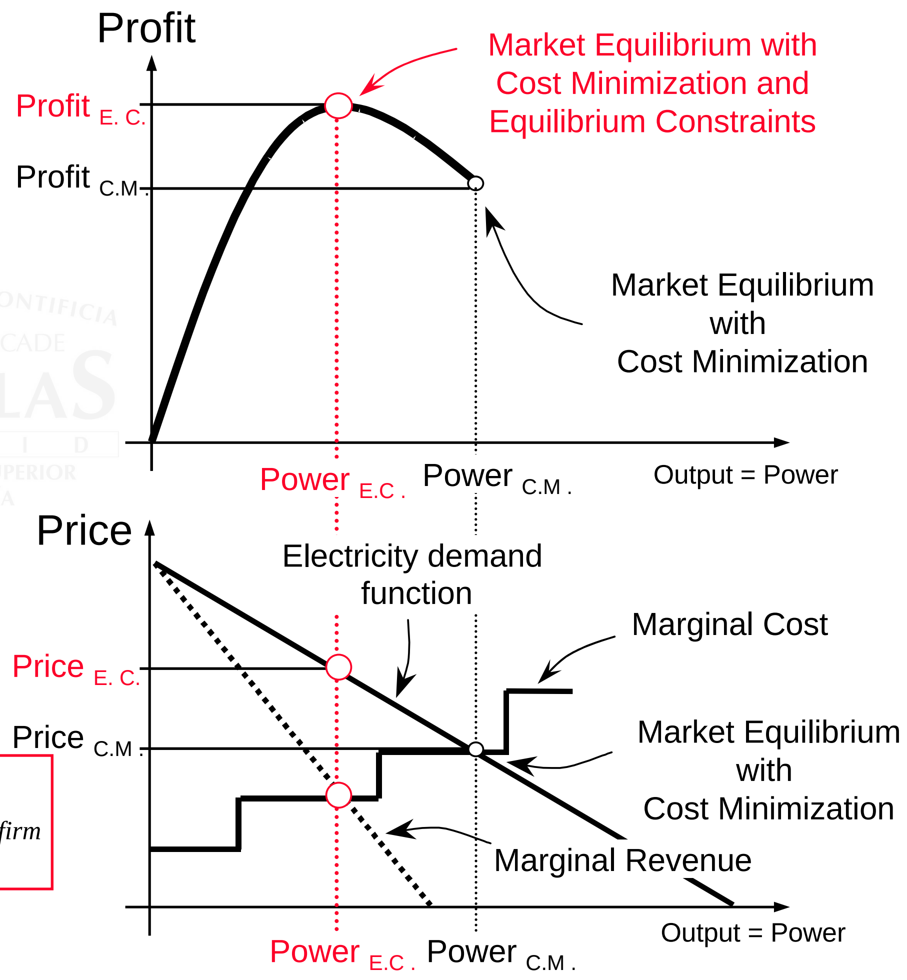
Market Equilibrium Model Overview (II): Equilibrium Constraints

- Equilibrium Constraints reproduce the first order optimality conditions of the firms' profit maximization objective

$$Profit_{firm} = Price \cdot Power_{firm} - Cost_{firm}$$

$$\frac{\partial Profit_{firm}}{\partial Power_{firm}} = 0$$

$$\underbrace{Price + Power_{firm} \cdot \frac{\partial Price}{\partial Power_{firm}}}_{Marginal\ Revenue} = Marginal\ Cost_{firm}$$



Production cost model with Equilibrium Constraints

Minimisation of:

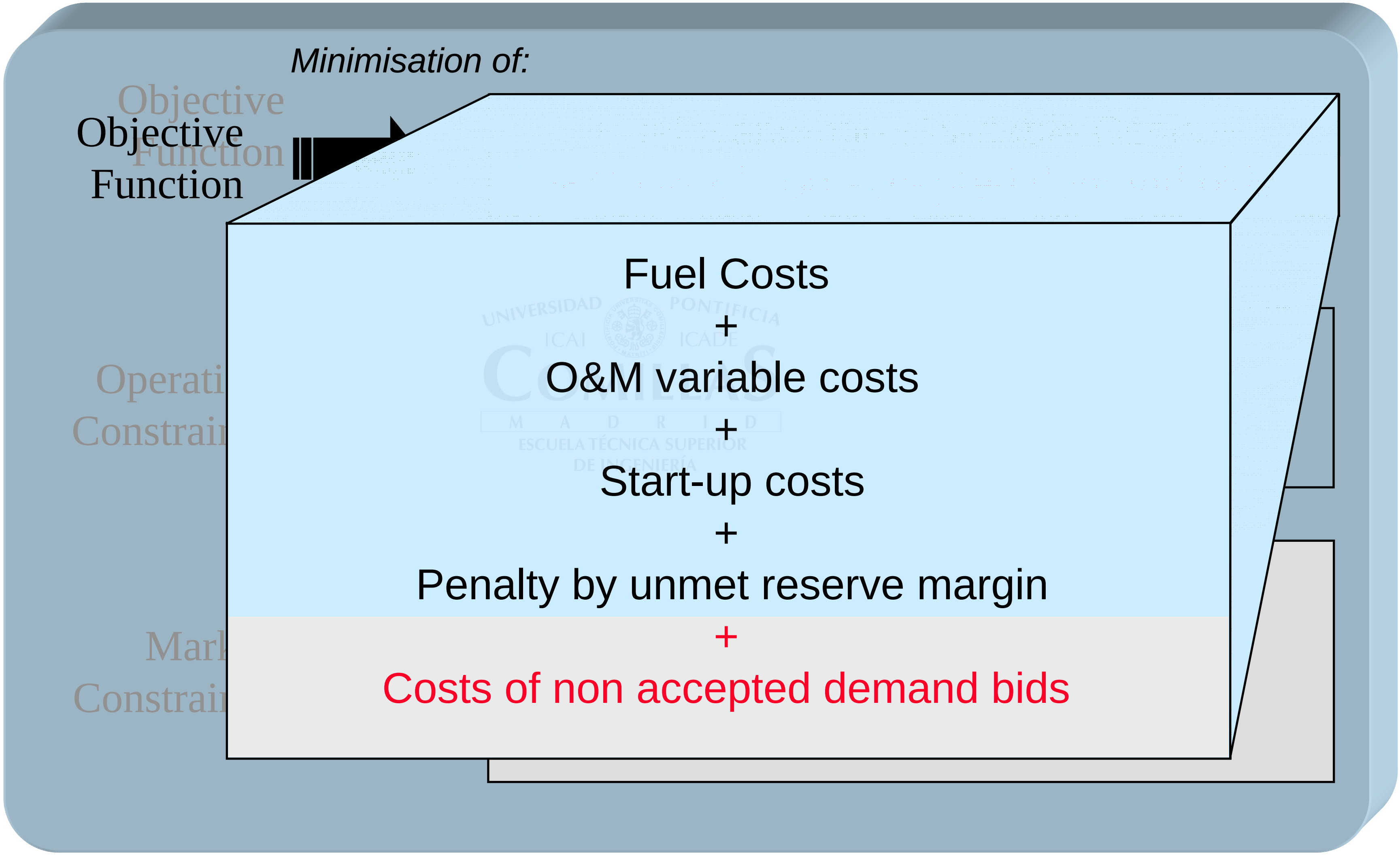
Objective Function → Total Generation Variable Costs +
+ Costs of non accepted demand bids

Subject to:

Operation Constraints →
- Interperiod Constraints
- Intraperiod Constraints

Market Constraints →
- Equilibrium Constraints
- Price equation
- Market Share Constraints

Objective Function



Operation Constraints

Minimisation of:

Objective Function → Total Generation Variable Costs +
+ Costs of non accepted demand bids

Subject to:

Operation Constraints

- Interperiod Constraints
  - Hydro management
  - Seasonal operation of pumped-hydro units
  - Fuel management
  - Maintenance scheduling
- Intraperiod Constraints
  - Balance between generation and demand
  - Generation Limits
  - Daily/Weekly pumped-storage units
  - Reserve Margin

Mark... Constrai...

Market Constraints

Minimisation of:

Objective Function → Total Generation Variable Costs + + Costs of non accepted demand bids

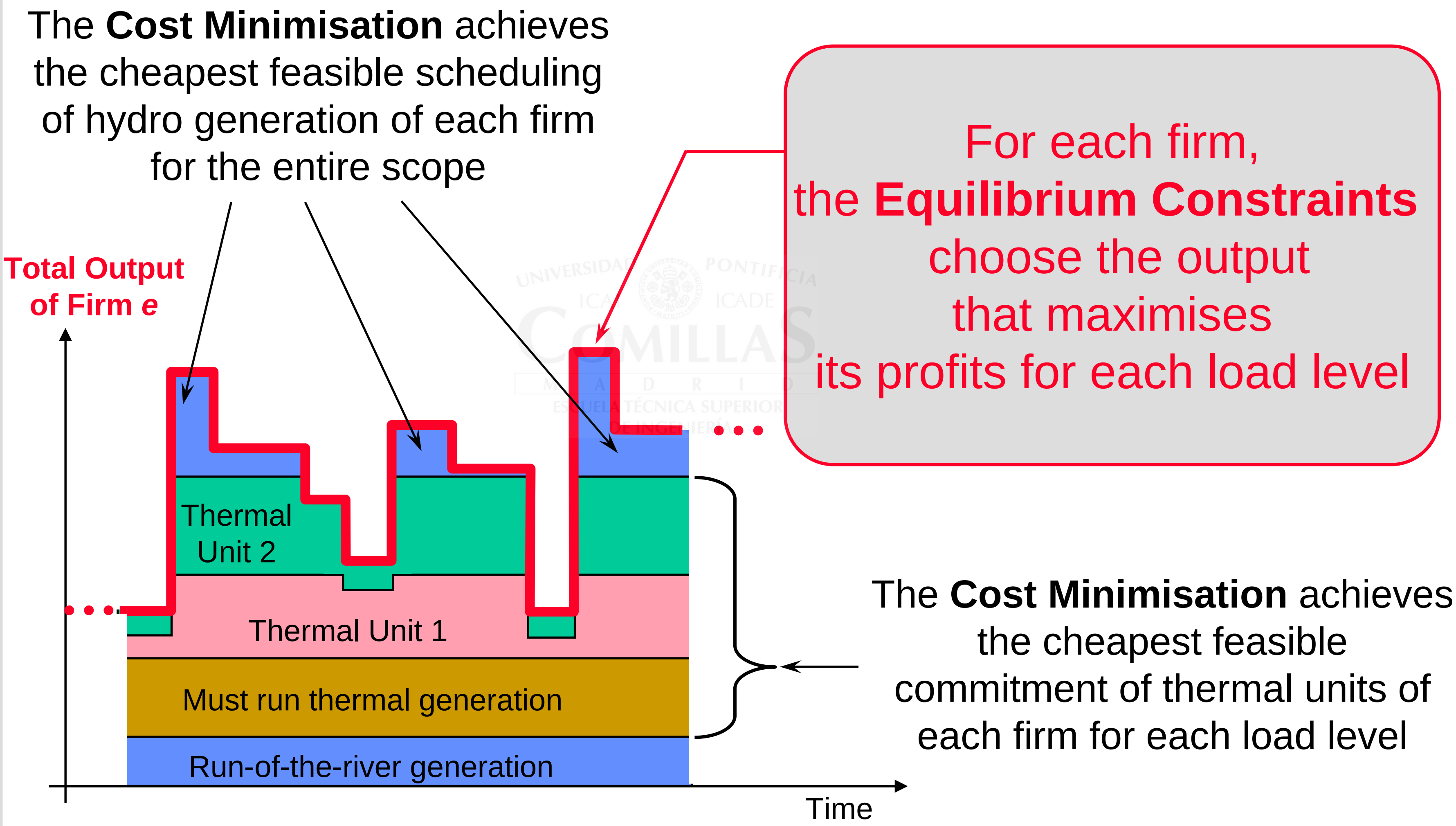
Subject to:

Operatio Constrain

Market Constraints

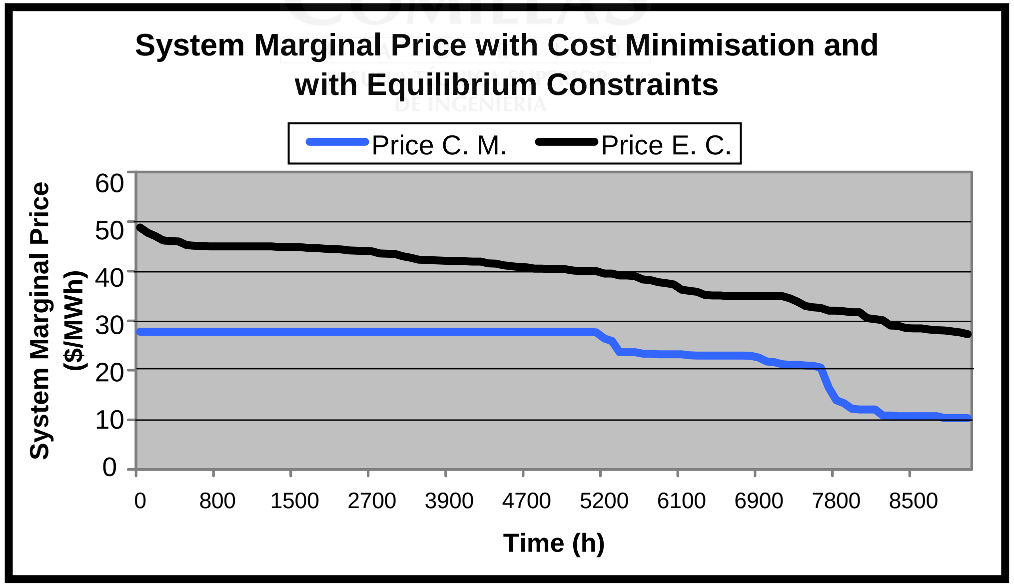
- Equilibrium Constraints
  - Marginal revenues equal marginal cost for each *strategic* firm
  - Marginal cost of each firm as a function of its committed units
- System Marginal Price equation
  - The price is a function of the served demand
- Market Share Constraints
  - The market share of each *leader in quantity* must be equal to its market share objective

How the Equilibrium Constraints Work



Case Study

- It has been applied to the Spanish power market: 73 thermal units and 30 equivalent hydro units.
- The size of the MIP is 25,000 continuous variables, 2,000 binary variables and 33,000 constraints.



Further work in Market Equilibrium Constraints Model

- Iterative computation of the marginal cost of each company because it is not fully captured by the explicit constraints
- Improvement in hydrothermal coordination to get more realistic results in hydro production by companies

Model Applications

- Use of results for analyzing strategies:
  - In the **long term**, it is essential to find **specific quantities** in order to maximize the profit
  - In the **short term**, **forecasted prices** help in defining bidding tactics in the wholesale market

Market Equilibrium Constraints Model Summary

- **Maximize** the **producer profit** while taking into account **operation constraints**

- The equilibrium constraints implies only **minor modifications** to traditional models

Comparison of MCP and Market Equilibrium Constraints

- MCP represents more accurately and intuitively the market equilibrium

- Market Equilibrium Constraints Approach has a more detailed representation of the generation system as traditional operation planning models