Electricity Markets and Power Systems Optimization

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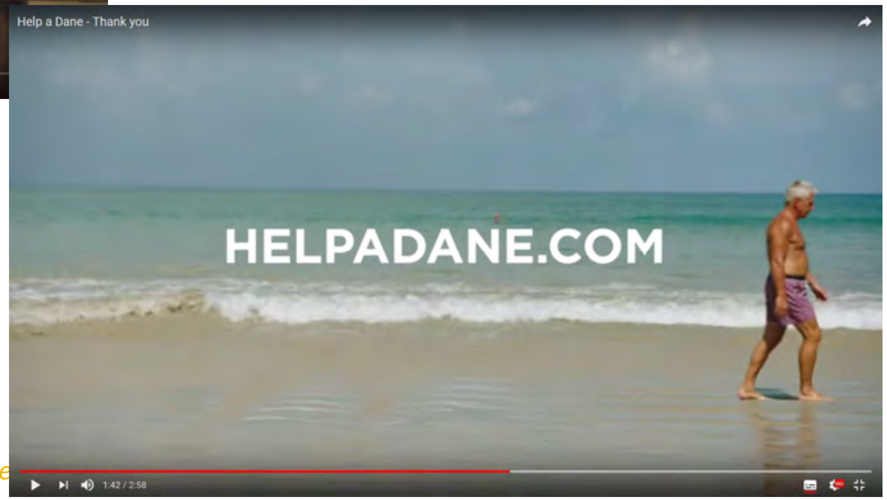
Help a Dane - Spain

https://www.youtube.com/watch?v=bvT4SVG8fMc

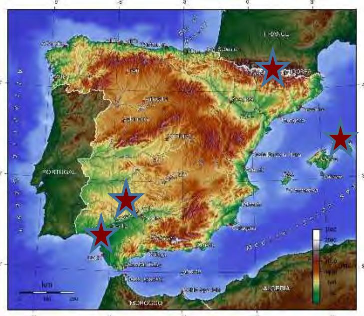
https://www.youtube.com/watch?v=sliLIGwlq_k



Spain

A. Mizielinska y D. Mizielinski *Atlas del mundo: Un insólito viaje por las mil curiosidades y maravillas del mundo* Ed. Maeva 2015

Which is the most Spanish beautiful landscape?



Aigüestortes National Park

Beach of Menorca

Mediterranean oak wood

Guadalquivir marshland

Introductions to

1. Power Systems
2. Optimization
3. Electricity Markets
4. Decision Support Models

1

Power Systems

(original material from Prof. Javier García)

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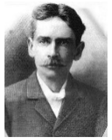
Earth at Night
More information available at:
http://antwrp.gsfc.nasa.gov/apod/ap020811.html
Astronomy Picture of the Day
2002 August 11
http://antwrp.gsfc.nasa.gov/apod/astropix.html

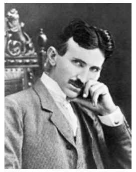
Introduction and basic concepts
The early history of electricity

- First systems date from 1870
  - Individual generators supplying arc lamps
- Thomas Edison invents incandescence lamp (1880)
  - The scale increases (one generator and many lamps)
- Local generation plus distribution systems (lightning)
- Invention of transformer
  - Allows to easily raise voltage (reduce losses)
- War of Currents: AC vs. DC
- Frequency is not homogenized: two groups
  - 60 Hz (EEUU, Canada, Center America)
    - The higher the frequency, the more compact equipment is
    - But reactance in line increases
  - 50 Hz (South America, Europe, Africa)


Edison


The Hungarian "ZBD" Team


Stanley


Tesla


Westinghouse

Images Source: Wikipedia

Evolution of production

Standardization of electricity led to a constant increase in consumption

Figure 5-3. World net electricity generation by fuel, 2012–40
trillion kilowatthours

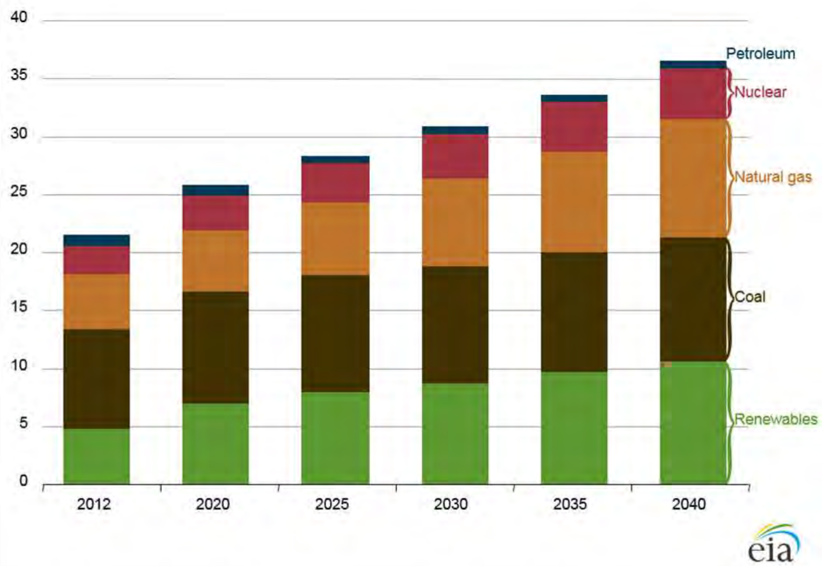
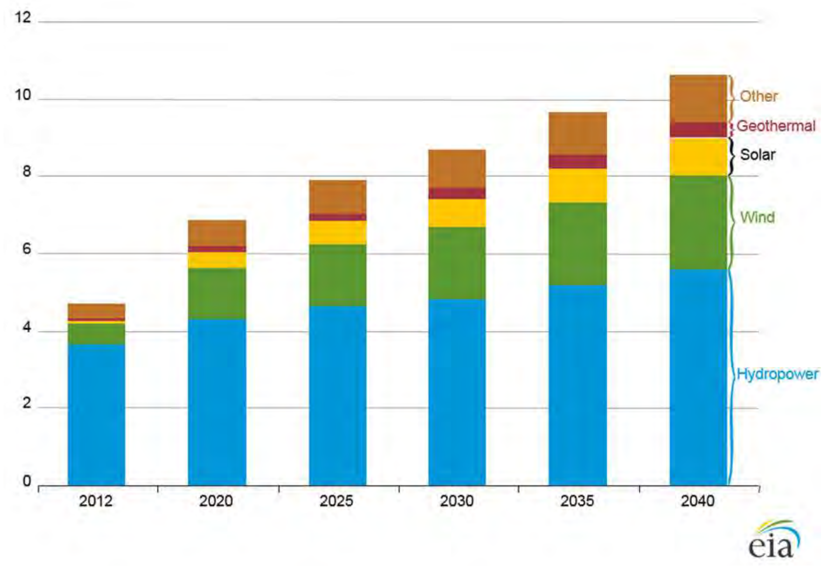


Figure 5-4. World net electricity generation from renewable power by fuel, 2012–40
trillion kilowatthours

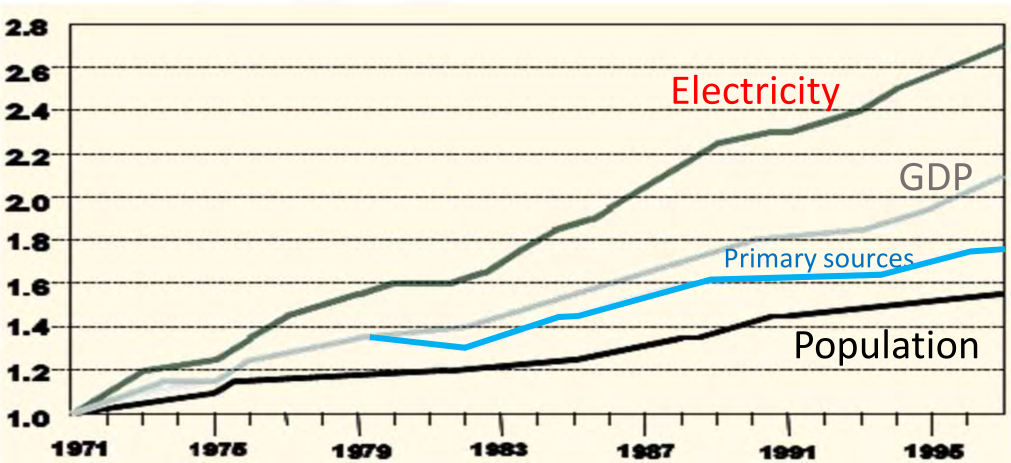


Source: http://www.eia.gov/

Introduction and basic concepts

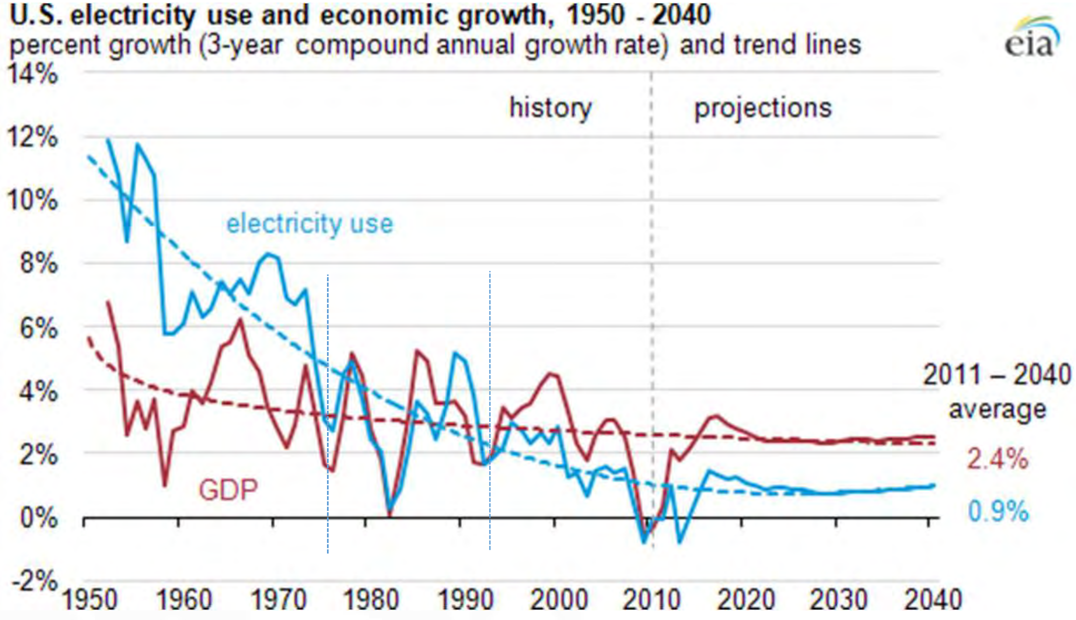
The importance of power systems

- Secondary energy source
  - Transformed from primary energy sources
- It is a versatile and clean (at the consumption place)
- Highly correlated with the GDP



The importance of power systems

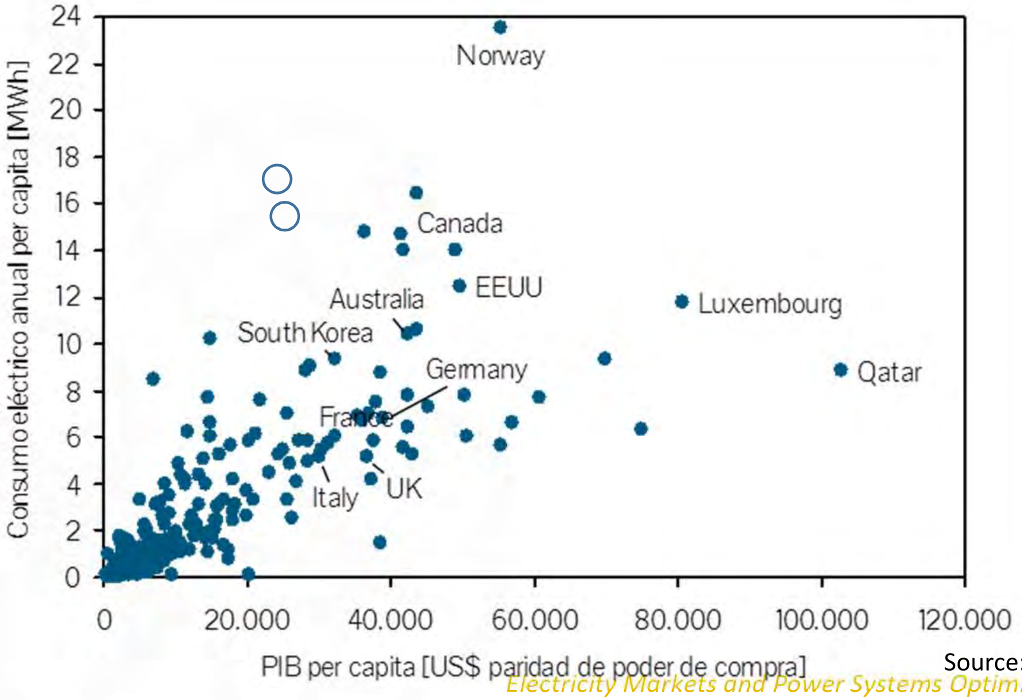
- Yearly variation of % electricity growth and GDP in developed countries



Source: EIA

The importance of power systems

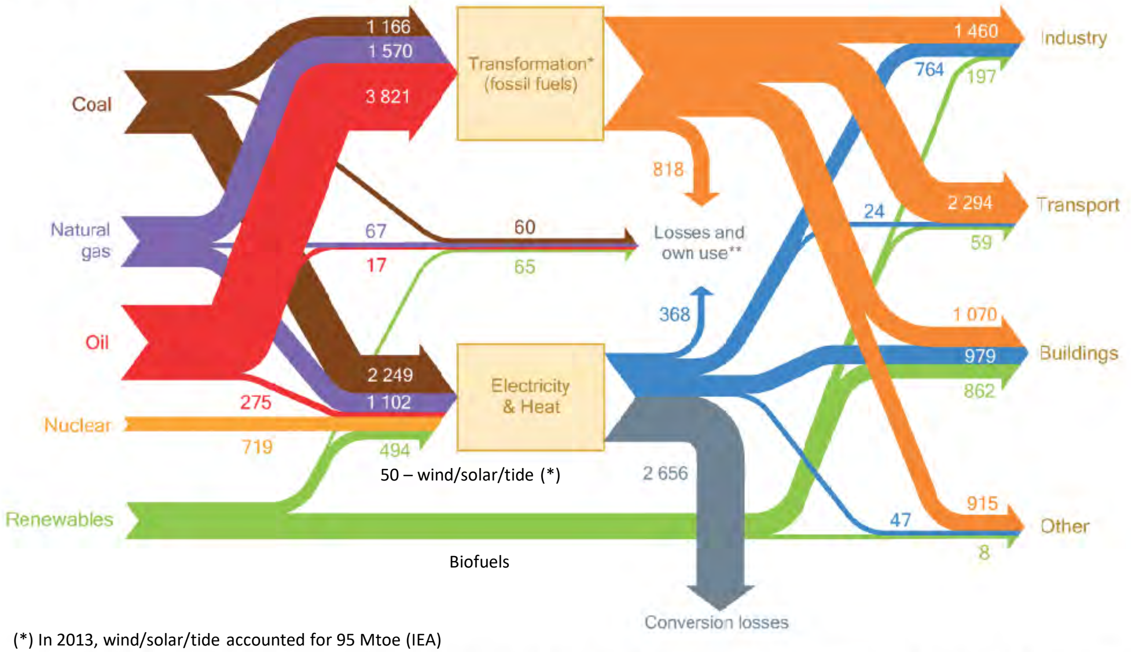
- Relationship between GDP and electricity consumption worldwide (per capita terms)



Source: Energía y sociedad

Introduction and basic concepts
Electricity in the global energy system

Figure 2.8 ▷ **The global energy system, 2010** (Mtoe)   1 Mtoe – 11.6 TWh



(*) In 2013, wind/solar/tide accounted for 95 Mtoe (IEA)

* Transformation of fossil fuels from primary energy into a form that can be used in the final consuming sectors. ** Includes losses and fuel consumed in oil and gas production, transformation losses and own use, generation lost or consumed in the process of electricity production, and transmission and distribution losses.

Introduction and basic concepts

Basic characteristics of electricity

It cannot be stored

- Consumption is produced (transported) in real time

It is injected and extracted in the different nodes, but the flow cannot be directed

- It follows Kirchhoff laws (not commercial transactions between two parties)
- From the moment a line is congested, the cheaper generation cannot always be dispatched

The electricity system is a dynamic system which has to ensure the generation-demand balance

- Failure of one element introduces perturbations
- Rapidly spread: reserves needed

The flows cannot be directed

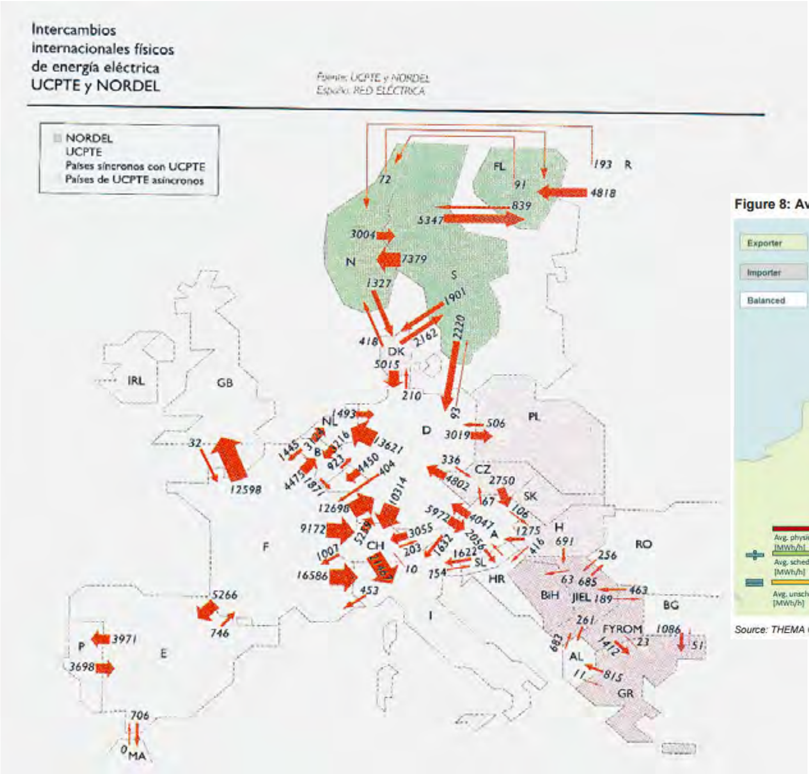
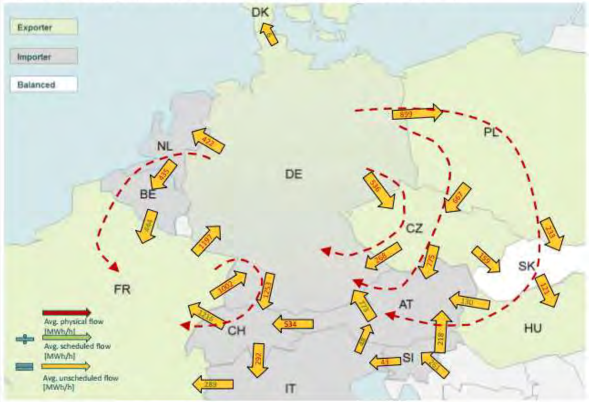


Figure 8: Average unscheduled flows for the years 2011 and 2012, MWh/h[8]

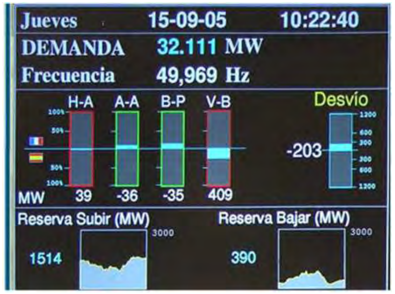


Source: THEMA Consulting Group, based on data from 16 TSOs

Introduction and basic concepts

Basic characteristics of electricity

- Control center REE (CECOEL y CECORE)



- Control center REE (CECRE)

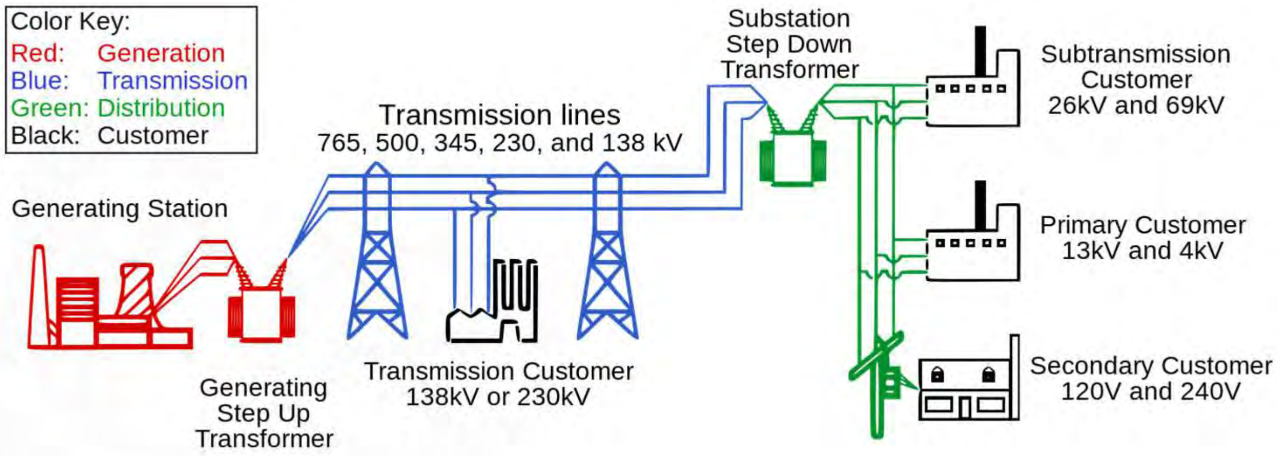
Continuous monitoring is needed

Powerful computers run models

- Estimate demand
- Simulate the generation
- Network flows
- Contingencies

Introduction and basic concepts

Structure and activities involved



Several available technologies
Investments (optimal mix)
Planning/Operation

Networks: Transmission /Distribution
- Investments
- Maintenance
- Operation

Metering
Billing

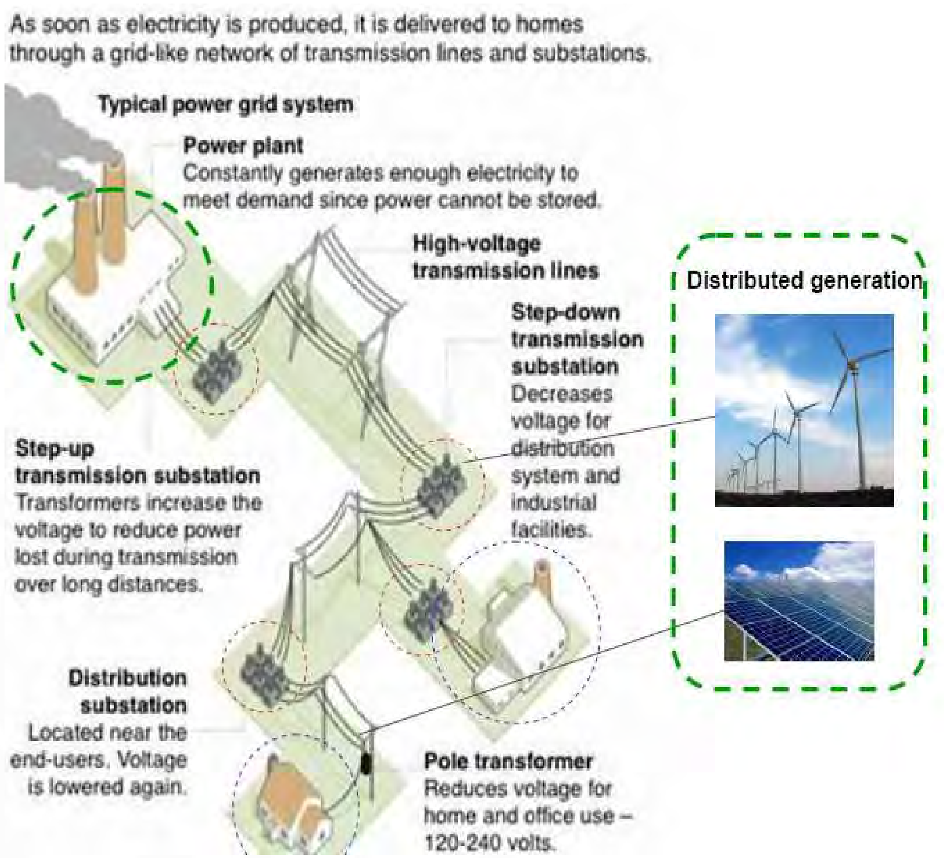
Coordination by the System Operator:
- Feasible production program
- International interchanges

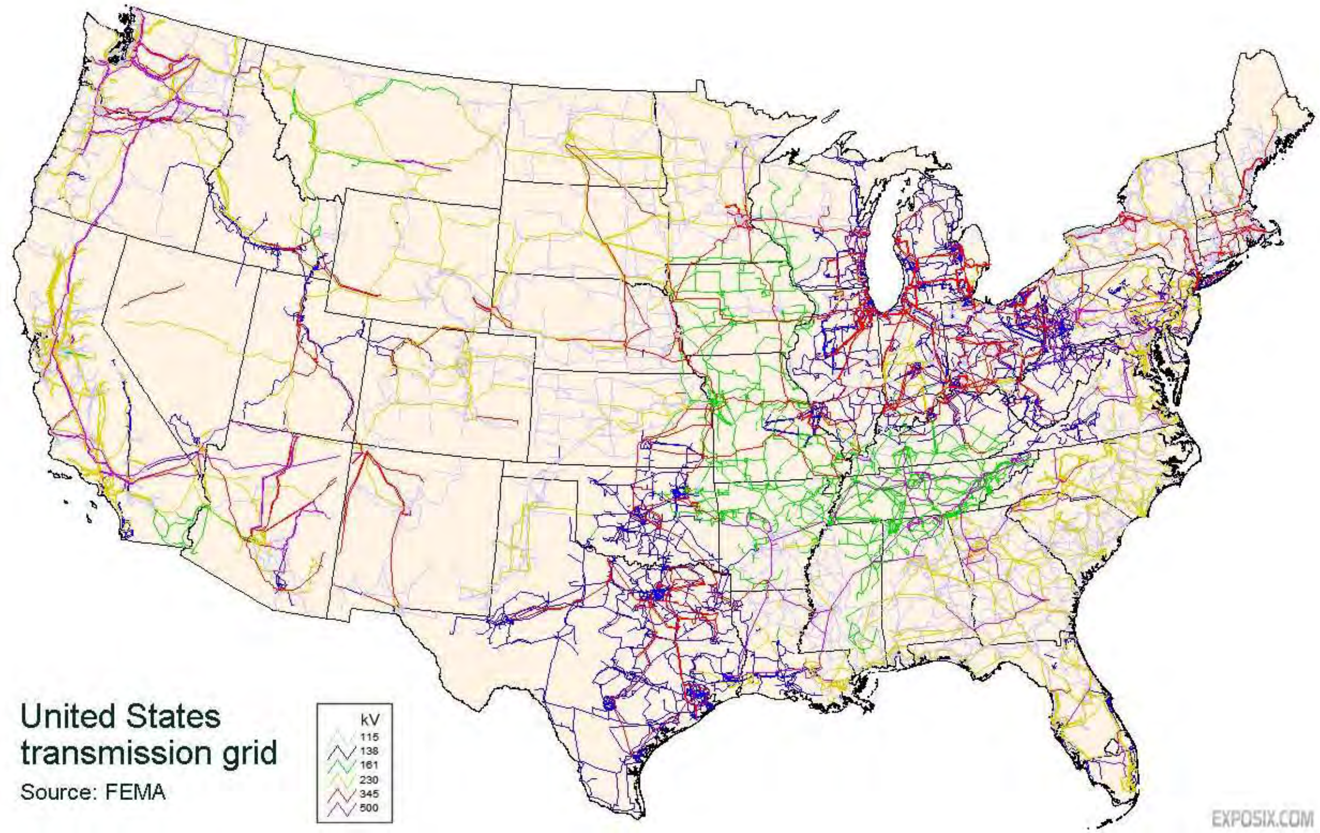
The need to transport electricity

- Electricity systems are conditioned by:
  - Location of demand
    - Urban and industrial areas
  - Location of generation
    - Large-scale generation is conditioned by the availability of resources
    - Distributed generation is conditioned to a much lesser extent
  - System geographical typology (e.g. radial or not)

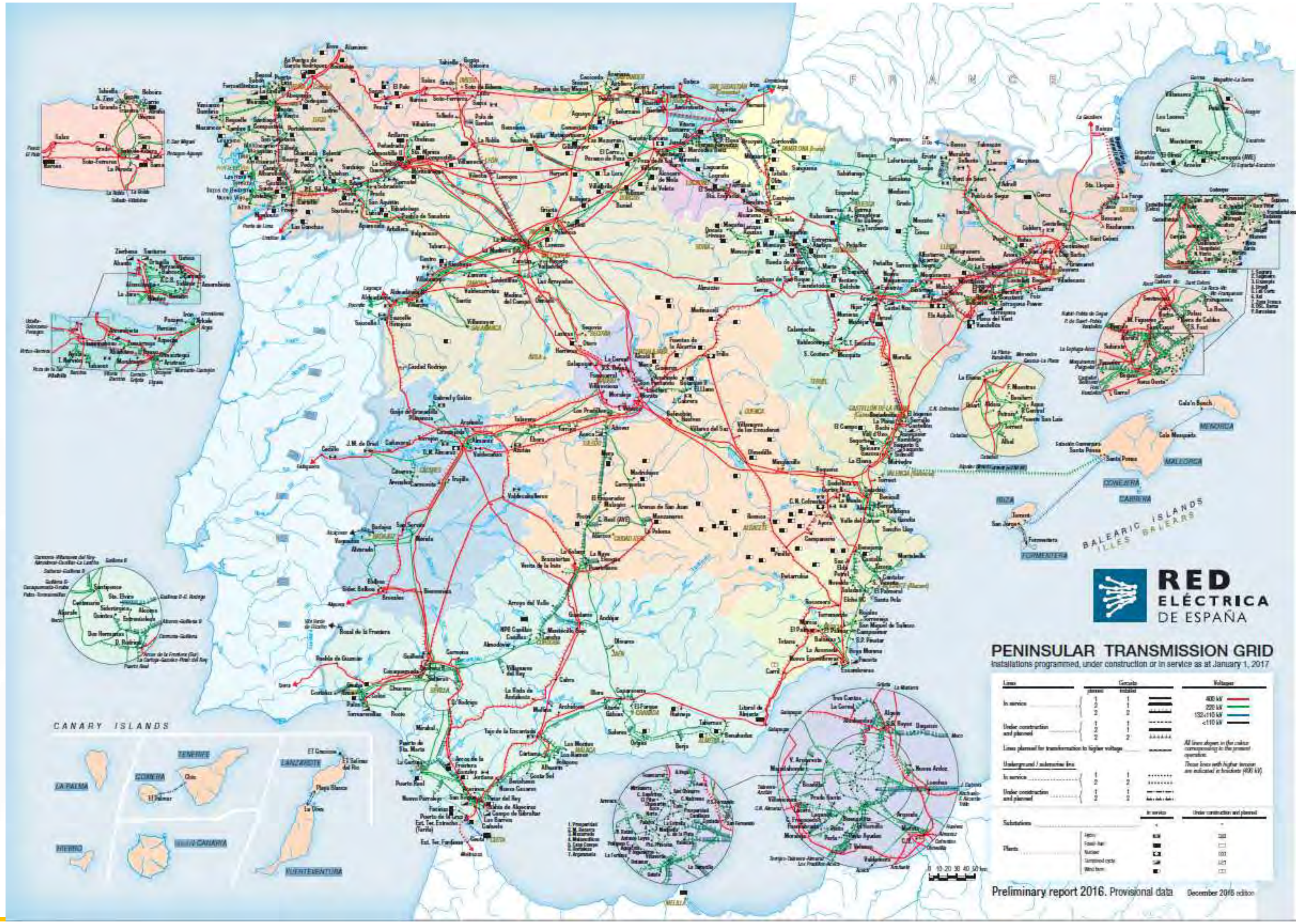
Images Source: Wikipedia

Description of power systems




United States
transmission grid
Source: FEMA
kV
115
138
161
230
345
500
EXPOSIX.COM


entsoe
Interconnected
network of
Continental Europe
FINLAND
ESTONIA
NORWAY
SWEDEN
LATVIA
LITHUANIA
DENMARK
RUSSIA
BELARUS
REPUBLIC OF
IRELAND
GREAT
BRITAIN
POLAND
UKRAINE
THE
NETHERLANDS
ATLANTIC OCEAN
NORTH SEA
BALTIC SEA
SLOVAKIA
MOLDOVA
HUNGARY
ROMANIA
AUSTRIA
FRANCE
CROATIA
BOSNIA
HERZEGOVINA
SERBIA
BLACK SEA
BULGARIA
ITALY
ADRIATIC SEA
MONTENEGRO
ALBANIA
TURKEY
SPAIN
GREECE
CYPRUS
MALTA
MEDITERRANEAN SEA
MOROCCO
ALGERIA
TUNISIA


PENINSULAR TRANSMISSION GRID
Installations programmed, under construction or in service as at January 1, 2017
RED ELÉCTRICA DE ESPAÑA
CANARY ISLANDS
BALEARIC ISLANDS
ILLES BALEARS
Preliminary report 2016. Provisional data
December 2016 edition

A global perspective

- EU-27
  - 4,3 Mkm2,
  - 493 Mhab,
  - 11597 b€ GDP

  - 741 GW installed capacity
  - 3309 TWh/year

(Installed capacity, annual production)

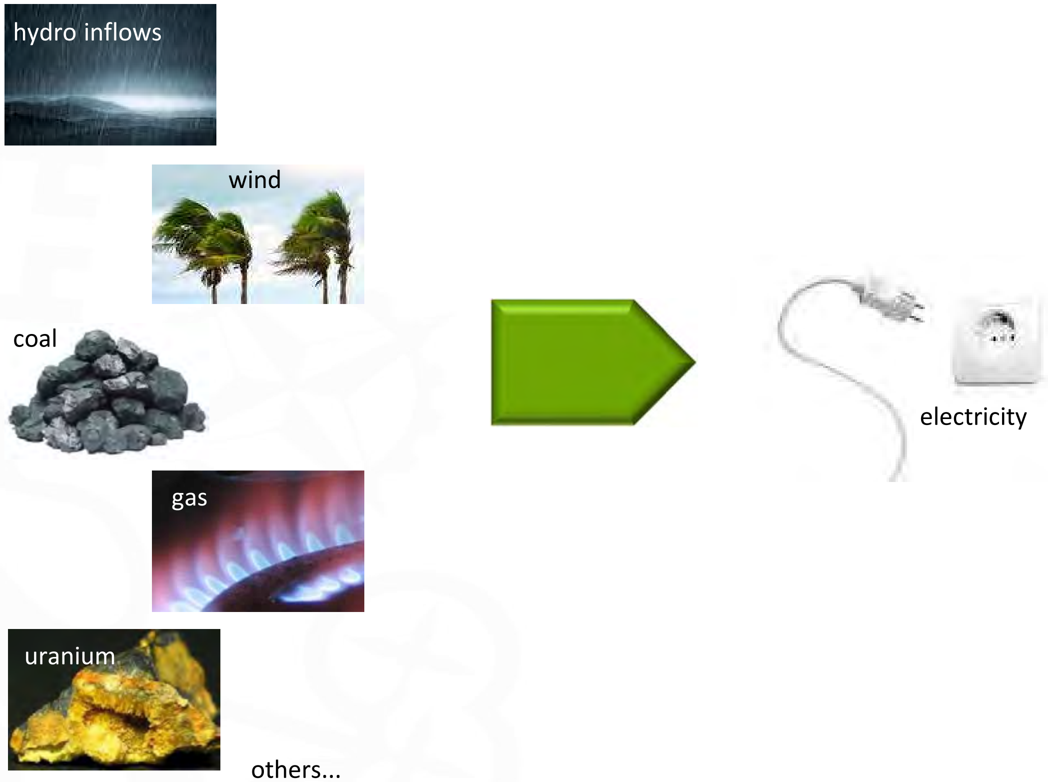
  - Germany (194 GW, 651 TWh)
  - France (129 GW, 546 TWh)
  - UK (81 GW, 336 TWh)
  - Italy (121 GW, 269 TWh)
  - Spain (108 GW, 248 TWh)

- USA
  - 9,8 Mkm2,
  - 300 Mhab,
  - 13195 b$ GDP

  - 1076 GW installed capacity
  - 4200 TWh/year

  - PJM (183 GW, 837 GWh)
  - ERCOT (80 GW, 347 TWh)
  - California (79 GW, 195 TWh)
  - NY-ISO (39 GW, 142 TWh)
  - NE-ISO (31 GW, 136 TWh)

Transforming “input” into “output”



Electricity as a commodity

- Electricity is considered a commodity, "a marketable item produced to satisfy wants or needs".
- The term commodity is used to describe a class of goods for which there is demand, but which is supplied without qualitative differentiation across a market.
- Its price is determined as a function of its market as a whole.
- Storing electricity in big quantities is uneconomical (at present). This makes this commodity a special one:

Electricity must be produced as soon as it is consumed

1.1

Power generation

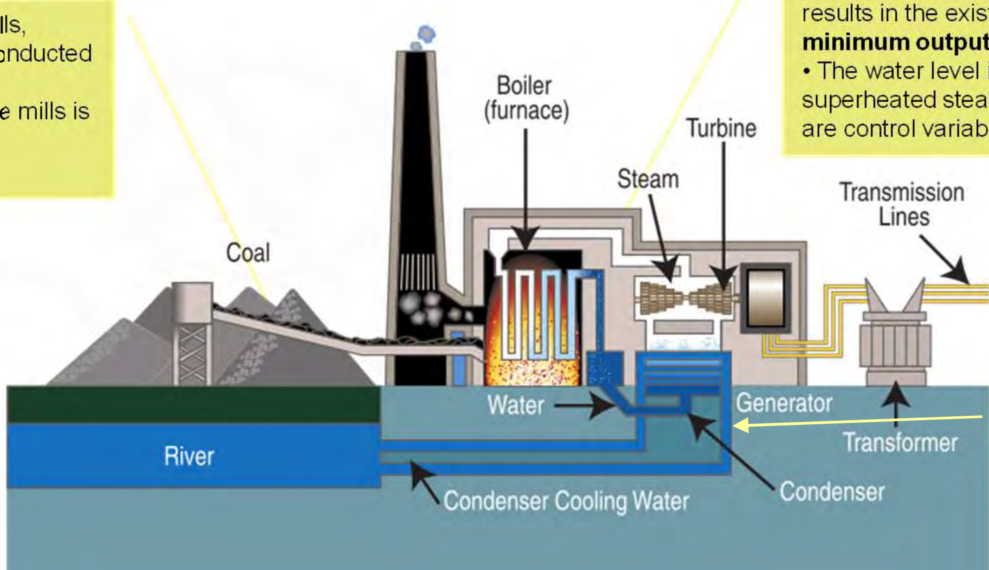
(original material from Prof. Javier García)

Generation units: Coal-fired

- Thermal generators are subject to many operational constraints due to their technical complexity:

• The coal is pulverized in the mills, mixed with hot primary air and conducted to the burner wind-box.
• The quantity of coal entering the mills is a control variable.

• Steam production in the burner.
• Combustion stability problems results in the existence of a **minimum output power.**
• The water level in drum & the superheated steam temperature are control variables.

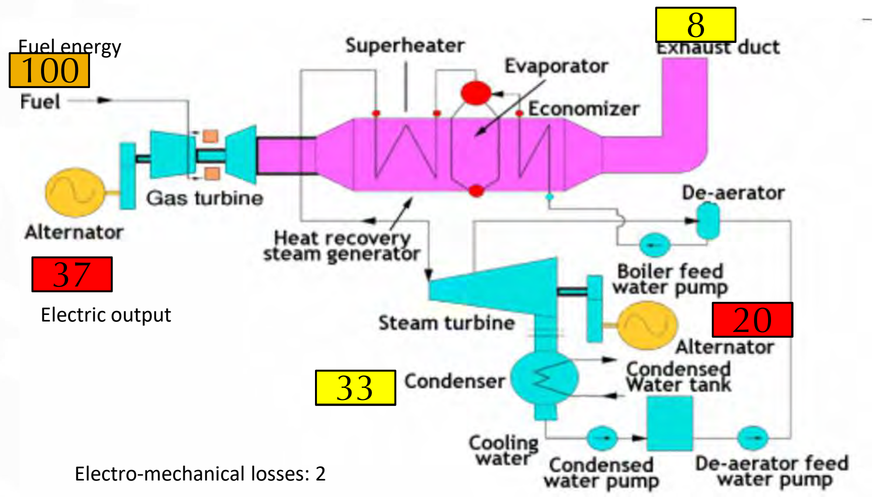


Source: Wikipedia

water is first evaporated to steam, which is then superheated, expanded through a turbine and then condensed back to water

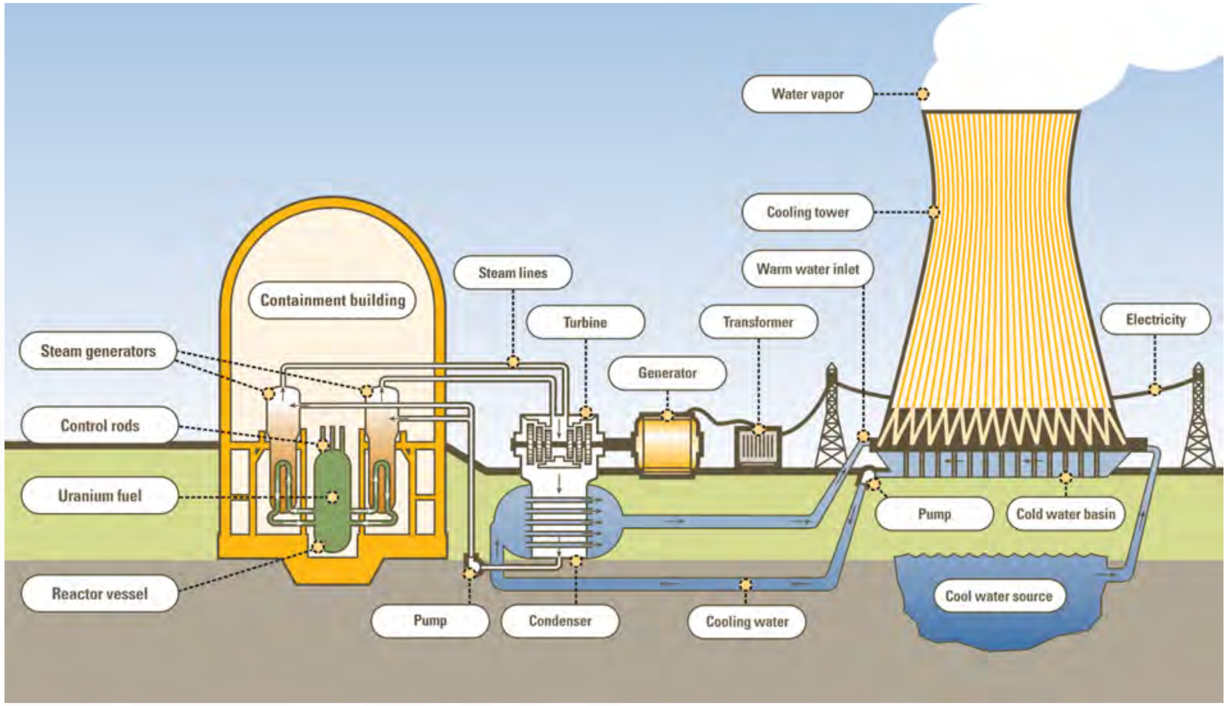
Generation units: CCGT

- Two thermodynamic cycles in the same system:
  - 1) the fluid is water steam
  - 2) the fluid is a hot gas result of the combustion



Courtesy: Alberto Abánades

Generation units: Nuclear generation



https://www.nuclear-power.net/nuclear-power-plant/

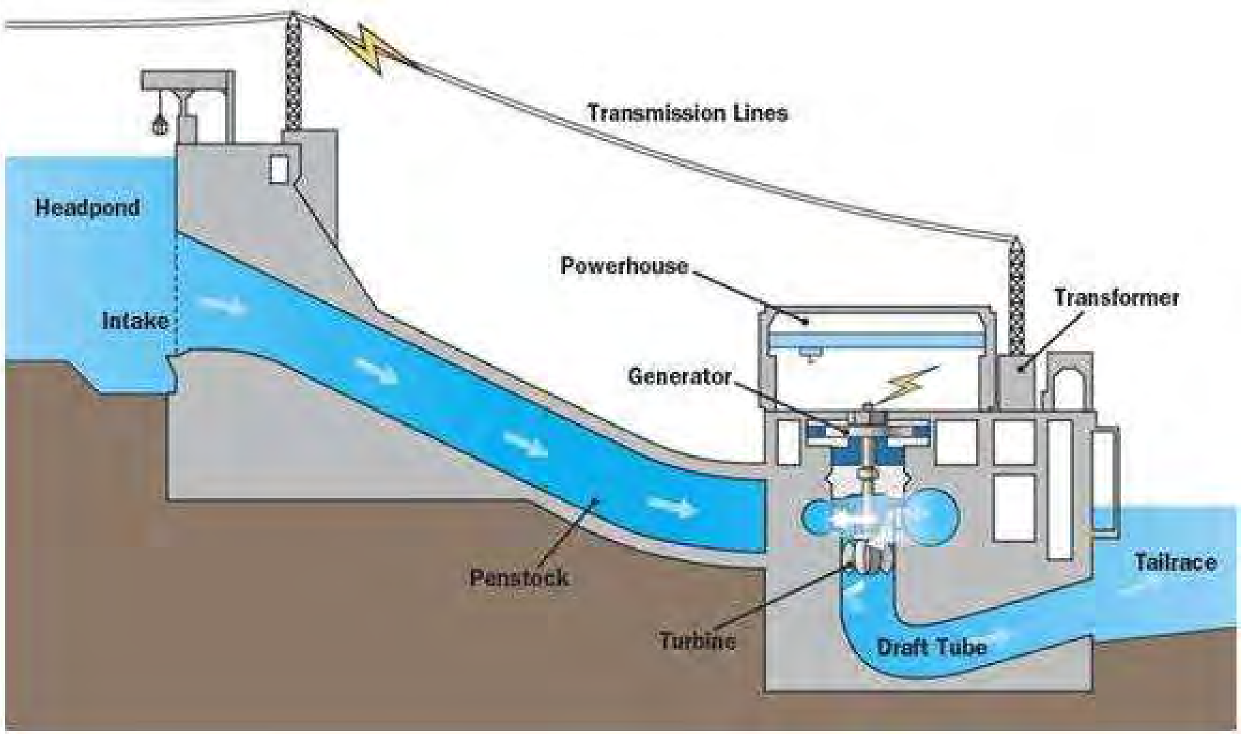
Comparison among thermal units

	Efficiency [%]	Heat rate [MBtu/MWh]	Capital cost [€/kW]	Construction time [months]	Land use [m2]	CO2 [kg/kWh]
CCGT plant	49 – 58	6.8-7.5	450	26 – 29	(400 MW) 30.000	≤ 0.45
Coal-fired plant	37 – 45	10-15	850	40	(1000 MW) 100.000	≥ 0.85 -1
Nuclear plant	34	10-15	1.500	60	(1000 MW) 70.000	---

Operation

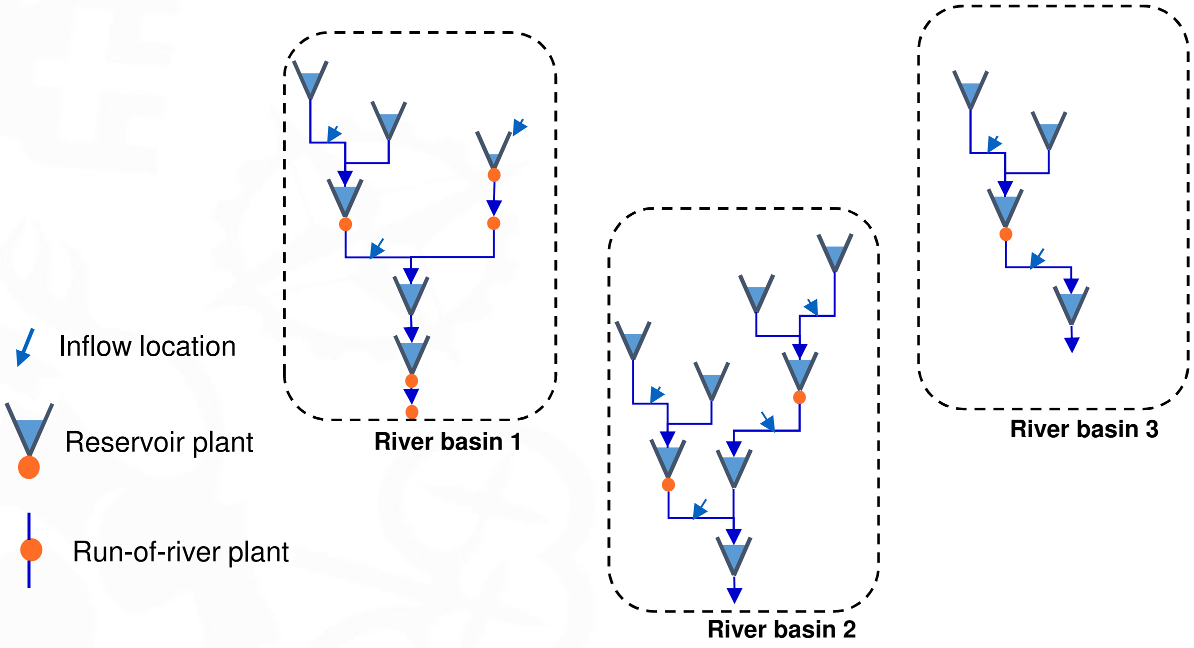
	Load change	Warm start-up to full load	Cold start-up to full power
CCGT plant	10% / minute	40 minutes	2 hours
Coal-fired plant	4% / minute	3 hours	7 hours

Scheme of a hydro plant

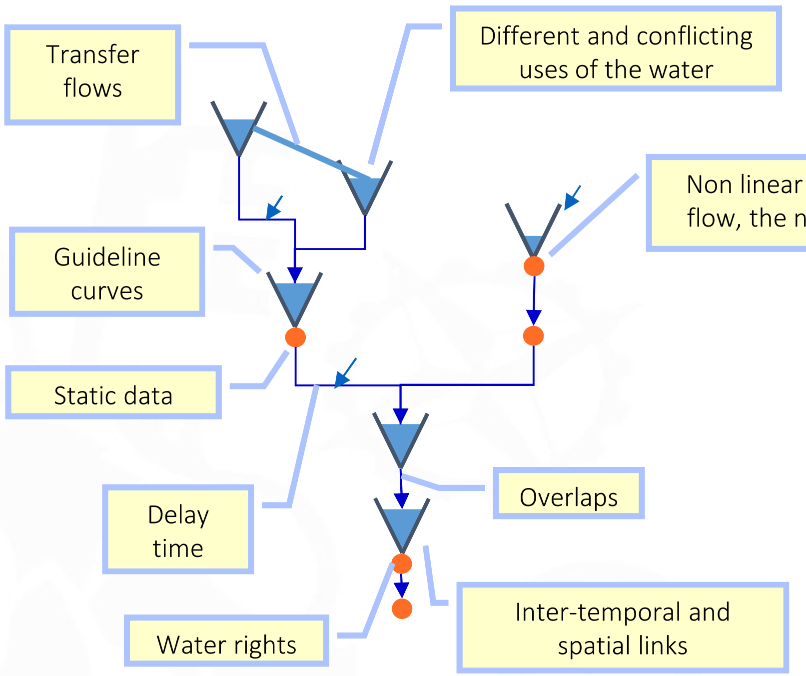


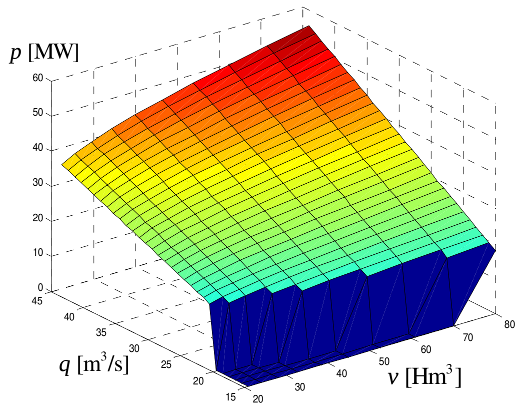
Generation units: Hydro generation

- Hydroelectric systems are commonly divided into a set of un-coupled basins

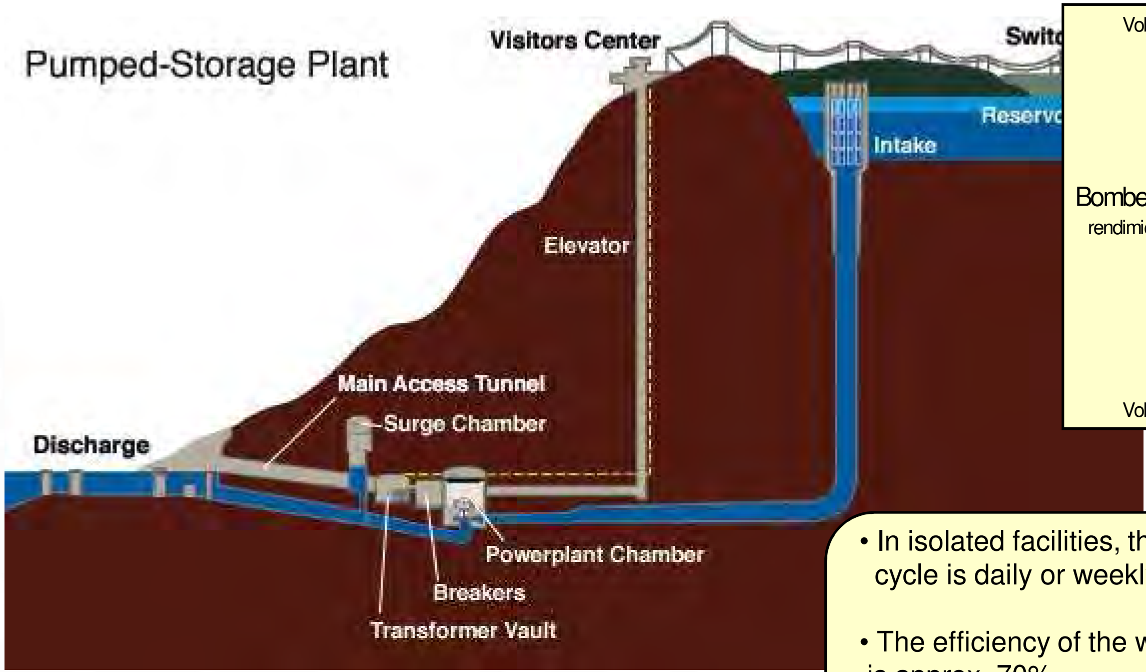


Hydro generation characteristics

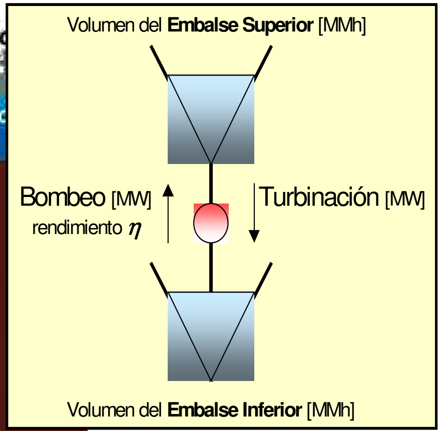




Pumped-storage hydro unit



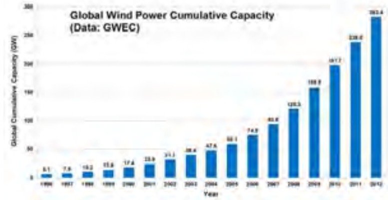
Source: Wikipedia



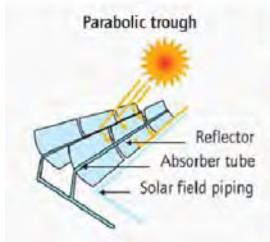
- In isolated facilities, the pumping cycle is daily or weekly
- The efficiency of the whole process is approx. 70%
- Normally, there are discrete functioning points when pumping.

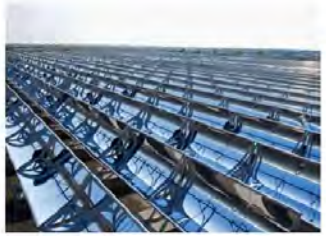
Renewable energy sources

- Wind power: onshore and offshore



- Solar: photovoltaics (PV) and concentrated solar power (CSP)





- Biomass
- Biofuel
- Geothermal energy
- Small hydropower

Question:

- How can it be possible to meet the demand at any time efficiently and reliably, for an infinite time horizon and under uncertainty?
- The answer: Use a temporal hierarchy of decisions
  - Decision functions hierarchically chained
  - Each function optimizes its own decisions subject to
    - Its own constraints
    - Constraints that are imposed from upper levels

Which are the main operation decisions to be made?

1.2

Hierarchy of models

(original material from Prof. Javier García)

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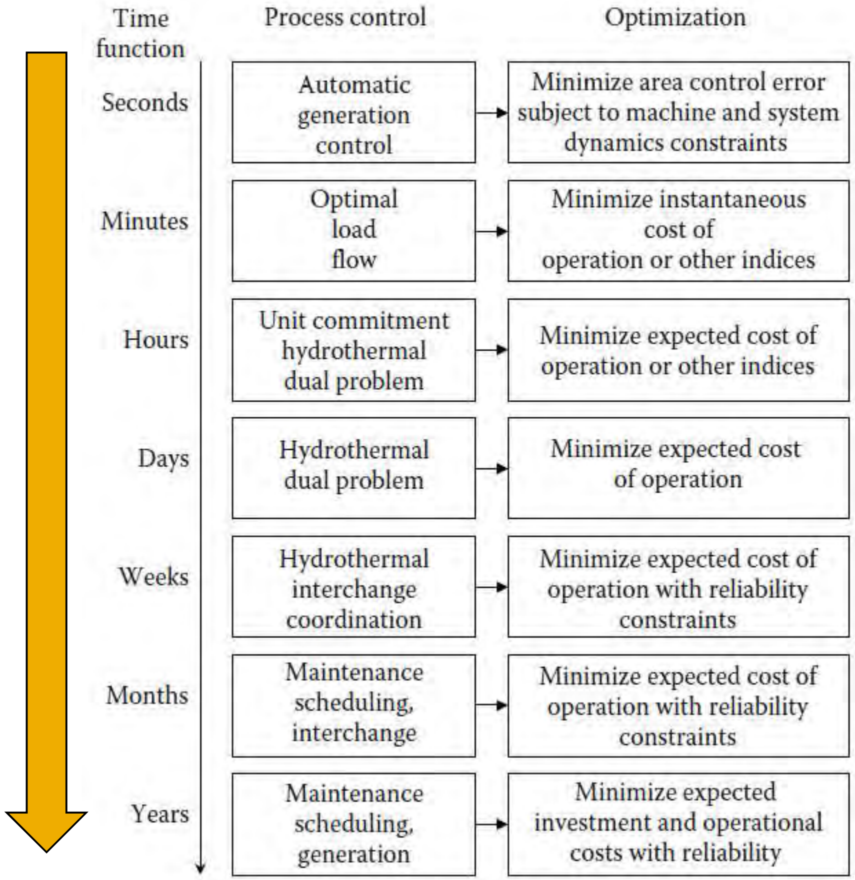
Time scales

- Real time operation
- Operation
- Operation planning
- Expansion planning

What decisions to take?

- Active and reactive power of the committed generators
- Load shedding
- Flow control of lines equipped with power electronics (FACTS and DC links)
- Phase shifter angles
- Transformer tap position
- Operating reserves
- Local control parameters
- Configuration of the network
- Commitment of the generators
- Hydro reservoir operation
- Maintenance schedules
- Introduction and retirement of generation facilities
- Network expansion



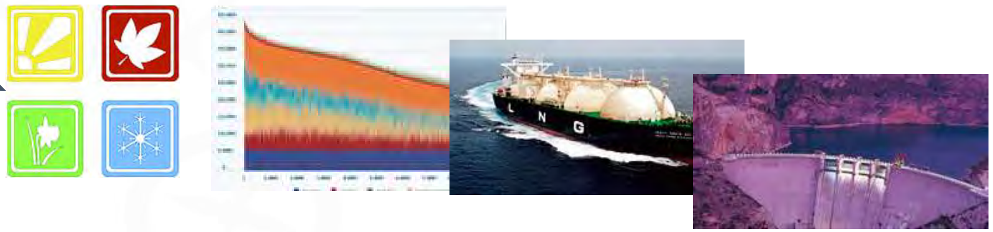
Not under control

- Load
- Equipment failure
- Faults
- Output of variable energy resources (but can curtail)
- Power flows in most lines (need to respect circuit Kirchhoff' laws)
- Fuel consumption of thermal units for a given output

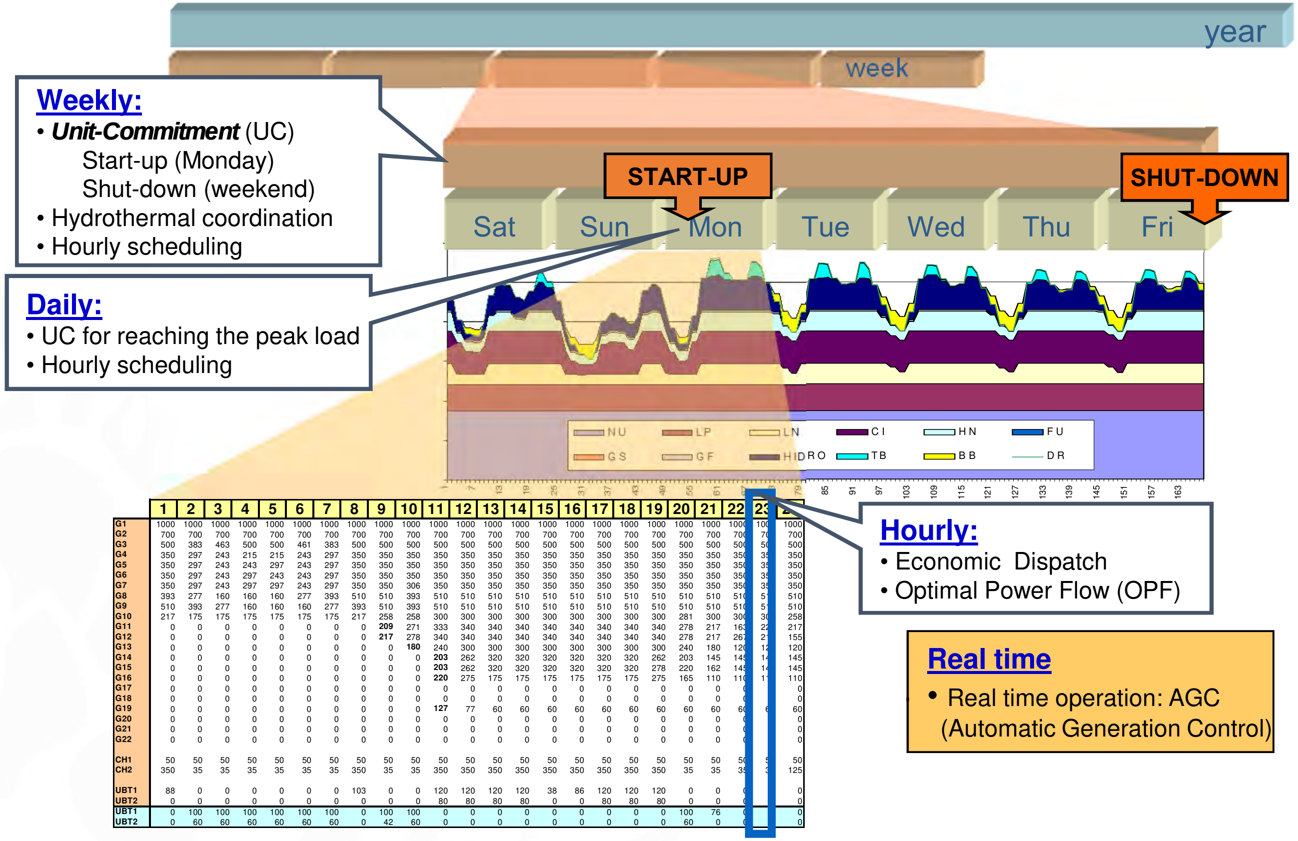
Generation planning
Hierarchical organization (1/2)

Long-term:
- Investment in new plants (divesting)
- Repowering existing ones
- Hyper-annual reservoirs op.
- Maintenances
- Nuclear cycle

Mid-Term:
- Fuel procurement
- Maintenances
- Mid-term hydrothermal coordination



Generation planning
Hierarchical organization (2/2)



2

Optimization

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Business Analytics Spectrum

- **Descriptive**: statistics (data analysis, analysis of variance, correlation)
- **Predictive**: simulation, regression, forecasting
- **Prescriptive**: optimization, heuristics, decision analysis

Competitive advantage ↑

Stochastic Optimization	How can we achieve the best outcome including the effects of variability?	***PRESCRIPTIVE***
Optimization	How can we achieve the best outcome?	↑
Predictive modeling	What will happen next if?	***PREDICTIVE***
Forecasting	What if these trends continue?	↑
Simulation	What could happen…?	
Alerts	What actions are needed?	
Query/drill down	What exactly is the problem?	***DESCRIPTIVE***
Ad hoc reporting	How many, how often, where?	
Standard reporting	What happened?	

Source: A. Fleischer et al. *ILOG Optimization for Collateral Management*

Example: Operation Planning

Glassware S.A. manufactures products of glass of high quality, including windows and doors. It has three factories. Factory 1 manufactures aluminum frames and metal parts. Factory 2 manufactures wooden frames and factory 3 manufactures glass and assembles the products.

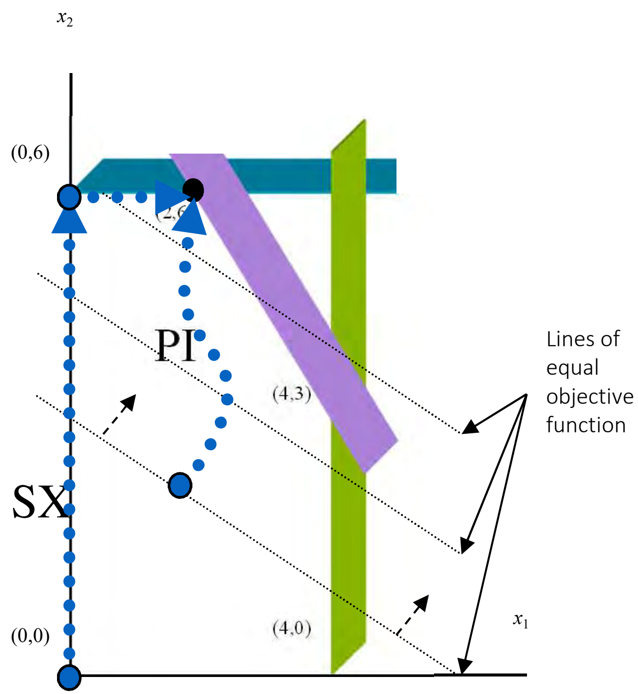
Due to revenue losses, the directorship has decided to change the product line. Unprofitable ones are going to be discontinued and two new ones with high selling potential are to be launched:

- Product no. 1: glass door with aluminum frame
- Product no. 2: glass window with wooden frame

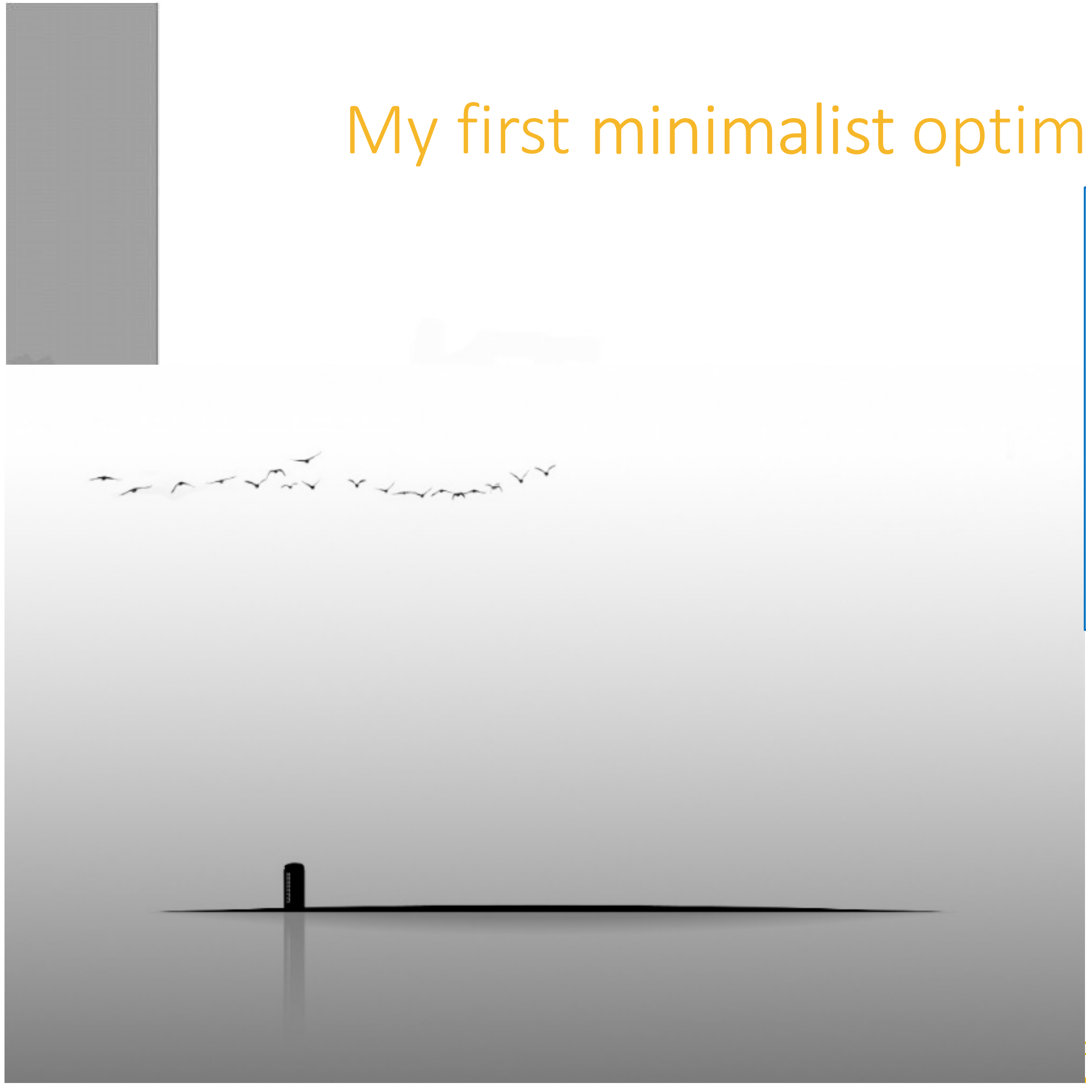
The first product requires to be processed in factories 1 and 3, while the second one needs 2 and 3. The Marketing Department estimates that as many doors and windows as can be manufactured can be sold. But given that both products compete by the factory 3 resources, we want to know the product mix that maximizes the company profits.

Example: Operation Planning

$$\max \ z = 3x_1 + 5x_2$$
$$x_1 \leq 4$$
$$2x_2 \leq 12$$
$$3x_1 + 2x_2 \leq 18$$
$$x_1, x_2 \geq 0$$



My first minimalist optimization model



```
positive variables x1, x2
         variable  z

equations of, e1, e2, e3 ;

of .. 3*x1 + 5*x2 =e=  z ;
e1 ..   x1         =l=  4 ;
e2 .. 2*x2         =l= 12 ;
e3 .. 3*x1 + 2*x2 =l= 18 ;

model minimalist / all /
solve minimalist maximizing z using LP
```

$$\max_{x_1,x_2} z = 3x_1 + 5x_2$$
$$x_1 \leq 4$$
$$2x_2 \leq 12$$
$$3x_1 + 2x_2 \leq 18$$
$$x_1, x_2 \geq 0$$

Transportation model

There are i can factories and j consumption markets. Each factory has a maximum capacity of a_i cases and each market demands a quantity of b_j cases (it is assumed that the total production capacity is greater than the total market demand for the problem to be feasible). The transportation cost between each factory i and each market j for each case is c_{ij}. The demand must be satisfied at minimum cost.
The decision variables of the problem will be cases transported between each factory i and each market j, x_{ij}.

Mathematical formulation

- Objective function

$$\min_{x_{ij}} \sum_{ij} c_{ij} x_{ij}$$

- Production limit for each factory i

$$\sum_{j} x_{ij} \leq a_i \quad \forall i$$

- Consumption in each market j

$$\sum_{i} x_{ij} \geq b_j \quad \forall j$$

- Quantity to send from each factory i to each market j

$$x_{ij} \geq 0 \quad \forall i \rightarrow j$$

Mathematical specification and formulation

- Definition of variables, equations, objective function, parameters
- Identification of problem type (LP, MIP, NLP)
- Emphasis in formulation accuracy and beauty
- Analysis of problem size and structure
- Categories of LP problems as a function of their size

	CONSTRAINTS	VARIABLES
SAMPLE CASE	100	100
MEDIUM SIZE	10000	10000
BIG SIZE	500000	500000
LARGE SCALE	>500000	>500000

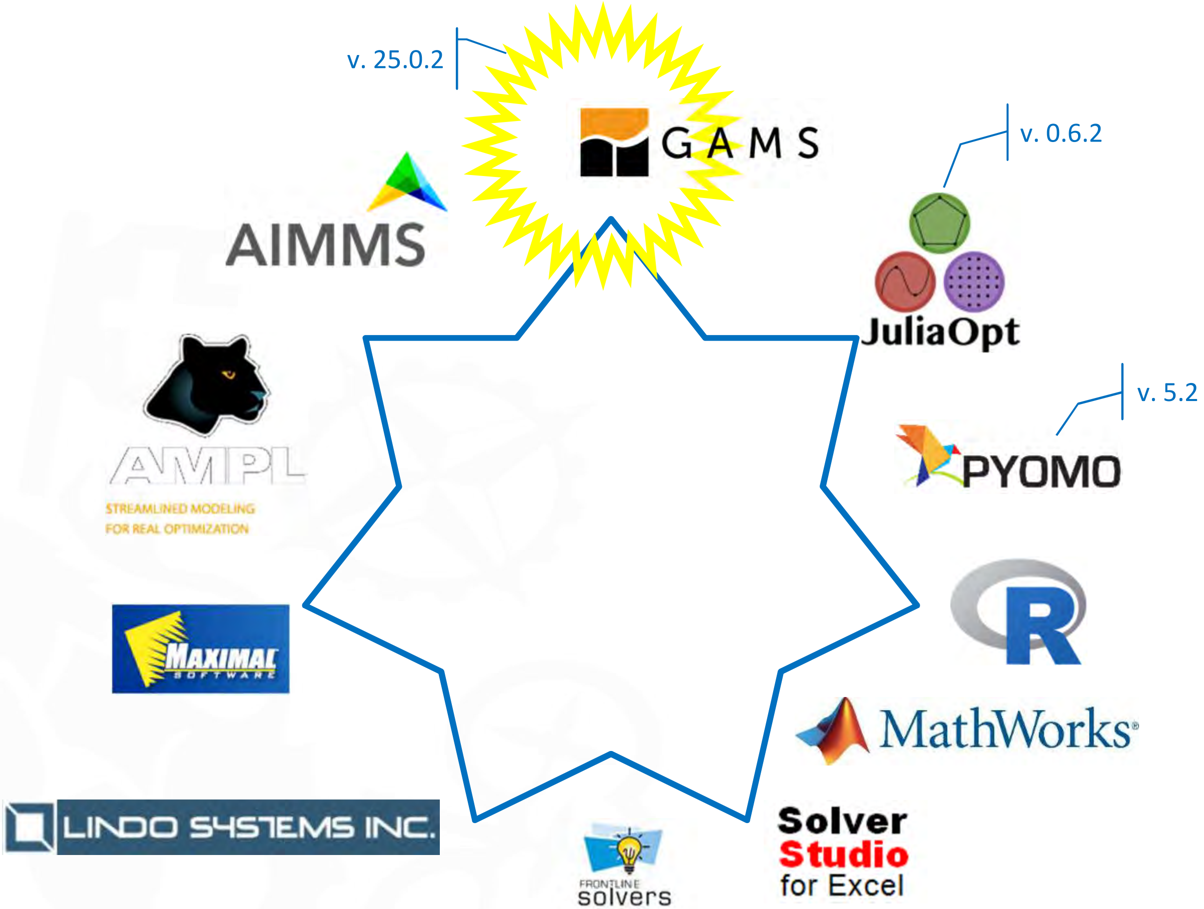
Algebraic modeling languages advantages (i)

- High level languages for compact formulation of large-scale and complex models
- Easy prototype development
- Documentation is made simultaneously to modeling
- Improve modelers productivity
- Structure good modeling habits
- Easy continuous reformulation
- Allow to build large maintainable models that can be adapted quickly to new situations

Algebraic modeling languages advantages (ii)

- Separation of interface, data, model and solver
- Formulation independent of model size
- Model independent of solvers
- Allow advanced algorithm implementation
- Easy implementation of NLP, MIP, and MCP
- Open architecture with interfaces to other systems
- Platform independence and portability among platforms and operating systems (MS Windows, Linux, Mac OS X, Sun Solaris, IBM AIX)

Search, compare and if you find something better use it



Interfaces, languages, solvers

Interface (graphical)
Excel
Access
SQL
Matlab

Mathematical Language	Algebraic Language
	GAMS
	AMPL
	AIMMS
Python	Pyomo
Julia	JuMP
MatLab	
Solver Studio	

Solver
IBM CPLEX
Gurobi
XPRESS
GLPK
CBC
PATH

Learning by reading first, and then by doing

- GAMS Model Libraries

  https://www.gams.com/latest/gamslib_ml/libhtml/index.html#gamslib

- Decision Support Models in the Electric Power Industry

  https://www.iit.comillas.edu/aramos/Ramos_CV.htm#ModelosAyudaDecision

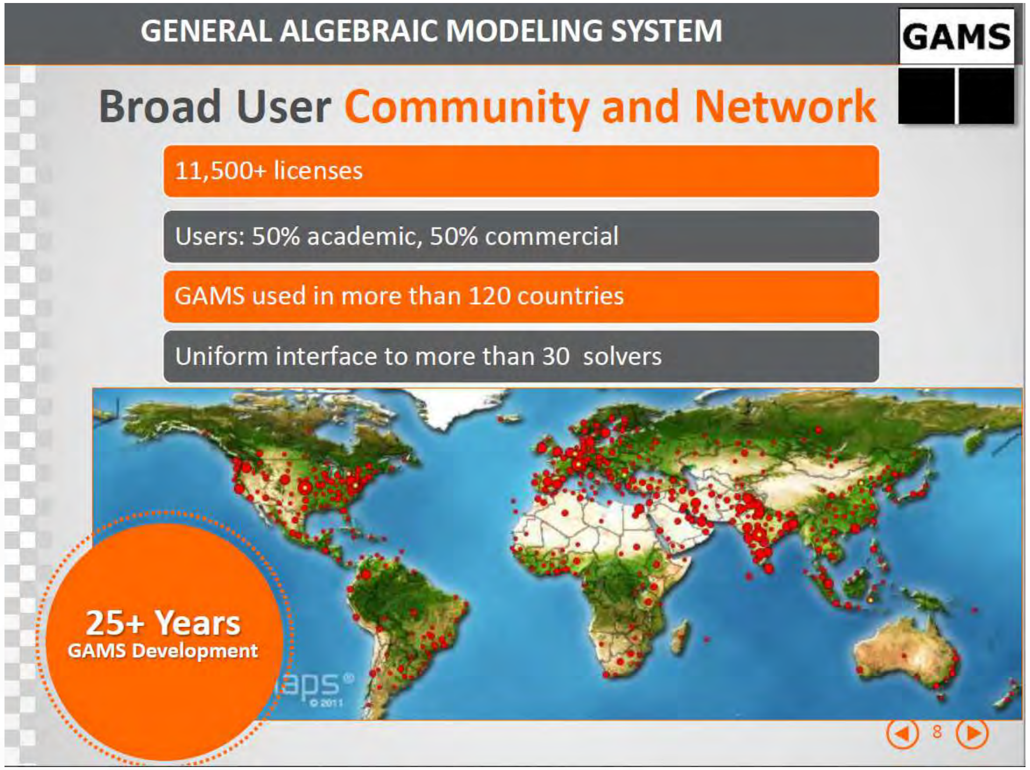
StarGen Lite (**Short Term Stochastic Daily Unit Commitment Model**) demo GAMS version
StarGen Lite (**Medium Term Stochastic Hydrothermal Coordination Model**) demo GAMS version
StarGen Lite (**Long Term Generation Expansion Planning Model**) demo GAMS version
StarGen Lite (**Probabilistic Production Cost Model**) demo GAMS version

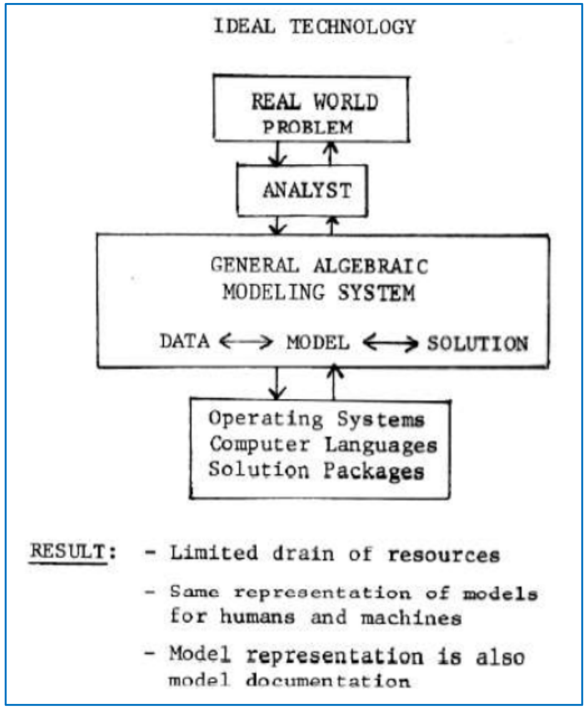
StarNet Lite (**Long Term Transmission Expansion Planning Model**) demo GAMS version

StarMkt Lite (**Cournot Market Equilibrium Model**) demo GAMS version
StarMkt Lite (**Bushnell Market Equilibrium Model**) demo GAMS version
StarMkt Lite (**Long Term Market Generation Expansion Planning Model**) demo GAMS version

StarGen Lite (**Short Term Stochastic Daily Unit Commitment Model**) demo Julia version

GAMS (General Algebraic Modeling System)





GAMS birth: 1976 World Bank slide

Developing in GAMS

- Development environment gamside

aaa.gpr

- Documentation
  - GAMS Documentation Center https://www.gams.com/latest/docs/
  - GAMS Support Wiki https://support.gams.com/
  - Bruce McCarl's GAMS Newsletter https://www.gams.com/community/newsletters-mailing-list/
- Users guide Help > GAMS Users Guide
- Solvers guide Help > Expanded GAMS Guide

- Model: FileName.gms
- Results: FileName.lst
- Process log: FileName.log

Blocks in a GAMS model

- Mandatory
  - variables
  - equations
  - model
  - solve
- Optional
  - sets: (alias)
    - alias (i,j) i and j can be used indistinctly
    - Checking of domain indexes
  - data: scalars, parameters, table

My first transportation model (classical organization)

```
sets
   I origins      / VIGO, ALGECIRAS /
   J destinations / MADRID, BARCELONA, VALENCIA /

parameters
   pA(i) origin capacity
       / VIGO      350
         ALGECIRAS 700 /

   pB(j) destination demand
       / MADRID    400
         BARCELONA 450
         VALENCIA  150 /

table pC(i,j) per unit transportation cost
           MADRID BARCELONA VALENCIA
VIGO        0.06      0.12      0.09
ALGECIRAS   0.05      0.15      0.11

variables
   vX(i,j) units transported
   vCost   transportation cost

positive variable vX

equations
   eCost          transportation cost
   eCapacity(i) maximum capacity of each origin
   eDemand   (j) demand supply at destination ;

eCost        .. sum[(i,j), pC(i,j) * vX(i,j)] =e= vCost ;
eCapacity(i) .. sum[   j ,             vX(i,j)] =l= pA(i) ;
eDemand   (j) .. sum[ i   ,             vX(i,j)] =g= pB(j) ;

model mTransport / all /
solve mTransport using LP minimizing vCost
```

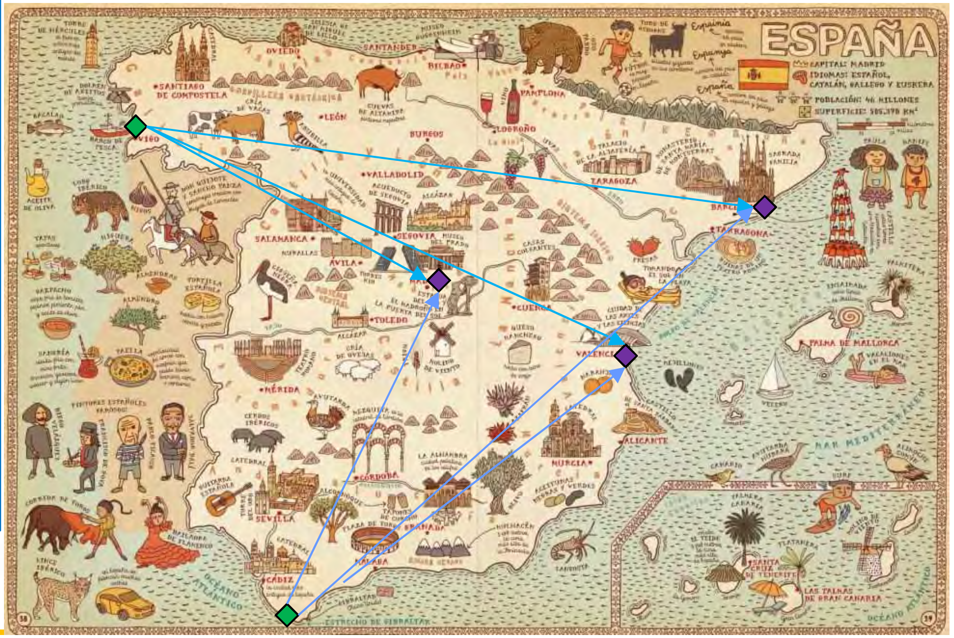
$$\min_{x_{ij}} \sum_{ij} c_{ij} x_{ij}$$

$$\sum_{j} x_{ij} \leq a_i \quad \forall i$$

$$\sum_{i} x_{ij} \geq b_j \quad \forall j$$

$$x_{ij} \geq 0$$

A. Mizielinska y D. Mizielinski *Atlas del mundo: Un insólito viaje por las mil curiosidades y maravillas del mundo* Ed. Maeva 2015



Unit commitment and economic dispatch

- S. Cerisola, A. Baillo, J.M. Fernandez-Lopez, A. Ramos, R. Gollmer *Stochastic Power Generation Unit Commitment in Electricity Markets: A Novel Formulation and A Comparison of Solution Methods* Operations Research 57 (1): 32-46 Jan-Feb 2009 (*http://or.journal.informs.org/cgi/content/abstract/57/1/32*)

Smart Charging of Electric Vehicles

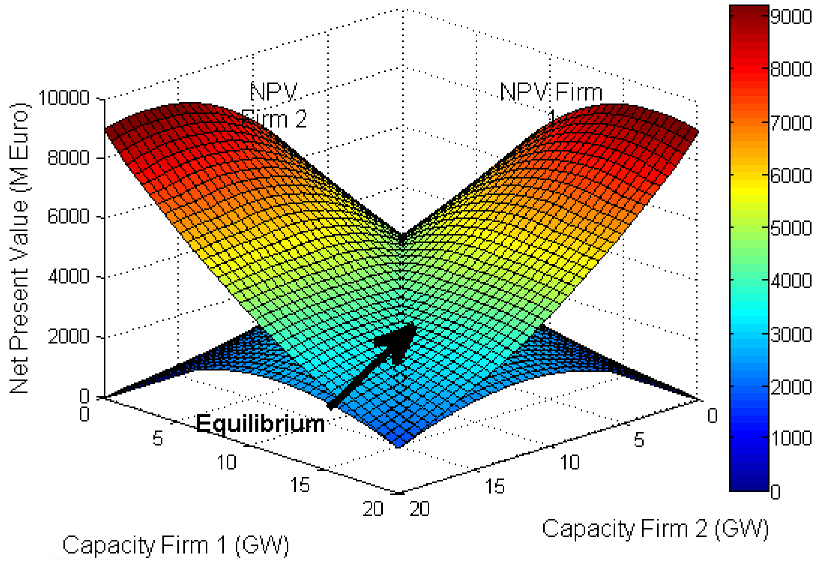
- P. Sánchez, G. Sánchez González *Direct Load Control Decision Model for Aggregated EV charging points* IEEE Transactions on Power Systems vol. 27 (3): 1577-1584 August 2012

Off-shore wind farm electric design

- S. Lumbreras and A. Ramos *Optimal Design of the Electrical Layout of an Offshore Wind Farm: a Comprehensive and Efficient Approach Applying Decomposition Strategies* IEEE Transactions on Power Systems 28 (2): 1434-1441, May 2013 10.1109/TPWRS.2012.2204906
- S. Lumbreras and A. Ramos *Offshore Wind Farm Electrical Design: A Review* Wind Energy 16 (3): 459-473 April 2013 10.1002/we.1498
- M. Banzo and A. Ramos *Stochastic Optimization Model for Electric Power System Planning of Offshore Wind Farms* IEEE Transactions on Power Systems 26 (3): 1338-1348 Aug 2011 10.1109/TPWRS.2010.2075944

Generation Capacity Expansion Problem

- S. Wogrin, E. Centeno, J. Barquín *Generation capacity expansion analysis: Open loop approximation of closed loop equilibria* IEEE Transactions on Power Systems vol. 28, no. 3, pp. 3362-3371, August 2013.



3

1. Power Systems
2. Optimization
3. Electricity Markets
4. Decision Support Models

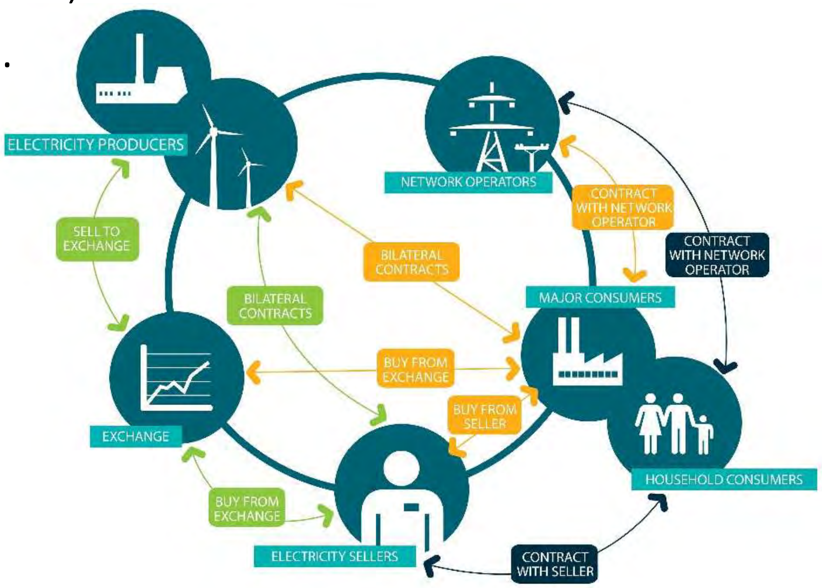
Electricity Markets

UNIVERSIDAD PONTIFICIA ICAI ICADE COMILLAS MADRID

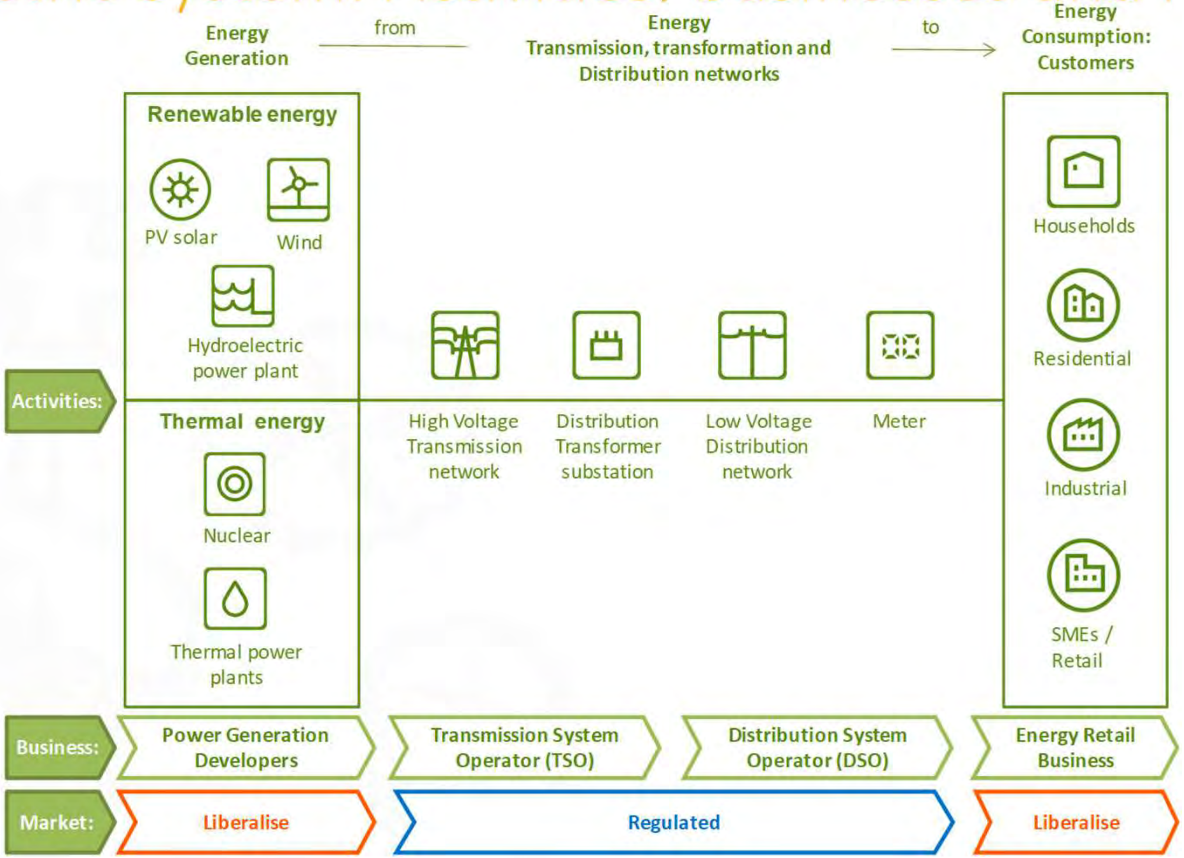
Market agents

- Regulator
- Market Operator (MO)
- Independent System Operator (ISO)
- Transmission System Operator (TSO)
- Generation companies (GenCos). Producers
- Distribution companies (DisCos)
- Retailers
- Consumers
- Prosumers

http://elering.ee/information-for-small-scale-consumers/

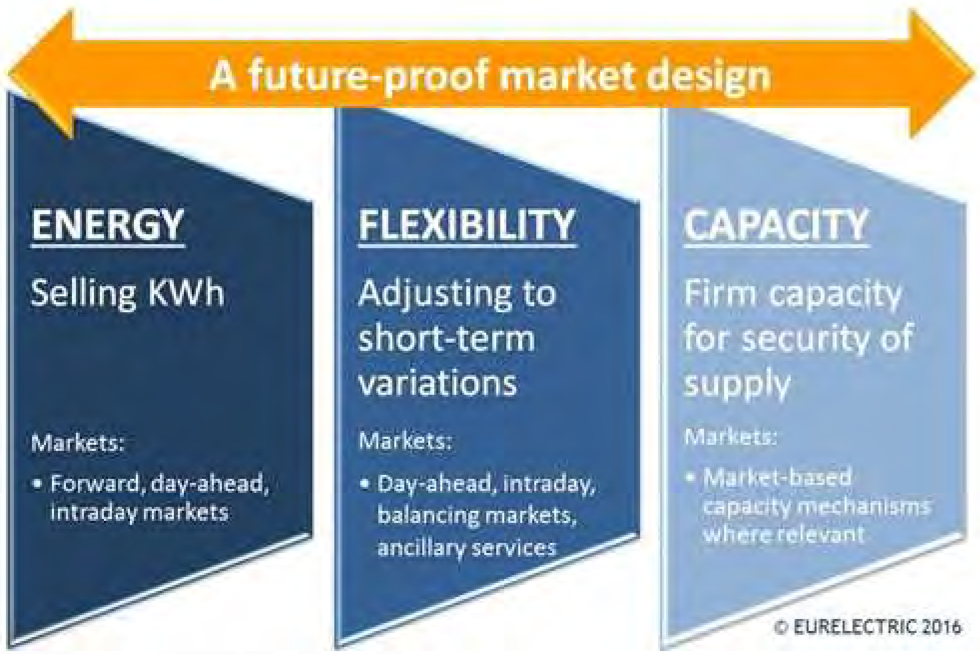


Electric System. Activities, businesses and markets



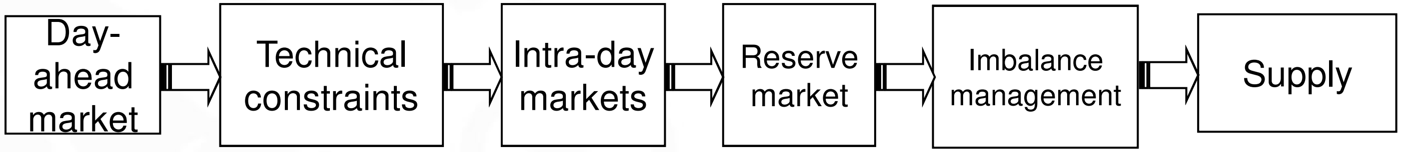
Source: Iberdrola

Wholesale Markets

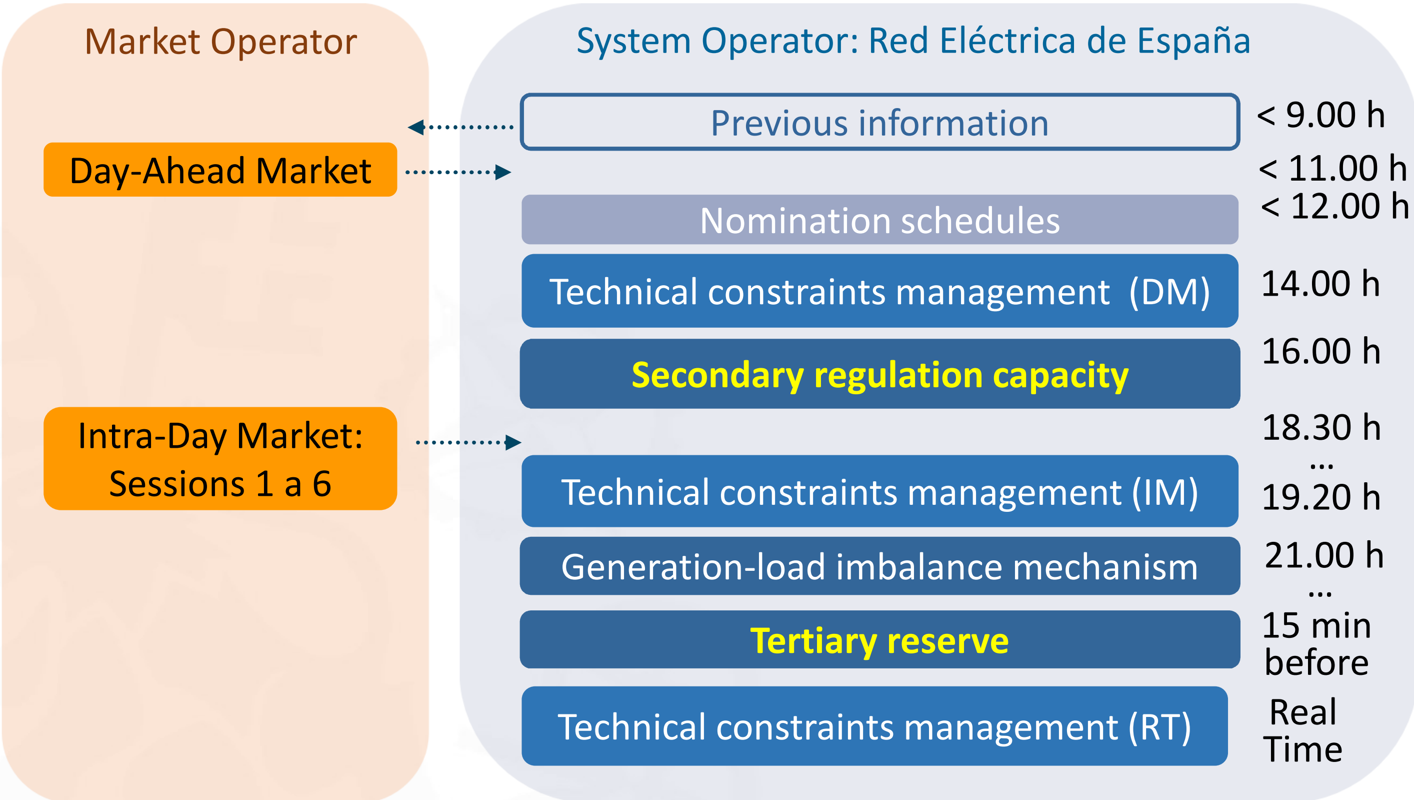


Spanish electricity market

- Starts January 1st, 1998
- Sequence of (energy and power) markets.
  - Day-ahead market
  - Adjustment services
    - Technical constraints
  - Intra-day market
  - Reserve market
    - Secondary reserve
    - Tertiary reserve
  - Imbalance management

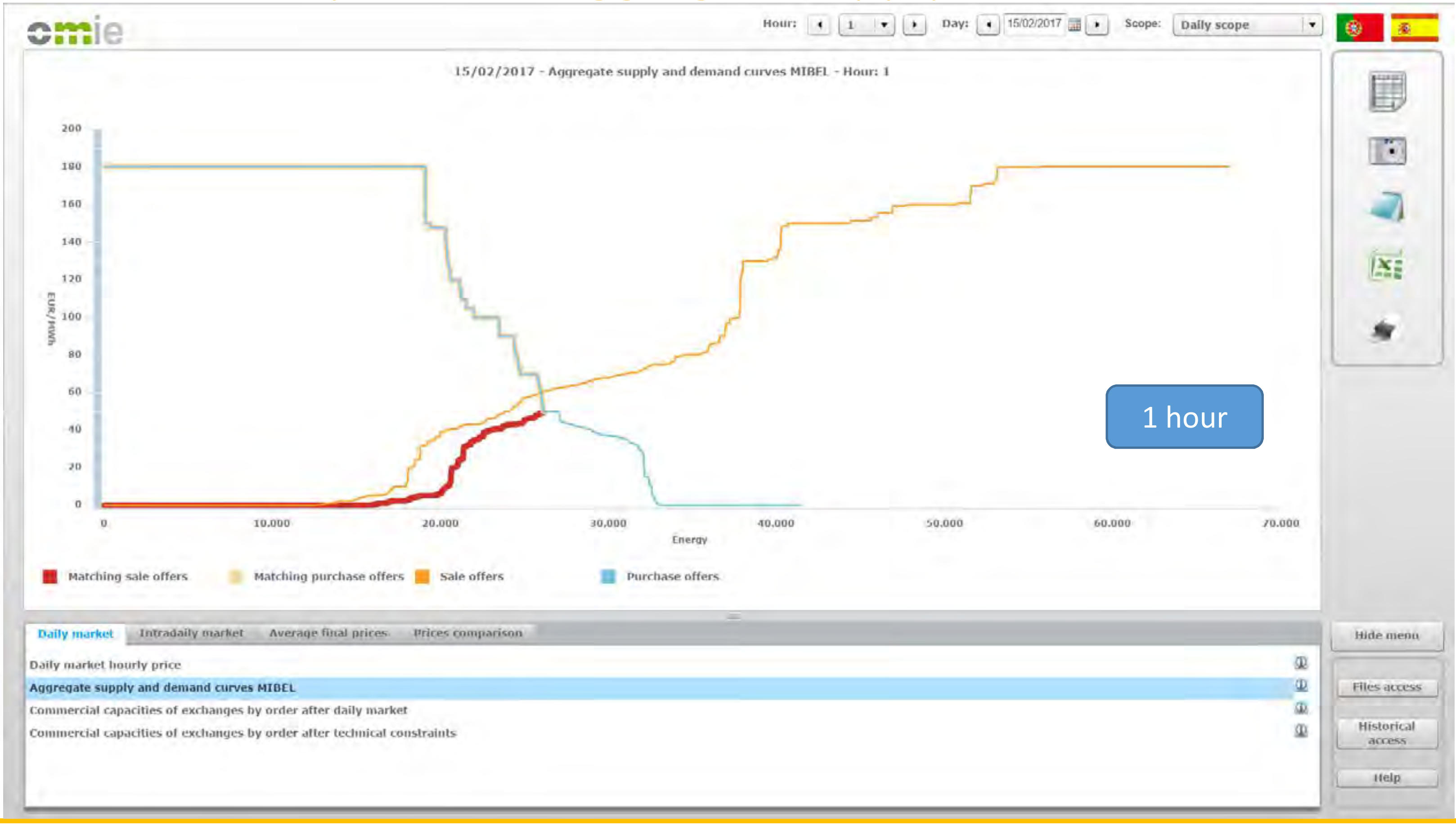


Sequence of markets

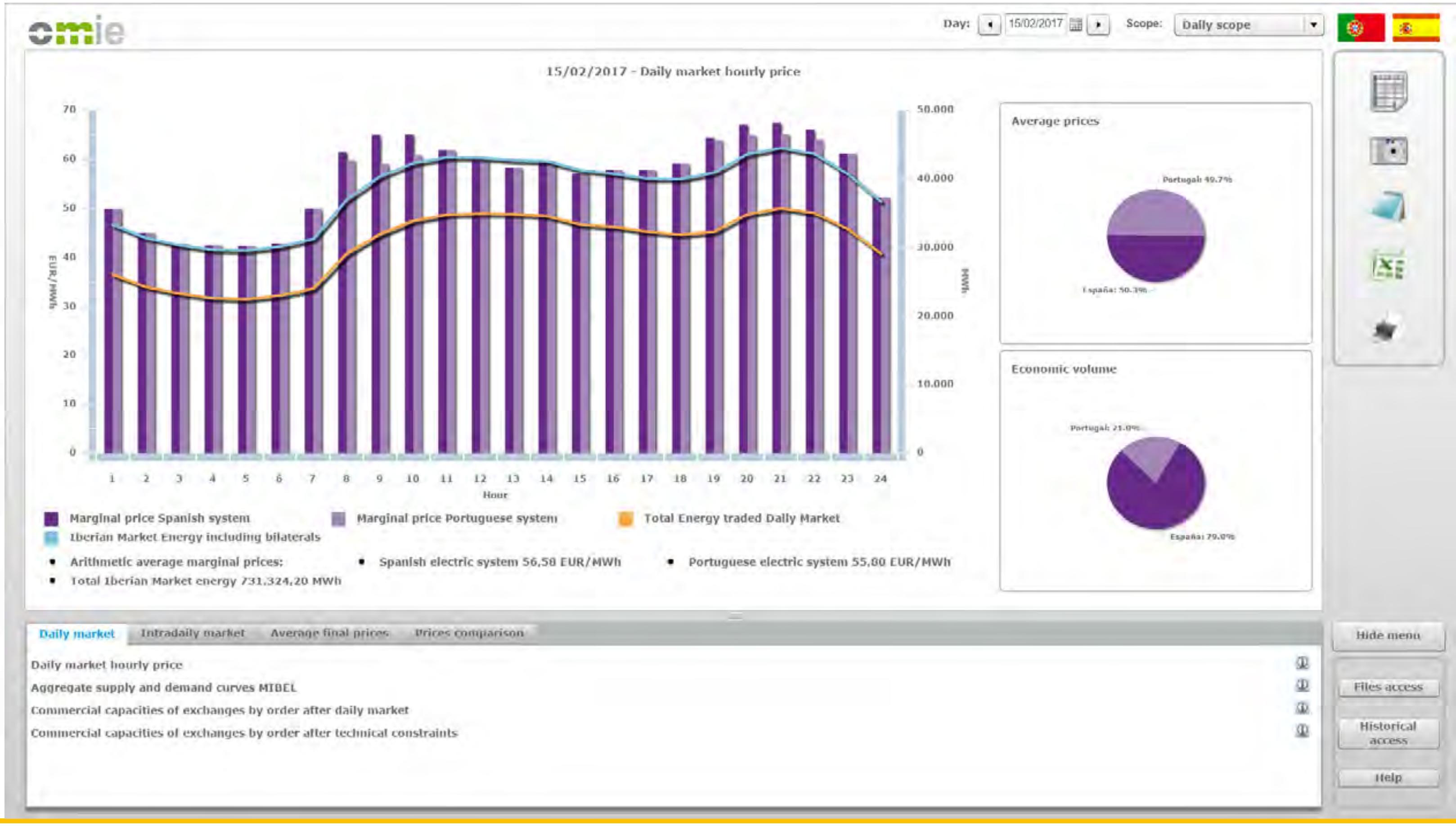


Source: M. de la Torre, J. Paradinas *Integration of renewable generation. The case of Spain*

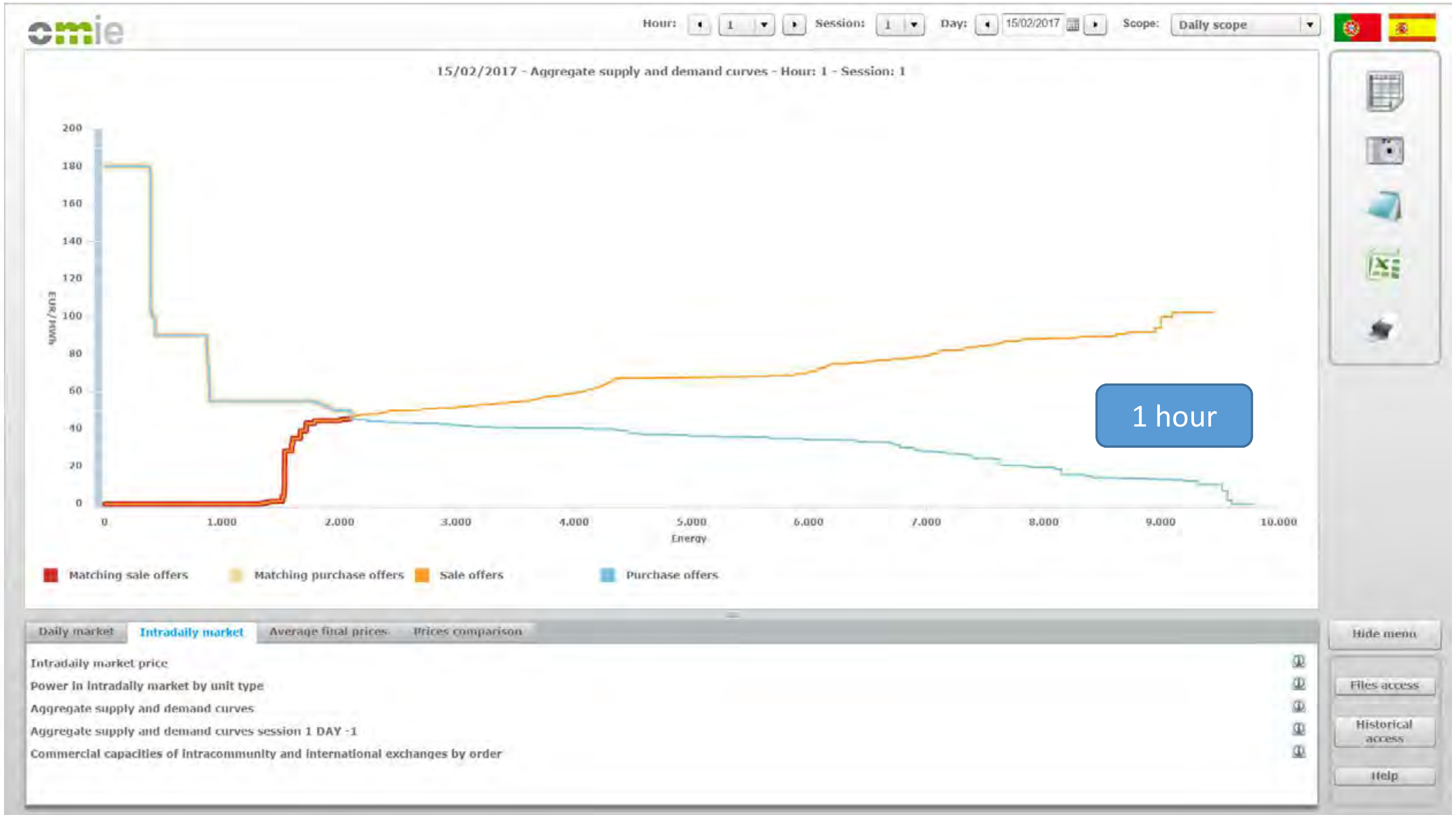
MIBEL. Daily market. Aggregate supply and demand curves



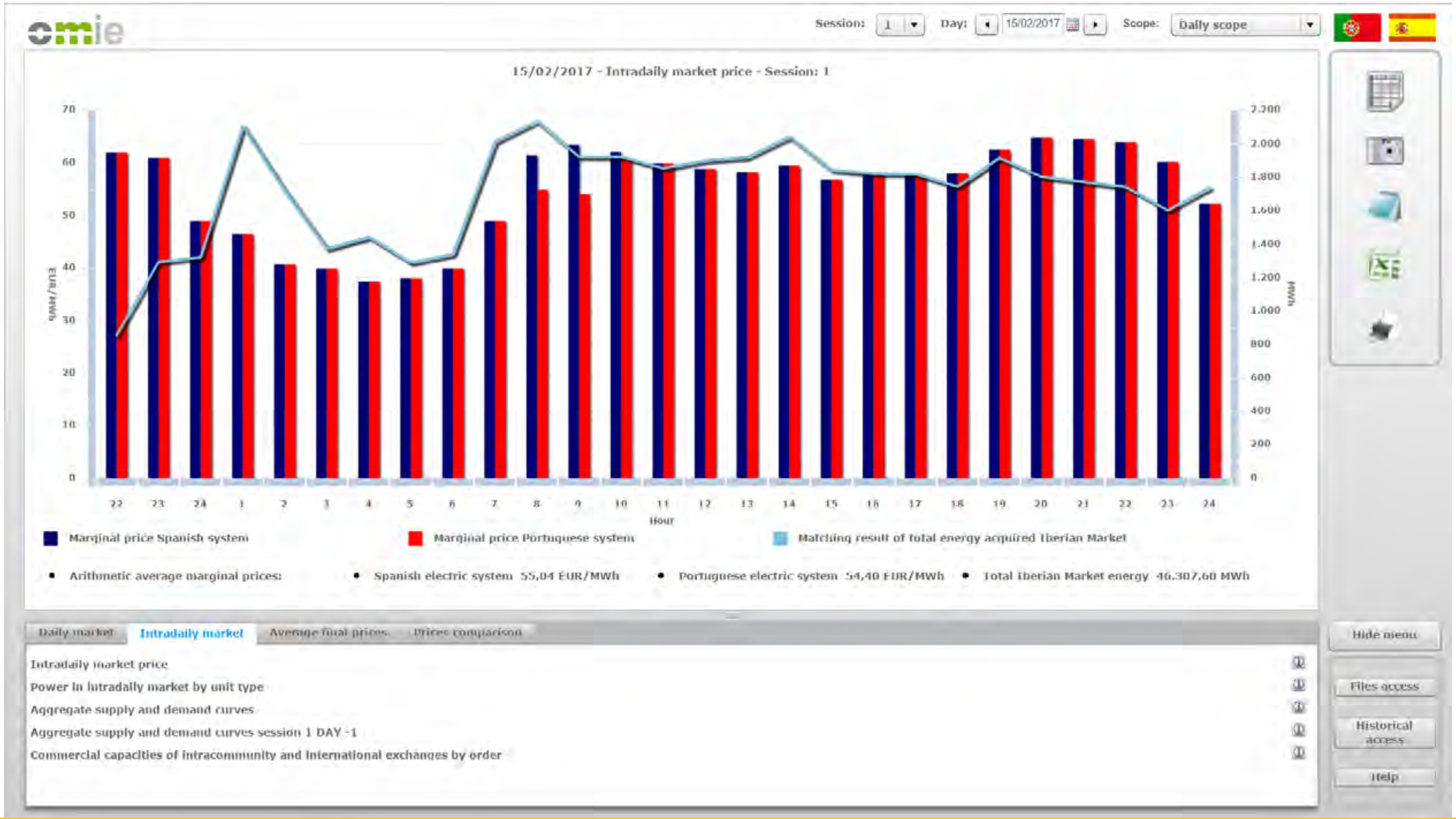
MIBEL. Daily market. Hourly prices



MIBEL. 1st Intra-day market. Aggregate supply and demand curves



MIBEL. 1st Intra-day market. Hourly prices



Regional wholesale electricity markets

- Central Western Europe (Austria, Belgium, France, Germany, the Netherlands, Switzerland)
- British Isles (UK, Ireland)
- Northern Europe (Denmark, Estonia, Finland, Latvia, Lithuania, Norway, Sweden)
- Apennine Peninsula (Italy)
- Iberian Peninsula (Spain and Portugal)
- Central Eastern Europe (Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia)
- South Eastern Europe (Greece and Bulgaria)

Average wholesale baseload electricity prices. 2016 Q3

https://ec.europa.eu/energy/en/data-analysis/market-analysis

3.1

Market Equilibrium Model

Bibliography

- M. Ventosa, A. Baíllo, A. Ramos, M. Rivier *Electricity Market Modeling Trends* Energy Policy 33 (7): 897-913 May 2005

- M. Rivier, M. Ventosa, A. Ramos, F. Martínez-Córcoles, A. Chiarri *"A Generation Operation Planning Model in Deregulated Electricity Markets based on the Complementarity Problem"* in the book M.C. Ferris, O.L. Mangasarian and J-S. Pang (eds.) *Complementarity: Applications, Algorithms and Extensions* pp. 273-295 Kluwer Academic Publishers 2001 ISBN 0792368169
- J. Bushnell (1998) "*Water and Power: Hydroelectric Resources in the Era of Competition in the Western US*"

  (http://www.ucei.berkeley.edu/PDF/pwp056.pdf)
- J. Barquín, E. Centeno, J. Reneses, "*Medium-term generation programming in competitive environments: A new optimization approach for market equilibrium computing*", IEE Proceedings-Generation Transmission and Distribution. vol. 151, no. 1, pp. 119-126, January 2004.

Why a market equilibrium model?

- Electricity generation business
  - Electricity production **market**
- Generating companies have new roles and responsibilities
  - **New** decision-making **tools and models** that take into account the **market**
  - Markets generally having only few companies
  - Companies' **decisions** are **mutually dependent**

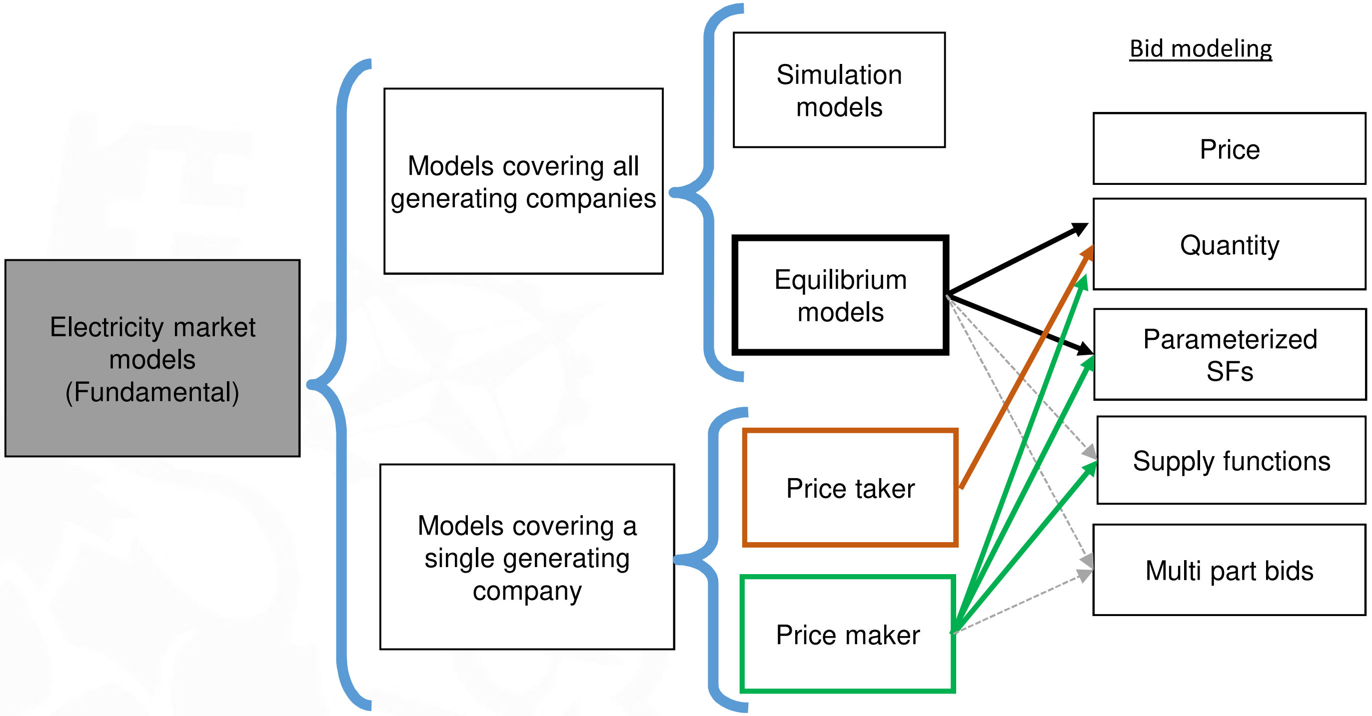
Electricity market models

- Quantitative approach
  - Application of different statistical techniques using available historical records
  - Assumes that all the market results that can occur are contained in historical series
- Fundamental approach
  - Detailed representation of the system and considers input variables:
    - Demand, fuel costs, hydro inflows, operation constraints, new installed capacity, generator ownership
  - Price is obtained as a result of the model

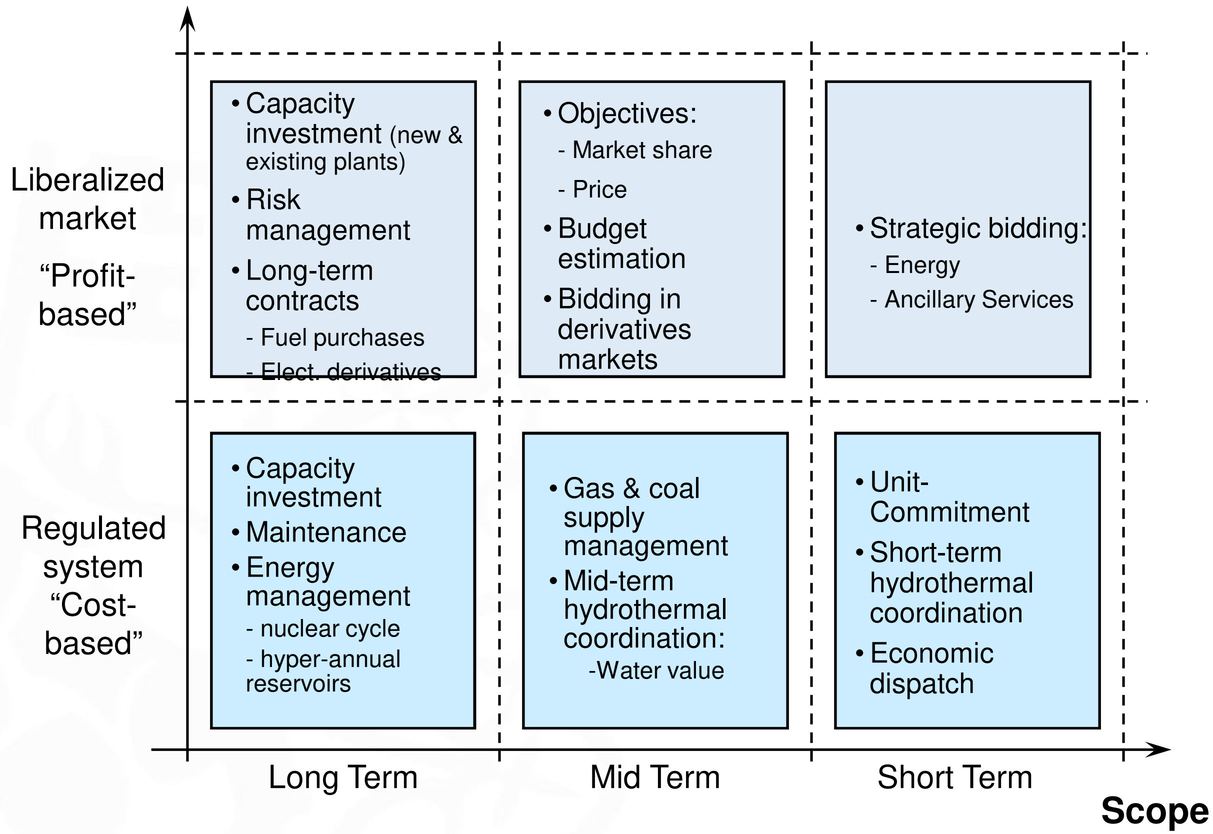
Planning functions

- UC
  - Network Constrained UC
  - Strategic UC
  - Self UC
- Network constrained optimal generation scheduling for hybrid AC/DC systems
- Strategic bidding models
- Short and Medium term hydro and hydrothermal scheduling
- Integrated water and energy models
- Electricity and natural gas market models
- Market equilibrium
- Risk management models
- Generation and transmission planning co-optimization
- EPEC and MPEC models

Fundamental models



Models' clasification



Why an equilibrium model based on the complementarity problem?

- Modeling the electricity market by a complementarity problem approach provides
  - A **flexible** representation of the market and its **medium- and long-term** operation
    - Modeling large-scale **electricity schedules**
  - A **technically feasible** solution
  - **Actual, unique** market equilibrium (in realistic conditions)
- Methods for **solving** complementarity problems (MCP)
  - Allow **realistic sizes: 10,000** variables
  - Although solution time is greater than in linear optimization
- Alternative formulations and numerical solutions exist, based on the **equivalent quadratic problem** (QP)
  - Same optimality conditions as the equilibrium problem
  - Iterative solution of a linear problem

3.2

Cournot model – conjectural variations

Session outline

Cournot model

- ✓ Thermal generation
- ✓ Single period

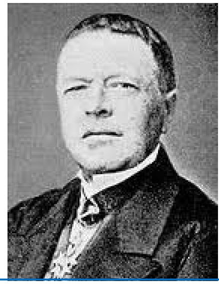
Bushnell model

- ✓ Hydro thermal generation
- ✓ Multi-period

Model based on the complementarity problem

- ✓ Means of production
  - Fuel stock management
  - Pumped storage hydro plants
- ✓ Market aspects
  - Contracts for differences
  - Take-or-pay contracts

Cournot model (1838)



French philosopher and mathematician (1801 –1877)

- Pioneer model to study companies' **strategic** behavior
- Simple model
  - Single generating plant
    - All the generating plants of each company are grouped
  - Inter-period constraints not considered
    - **Single period** equilibrium
  - Assumes perfect information
- Applicable to **medium-** and **long-term** analyses of thermal systems

Cournot model: approach

- Main characteristics
  - It explicitly considers
    - Each company's objective is to **maximize profits**
    - Company decisions are **interdependent**
    - Consumer behavior
  - **Nash** equilibrium in **quantity** strategies: each firm chooses an output quantity to maximize its profit. The Nash-Cournot market equilibrium defines a set of outputs such that no firm, taking its competitors' output as given, wishes to change its own output unilaterally
  - Price is derived from the **inverse demand function**
- These components are enough to interpret it as the origin of more complex models, such as the model based on the complementarity problem

Cournot model: formulation

(https://www.iit.comillas.edu/aramos/StarMrkLite_CournotEn.gms)

- Objective function: profits

$$B_e = p \cdot q_e - C_e$$

- Inverse demand function

$$p = f\left(\sum_e q_e\right)$$

- Cournot conjecture: vertical supply

$$\frac{\partial p}{\partial q_e} = \frac{\partial p}{\partial q}\frac{\partial (q_e + q_{e^*})}{\partial q_e} = p' \leftrightarrow \frac{\partial q_{e^*}}{\partial q_e} = 0$$

- Optimality conditions

$$\frac{\partial B_e}{\partial q_e} = 0 \rightarrow MR_e = p + q_e p' = MC_e\left(q_e\right) \rightarrow q_e = \frac{p - MC_e\left(q_e\right)}{-p'}$$

System of equations

Own output decision will not have an effect on the decisions of the competitors

e	Company
e^*	Other companies
B_e	Profits
p	Price
q_e	Output
C_e	Variable costs
MC_e	Marginal cost
MR_e	Marginal revenue
$p\text{-}MC_e$	**Price mark-up**

Cournot model: conclusion

- In equilibrium, for each company (utility) e, marginal cost and marginal revenue must be equal $$MR_e = p + p' q_e = MC_e(q_e)$$
- Marginal revenue has two components:
  - 1 additional MWh earns the market price p
  - But because of the greater production, market price decreases an amount p'. The price fall impacts on all the energy sold in the market, that we assume to be the total generation.
- Price mark-up $p - MC_e(q_e)$
  - Small mark-up means competitive behavior
  - Large mark-up implies strategic behavior

Cournot model with contracts

- Objective function

$$B_e = p(q_e - L_e) - C_e + p_c L_e$$

- Optimality conditions

$$\frac{\partial B_e}{\partial q_e} = 0$$

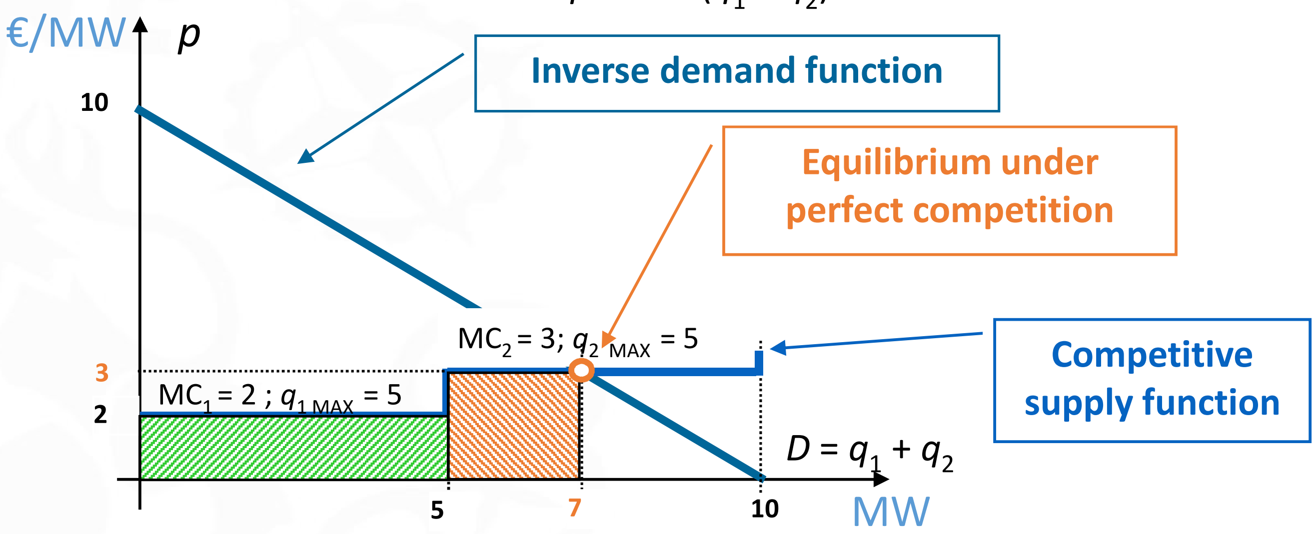
$$MR_e = p + (q_e - L_e)p' = MC_e(q_e)$$

$$q_e = \frac{p - MC_e(q_e)}{-p'} + L_e$$

e	Company
B_e	Profits
p	Price
q_e	Output
L_e	Contracted output
p_c	Contract price
C_e	Variable costs
MC_e	Marginal cost
MR_e	Marginal revenue

Cournot model: example (I)

- Perfect competition
  - Company 1: $MC_1 = 2$ €/MW $q_{1\ MAX} = 5$ MW
  - Company 2: $MC_2 = 3$ €/MW $q_{2\ MAX} = 5$ MW
  - Inverse demand function: $p = 10 - (q_1 + q_2)$



Cournot model: example (II)

- Duopoly
  - Company 1: $MC_1 = 2$ €/MW
  - Company 2: $MC_2 = 3$ €/MW
  - IDF: $p = 10 - (q_1 + q_2)$; $p' = -1$

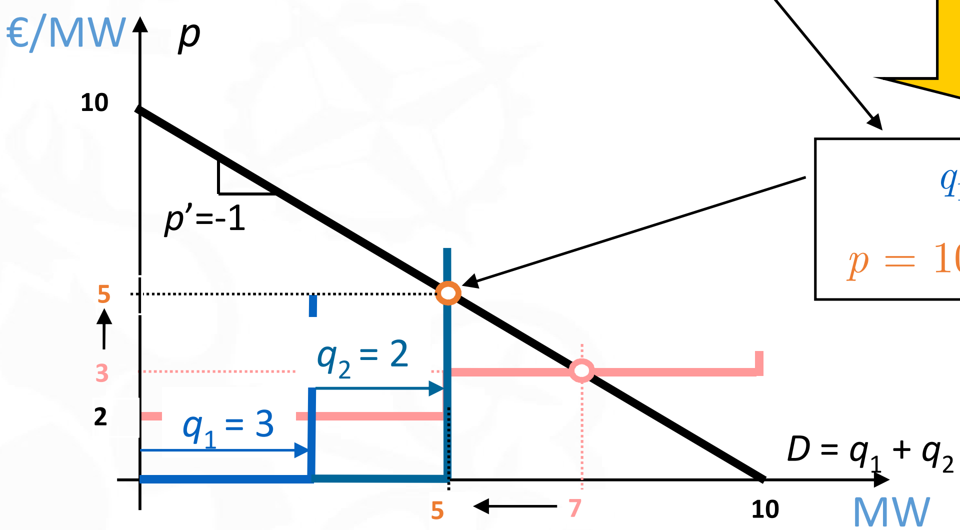
Cournot

$$\frac{\partial B_1}{\partial q_1} = 0 \rightarrow p + q_1 \cdot (-1) = 2$$
$$\frac{\partial B_2}{\partial q_2} = 0 \rightarrow p + q_2 \cdot (-1) = 3$$

Solving

$q_1 = 3,\ q_2 = 2$

$p = 10 - (q_1 + q_2) = 5$



From Cournot to conjectural variations (CV)

e	Company
B_e	Profits
p	Price
q_e	Output
C_e	Variable costs
MC_e	Marginal cost
MR_e	Marginal revenue

- Objective function

$$\max B_e = p \cdot q_e - C_e$$

- Inverse demand function

$$p = f\left(\sum_e q_e\right)$$

- Conjecture: **every company sees its residual demand**

$$\frac{\partial p}{\partial q_e} = p'_e$$

$\rightarrow$ **generalization of the model based on CV**

- Optimality conditions

$$\frac{\partial B_e}{\partial q_e} = 0 \rightarrow MR_e = p + q_e p'_e = MC_e\left(q_e\right)$$

Conjectural variation (CV)

- Other names:
  - Cross elasticity of demand between firms
  - Strategic parameter
  - Implicit residual demand slope
  - Conjectured price response
- It is a measure of the interdependence between firms. It captures the extent to which one firm reacts to changes in strategic variables (quantity) made by other firms
- The CV approach considers the reaction of competitors when a firm is deciding its optimal production. This reaction comes from firm's demand curve and supply functions (residual demand function). This curve is different for each firm and relates the market price with the firm's production
- Values of 0-10 c€/MWh/MW can be sensible

Some publications on computing CV

- Optimization approach
  - S. López, P. Sánchez, J. de la Hoz-Ardiz, J. Fernández-Caro, "*Estimating conjectural variations for electricity market models*", European Journal of Operational Research. vol. 181, no. 3, pp. 1322-1338, September 2007.
- Econometric approach
  - A. García, M. Ventosa, M. Rivier, A. Ramos, G. Relaño, "*Fitting electricity market models. A conjectural variations approach*", 14th PSCC Conference, Session 12-3, pp. 1-8. Sevilla, Spain, 24-28 June 2002

    (http://www.pscc-central.org/uploads/tx_ethpublications/s12p03.pdf)

Cournot model: from system of equations to NLP

$$MC_e = MR_e = p + p'_e q_e$$

$$D = D_0 - D_1 p$$

$$\sum_e q_e = D$$

Marginal cost = Marginal revenue

Inverse demand function

Balance between generation and demand

Cournot model: NLP equivalent problem

- It is easy to check that previous system of equations are just the KKT optimality conditions of the problem

$$\max_{q_e, D} U(D) - \sum_e \overline{C}_e(q_e)$$
$$\sum_e q_e = D \quad \perp p$$

Price is the multiplier

- Demand utility: $$U(D) = \int_0^D p \cdot dD = \frac{1}{D_1}\left(D \cdot D_0 - \frac{D^2}{2}\right)$$

- Effective cost: $$\overline{C}_e(q_e) = C_e(q_e) - \frac{p'_e}{2} q_e^2$$

Cournot model and CV: conclusions

- **Solving Cournot** equilibrium or equilibrium based on **conjectural variations** requires solving a **system** of **equations (MCP)**
- This system of equations is **linear** if:
  - **Inverse demand function** is linear
  - **Marginal cost** function is linear
- It can also be solved as a **nonlinear programming problem (NLP)**

3.3

Bushnell model

Session outline

Cournot model
- ✓ Thermal generation
- ✓ Single period

Bushnell model
- ✓ Hydrothermal generation
- ✓ Multi-period

Model based on the complementarity problem
- ✓ Means of production
  - Fuel stock management
  - Pumped storage hydro plants
- ✓ Market aspects
  - Contracts for differences
  - Take-or-pay contracts

Bushnell model (1998)

- Extensions of the Cournot model to
  - Electricity markets
- Representation of **storage hydro plants**
  - Constraint on available hydro energy
    - Optimization problem with some **constraints**
  - **Multi-period equilibrium** when the available energy constraint involves several periods
    - Increased solution time
- Definition of the **water value in electricity markets**

Bushnell model: formulation I

(https://www.iit.comillas.edu/aramos/StarMrkLite_BushnellEn.gms)

- Objective function

$$B_e = \sum_p \left[p_p \left(q^T_{p,e} + q^H_{p,e} \right) - C^T_{p,e} \right]$$

- Available hydro energy:

$$\sum_p q^H_{p,e} \leq Q^H_e \quad \perp \lambda^H_e$$

- Inverse demand function

$$p_p = f_p \left(\sum_e \left(q^T_{p,e} + q^H_{p,e} \right) \right)$$

e	Company
p	Period (duration 1)
B_e	Profits
p	Price
q^T	Thermal output
q^H	Hydro output
C_e	Variable costs
Q_e^H	Available energy
λ_e	Water value

Bushnell model: formulation II

- Lagrangian function **(equivalent optimization problem but without constraints)**

$$\mathcal{L}_e = \sum_p \left[p_p \left(q^T_{p,e} + q^H_{p,e} \right) - C^T_{p,e}\left(q^T_{p,e} \right) \right]$$
$$+\lambda^H_e \left[\sum_p q^H_{p,e} - Q^H_e \right]$$

e	Company
p	Period (duration 1)
B_e	Profits
p	Price
q^T	Thermal output
q^H	Hydro output
C_e	Variable costs
Q_e^H	Available energy
λ_e	Water value
MC_e	Marginal cost
MR_e	Marginal revenue

- Optimality conditions

$$\frac{\partial \mathcal{L}_e}{\partial q^T_{p,e}} = 0 \rightarrow MR_{p,e} = p_p + \left(q^T_{p,e} + q^H_{p,e} \right) p'_p = MC^T_{p,e}\left(q^T_{p,e} \right)$$

$$\frac{\partial \mathcal{L}_e}{\partial q^H_{p,e}} = 0 \rightarrow MR_{p,e} = p_p + \left(q^T_{p,e} + q^H_{p,e} \right) p'_p = -\lambda^H_e$$

Bushnell model: comments

- The "**Bushnell conjecture**" is the Cournot conjecture extended to all the periods (*e** = all other companies)

$$\frac{\partial \sum_{e*} q_{p',e*}}{\partial q_{p,e}} = 0$$

- **Qualitative conclusions** are drawn from the **optimality conditions**
  - Total optimal output (as in Cournot)

$$\frac{\partial \mathcal{L}_e}{\partial q^T_{p,e}} = 0 \quad \rightarrow q^T_{p,e} + q^H_{p,e} = \frac{p_p - MC^T_{p,e}\left(q^T_{p,e}\right)}{-p'_p}$$

  - **Water value**

$$\frac{\partial \mathcal{L}_e}{\partial q^T_{p,e}} = 0; \frac{\partial \mathcal{L}_e}{\partial q^H_{p,e}} = 0 \rightarrow \boxed{MR_{p,e} = MC^T_{p,e} = -\lambda^H_e}$$

Water value in electricity markets

- Very important concept in hydrothermal coordination
  - **Final decision** on **hydro** output
- The objective function changes when the amount of hydro energy available increases
  - In centralized planning
    - Reduces **system** operating **costs**
  - In electricity markets
    - Increases in each **company's profits**
- Calculated as the **dual variable** of the **available** hydro **energy** constraint

Water value: Bushnell model

- Hydro output attempts to equal inter-period marginal revenues

$$\frac{\partial \mathcal{L}_{\mathrm{e}}}{\partial q^{T}_{p,e}} = 0; \frac{\partial \mathcal{L}_{\mathrm{e}}}{\partial q^{H}_{p,e}} = 0 \rightarrow MR_{p,e} = MC^{T}_{p,e} = -\lambda^{H}_{e}$$

- Each company regards its water to be marginal revenue, whose value coincides with the marginal cost of **its** thermal plant

- Intuitively, when a company replaces **1 MW of thermal** output with **1 MW of hydro** generation, the savings equal its marginal cost

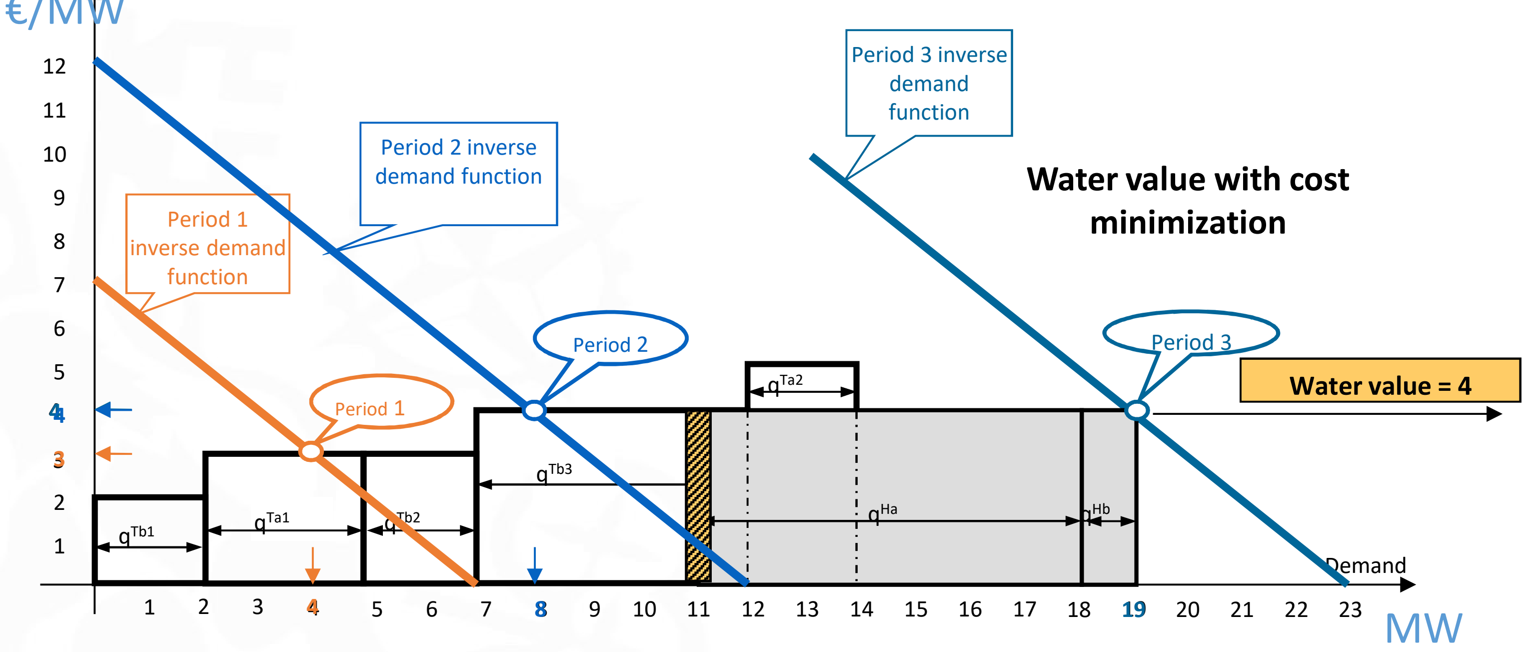
$$q^{T}_{p,e} + q^{H}_{p,e} = \frac{p_{p} - MC^{T}_{p,e}\left(q^{T}_{p,e}\right)}{-p'_{p}}$$

Bushnell model: Example data

- Demand data (3 periods lasting 1 h each):
  - *period* 1 $p_1 = 7 - Dem_1$
  - *period* 2 $p_2 = 12 - Dem_2$
  - *period* 3 $p_3 = 23 - Dem_3$
- Company A data:
  - $q^{Ta1} = 3$ MW $MC^{Ta1} = 3$ €/MW
  - $q^{Ta2} = 2$ MW $MC^{Ta2} = 5$ €/MW
  - $q^{Ha} = 7$ MW $Q^{Ha} = 7$ MWh
- Company B data:
  - $q^{Tb1} = 2$ MW $MC^{Tb1} = 2$ €/MW
  - $q^{Tb2} = 2$ MW $MC^{Tb2} = 3$ €/MW
  - $q^{Tb3} = 5$ MW $MC^{Tb3} = 4$ €/MW
  - $q^{Hb} = 1$ MW $Q^{Hb} = 1$ MWh

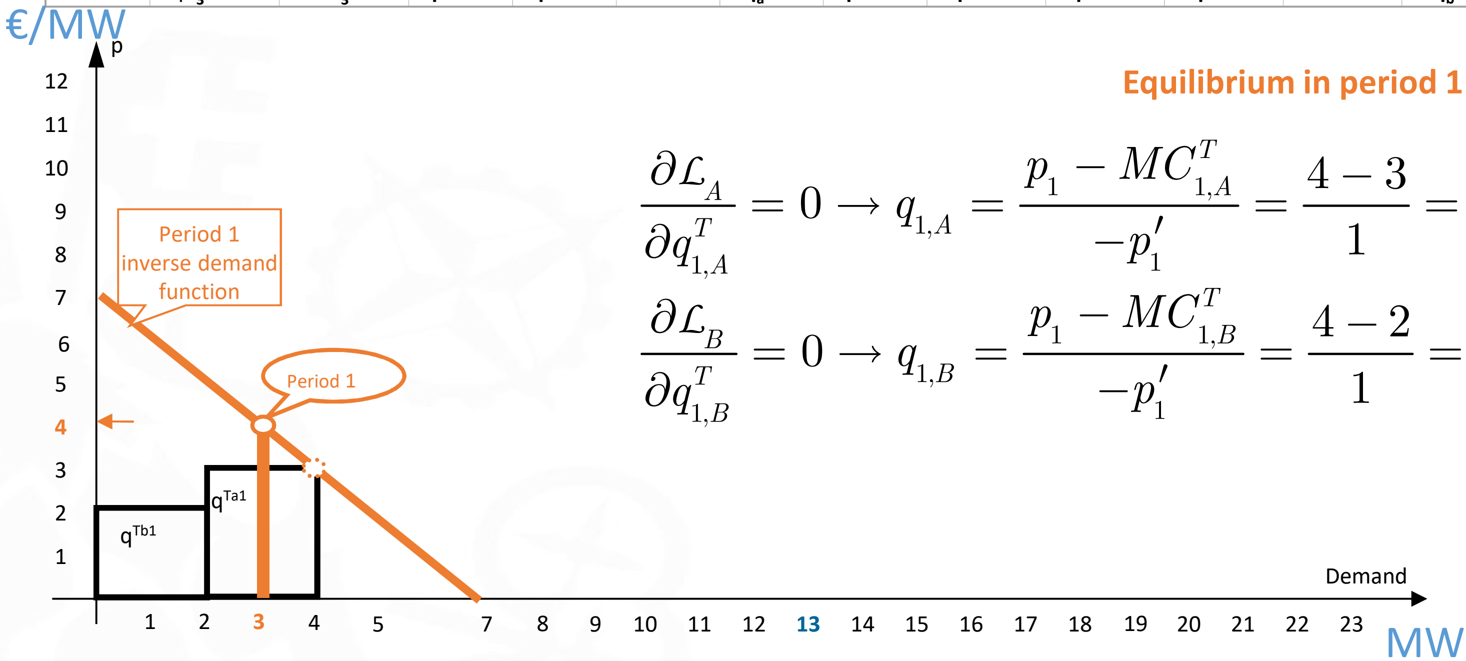
Example: Perfect competition or minimum cost dispatch

Period 1	**$p_1 = 3$**	$Dem_1 = 4$	**$q^{Ta1} = 2$**	$q^{Ta2} = 0$	$q^{Ha} = 0$	$q^{Tb1} = 2$	$q^{Tb2} = 0$	$q^{Tb3} = 0$	$q^{Hb} = 0$
Period 2	**$p_2 = 4$**	$Dem_2 = 8$	$q^{Ta1} = 3$	$q^{Ta2} = 0$	$q^{Ha} = 0$	$q^{Tb1} = 2$	$q^{Tb2} = 2$	**$q^{Tb3} = 1$**	$q^{Hb} = 0$
Period 3	**$p_3 = 4$**	$Dem_3 = 19$	$q^{Ta1} = 3$	$q^{Ta2} = 0$	$q^{Ha} = 7$	$q^{Tb1} = 2$	$q^{Tb2} = 2$	**$q^{Tb3} = 4$**	$q^{Hb} = 1$



Example: dispatch under the Bushnell model

Period 1	$p_1 = 4$	$Dem_1 = 3$	$q^{Ta1} = 1$		$MC^a = 3$	$q_a = 1$	$q^{Tb1} = 2$				$MC^b = 2$	$q_b = 2$
Period 2	$p_2 = 6$	$Dem_2 = 6$	$q^{Ta1} = 1$	$q^{Ha} = 2$	$MC^a = 3$	$q_a = 3$	$q^{Tb1} = 2$	$q^{Tb2} = 1$			$MC^b = 3$	$q_b = 3$
Period 3	$p_3 = 10$	$Dem_3 = 13$	$q^{Ta1} = 2$	$q^{Ha} = 5$	$MC^a = 3$	$q_a = 7$	$q^{Tb1} = 2$	$q^{Tb2} = 2$	$q^{Tb3} = 1$	$q^{Hb} = 1$	$MC^b = 4$	$q_b = 6$



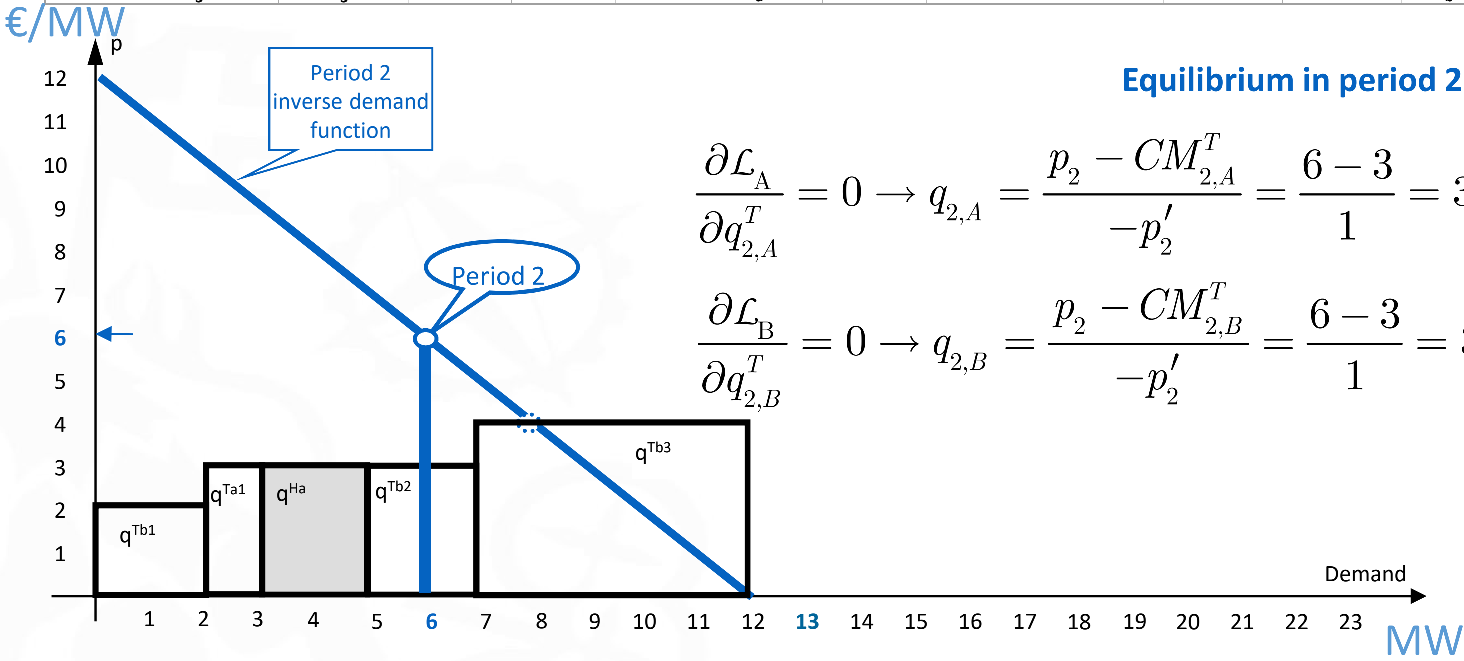
Equilibrium in period 1

$$\frac{\partial \mathcal{L}_A}{\partial q^T_{1,A}} = 0 \rightarrow q_{1,A} = \frac{p_1 - MC^T_{1,A}}{-p'_1} = \frac{4-3}{1} = 1$$

$$\frac{\partial \mathcal{L}_B}{\partial q^T_{1,B}} = 0 \rightarrow q_{1,B} = \frac{p_1 - MC^T_{1,B}}{-p'_1} = \frac{4-2}{1} = 2$$

Example: dispatch under the Bushnell model

Period 1	$p_1 = 4$	$Dem_1 = 3$	$q^{Ta1} = 1$		$MC^a = 3$	$q_a = 1$	$q^{Tb1} = 2$				$MC^b = 2$	$q_b = 2$
Period 2	$p_2 = 6$	$Dem_2 = 6$	$q^{Ta1} = 1$	$q^{Ha} = 2$	$MC^a = 3$	$q_a = 3$	$q^{Tb1} = 2$	$q^{Tb2} = 1$			$MC^b = 3$	$q_b = 3$
Period 3	$p_3 = 10$	$Dem_3 = 13$	$q^{Ta1} = 2$	$q^{Ha} = 5$	$MC^a = 3$	$q_a = 7$	$q^{Tb1} = 2$	$q^{Tb2} = 2$	$q^{Tb3} = 1$	$q^{Hb} = 1$	$MC^b = 4$	$q_b = 6$



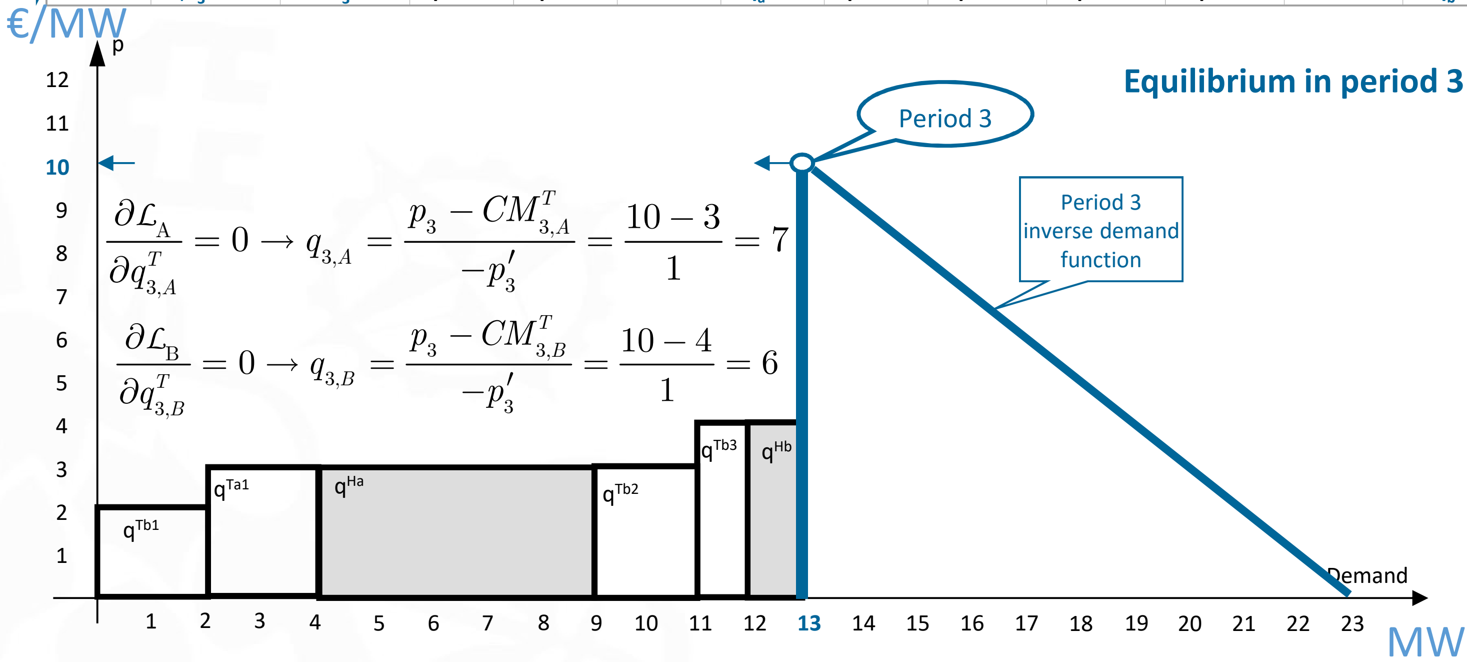
Equilibrium in period 2

$$\frac{\partial \mathcal{L}_A}{\partial q^T_{2,A}} = 0 \rightarrow q_{2,A} = \frac{p_2 - CM^T_{2,A}}{-p'_2} = \frac{6-3}{1} = 3$$

$$\frac{\partial \mathcal{L}_B}{\partial q^T_{2,B}} = 0 \rightarrow q_{2,B} = \frac{p_2 - CM^T_{2,B}}{-p'_2} = \frac{6-3}{1} = 3$$

Example: dispatch under the Bushnell model

Period 1	**$p_1 = 4$**	**$Dem_1 = 3$**	**$q^{Ta1} = 1$**		**$MC^a = 3$**	**$q_a = 1$**	**$q^{Tb1} = 2$**				**$MC^b = 2$**	**$q_b = 2$**
Period 2	**$p_2 = 6$**	**$Dem_2 = 6$**	**$q^{Ta1} = 1$**	**$q^{Ha} = 2$**	**$MC^a = 3$**	**$q_a = 3$**	**$q^{Tb1} = 2$**	**$q^{Tb2} = 1$**			**$MC^b = 3$**	**$q_b = 3$**
Period 3	**$p_3 = 10$**	**$Dem_3 = 13$**	**$q^{Ta1} = 2$**	**$q^{Ha} = 5$**	**$MC^a = 3$**	**$q_a = 7$**	**$q^{Tb1} = 2$**	**$q^{Tb2} = 2$**	**$q^{Tb3} = 1$**	**$q^{Hb} = 1$**	**$MC^b = 4$**	**$q_b = 6$**

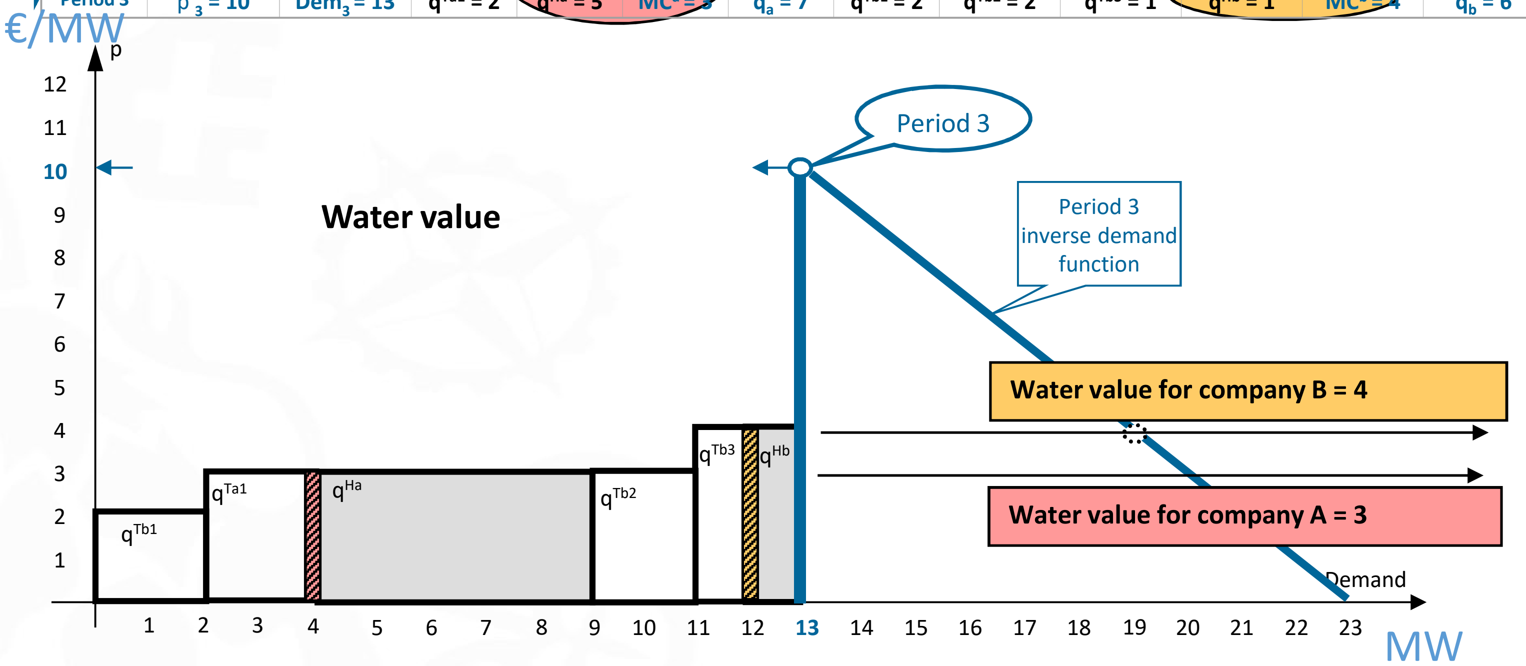


$$\frac{\partial \mathcal{L}_A}{\partial q^T_{3,A}} = 0 \rightarrow q_{3,A} = \frac{p_3 - CM^T_{3,A}}{-p'_3} = \frac{10-3}{1} = 7$$

$$\frac{\partial \mathcal{L}_B}{\partial q^T_{3,B}} = 0 \rightarrow q_{3,B} = \frac{p_3 - CM^T_{3,B}}{-p'_3} = \frac{10-4}{1} = 6$$

Example: dispatch under the Bushnell model

Period 1	$p_1 = 4$	$Dem_1 = 3$	$q^{Ta1} = 1$		$MC^a = 3$	$q_a = 1$	$q^{Tb1} = 2$				$MC^b = 2$	$q_b = 2$
Period 2	$p_2 = 6$	$Dem_2 = 6$	$q^{Ta1} = 1$	$q^{Ha} = 2$	$MC^a = 3$	$q_a = 3$	$q^{Tb1} = 2$	$q^{Tb2} = 1$			$MC^b = 3$	$q_b = 3$
Period 3	$p_3 = 10$	$Dem_3 = 13$	$q^{Ta1} = 2$	$q^{Ha} = 5$	$MC^a = 3$	$q_a = 7$	$q^{Tb1} = 2$	$q^{Tb2} = 2$	$q^{Tb3} = 1$	$q^{Hb} = 1$	$MC^b = 4$	$q_b = 6$



Bushnell model: conclusions

- **Solving Bushnell** equilibrium (without less than or equal to constraints) entails solving a **multi-period system** of **equations**
- The system of equations is **linear** if:
  - **Inverse demand function** is linear
  - **Marginal cost** function is linear

Optimization problems for both companies (i)

$$\max B_A = \sum_p \left[p_p \left(\sum_t q^t_{p,A} + \sum_h q^h_{p,A} \right) - C^T_{p,A} \right]$$

$$\sum_p q^h_{p,A} \le Q^h_A \quad \perp \lambda^h_A$$

$$q^t_{p,A} \ge 0 \quad \perp \mu^t_{p,A}$$

$$q^h_{p,A} \ge 0 \quad \perp \mu^h_{p,A}$$

$$q^t_{p,A} \le \overline{q}^t \quad \perp \nu^t_{p,A}$$

$$q^h_{p,A} \le \overline{q}^h \quad \perp \nu^h_{p,A}$$

$$\max B_B$$

$$p_p = \alpha_p + \beta_p \left[\sum_t q^t_{p,A} + \sum_h q^h_{p,A} + \sum_t q^t_{p,B} + \sum_h q^h_{p,B} \right]$$

Minimization

Optimization problems for both companies (ii)

$$\mathcal{L}_A = -\sum_p \left[p_p \left(\sum_t q^t_{p,A} + \sum_h q^h_{p,A} \right) - C^T_{p,A} \right] + \lambda^h_A \left[\sum_p q^h_{p,A} - Q^h_A \right] +$$

$$+ \mu^t_{p,A} q^t_{p,A} + \mu^h_{p,A} q^h_{p,A} + \nu^t_{p,A} \left[q^t_{p,A} - \overline{q}^t \right] + \nu^h_{p,A} \left[q^h_{p,A} - \overline{q}^h \right]$$

$$\lambda^h_A, \nu^t_{p,A}, \nu^h_{p,A} \geq 0; \mu^t_{p,A}, \mu^h_{p,A} \leq 0$$

$$\mathcal{L}_B$$

$$p_p = \alpha_p + \beta_p \left[\sum_t q^t_{p,A} + \sum_h q^h_{p,A} + \sum_t q^t_{p,B} + \sum_h q^h_{p,B} \right]$$

Optimization problems for both companies (iii)

$$\frac{\partial \mathcal{L}_A}{\partial q^t_{p,A}} = -p_p - p'_p \left(\sum_t q^t_{p,A} + \sum_h q^h_{p,A} \right) + MC^T_{p,A} + \mu^t_p + \nu^t_p = 0$$

$$\frac{\partial \mathcal{L}_A}{\partial q^h_{p,A}} = -p_p - p'_p \left(\sum_t q^t_{p,A} + \sum_h q^h_{p,A} \right) + \lambda^h_A + \mu^t_p + \nu^t_p = 0$$

$$\lambda^h_A \left[\sum_p q^h_{p,A} - Q^h_A \right] = 0$$

$$\mu^t_p q^t_{p,A} = 0; \quad \mu^h_p q^h_{p,A} = 0$$

$$\nu^t_p \left[q^t_{p,A} - \overline{q}^t \right] = 0; \quad \nu^h_p \left[q^h_{p,A} - \overline{q}^h \right] = 0$$

$$p_p = \alpha_p + \beta_p \left[\sum_t q^t_{p,A} + \sum_h q^h_{p,A} + \sum_t q^t_{p,B} + \sum_h q^h_{p,B} \right]$$

$$\lambda^h, \nu^t_p, \nu^h_p \geq 0; \mu^t_p, \mu^h_p \leq 0$$

4

1. Power Systems
2. Optimization
3. Electricity Markets
4. Decision Support Models

Decision Support Models

Decision Support Tool or Model

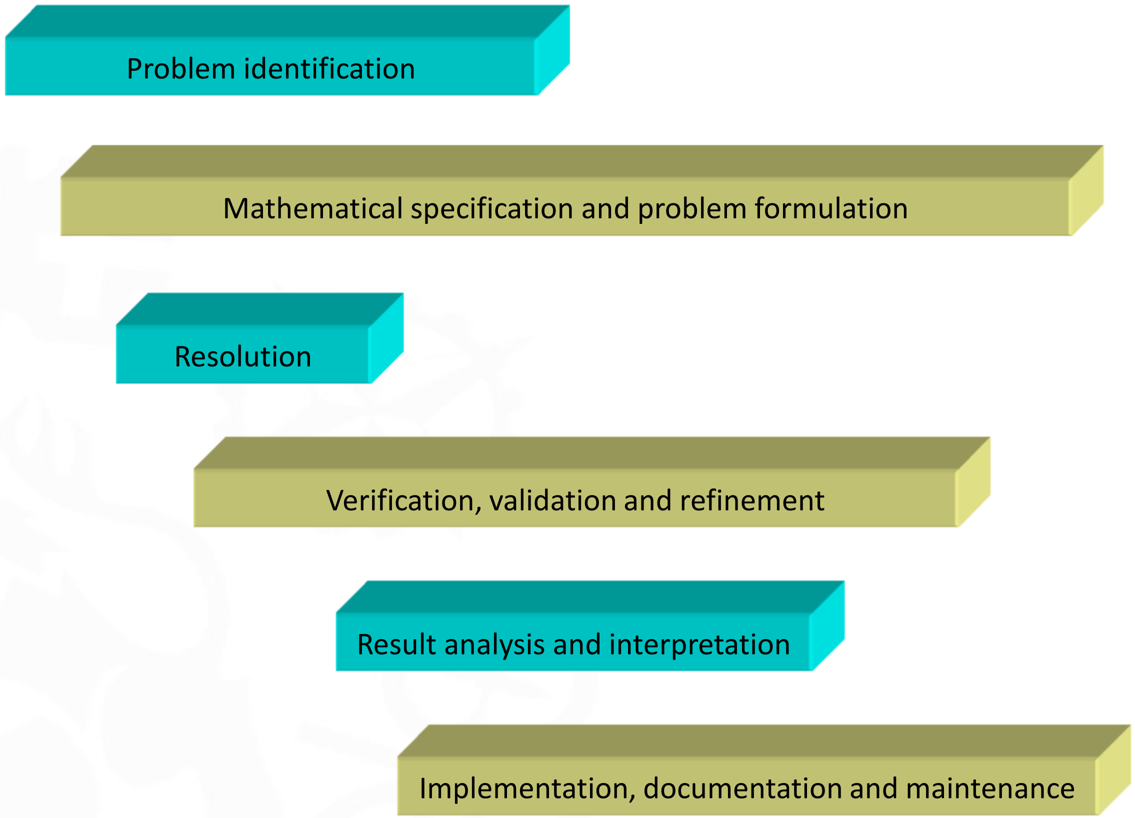
- Definition
  - Simplified description, especially a mathematical one, of a system or process, to assist calculations and predictions. (Oxford Dictionary)
- Accurate representation of a reality
- May involve a multidisciplinary team
- Balance between a detailed representation and the skill to obtain a solution

Model development team

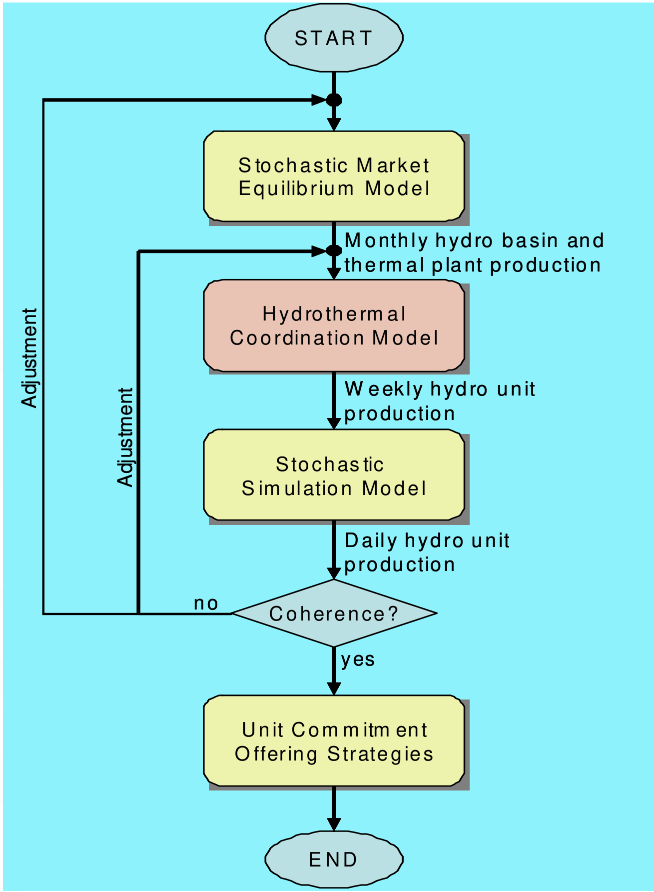
- Managers (decision makers)
  - Are the most involved with the problem and have preferences about how the solution should be.
  - Have less knowledge about the formulation and solution techniques that could be applied: *"do the same as last time because we are too busy to devise a different way"*
- Software expert
  - Might have experience with standard formulations, modifying general purpose solution algorithms, commercial software and IT issues
  - Have less knowledge about the particular problem: *"buy a good package and apply it"*
- OR/MS analyst (*):
  - Has some knowledge of the problem and its context.
  - Knows the techniques that can help to solve it and might have multi-industry and multi-discipline experience: *"understand the problem and fit or devise a technique for it"*
  - Academic or consulting environment (e.g., IIT)
  - Tailor made tool

(*) OR/MS: "Operations research" and "management science" are terms that are used interchangeably to describe the discipline of applying advanced analytical techniques to help make better decisions and to solve problems.

Stages in model development



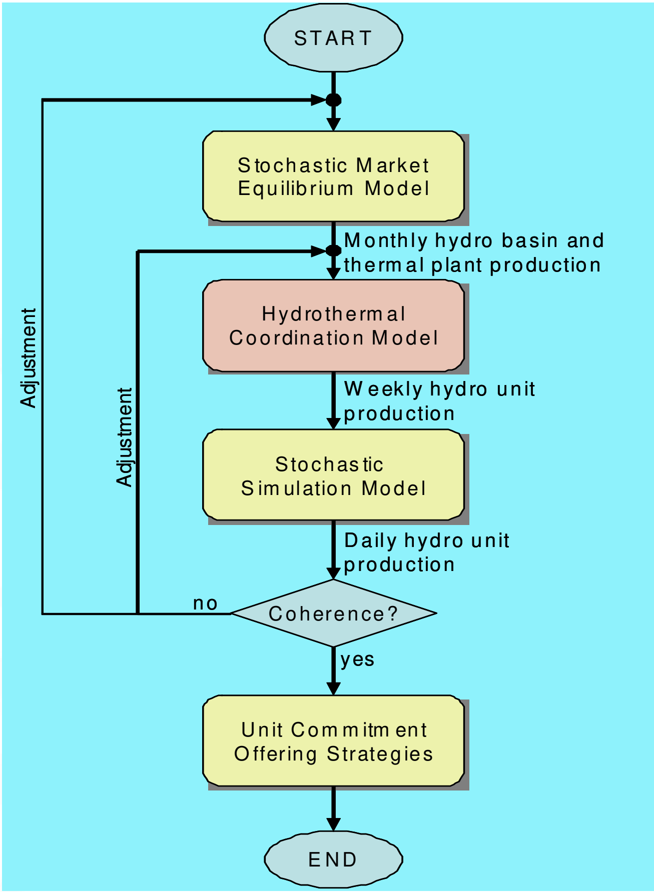
Hierarchy of Operation Planning Models



4.1

MOES Stochastic

Hierarchy of Operation Planning Models

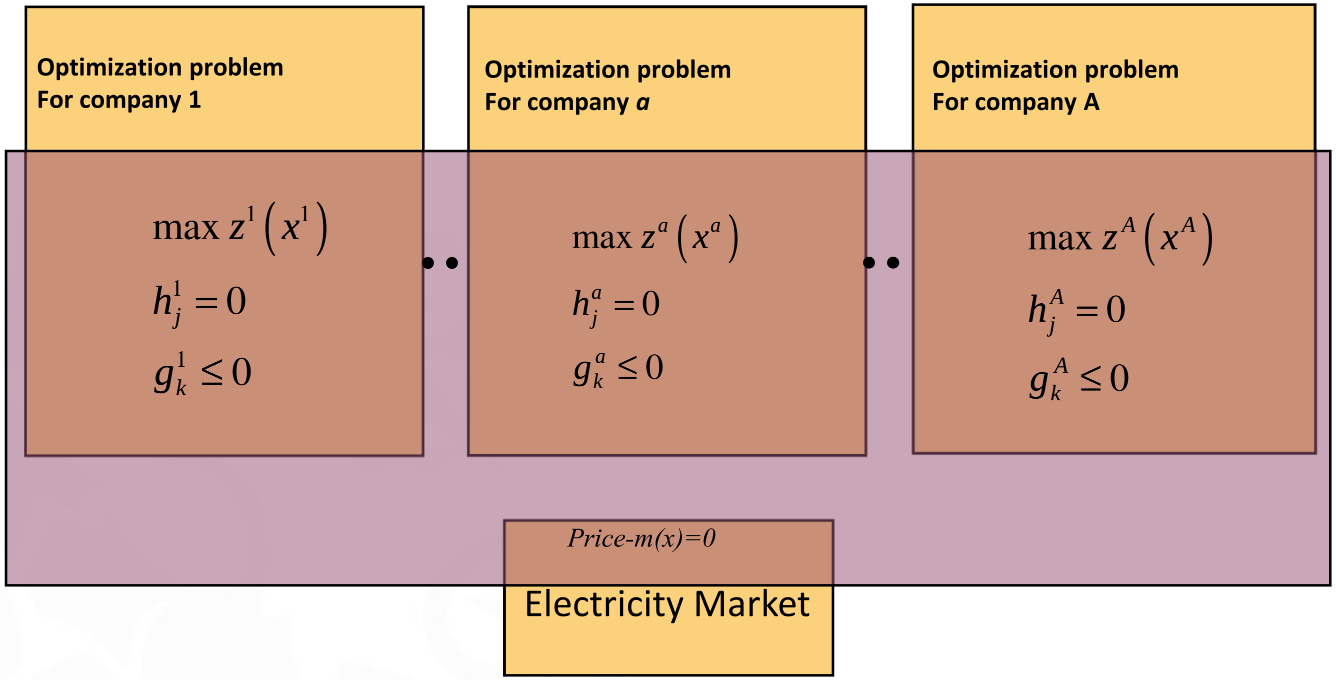


MOES Stochastic

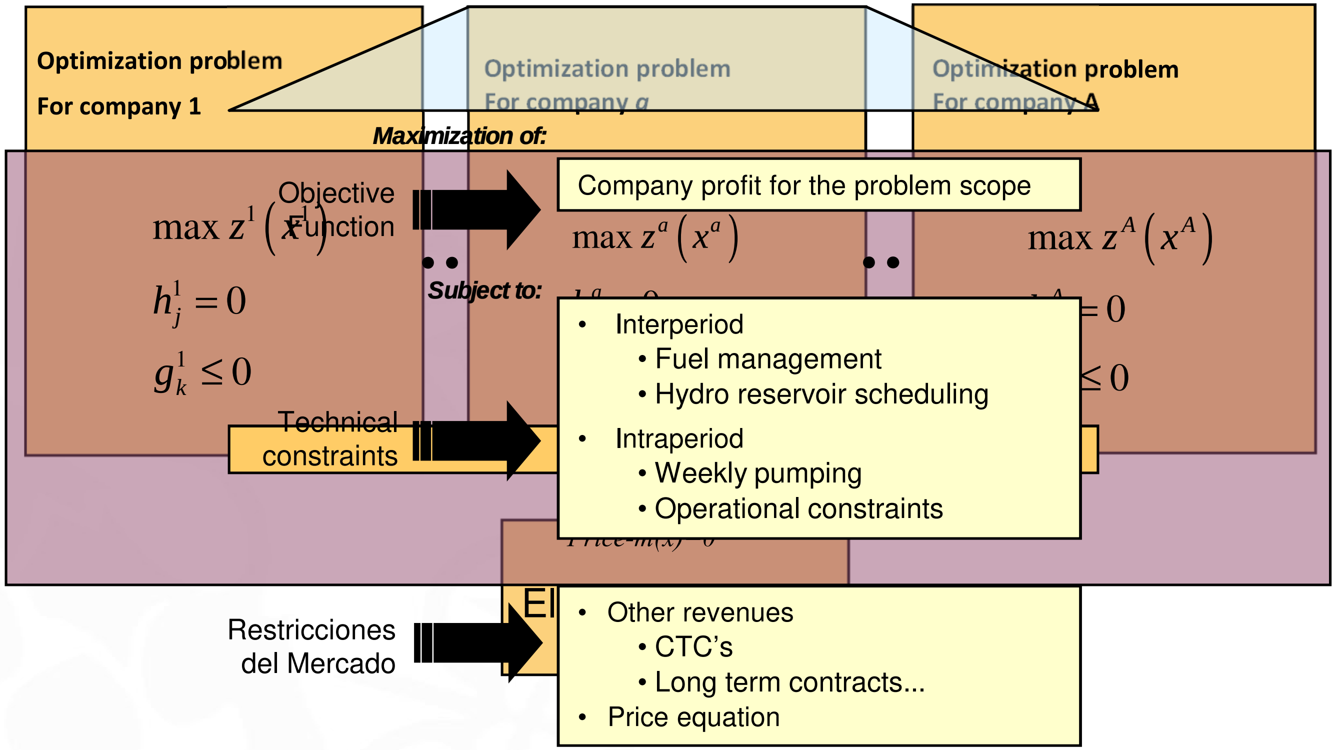
- Purpose
  - Medium-term generation operation
  - Market equilibrium model
  - Conjectural variations approach
  - Implicit elasticity of residual demand function
- Main characteristics
  - Market equilibrium model based on the complementarity problem (MCP)
- References

  - J. Cabero, Á. Baíllo, S. Cerisola, M. Ventosa, A. García, F. Perán, G. Relaño, "A Medium-Term Integrated Risk Management Model for a Hydrothermal Generation Company," *IEEE Transactions on Power Systems*. vol. 20, no. 3, pp. 1379-1388, August 2005
  - J. Cabero, Á. Baíllo, S. Cerisola, M. Ventosa, "Application of benders decomposition to an equilibrium problem," *Proceedings of the 15th PSCC, Power Systems Computing Conference. Liege, Belgium, 22-26 Agosto 2005*
  - M. Ventosa, A. Baíllo, A. Ramos, M. Rivier *Electricity Market Modeling Trends* Energy Policy Vol. 33 (7) pp. 897-913 May 2005
  - A. García-Alcalde, M. Ventosa, M. Rivier, A. Ramos, G. Relaño *Fitting Electricity Market Models. A Conjectural Variations Approach* 14th Power Systems Computation Conference (PSCC '02) Seville, Spain June 2002
  - M. Rivier, M. Ventosa, A. Ramos, F. Martínez-Córcoles and A. Chiarri *A Generation Operation Planning Model in Deregulated Electricity Markets based on the Complementarity Problem* in book *Complementarity: Applications, Algorithms and Extensions* Kluwer Academic Publishers. Dordrecht, The Netherlands. pp. 273-295. 2001

Optimization problem statement



Problem statement for each company



Practical difficulties

- Good theoretical statement
- However, no solver available to solve such mathematical problem:
  - Several optimization problems tied by price variable
- Look for another equivalent mathematical problem
  - With the same solution values
  - Numerically solvable
- Several alternatives
  - Complementarity problem [Ventosa, Hobbs]
  - Equivalent quadratic problem [Barquín, Hobbs]

Practical difficulties. Alternative approaches

- **Complementarity problem**
  - M. Rivier, M. Ventosa, A. Ramos *A Generation Operation Planning Model in Deregulated Electricity Markets based on the Complementarity Problem* 2nd International Conference on Complementarity Problems (ICCP 99) Madison, WI, USA June 1999
  - B.F. Hobbs. “*LCP Models of Nash – Cournot Competition in Bilateral and POOLCO–Based Power Markets*.” In Proc. IEEE Winter Meeting, New York, 1999
- **Equivalent quadratic system**
  - J. Barquín, E. Centeno, J. Reneses, "*Medium-term generation programming in competitive environments: A new optimization approach for market equilibrium computing*", IEE Proceedings-Generation Transmission and Distribution. vol. 151, no. 1, pp. 119-126, Enero 2004.
  - B.F. Hobbs. “*Linear Complementarity Models of Nash–Cournot competition in Bilateral and POOLCO Power Markets*” IEEE Transactions on Power Systems, 16 (2), May 2001
- **Variational inequalities**
  - W. Jing-Yuan and Y. Streets, “*Spatial oligopolistic electricity models with Cournot generators and regulated transmission prices*,” Operations Res., vol. 47, no. 1, pp. 102–112, 1999

Equivalent mixed complementarity problem for all the companies

Company 1's optimality conditions

$$\nabla_x \mathcal{L}^1(x,\lambda,\mu) = \frac{\partial \mathcal{L}^1}{\partial x^1} = 0$$

$$\nabla_\lambda \mathcal{L}^1(x,\lambda,\mu) = \frac{\partial \mathcal{L}^1}{\partial \mu_j^1} = h_j^1 = 0$$

$$\lambda_k^1 \cdot g_k^1 = 0 \quad g_k^1 \le 0 \quad \lambda_k^1 \le 0$$

• •

Company *e*'s optimality conditions

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

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

$$\lambda_k^e \cdot g_k^e = 0 \quad g_k^e \le 0 \quad \lambda_k^e \le 0$$

• •

Company E's optimality conditions

$$\nabla_x \mathcal{L}^E(x,\lambda,\mu) = \frac{\partial \mathcal{L}^E}{\partial x^E} = 0$$

$$\nabla_\lambda \mathcal{L}^E(x,\lambda,\mu) = \frac{\partial \mathcal{L}^E}{\partial \mu_j^E} = h_j^E = 0$$

$$\lambda_k^E \cdot g_k^E = 0 \quad g_k^E \le 0 \quad \lambda_k^E \le 0$$

Price-m(y)=0

Electric power market

Detailed system modeling (I)

- **Market** modeling
  - **Demand**-side behavior
    - Price is a **linear function of demand**
    - Load-duration curve per period
  - **Cournot or CV** company competition
    - Simultaneous maximization of profits
    - Market revenues are a **quadratic function of price**
  - Other market characteristics
    - **Contracts** for differences (sales)
    - **Take-or-pay contracts** (purchase)

Detailed system modeling (II)

- **Thermal generation**
  - Output limits
  - Fuel **consumption** is **quadratic**
  - Scheduled maintenance
  - Deterministic modeling of unit outages
  - Linear **fuel stock management**
- **Hydro generation**
  - **Storage** hydro plants with reservoirs
  - Run-of-the-river hydro plants
  - **Pumped** storage hydro plants
  - Linear **reservoir management**

Mixed linear complementarity problem (MLCP)

- Medium-term problem formulated with
  - **linear constraints**
  - **quadratic objective function**

System of equations with a **mixed linear complementarity problem** structure

$$\max c^T x + \frac{1}{2} x^T Q x$$
$$Ax \le b \quad \perp \lambda$$
$$Cx = d \quad \perp \mu$$

$$\max \mathcal{L} = c^T x + \frac{1}{2} x^T Q x + \lambda^T (Ax - b) + \mu^T (Cx - d)$$

$$\begin{Bmatrix} c + Qx + \lambda^T A + \mu^T C = 0 \\ Cx = d \end{Bmatrix}$$
$$\begin{Bmatrix} \lambda \le 0 \\ Ax \le b \\ \lambda^T \left(Ax - b\right) = 0 \end{Bmatrix}$$

Existence and unicity

- In a medium-term model formulated with
  - **linear constraints**
  - **quadratic objective function**

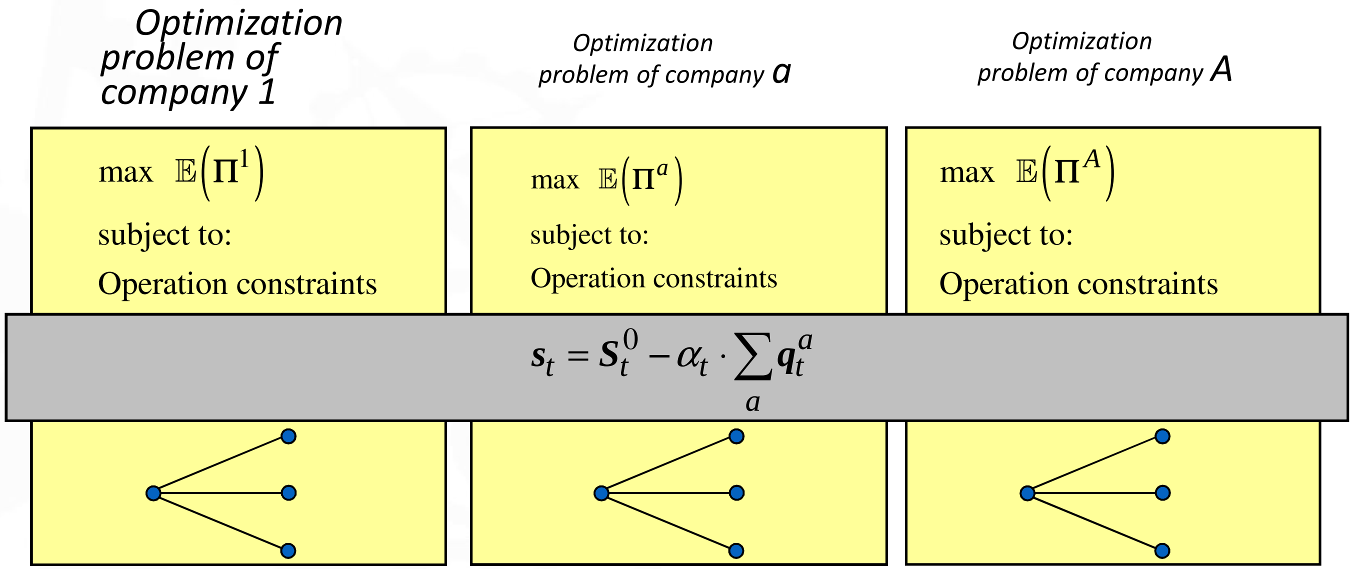
System of equations with a **mixed linear complementarity problem** structure

- Sufficient conditions for **existence and unicity:**

An **increasing and** strictly monotonic **marginal cost** function and a **decreasing** linear **inverse demand** function

Stochastic optimization problem without risk

- Simultaneous agents' stochastic optimization problems with price equation

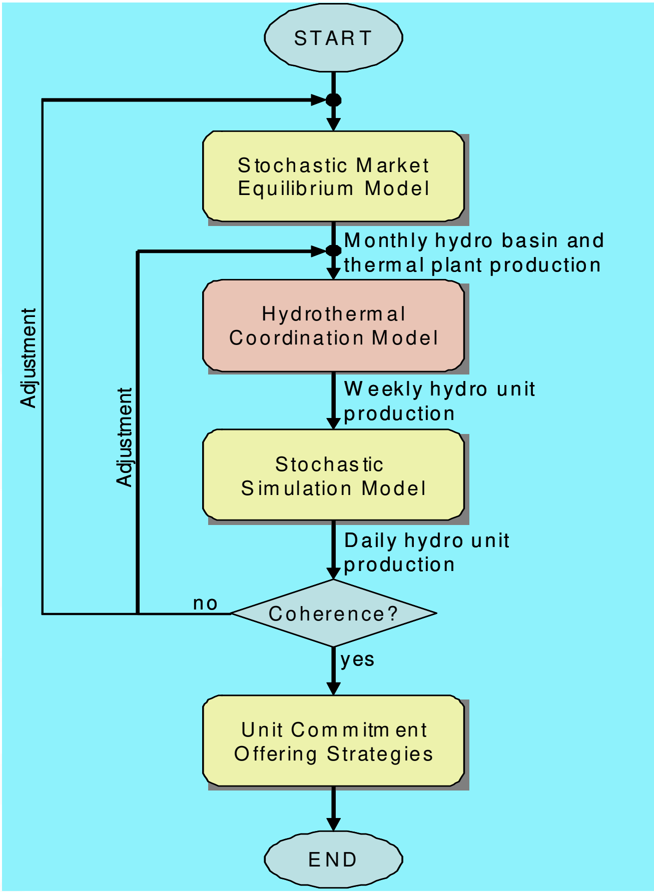


4.2

MHE

UNIVERSIDAD PONTIFICIA ICAI ICADE COMILLAS MADRID

Hierarchy of Operation Planning Models



Keys to success

- According to [Labadie, 2004] "the keys to success in implementation of reservoir system optimization models are:
  - (1) improving the levels of trust by more interactive of decision makers in system development;
  - (2) better "packaging" of these systems; and
  - (3) improved linkage with simulation models which operators more readily accept".

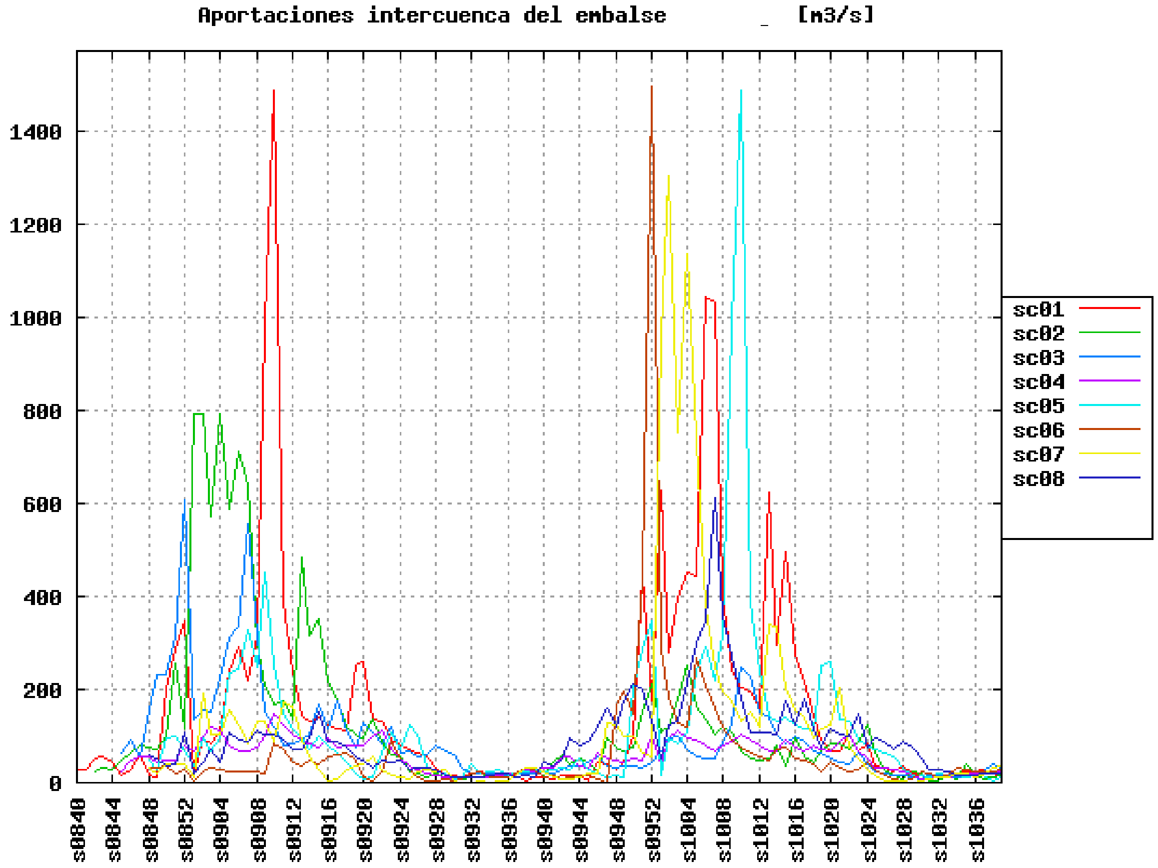
MHE

- Purpose
  - Determine the optimal yearly operation of all the thermal and hydro power plants
  - Medium term stochastic hydrothermal model for a complex multi-reservoir and multi-cascaded hydro subsystem
- Main characteristics
  - General reservoir system topology
  - Cost minimization model
  - Thermal and hydro units considered individually
  - Nonlinear water head effects modeled for large reservoirs (NLP Problem)
  - Stochastic nonlinear optimization problem solved directed by a nonlinear solver given a close initial solution provided by a linear solver
- References
  - A. Ramos, S. Cerisola, J.M. Latorre, R. Bellido, A. Perea, and E. Lopez *A Decision Support Model for Weekly Operation of Hydrothermal Systems by Stochastic Nonlinear Optimization* in the book G. Consigli, M. Bertocchi and M.A.H. Dempster (eds.) *Stochastic Optimization Methods in Finance and Energy*. Springer 2011 ISBN 9781441995858 (Table of contents) 10.1007/978-1-4419-9586-5_7

Hydro subsystem

- Different modeling approach for hydro reservoirs depending on:
  - Owner company
  - Relevance of the reservoir
- Reservoirs belonging to other companies modeled in energy units [GWh]
- Own reservoirs modeled in water units [hm^3, m^3/s]
- Important reservoirs modeled with water head effects
- Very diverse hydro subsystem:
  - Hydro reservoir volumes from 0.15 to 2433 hm^3
  - Hydro plant capacities from 1.5 to 934 MW

Natural inflows: scenario tree



Solution algorithm

- Algorithm:
  - Successive LP
  - Direct solution by a NLP solver
- Very careful implementation
  - Natural scaling of variables
  - Use of simple expressions
  - Initial values and bounds for all the nonlinear variables computed from the solution provided by linear solver (CPLEX 10.2 IPM)
  - Nonlinear solvers
    - CONOPT 3.14 [Generalized Reduced Gradient Method]
    - KNITRO 5.1.0 [Interior-Point or an Active-Set Method]
    - MINOS 5.51 [Project Lagrangian Algorithm]
    - IPOPT 3.3 [Primal-Dual Interior Point Filter Line Search Algorithm]
    - SNOPT 7.2-4 [Sequential Quadratic Programming Algorithm]

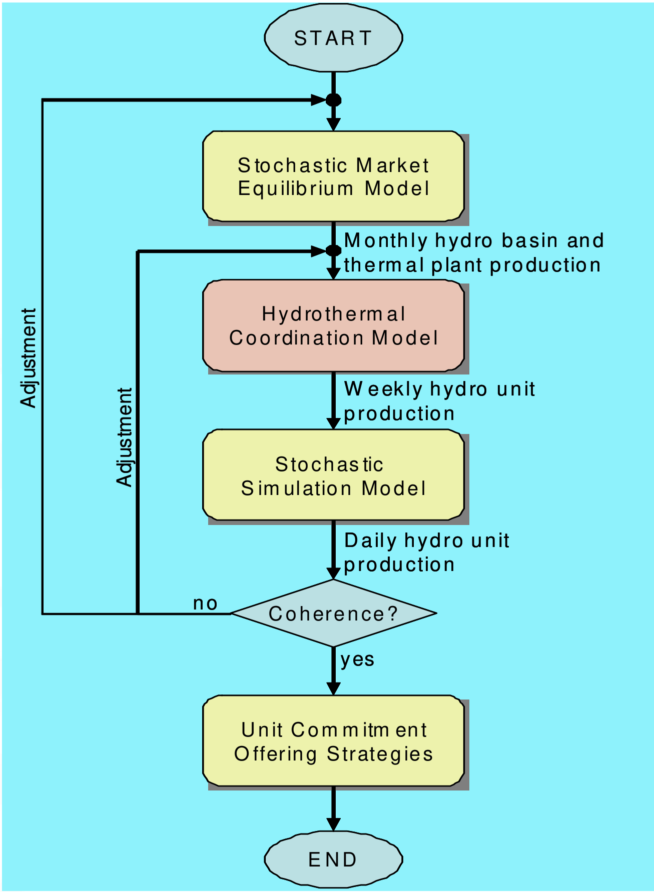
Two-year long case study

- Spanish electric system
  - 130 thermal units
  - 3 main basins with 50 hydro reservoirs/plants and 2 pumped storage hydro plants
  - 12 scenarios

4.3

Simulador

Hierarchy of Operation Planning Models



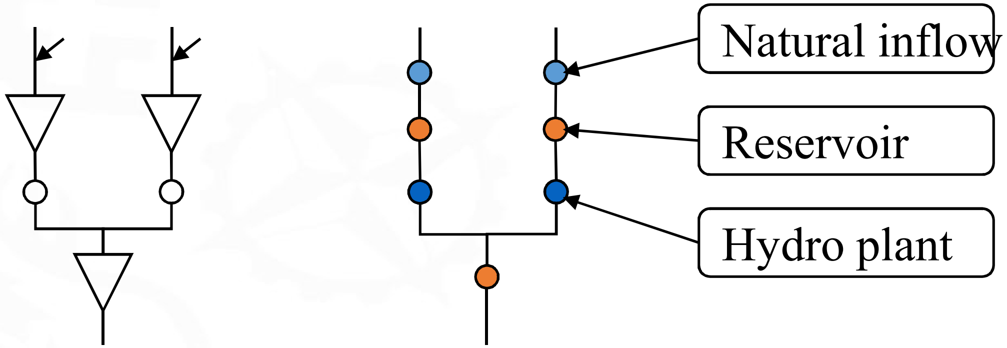
Simulador

- Purpose
  - Analyze and test different management strategies of hydro plants
  - Economic planning of hydro operation:
    - Yearly and monthly planning
  - Update the yearly forecast:
    - Operation planning up to the end of the year
  - Short term detailed operation:
    - Detailed operation analysis of floods and droughts, changes in irrigation or recreational activities, etc.
- Main characteristics
  - Simulation technique
  - It has been proposed a general simulation method for hydro basins
  - A three phase method implements the maximize hydro production objective
  - Object Oriented Programming has been used
  - A flexible computer application implements this method
- References

  - J.M. Latorre, S. Cerisola, A. Ramos, R. Bellido, A. Perea *Creation of Hydroelectric System Scheduling by Simulation* in the book H. Qudrat-Ullah, J.M. Spector and P. Davidsen (eds.) *Complex Decision Making: Theory and Practice* pp. 83-96 Springer October 2007 ISBN 9783540736646 10.1007/978-3-540-73665-3_5
  - J.M. Latorre, S. Cerisola, A. Ramos, A. Perea, R. Bellido *Simulación de cuencas hidráulicas mediante Programación Orientada a Objetos* VIII Jornadas Hispano-Lusas de Ingeniería Eléctrica Marbella, España Julio 2005

Data representation (i)

- Basin topology is represented by a graph of nodes where each node is an element:



- Connections among nodes are physical junctions through the river.
- This structure induces the use of

Data representation (ii)

- Five types of nodes (objects) are needed:
  - Reservoir
  - Channel
  - Plant
  - Inflow point
  - River junction

- Each node is independently operated although it may require information from other elements

Reservoir operation strategies

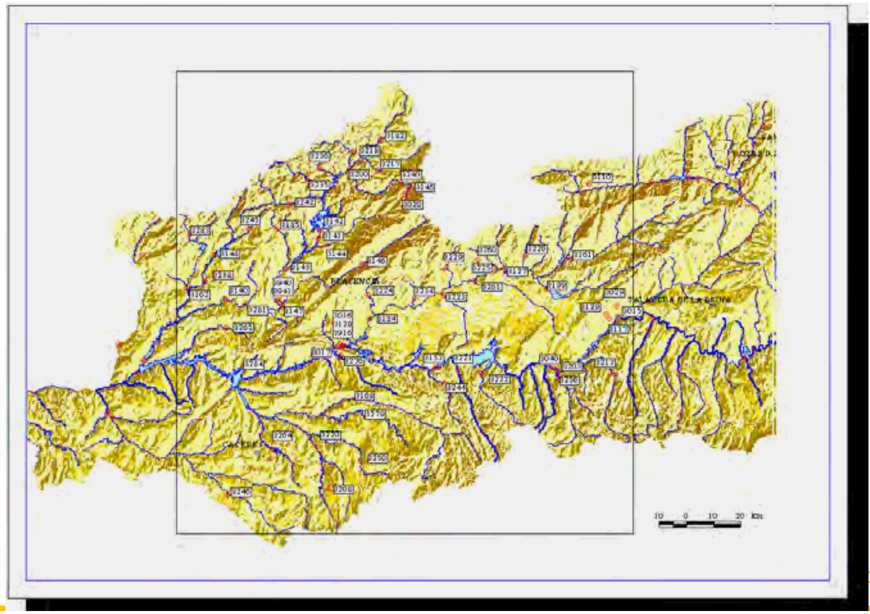
1. Optimal outflow decision taken from a precalculated optimal water release table depending on:
    - Week of the simulated day
    - Hydrologic index of the basin inflows (type of year)
    - Volume of the own reservoir
    - Volume of a reference reservoir
   - Table calculated by a long term hydrothermal model
   - Usually for the main reservoirs of the basin
2. Outflow equals incoming inflow (usually for small reservoirs)
3. Go to minimum target curve (spend as much as possible)
4. Go to maximum target curve (keep water for the future)

Simulation method (I)

- Main objective:
  - Maximize hydro production following the reservoir operation strategies
  - Other objectives:
    - Avoid spillage
    - Satisfaction of minimum outflow (irrigation)
- Proposed method requires three phases:
  1. Decides the initial management
  2. Modifies it to avoid spillage and produce minimum outflows
  3. Determines the electricity output for previous inflows

Case study

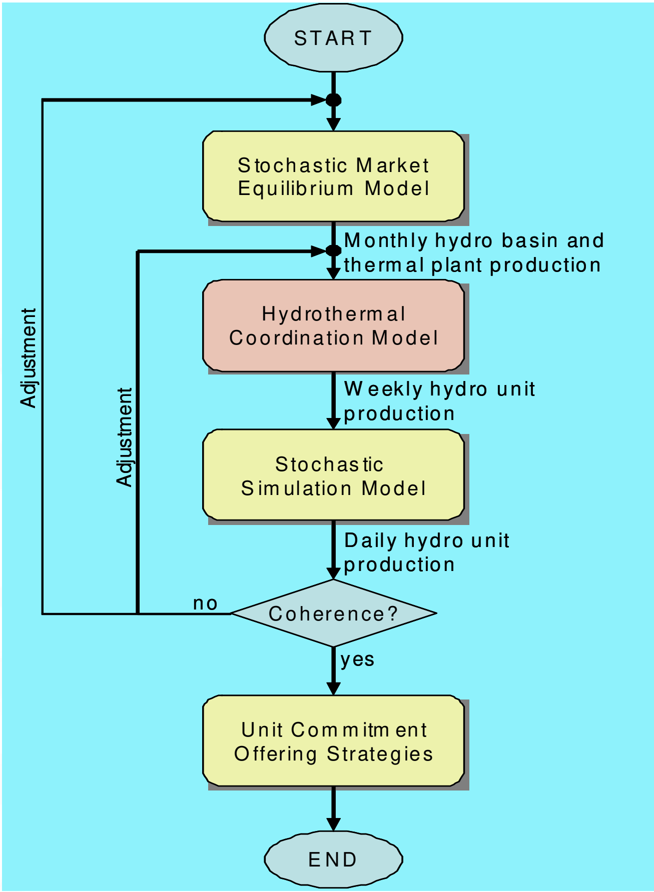
- Application to the Tajus basin belonging to Iberdrola with:
  - 9 reservoirs of different sizes
  - 8 hydro plants
  - 6 natural inflow points
  - 27 historical series of daily inflows



4.4

MAFO

Hierarchy of Operation Planning Models

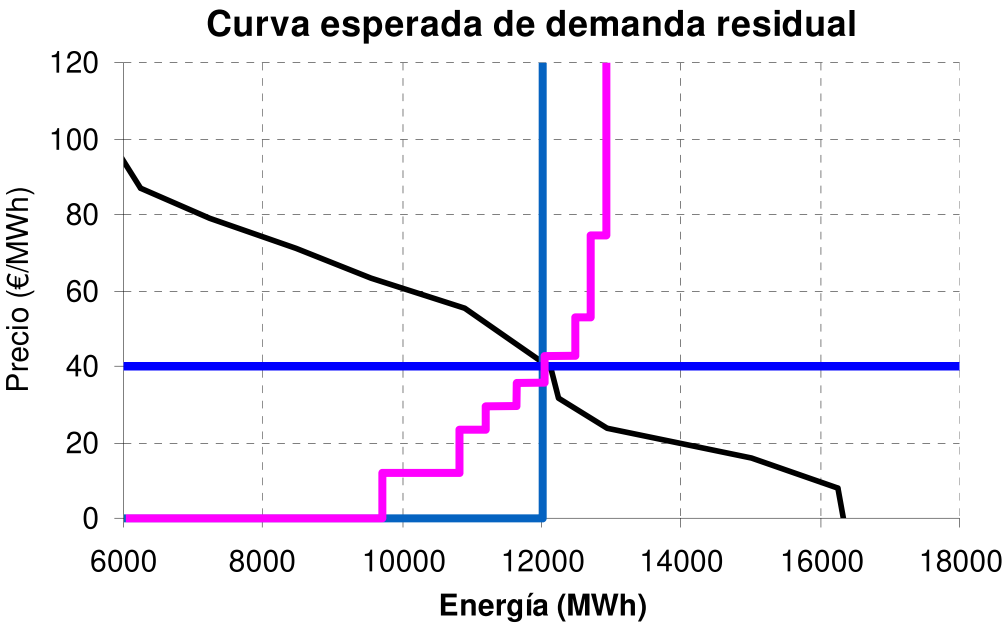


MAFO

- Purpose
  - Short-term generation operation
  - Strategic Unit Commitment development of offering strategies
  - Daily and adjustment markets
- Main characteristics
  - Decomposition techniques (Benders, Lagrangian relaxation)
- References
  - A. Baillo, S. Cerisola, J. Fernandez-Lopez, A. Ramos *Stochastic Power Generation Unit Commitment in Electricity Markets: A Novel Formulation and A Comparison of Solution Methods* Operations Research (accepted) _ JCR impact factor 1.234 (2006)
  - J.M. Fernandez-Lopez, Á. Baíllo, S. Cerisola, R. Bellido, "Building optimal offer curves for an electricity spot market: a mixed-integer programming approach," *Proceedings of the 15th PSCC, Power Systems Computing Conference. Liege, Belgium, 22-26 Agosto 2005*
  - Á. Baíllo, M. Ventosa, M. Rivier, A. Ramos, "Optimal offering strategies for generation companies operating in electricity spot markets," *IEEE Transactions on Power Systems*. vol. 19, no. 2, pp. 745-753, May 2004
  - A. Baíllo, M. Ventosa, M. Rivier, A. Ramos, G. Relaño *Bidding in a Day-Ahead Electricity Market: A Comparison of Decomposition Techniques* 14th Power Systems Computation Conference (PSCC '02) Seville, Spain June 2002
  - A. Baíllo, M. Ventosa, A. Ramos, M. Rivier, A. Canseco *Strategic unit commitment for generation companies in deregulated electricity markets* in book *The Next Generation of Electric Power Unit Commitment Models* Kluwer Academic Publishers Boston, MA, USA pp. 227-248 2001

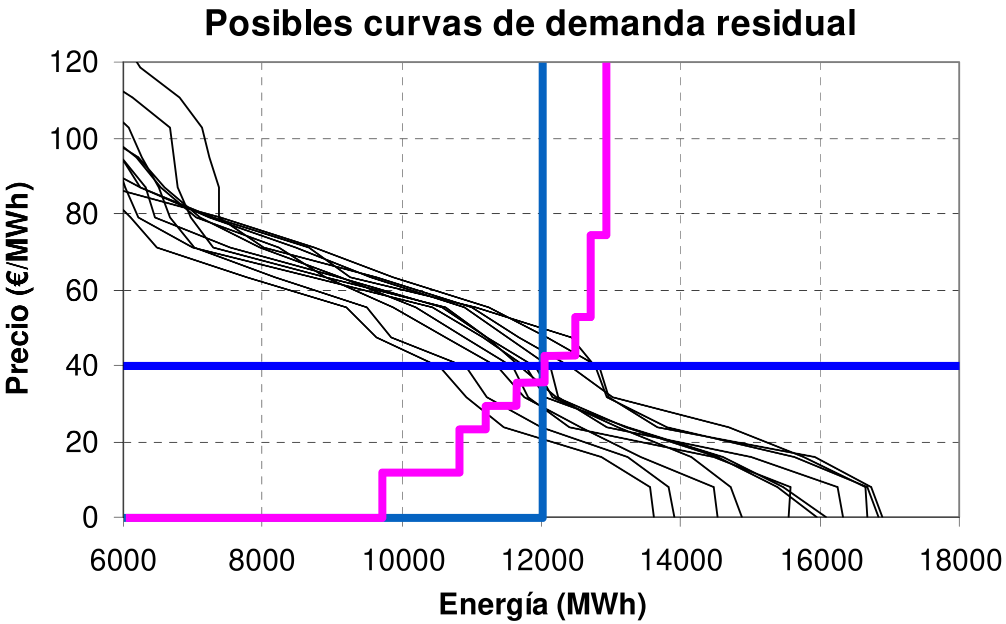
Modeling short term uncertainty: multistage approach

- Generation company doesn't know the residual demand curve for each hour:



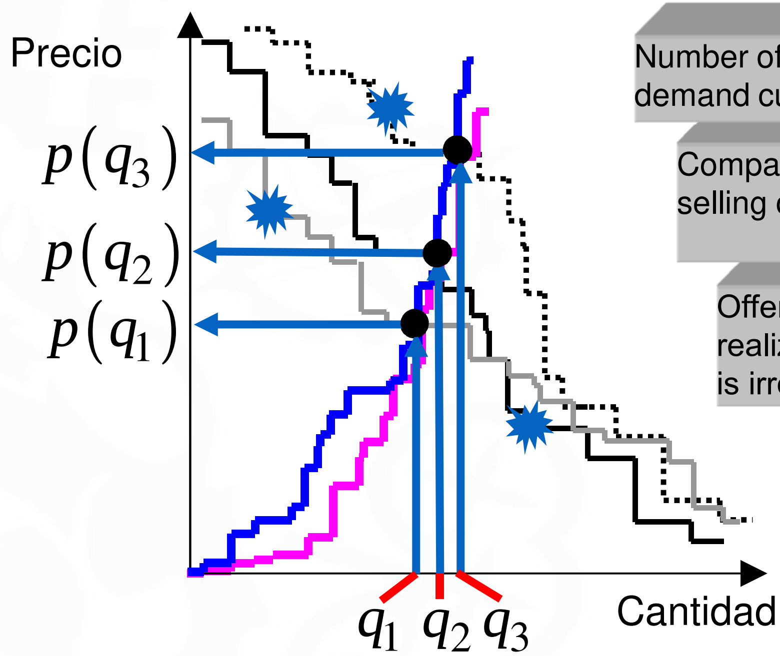
Modeling short term uncertainty: multistage approach

- Explicit recognition of uncertainty justifies the importance of offering strategies:



Modeling short term uncertainty: multistage approach

- Hypothesis: probability distribution of residual demand curve has finite support:



Number of possible realizations of residual demand curve is finite

Company decisions are reduced to chose selling output for each residual demand

Offering curve between two possible realizations of residual demand curve is irrelevant

Selling offers have to build an increasing curve

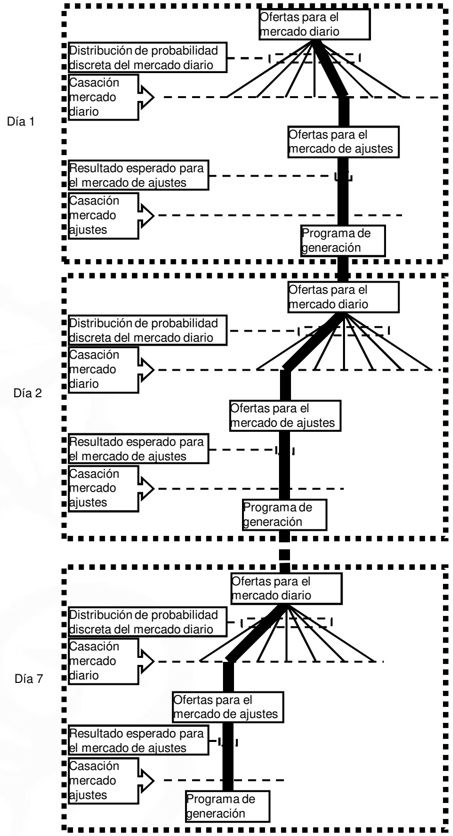
Solution problem strategy

- Solution in two phases:
  - Stochastic *unit commitment*
  - Optimal offering strategies under uncertainty.
- Structure of these problems.
- Possible decomposition techniques:
  - Benders.
  - Lagrangian relaxation.

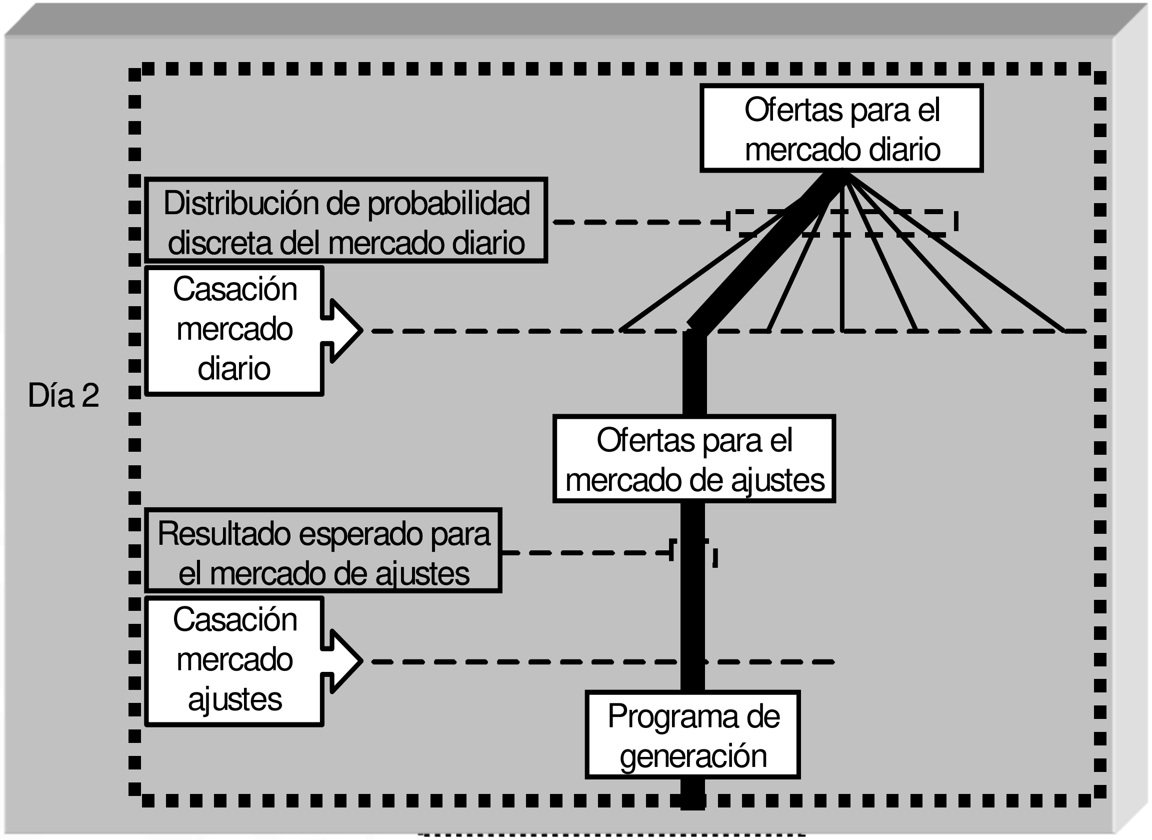
First problem:
weekly stochastic multistage planning

- Scope of short term decisions is one week:
  - Startup and shutdown planning: *unit commitment*.
  - Daily hydro scheduling: hydrothermal coordination.
- This weekly problem can be seen as a sequence of two-stage stochastic problems, one for each day of the week.

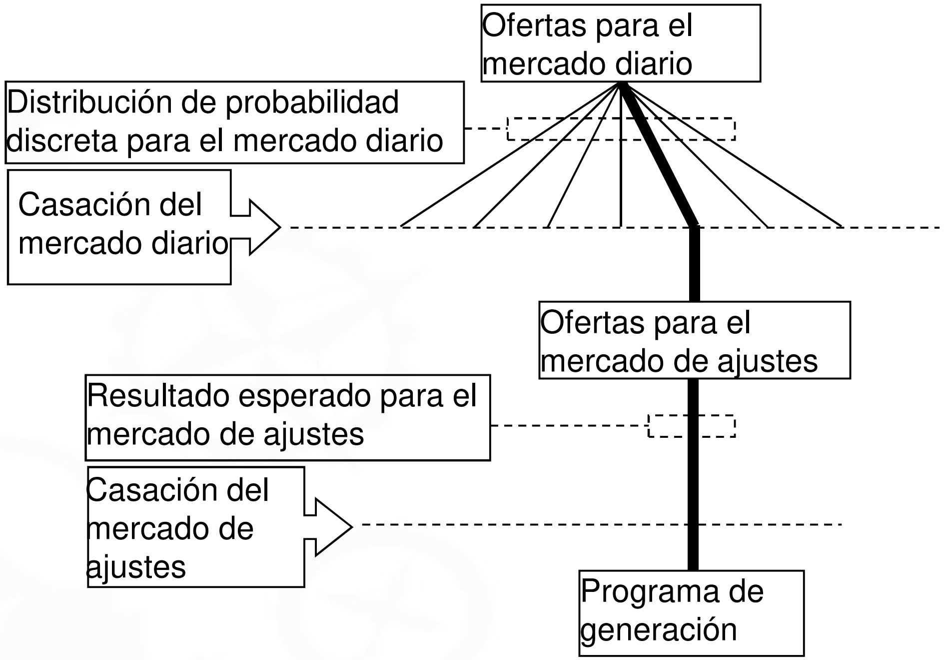
First problem:
weekly stochastic multistage planning



First problem:
detail for each day of the week



Second problem: two-stage problem of offering strategies



4.5

Other models

Market Equilibrium

		Iberdrola	Endesa	Gas Natural Fenosa	E.ON España	Red Eléctrica	IIT
Back Office Long Term Expansion Planning	Generation and transmission		BEST MORSE EXPANDE				OWL TEPES
Back Office Medium Term Operation Planning	Market Equilibrium	MOES MPO	VALORE	MARAPE	PLAMER		PREMED
	Hydro Subsystem	MHE Simulador	EXLA				
	Renewable sources integration. EV, VPP					MEMPHIS	ROM
	Transmission Network					SIMUPLUS	StarNet SECA
	Generation reliability assessment						FLOP
Front Office Short Term Offer Strategies and Operation Planning	UC and operation reserves	MAFO	SGO		GRIMEL		

Valore

• Purpose

- Oligolopolistic electricity markets simulation

• Main characteristics

- Based on quadratic optimization (QP)
- Medium-term
  - Allows detailed physical assets modeling
  - Extended for stochastic optimization (i.e. water inflows)
  - Network constraints (explicit and implicit transmission auctions)

• References

- J. Barquín, M. Vázquez, Cournot Equilibrium Calculation in Power Networks: An Optimization Approach With Price Response Computation, *IEEE Trans. on Power Systems*, 23, no. 2, 317-326, May, 2008
- J. Barquín, E. Centeno, J. Reneses , Stochastic Market Equilibrium Model For Generation Planning, *Probability in the Engineering and Informational Sciences*, 19, 533-546, August, 2005

Fuzzy Valore

• Purpose

- Proposing an electricity market model based on the conjectural-price-response equilibrium when uncertainty of RDC is modeled using the possibility theory

• Main characteristics

- Compute robust Cournot equilibrium by using possibilistic VAR for medium term analysis
- Determine possibility distributions of main outputs (prices and incomes)
- Novel variational inequalities (VI) algorithms with global and proved convergence that iteratively solve quadratic programming (QP) models

• References

- F.A. Campos, J. Villar, J. Barquín, J. Reneses, "Variational inequalities for solving possibilistic risk-averse electricity market equilibrium," *IET Gener. Transm. Distrib.* vol. 2, no. 5, pp. 632-645, Sep 2008
- F.A. Campos, J. Villar, J. Barquín, J. Ruipérez, "Robust mixed strategies in fuzzy non-cooperative Nash games," *Engineering Optimization*. vol. 40, no. 5, pp. 459-474, May 2008
- F.A. Campos, J. Villar, J. Barquín, "Application of possibility theory to robust Cournot equilibriums in electricity market," *Probability in the Engineering and Informational Sciences*. vol. 19, no. 4, pp. 519-531, October 2005

Generation Expansion Planning

		Iberdrola	Endesa	Gas Natural Fenosa	E.ON España	Red Eléctrica	IIT
Back Office Long Term Expansion Planning	Generation and transmission		BEST MORSE EXPANDE				OWL TEPES
Back Office Medium Term Operation Planning	Market Equilibrium	MOES MPO	VALORE	MARAPE	PLAMER		PREMED
	Hydro Subsystem	MHE Simulador	EXLA				
	Renewable sources integration. EV, VPP					MEMPHIS	ROM
	Transmission Network					SIMUPLUS	StarNet SECA
	Generation reliability assessment						FLOP
Front Office Short Term Offer Strategies and Operation Planning	UC and operation reserves	MAFO	SGO		GRIMEL		

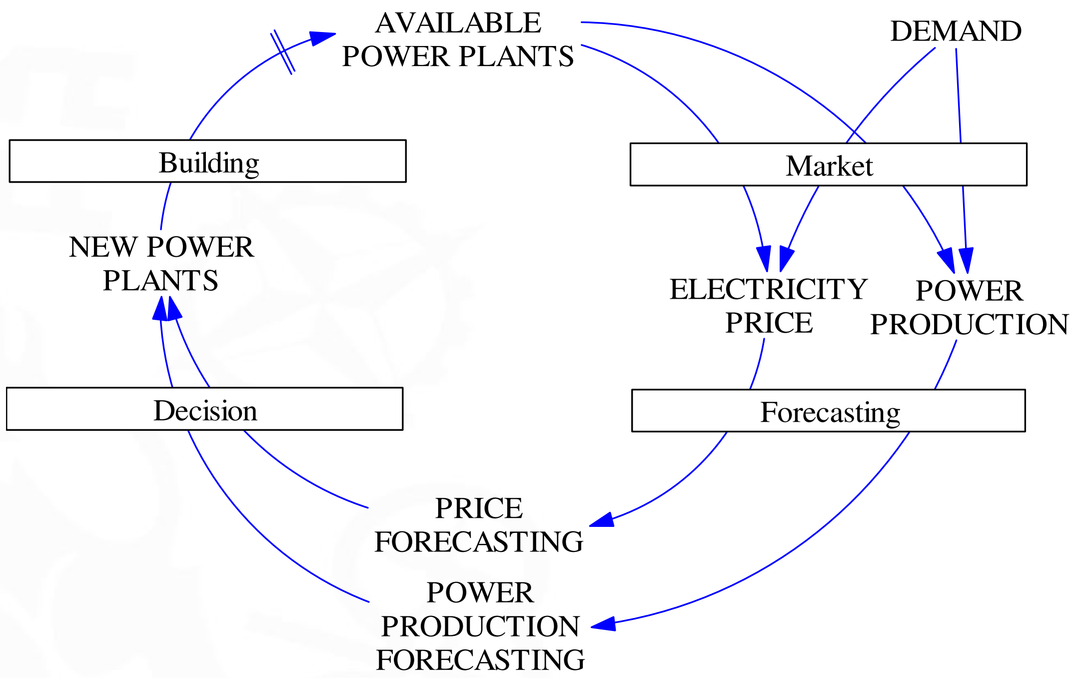
BEST

- Purpose
  - Assessment of investments in generation assets and other strategic decisions
- Main characteristics
  - Long-term scope (20-30 years)
  - System-dynamics based simulation (Business Dynamics)
  - Includes a detailed representation of agents' market behavior based on endogenously-computed conjectured price variation
  - Includes a detailed representation of decisions evaluation based on Merton-Black-Scholes theory
- References

  - E. Centeno, J. Barquín, A. López-Peña, J.J. Sánchez, "Effects of gas-production constraints on generation expansion," *16th Power Systems Computation Conference - PSCC 08. Glasgow, Scotland, 14-18 Julio 2008*
  - J.J. Sánchez, J. Barquín, E. Centeno, "Fighting market power by auctioning generation: A system dynamics approach," *INFORMS Annual Meeting 2007. Seattle, USA, 4-7 Noviembre 2007*
  - J.J. Sánchez, J. Barquín, E. Centeno, A. López-Peña, "System dynamics models for generation expansion planning in a competitive framework: Oligopoly and market power representation," *Twenty-Fifth International System Dynamics Conference. Boston, Massachusetts, USA, 29 Julio-2 Agosto 2007*

BEST

- Overall structure



Hydro Scheduling

		Iberdrola	Endesa	Gas Natural Fenosa	E.ON España	Red Eléctrica	IIT
Back Office Long Term Expansion Planning	Generation and transmission		BEST MORSE EXPANDE				OWL TEPES
Back Office Medium Term Operation Planning	Market Equilibrium	MOES MPO	VALORE	MARAPE	PLAMER		PREMED
	Hydro Subsystem	MHE Simulador	EXLA				
	Renewable sources integration. EV, VPP					MEMPHIS	ROM
	Transmission Network					SIMUPLUS	StarNet SECA
	Generation reliability assessment						FLOP
Front Office Short Term Offer Strategies and Operation Planning	UC and operation reserves	MAFO	SGO		GRIMEL		

EXLA

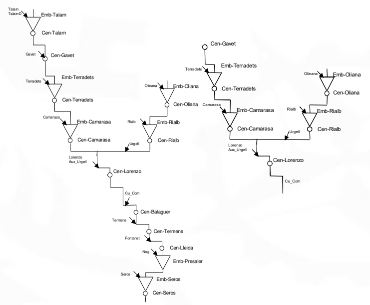
- ## Purpose
  - Optimal planning of hydroelectric reservoirs in the mid-term
- ## Main characteristics
  - Deterministic & stochastic approach
  - Profit-based & demand-based
  - LP in an iterative under-relaxed process, MILP or QCP
  - Mid-term: weekly periods, with load blocks.
  - Very detailed representation of hydro systems peculiarities
  - Used by Endesa to manage their reservoirs in the Spanish system.
- ## References

  - R. Moraga, J. García-González, E. Parrilla, S. Nogales, "Modeling a nonlinear water transfer between two reservoirs in a midterm hydroelectric scheduling tool," Water Resources Research. vol. 43, no. 4-W04499, pp. 1-11, April 2007
  - J. García-González, R. Moraga, S. Nogales, A. Saiz-Chicharro, "Gestión óptima de los embalses en el medio-largo plazo bajo la perspectiva," Anales de Mecánica y Electricidad. vol. LXXXII, no. IV, pp. 18-27, July 2005

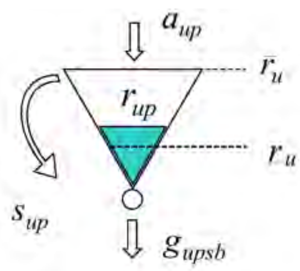
EXLA

Datos físicos [Hm³],[m³/s]
- topología de los subsistemas
- caudales de aportaciones
- servidumbres
- curvas de garantía
- consignas de cotas de los embalses
- datos estáticos de emb. y cen., etc...

Modelo equivalente
[MWh],[MW]
producible
- potencia fluyente
- reservas máximas y mínimas
- reservas iniciales
- energías máximas y mínimas, etc...



Modelo de coordinación hidrotérmica de medio plazo



Resultados detallados
- producciones por central
- caudales turbinados por central
- caudales vertidos
- políticas de desembalse
- evolución de cotas
- identificación de riesgo de vertidos, etc...

Resultados agregados
- producción de cada UGH
- evolución de las reservas

Renewable Integration

		Iberdrola	Endesa	Gas Natural Fenosa	E.ON España	Red Eléctrica	IIT
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Back Office Medium Term Operation Planning	Market Equilibrium	MOES MPO	VALORE	MARAPE	PLAMER		PREMED
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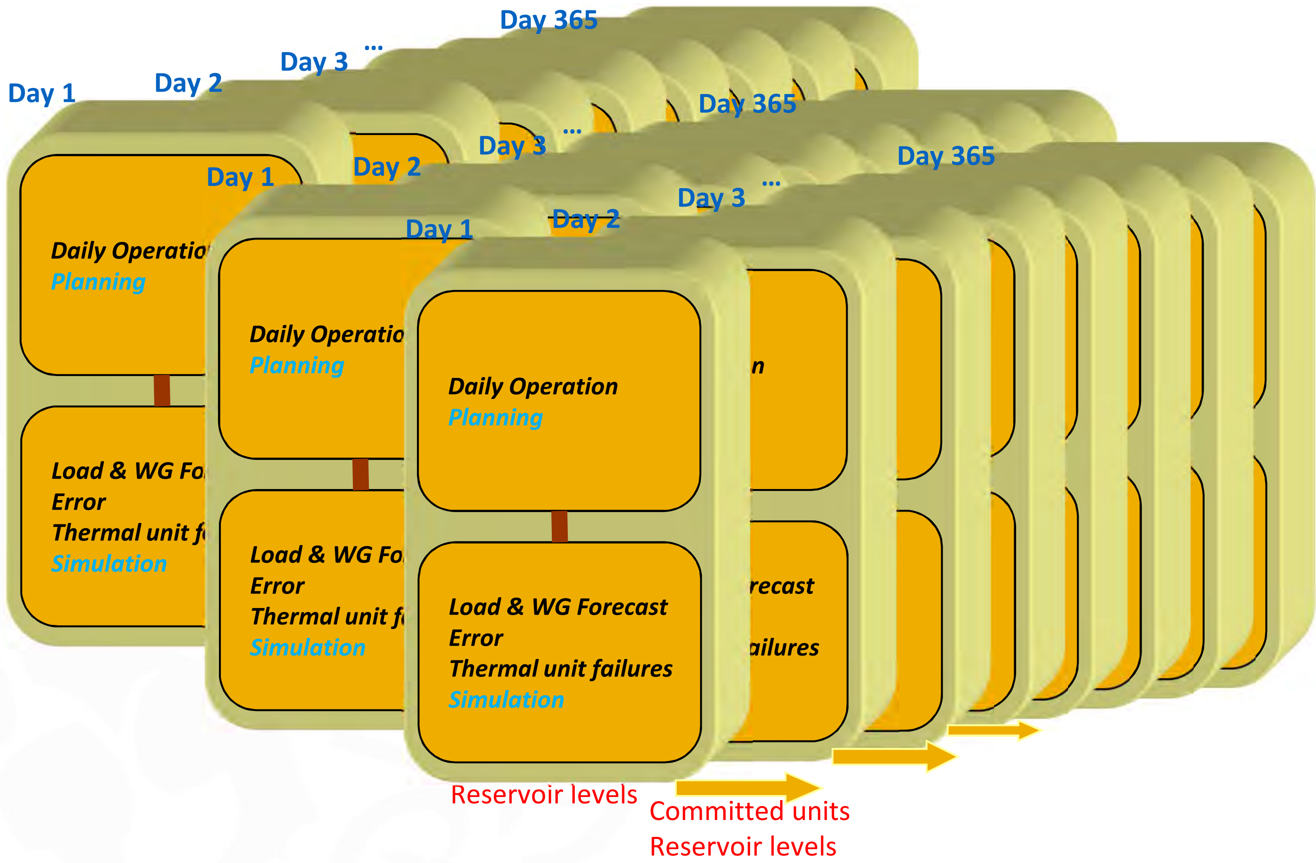
ROM (Reliability and Operation Model for Renewable Energy Sources) (https://www.iit.comillas.edu/aramos/ROM.htm)

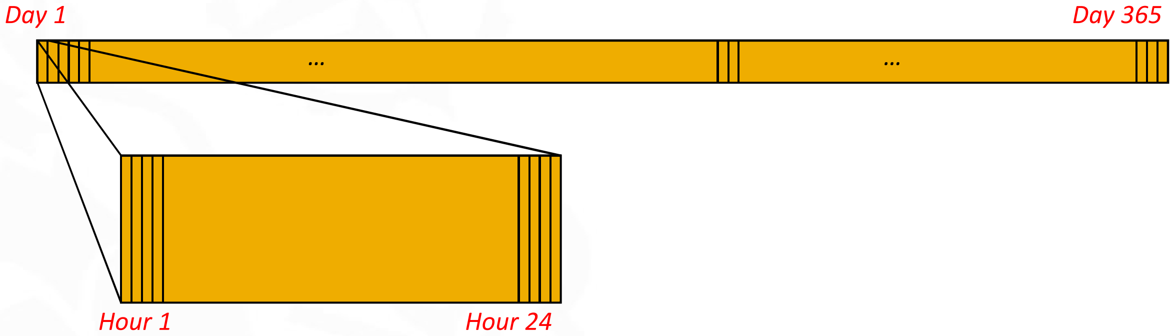
- Determine the technical and economic impact of intermittent generation (IG) and other types of emerging technologies (active demand response, electric vehicles, concentrated solar power, CAES, and solar photovoltaic) into the medium-term system operation including reliability assessment.
- The model scheme based on a daily sequence of planning and simulation is similar to an open-loop feedback control used in control theory.

General overview



Time division

- Scope
  - 1 year
- Period
  - 1 day (consecutive chronological operation)
- Subperiod
  - 1 hour



Thank you for your attention

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