MITEI-IAP24

Computational modeling for clean, reliable, and affordable electricity

Massachusetts Institute of Technology (MIT)

Generation Expansion Planning

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Motivation

- To give an indication about what it is possible to analyze with this decision tool
  - Capabilities and limitations
- To become familiar with generation expansion modeling techniques
- To give the mathematical foundation

Smart Power Generation - The Future Of Electricity Production

Source: Wartsila Corp

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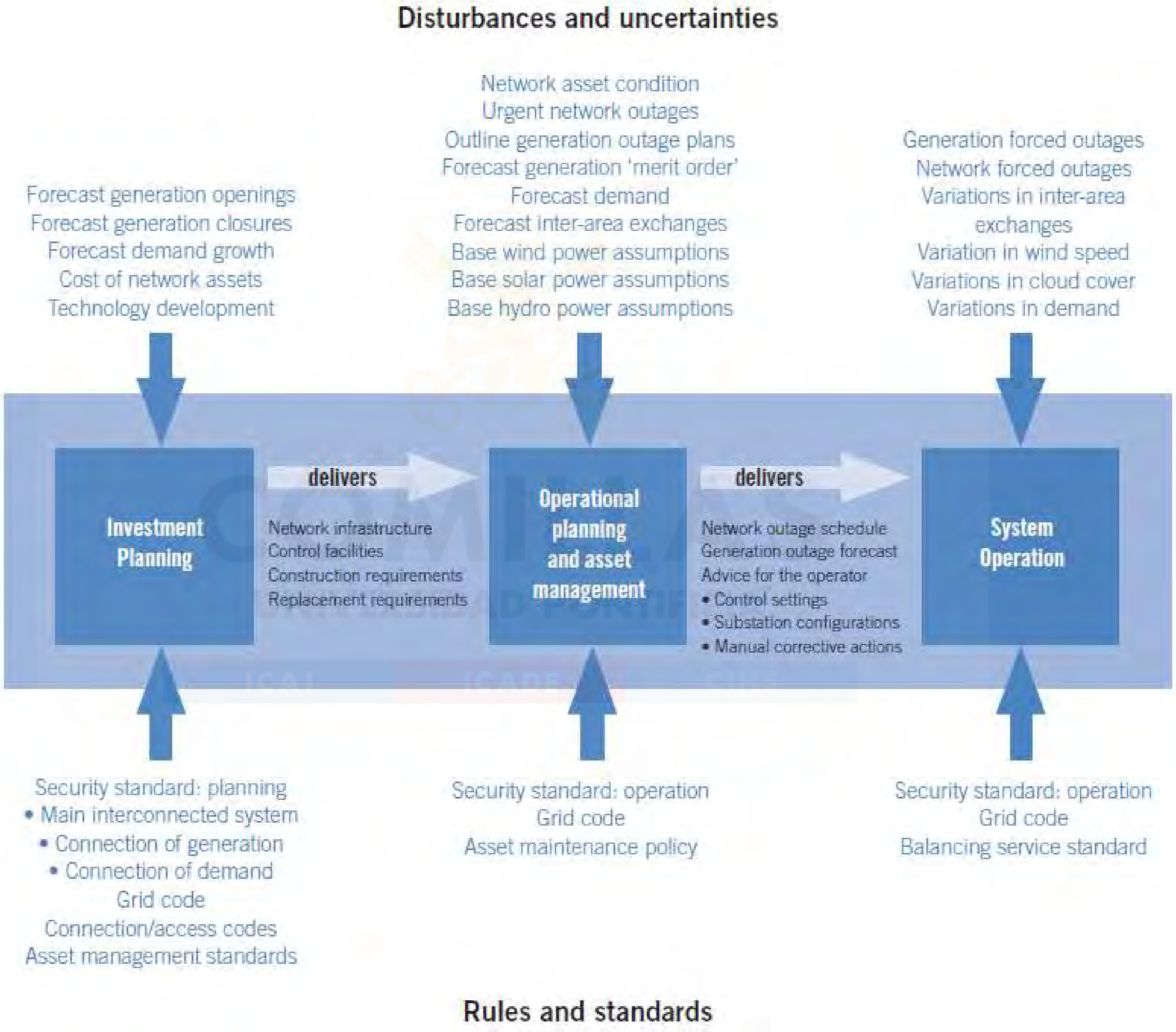
1

Generation expansion planning

Generation planning functions

Functions	Long term	Medium term	Short term
New liberalized market functions	• Capacity investments • Risk management • Long term contracts: - Fuel acquisition - Electricity selling	• Objectives: - Market share - Price • Budget planning • Future derivatives market bids	• Strategic bidding: - Energy - Power reserve - Other ancillary services
Traditional regulated operation functions	**• Capacity investments** **- Installation** **- Repowering** **• Maintenance** **• Energy management** **- Nuclear cycle** **- Multiannual reservoirs**	• Fuel management • Annual reservoir and seasonal pumped storage management - Water value assessment	• Startup and shut-down of thermal units • Pumped storage operation • Economic dispatch

Investment Planning functions



Generation Expansion Planning (GEP). Statement

- Determine which power plants and when to build "optimizing"
  - Total investment and operation costs
  - Economic and financial requirements
  - Reliability criteria
  - Environmental impact
  - Diversification and/or use of domestic fuels

  considering
  - Long term scope (10 – 30 years)
  - Load forecast
  - Existing and committed generation
  - Generation technologies available and investment costs
  - Resource availability (fuel, financial)
  - Environmental constraints
  - Fuel price forecast
  - Political and administrative constraints (renewable energy sources)

Generation Expansion Planning. Characteristics

- Very complex decision problem, with multiple criteria
- Operation decisions and constraints are a subset of the generation expansion problem. Large-scale problem
- Important strategic decision
- Decisions require long building periods and have long book life
- Huge uncertainty: demand or fuel prices
- Technologies may have economies of scale
- Technologies differ in variable and fixed costs, technical characteristics and operation requirements

Generation Expansion Planning. Results

- Investment
  - Investing (building, purchase) or divesting (close, sale) power plants
  - Extension of life cycle, repowering, fuel switching
  - Size, date and (location)
- Operation
  - Fuel consumption
  - Unit output (thermal, storage hydro and pumped storage hydro)
  - CO2 Emissions
  - Technologies and fuels used in new power plants
- Economic
  - Investment and operation costs
  - Long run marginal costs
  - Profits and market evolution

Generation Expansion Planning. System vs. Company

System (or regulator) approach

- Produce a publicly available **reference plan** to guide private company decisions
- **Tactical** planning (long term) up to 10 years
- **Strategic** planning (very long term) more than 10 years in advance
- Analysis or **support of regulatory decisions**
- May represent **centralized** decisions (perfect competition) or **liberalized** decisions (market imperfection)

Small company approach

- **Project assessment** (repowering or building a single power unit)
- Plant location (connection to electric and/or gas networks)

Generation Expansion Planning. Centralized vs. Liberalized

Centralized (traditional, perfect competition) planning

- Minimize investment and operation costs to supply the demand subject to a certain reliability criterion, environmental and operation constraints
- Support of renewable energy sources
- Technology diversification
- Use of domestic fuels
- Coordination with transmission expansion and gas network expansion

Liberalized markets

- Companies take their own decisions to
    - Maximize profit or share value
    - Maximize market share
    - Minimize risk or diversify their investments
- Are free to decide which technologies or power plants (given that have the corresponding permits)
- Regulator may have control mechanisms (reference plan, capacity payment)
- Difficulties for new entering agents

Generation Expansion Planning. Solving Techniques

Optimization

- Metaheuristics
- Mixed integer programming (MIP)
- Dynamic programming (DP)
- Approximate Dynamic programming (ADP)
- Stochastic programming and decomposition methods
- Bilevel programming

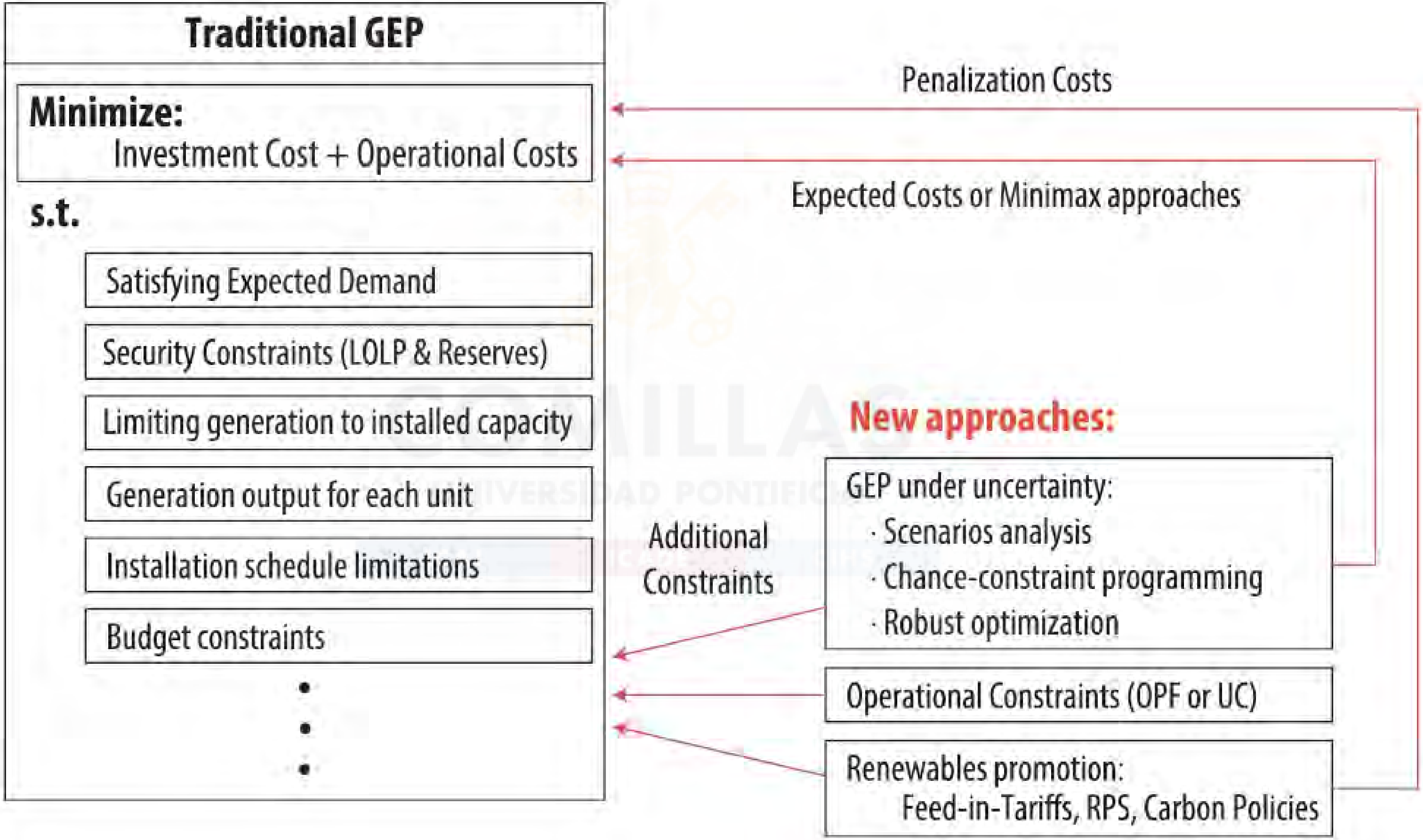
Simulation

- Business dynamics. System dynamics
- Agent-based simulation
- Monte Carlo simulation
- Probabilistic Production Cost Models

Other

- Decision theory
- Multicriteria decision making
- Real options analysis

Generation expansion planning model



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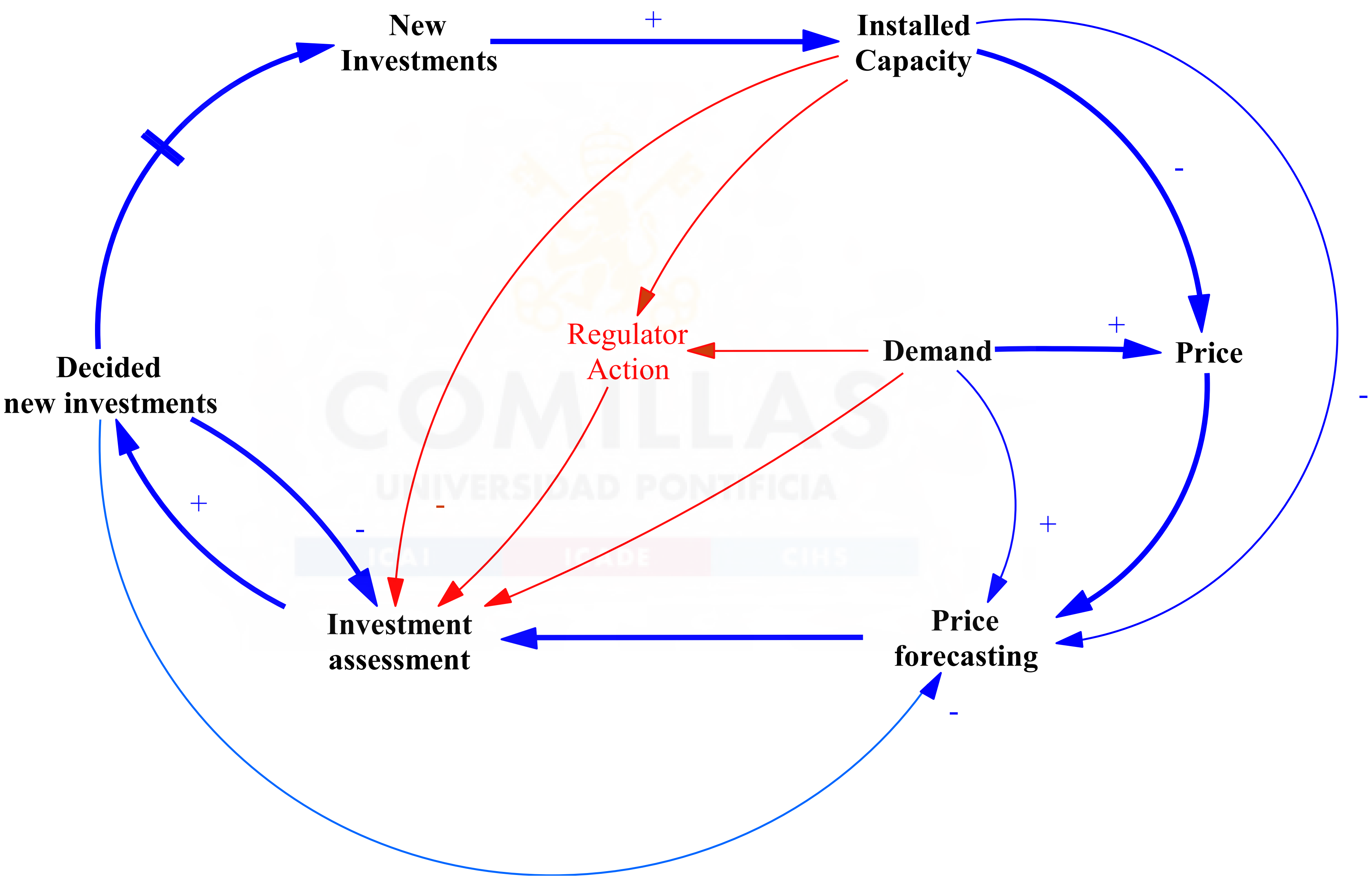
Generation expansion planning: Business dynamics example



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Simple GEP models

Centralized GEP

- O.F.: minimize investment and variable operating costs of all the companies
- Constraints:
  - Total emission cap: the emission of a certain quantity of pollutant (CO2 in the model) during the period is upper bounded
  - Operation bounds and investment limits
- Variables: thermal installed capacity IC_y and thermal generation P_t for all the thermal units t

$$max - \sum_t v_t P_t - v' ENS - \sum_t f_t' IC_t$$ Investment and variable operating costs

$$\sum_t P_t + ENS = D$$ Load balance

$$\sum_t e_t P_t \leq \bar{E}$$ Total emission cap

$$0 \leq P_t \leq \bar{P}_t + IC_t \quad \forall t$$ Thermal operating bounds

$$0 \leq IC_t \leq \overline{IC}_t \quad \forall t$$ Investment decision constraints

GEP under a market equilibrium model

- Simultaneous **profit maximization** (market revenues – investment, operating and emission costs) **of all the GenCos**
- All the GenCos decide simultaneously which capacity to install IC_t and how much to use of this capacity P_t

Market closure

- Inverse demand function: market price π determined endogenously by a linear function

$$\pi = f\left(\sum_{e} q_e\right) = D_0 - D_1 \sum_{e} q_e$$

- Total generation of GenCo *e* = sum of the generation of all the units

$$q_e = \sum_{t \in e} P_t$$

Emission cap

- Participants in the allowance market are only the electric companies, which trade with the allowances, and the Government, which fixes the number of allowances inside the market and may also trade directly on it. We are assuming a perfect competitive allowance market. The allowances are auctioned by the Government at an allowance price.
- Total CO2 emissions of the system
  - Price of the allowance γ is such that it is equal to the dual variable of this constraint, so the increase of profit that every company should gain relaxing that constraint is the same, and it is equal to the cost of purchasing the allowance, so the allowance market is at its equilibrium

$$\sum_t e_t P_t \leq \bar{E} \quad \perp \gamma$$

GEP under a market equilibrium model of GenCo *e*

- O.F.: profit maximization (market revenues – investment cost - variable operating costs - emission cost) of GenCo ***e***
- Constraints:
  - Operation bounds
  - Investment constraints
- Variables: thermal installed capacity and thermal generation

$$\max \sum_{t\in e} \pi P_t - \sum_{t\in e} v_t P_t - \sum_{t\in e} f_t' IC_t - \sum_{t\in e} \gamma e_t P_t$$

$$0 \le P_t \le \bar{P}_t + IC_t \qquad \perp \mu_t, \nu_t \qquad \forall t \in e$$

$$0 \le IC_t \le \overline{IC}_t \qquad \perp \rho_t, \sigma_t \qquad \forall t \in e$$

Market revenues - variable operating costs

Thermal operating bounds

Investment decision constraints

KKT Optimality conditions for each company

$$\max z^e(x)$$

subject to:

$$g_k^e(x) \leq 0 \quad \perp \lambda_k^e$$
$$h_j^e(x) = 0 \quad \perp \mu_j^e$$

Lagrange function

$$\mathcal{L}^e(x,\lambda,\mu) = z^e + \sum_k \lambda_k^e g_k^e + \sum_j \mu_j^e h_j^e$$

KKT optimality conditions

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

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

$$\lambda_k^e g_k^e = 0 \quad g_k^e \leq 0 \quad \lambda_k^e \leq 0$$

GEP under a market equilibrium model of GenCo e. Langrangian function

$$\mathcal{L} = \sum_{t\in e} \pi P_t - \sum_{t\in e} v_t P_t - \sum_{t\in e} f_t' IC_t - \sum_{t\in e} \gamma e_t P_t + \\ + \mu_t (P_t) + \nu_t (P_t - \overline{P}_t \underline{\ \ } IC_t) + \\ + \rho_t (IC_t) + \sigma_t (IC_t - \overline{IC}_t)$$

GEP under a market equilibrium model of GenCo e. KKT Optimality conditions. Mixed complementarity problem (MCP) problem

$$\frac{\partial \mathcal{L}}{\partial P_t} = \pi + \pi' P_t - v_t - \gamma e_t + \mu_t + \nu_t = 0$$

$$\frac{\partial \mathcal{L}}{\partial IC_t} = -f_t' - \nu_t + \rho_t + \sigma_t = 0$$

$$P_t \geq 0 \quad \perp \quad \mu_t \geq 0$$

$$P_t \leq \overline{P}_t + IC_t \quad \perp \quad \nu_t \leq 0$$

$$IC_t \geq 0 \quad \perp \quad \rho_t \geq 0$$

$$IC_t \leq \overline{IC}_t \quad \perp \quad \sigma_t \leq 0$$

Equality constraints

Complementarity conditions and non negativity of variables

GEP under a market equilibrium model of GenCo 1 to E.

N

$$\frac{\partial \mathcal{L}}{\partial P_t} = \pi + \pi' P_t - v_t - \gamma e_t + \mu_t + \nu_t = 0$$

$$\frac{\partial \mathcal{L}}{\partial IC_t} = -f_t' - \nu_t + \rho_t + \sigma_t = 0$$

$$P_t \geq 0 \quad \perp \quad \mu_t \geq 0$$

$$P_t \leq \overline{P}_t + IC_t \quad \perp \quad \nu_t \leq 0$$

$$IC_t \geq 0 \quad \perp \quad \rho_t \geq 0$$

$$IC_t \leq \overline{IC}_t \quad \perp \quad \sigma_t \leq 0$$

$$\pi = f\left(\sum_e q_e\right) = D_0 - D_1 \sum_e q_e$$

$$q_e = \sum_{t \in e} P_t$$

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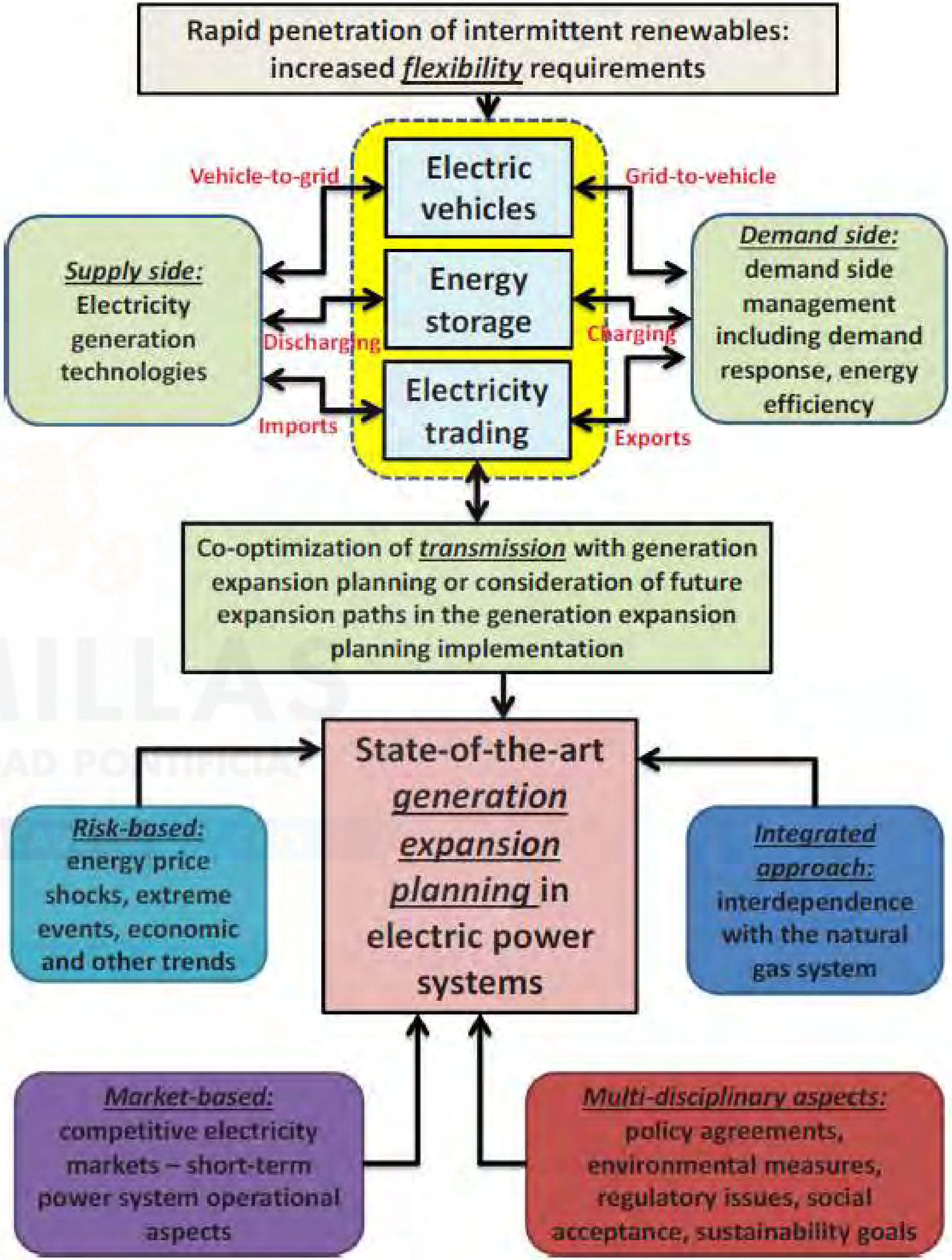
3

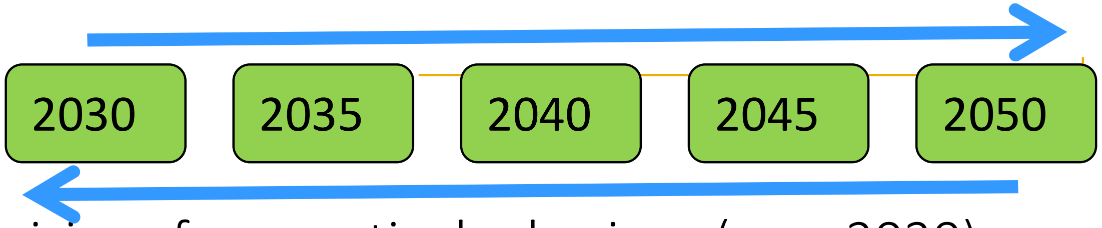
Modeling issues

Methodological framework



Nikolaos E. Koltsaklis, Athanasios S. Dagoumas *State-of-the-art generation expansion planning: A review* Applied Energy 230 (2018) 563–589

Modeling issues. Time scope



- Static planning
  - Determine optimal investment decisions for a particular horizon (year 2030) without representing how to achieve this optimal solution from now on
  - Can be useful as a “ideal” reference for very long-time horizons
- Dynamic planning
  - Determine optimal investment decisions since nowadays up to a particular horizon
  - More cumbersome to solve
- Ending effects or residual value of power plants
  - Complex to take care of
  - Time scope extended to “infinity”
  - Results must be stable w.r.t. this time scope
  - Alternatively, plants may have a residual value at the end of the horizon

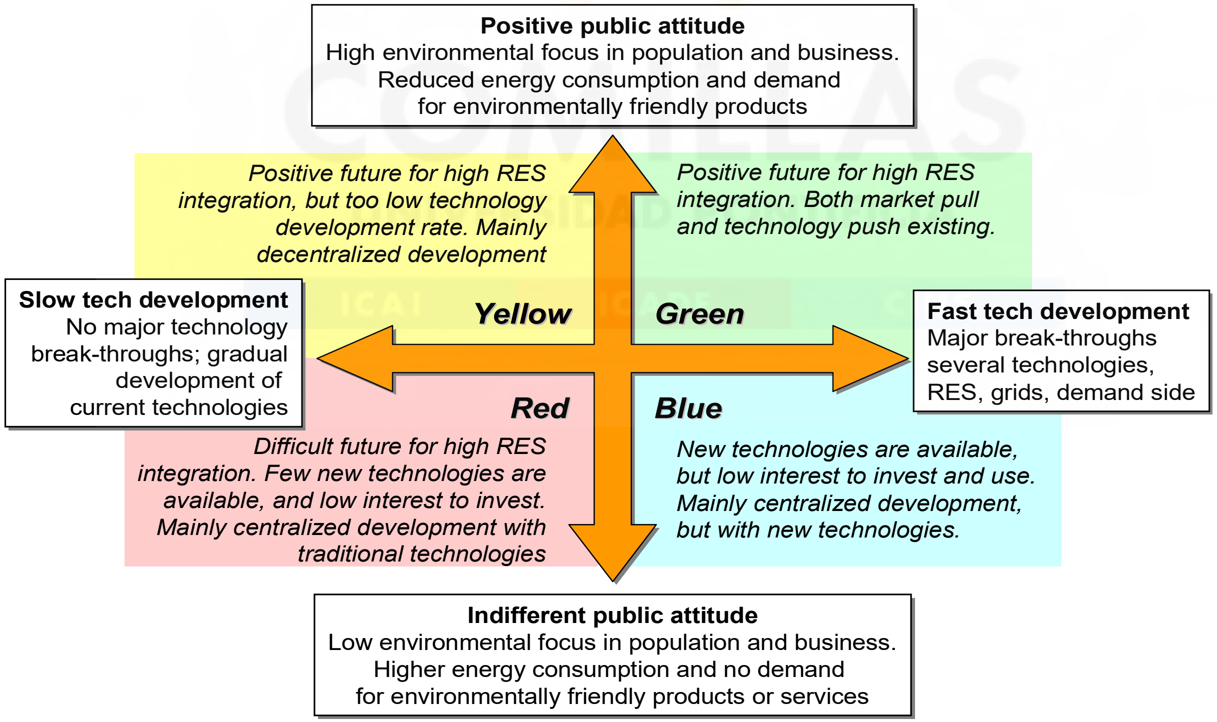
Modeling issues. Uncertainty

- Sources of uncertainty
  - Electricity demand growing or stagnating. Macroeconomic data
  - Demand side management programs
  - Cost and availability of fuels and generation technologies
  - Inflation and discount rate
  - Plant building time. Generator reliability
  - Climate conditions (hydro inflows, wind, sun, temperature)
  - Connected markets behavior
  - Regulatory changes (capacity payments, subsidies to renewable energy)
  - Public opinion
- Modeling uncertainty
  - Deterministic approach usually leads to optimistic results
  - Scenario or sensitivity analysis
    - Robustness
    - Flexibility
  - Stochastic approach as a way of doing risk management

General Scope

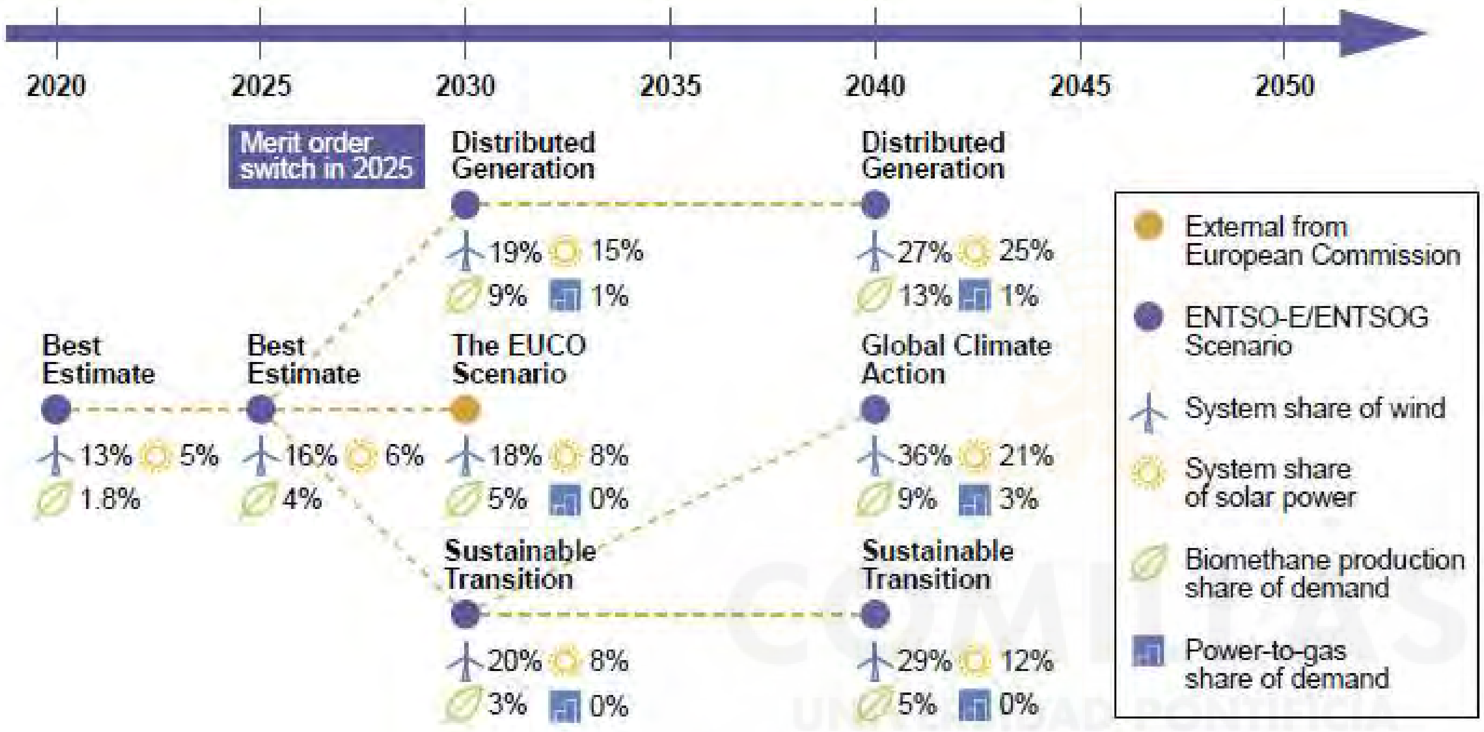
- Generation Expansion Planning (GEP) or Integrated Resource Planning (IRP)
  - GEP included in the optimization: GEP+TEP
  - GEP as an external input
    - Single scenario vs. uncertain GEP

Implies using methods to cope with non-random uncertainties (exogenous storylines/pathways/options)

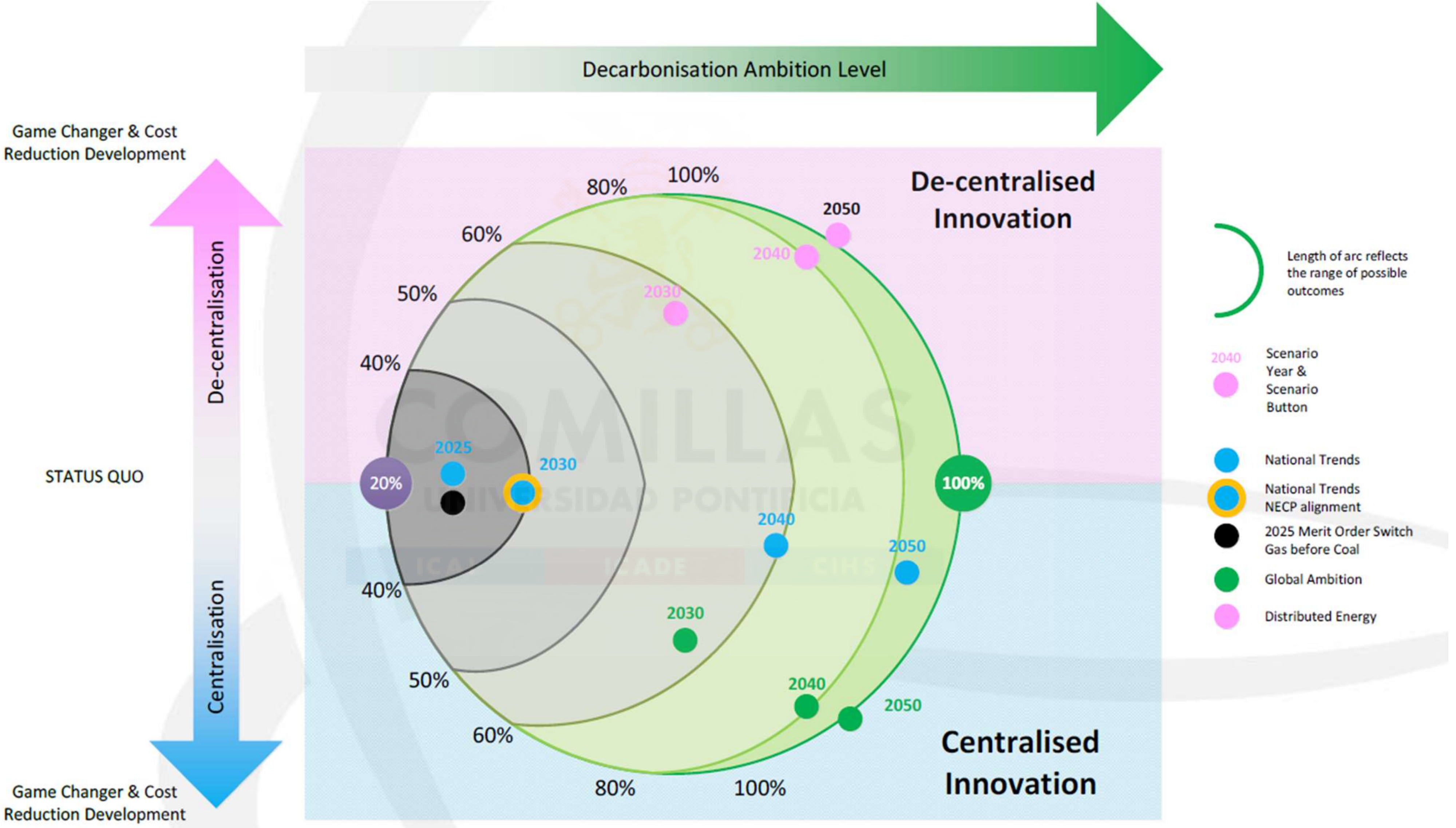


Source: SUSPLAN (http://www.susplan.eu/) Planning for Sustainability

Future storylines for TYNDP 2018



TYNDP. Scenario Report



https://www.entsos-tyndp2020-scenarios.eu/#download

Modeling issues. Demand

- Base data:
  - Load duration curve represented by load levels
  - Chronological hourly data
- High penetration of RES generation introduces additional complexities (variability and uncertainty)
- Load profile changes due to demand response actions
- Yearly growing rate depending on macroeconomic parameters (GDP)

Modeling issues. Economic parameters

- Investment cost
  - Charged over the life span
  - Net present value (NPV) is computed
  - Discount rate considered (WACC, weighted average capital cost)

- Operation cost
  - Strongly dependent of the fuel cost

- Each technology has a different time profile on investment and operation cost

Levelized costs of electricity (LCOE)

Figure 4.16a: United States – levelised costs of electricity
(at 5% discount rate)

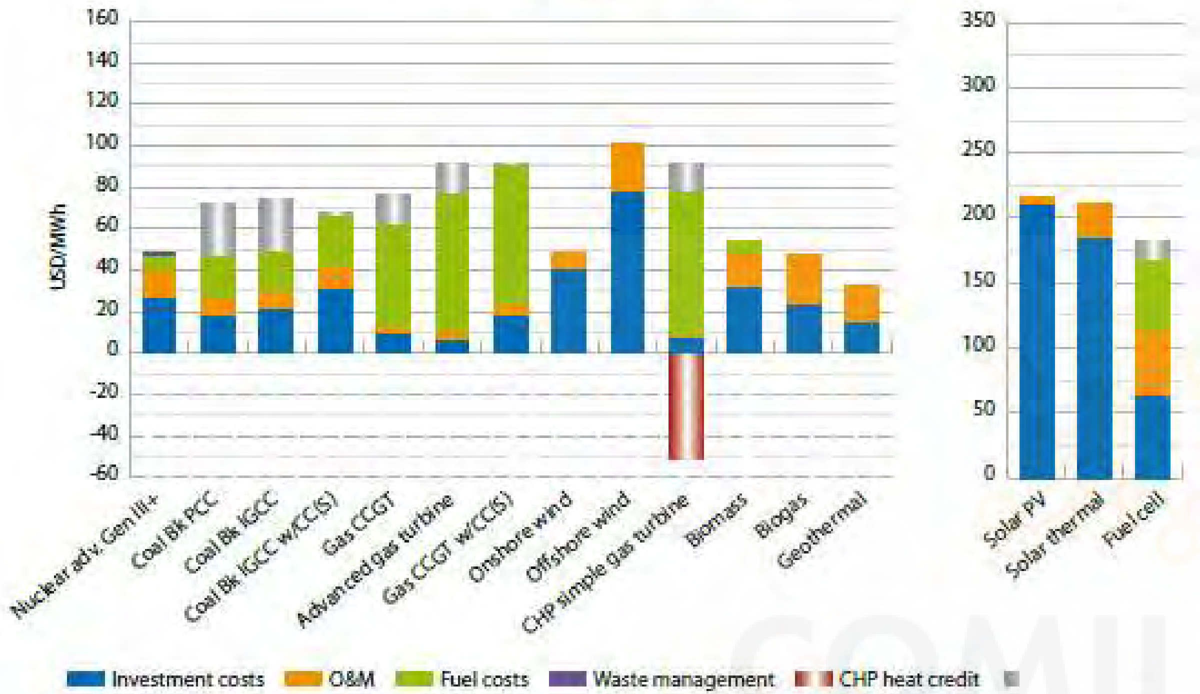
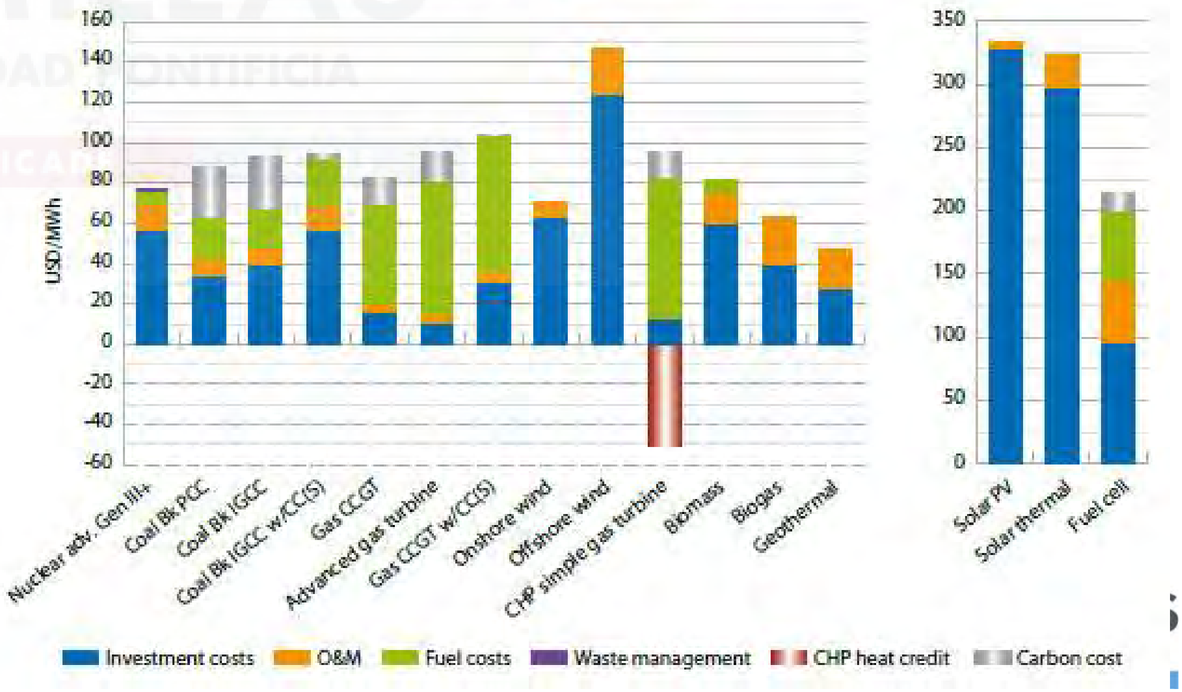


Figure 4.16b: United States – levelised costs of electricity
(at 10% discount rate)



Source: Projected Cost of Generating Electricity – 2010 Edition. International Energy Agency.

Levelized costs of electricity (LCOE)

Figure 4.23a: US EPRI levelised costs of electricity
(at 5% discount rate)

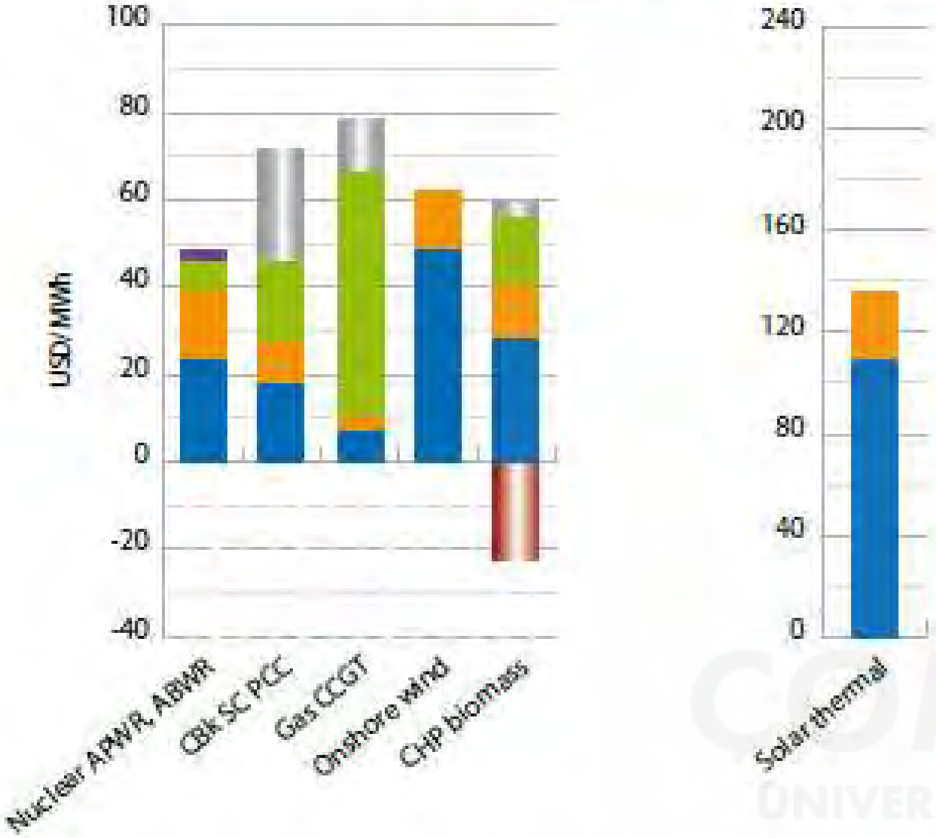
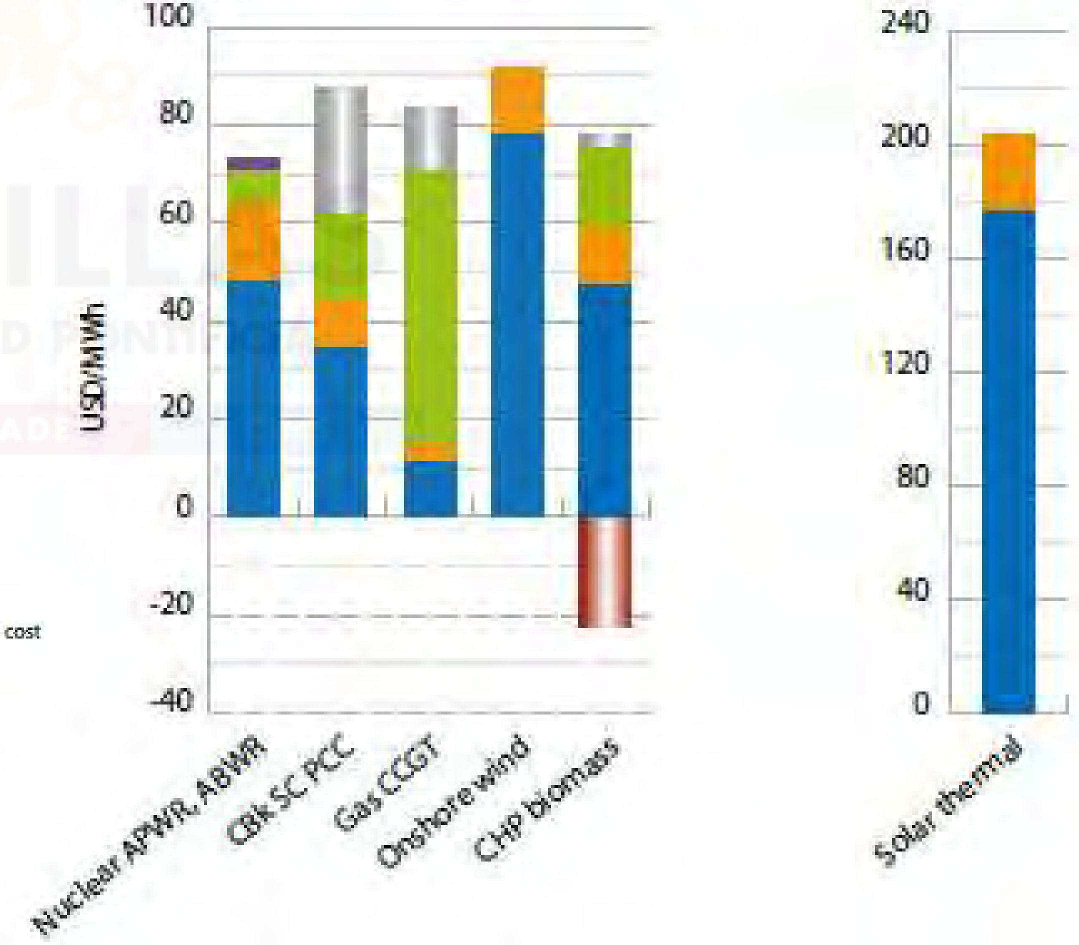


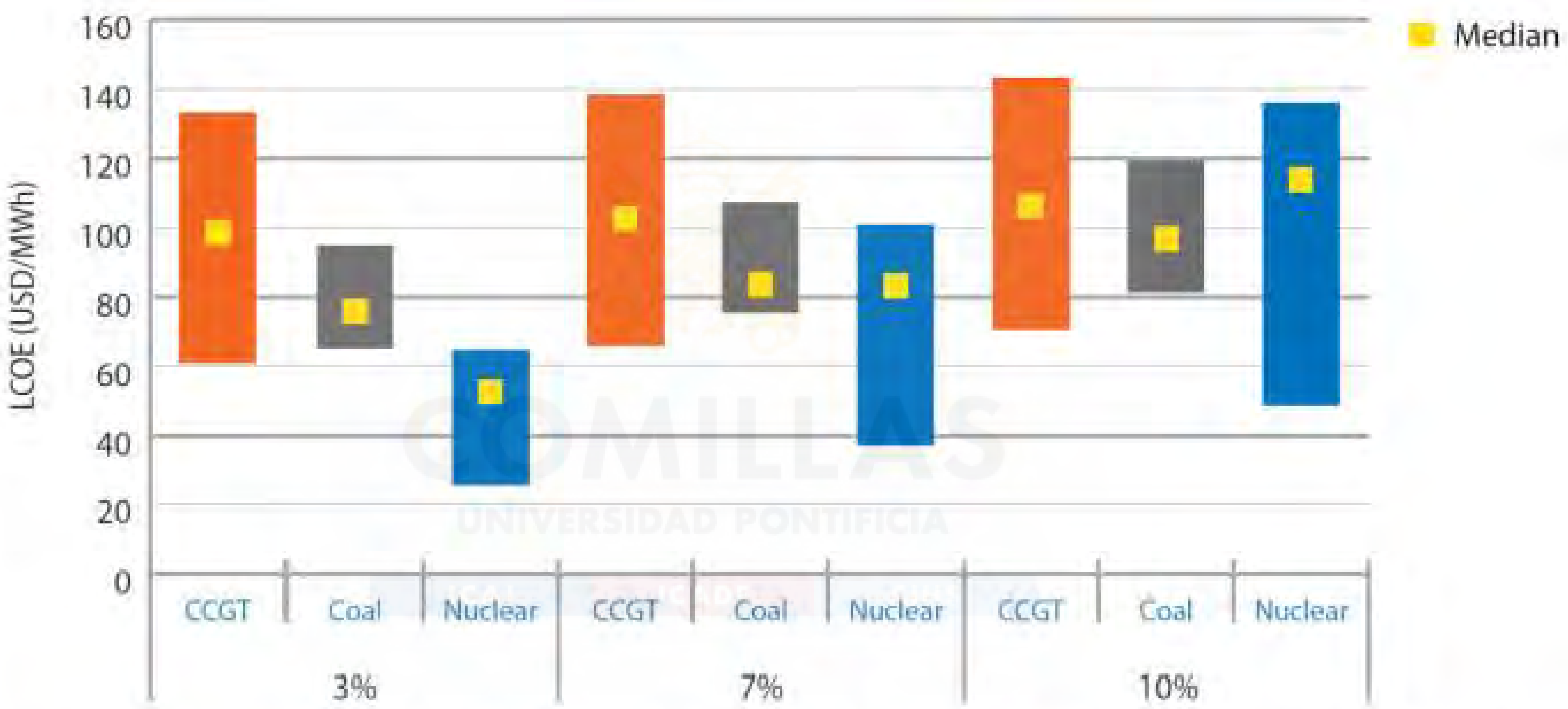
Figure 4.23b: US EPRI levelised costs of electricity
(at 10% discount rate)



Investment costs O&M Fuel costs Waste management CHP heat credit Carbon cost

Source: Projected Cost of Generating Electricity – 2010 Edition. International Energy Agency.

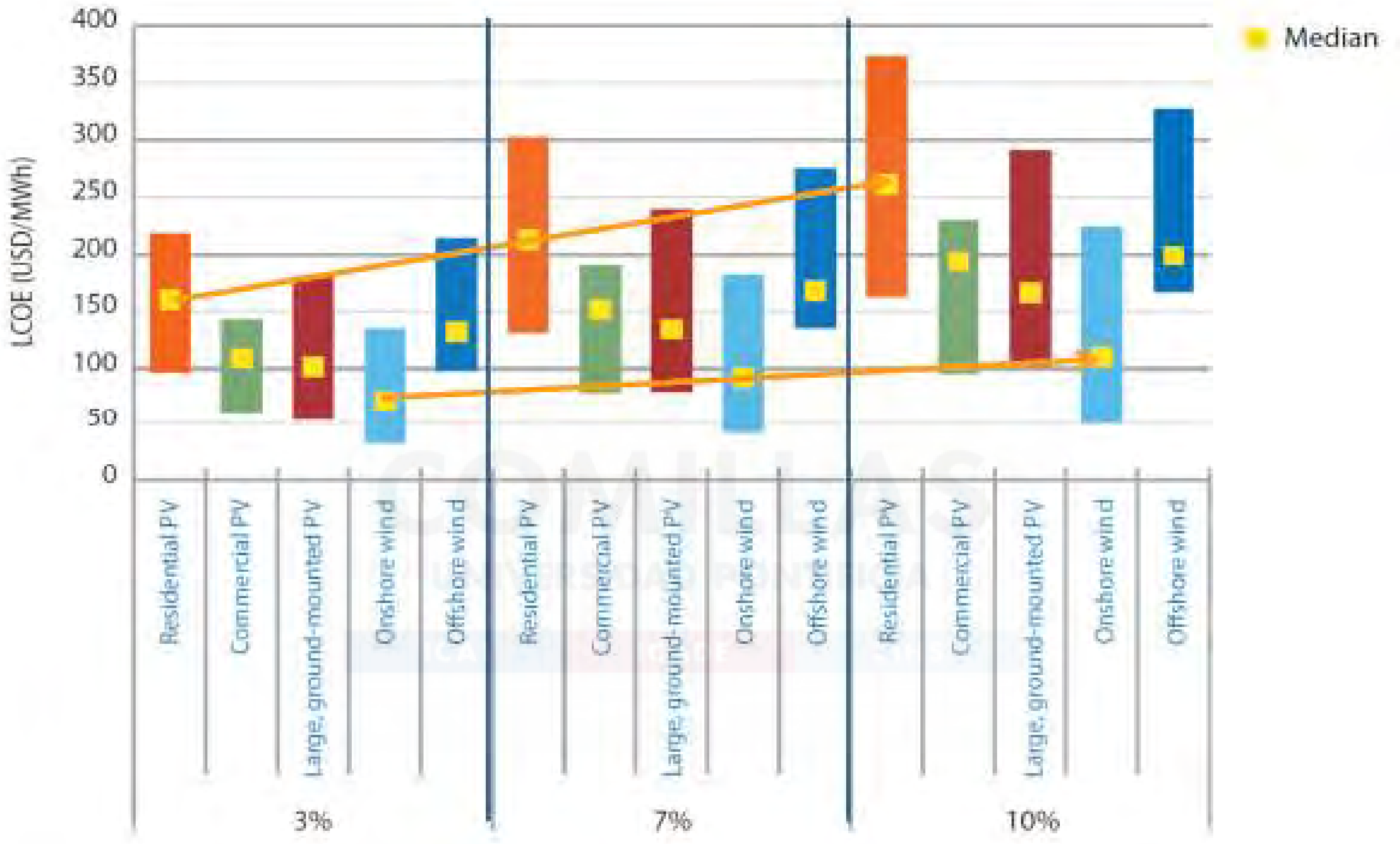
Levelized costs of electricity (LCOE) 2015



Note: Assumes region-specific fuel prices for US, Europe, Asia; 85% load factor; CO_2 price of 30 USD/tonne.

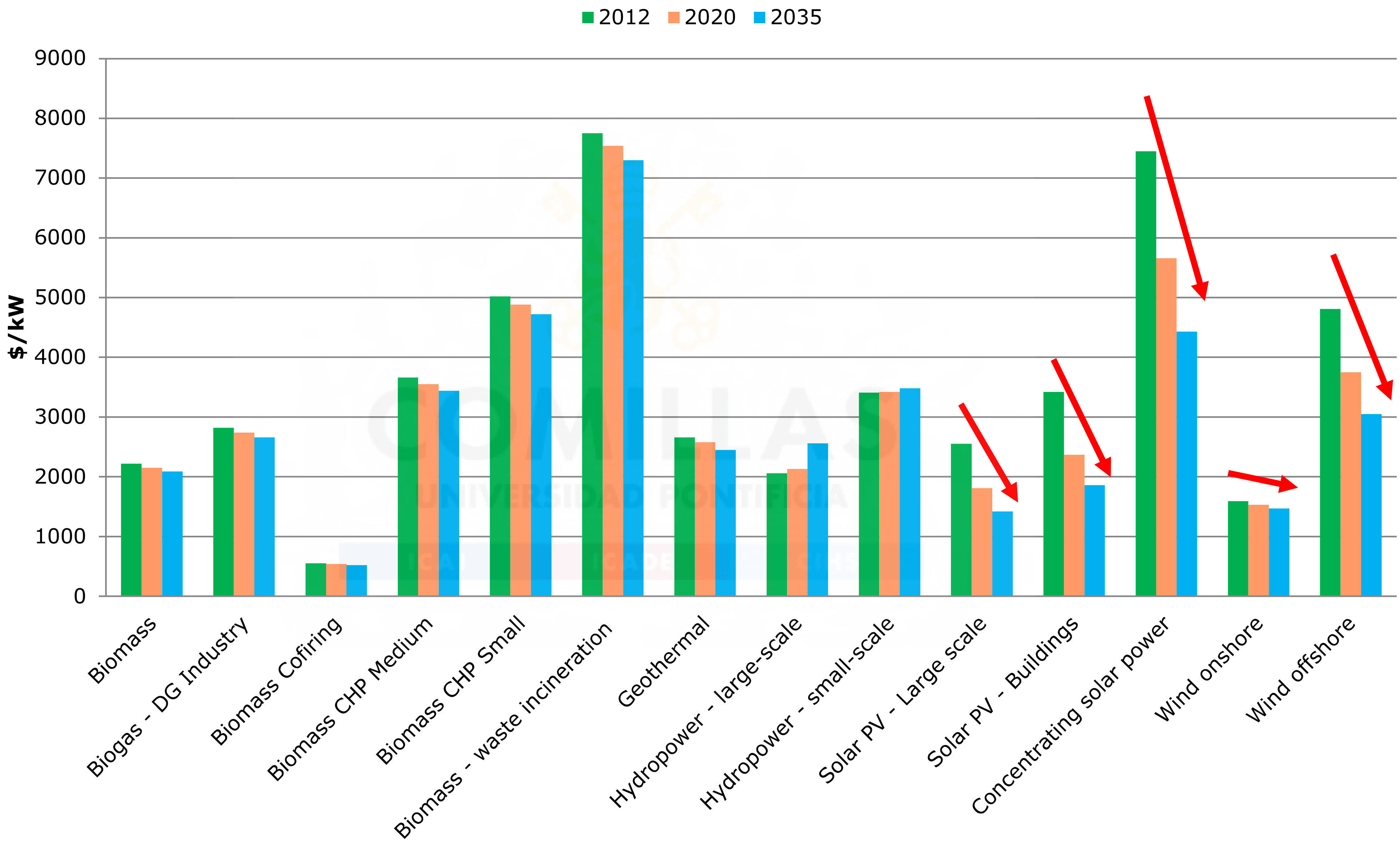
IEA *Projected Costs of Generating Electricity 2015 Edition* https://www.iea.org/Textbase/nptoc/ElecCost2015TOC.pdf

Levelized costs of electricity (LCOE) 2015



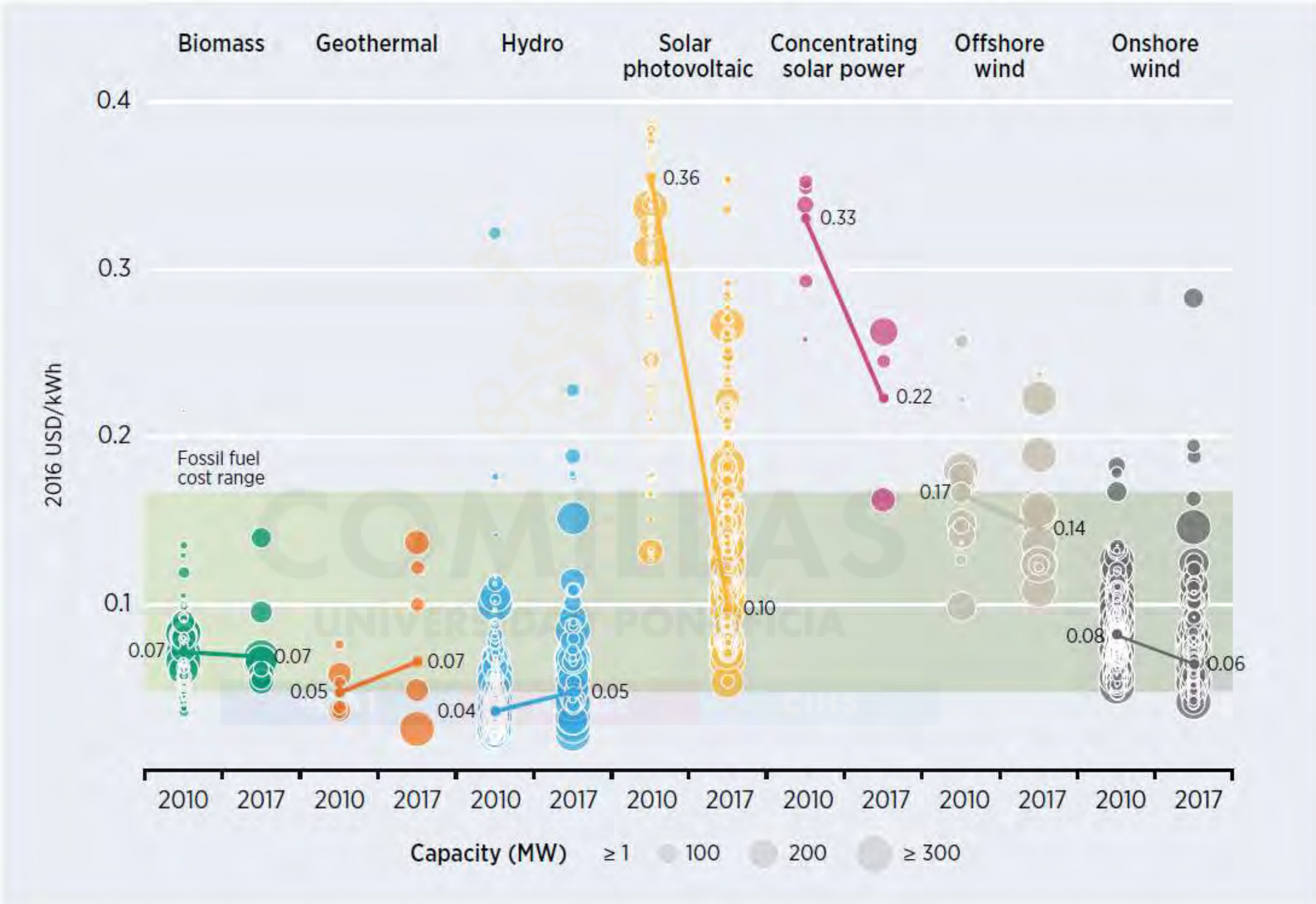
IEA *Projected Costs of Generating Electricity 2015 Edition* https://www.iea.org/Textbase/nptoc/ElecCost2015TOC.pdf

Investment cost for RES



Source: Own elaboration based on IEA (2014). World Energy Outlook

Global LCOE from utility-scale RES technologies



Source: IRENA Renewable Cost Database.

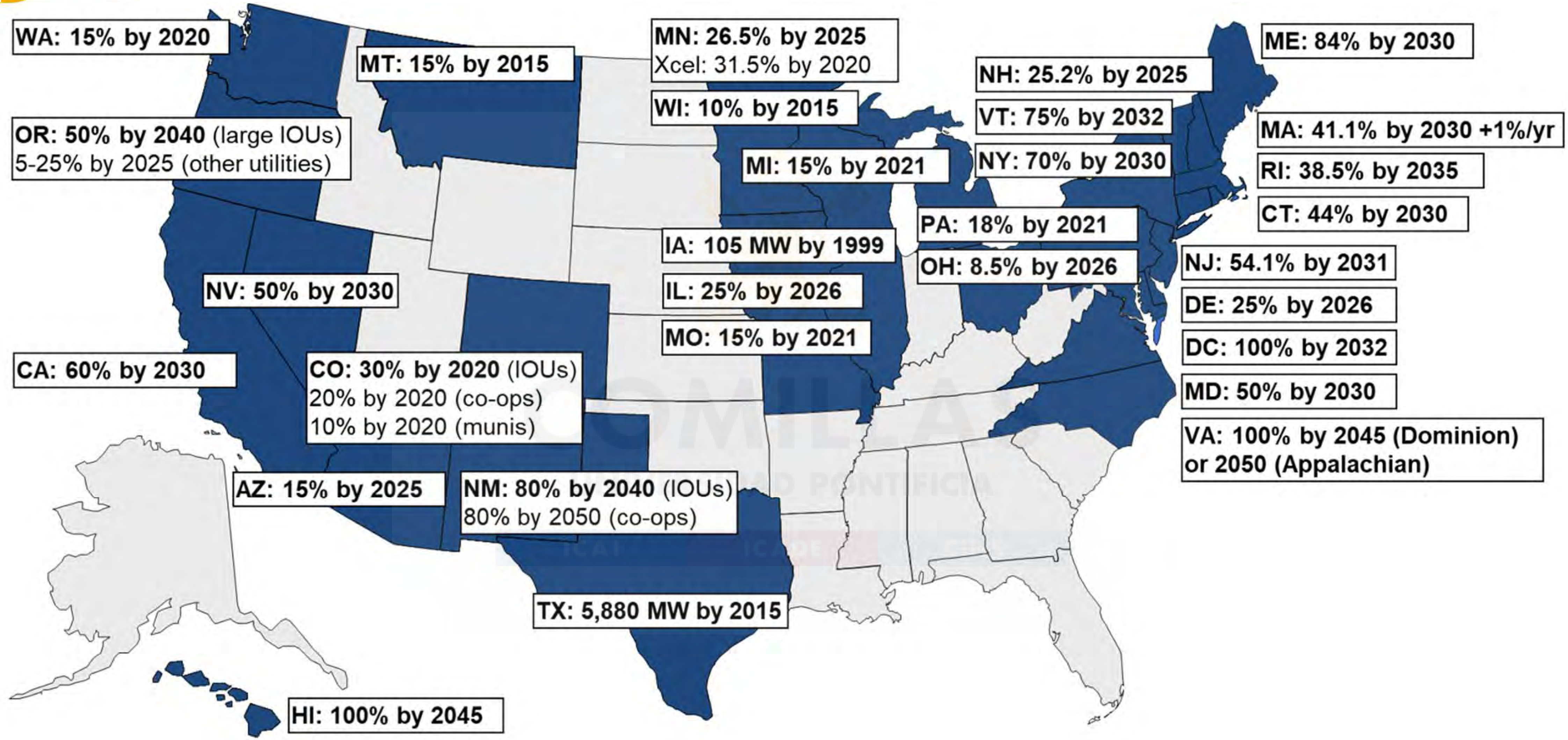
Note: The diameter of the circle represents the size of the project, with its centre the value for the cost of each project on the Y axis. The thick lines are the global weighted average LCOE value for plants commissioned in each year. Real weighted average cost of capital is 7.5% for OECD countries and China and 10% for the rest of the world. The band represents the fossil fuel-fired power generation cost range.

http://www.irena.org/publications/2018/Jan/Renewable-power-generation-costs-in-2017

Modeling issues. Environment

- Usually included as constraints
- CO2 emission allowance markets require a more complex representation
- Subsidies to the use of renewable energy sources are political decisions

USA Renewable Portfolio Standards (RPS). July 2019



https://emp.lbl.gov/projects/renewables-portfolio

Modeling issues. Reliability

- Typically used as a reference criterion from regulator point of view
- Deterministic measure:
  - Reserve margin
- Probabilistic measures:
  - Loss of Load Probability (LOLP)
  - Expected Energy Not Served (EENS)
- Emergency operation actions as contracted load shedding can be incorporated

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Prototype GEP. Mathematical formulation

Mathematical formulation

- Objective function
  - Minimize the total investment and operation costs
- Investment variables
  - *Investment decisions (what capacity to install)*
- Operation variables for each year
  - Commitment, startup and shutdown of thermal units
  - Thermal, storage hydro and pumped storage hydro output
- Investment constraints
  - Operating capacity lower than installed capacity
- Operation constraints for each year
  - Inter-period
    - Storage hydro and pumped storage hydro scheduling
  - Intra-period
    - Load and reserve balance
    - Detailed hydro basin modeling
    - Thermal, hydro and pumped-storage operation constraints

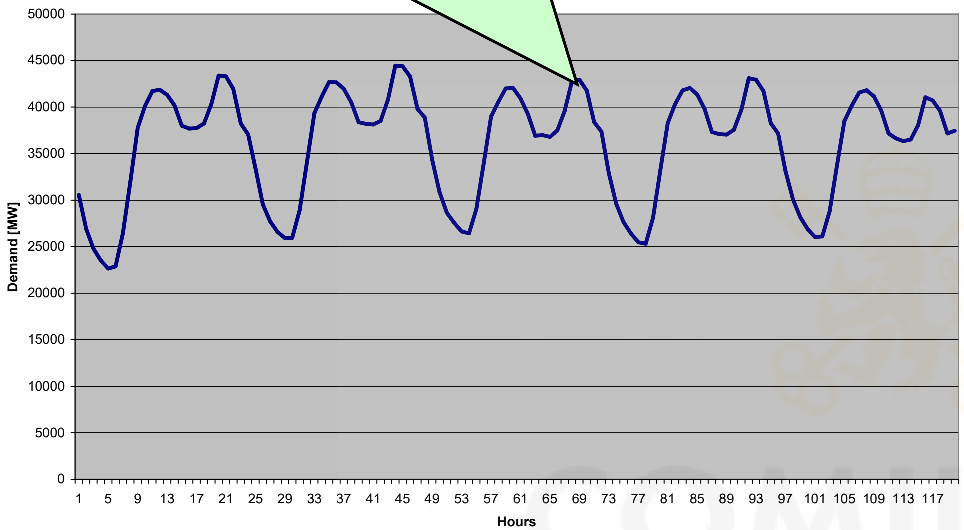
Indices

- Time scope
  - 5 years
- Period
  - 1 month
- Subperiod
  - weekdays and weekends
- Load level
  - peak, shoulder and off-peak

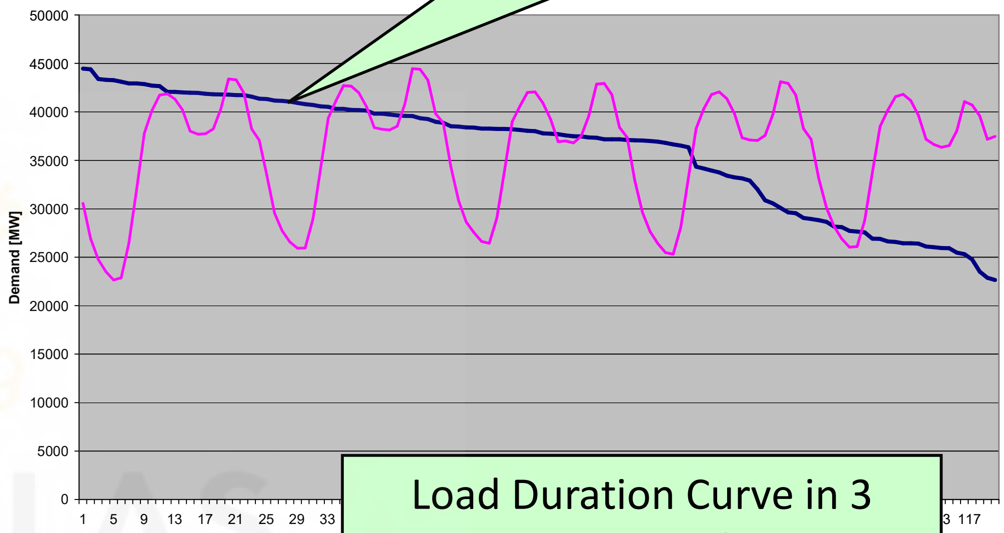
$Year$	y
$Period$	p
$Subperiod$	s
$Load\ level$	n

Demand (5 weekdays)

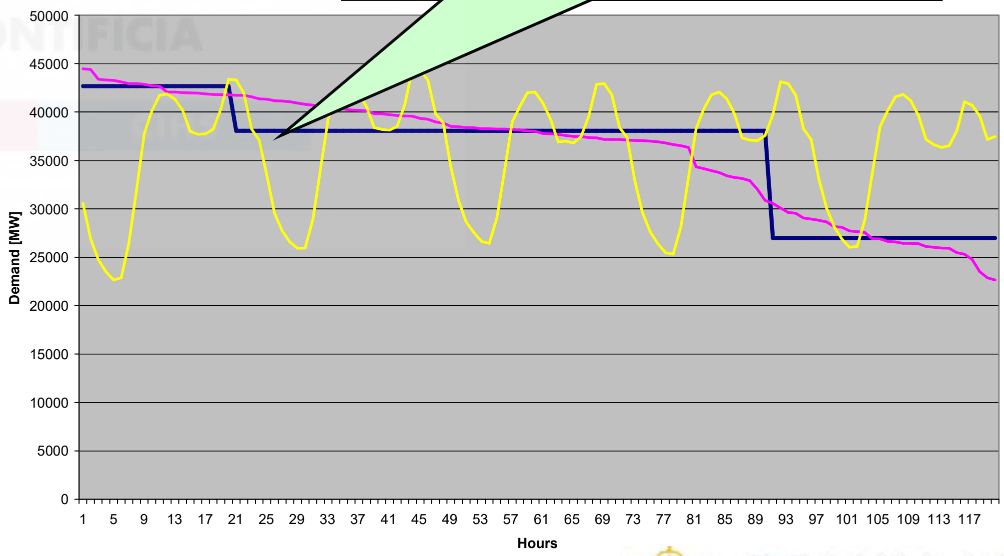
Chronological Load Curve



Load Duration Curve



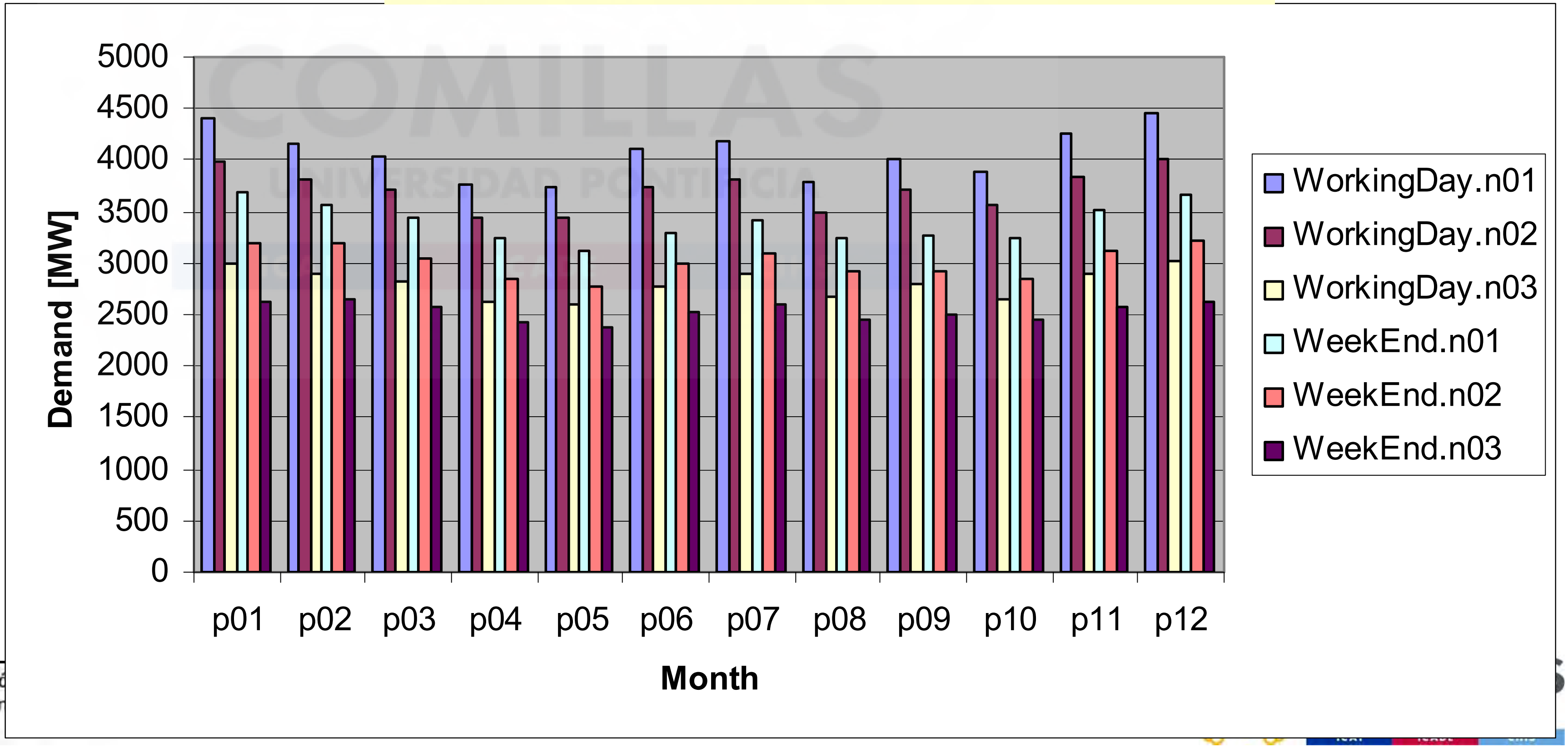
Load Duration Curve in 3 Load Levels



Demand

- Monthly demand with several load levels
  - Peak, shoulder and off-peak for weekdays and weekends
- All the weekdays of the same month are similar (same for weekends)

Demand	[MW]	D_{psn}
Duration	[h]	d_{psn}
Cumm. yearly demand growth	[p.u.]	I_y



Technical characteristics of thermal units (t)

- Maximum and minimum output
- Fuel cost
- Slope and intercept of the heat rate straight line
- Operation and maintenance (O&M) variable cost
  - No load cost = fuel cost x heat rate intercept
  - Variable cost = fuel cost x heat rate slope + O&M cost
- Cold startup and shutdown cost
- Equivalent forced outage rate (EFOR)

Max and min output of existing capacity	[MW]	$\overline{p}_t, \underline{p}_t$
No load cost	[€/h]	f_t
Variable cost	[€/MWh]	v_t
Startup, shutdown cost	[€]	su_t, sd_t
EFOR	[p.u.]	q_t

Technical characteristics of new hydro and thermal units (t) (h)

- Investment cost
- Fixed charge rate
  - Annual investment cost = Overnight investment cost x Fixed charge rate
- Maximum installed capacity by year

Annual investment cost	[€ / kW]	f'_t, f'_h
Maximum installed capacity	[MW]	$\overline{ic}_t, \overline{ic}_h$

Technical characteristics of hydro plants (h)

- Maximum and minimum output
- Production function (efficiency for conversion of water inflow to electric power)
- Round-trip efficiency of pumped storage hydro plants
  - Only this ratio of the energy consumed to pump the water is recovered by turbining it

Max and min output	$[MW]$	$\overline{p}_h, \underline{p}_h$
Production function	$[kWh/m^3]$	c_h
Efficiency	$[p.u.]$	η_h

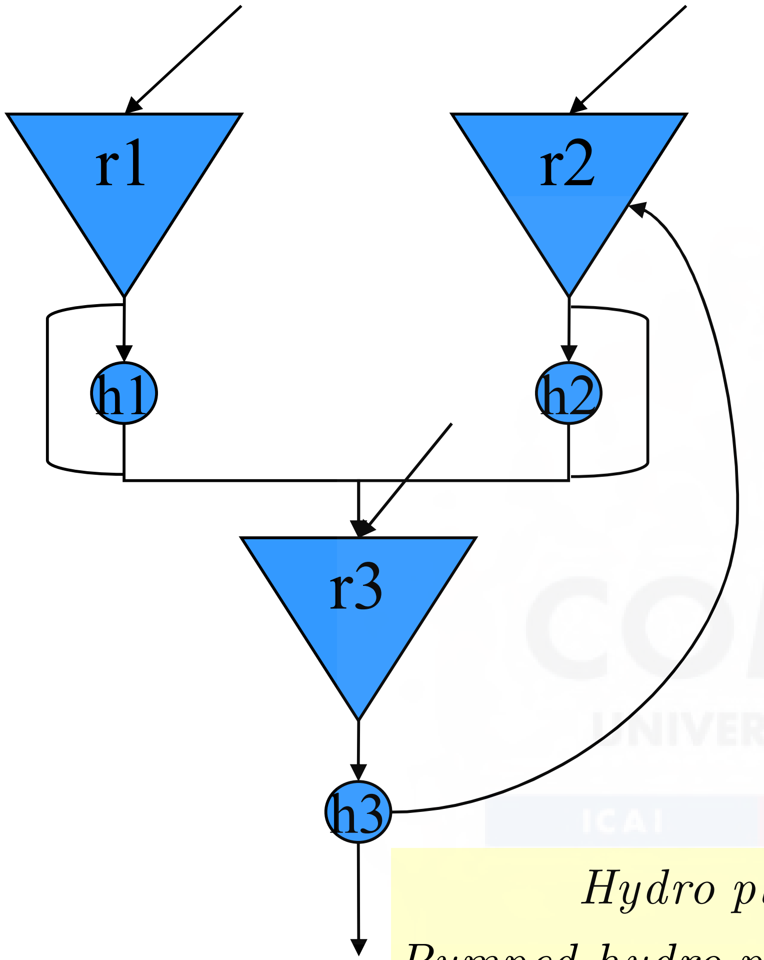
Technical characteristics of hydro reservoirs (r)

- Maximum and minimum reserve
- Initial reserve for every year
  - Final reserve = initial reserve
- Stochastic inflows independent for every year

- Assumption: There is no coupling in reservoir levels or inflows between consecutive years

Max and min reserve	$[hm^3]$	$\overline{r}_r, \underline{r}_r$
Initial and final reserve	$[hm^3]$	r'_r
Stochastic inflows	$[m^3/s]$	i^{ω}_{pr}

Hydro topology



Only one spillage per reservoir can be considered

Hydro plant upstream of reservoir	$h \in up(r)$	$hur(h,r)$	$(h1,r3)$
Pumped hydro plant upstream of reservoir	$h \in up(r)$	$hpr(h,r)$	$(h3,r2)$
Reservoir upstream of hydro plant	$h \in dw(r)$	$ruh(r,h)$	$(r2,h2)$
Reservoir upstream of pumped hydro plant	$h \in dw(r)$	$rph(r,h)$	$(r3,h3)$
Reservoir upstream of reservoir	$r' \in up(r)$	$rur(r,r)$	$(r1,r3)$

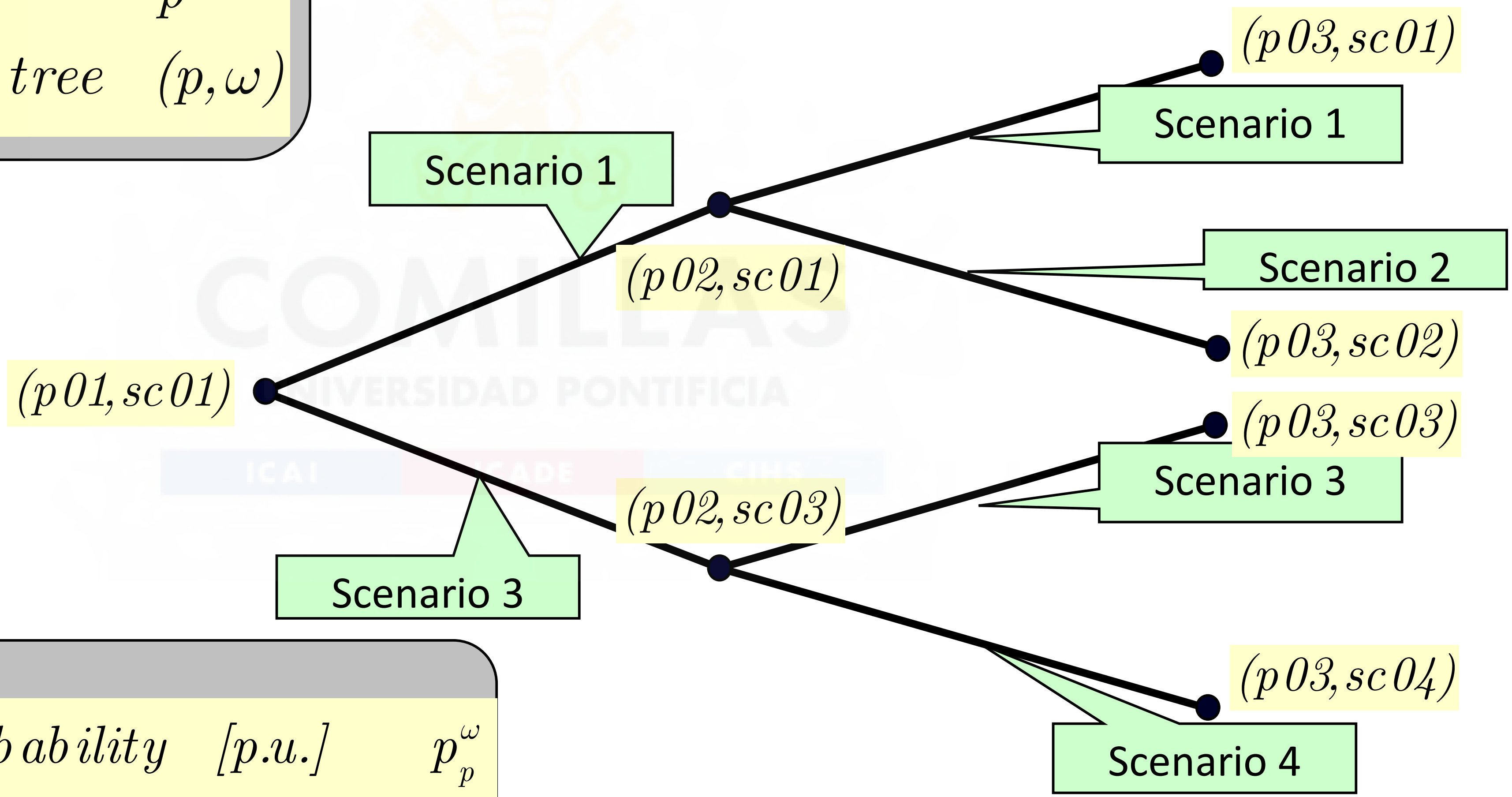
Scenario tree. Ancestor and descendant

Tree structure

Scenario	ω
Period	p
Scenario tree	(p,ω)

Tree relations

$$\omega' \in a(\omega) \quad (p02,sc03) \in a\left[(p03,sc03)\right]$$



Tree data

Scenario probability	[p.u.]	p_p^ω
Stochastic inflows	$[m^3/s]$	i_{pr}^ω

Other system parameters

- Non served energy cost
- Non served operating power reserve
- Operating power reserve

Non served energy cost	[€/MWh]	v'
Non served power cost	[€/MW]	v''
Operating reserve	[MW]	O_{ps1}

Investment variables

- New installed capacity of a generating unit in every year

$$Installed\ capacity\ of\ any\ unit\ in\ year\ y \quad [MW] \quad IC_{yt}, IC_{yh}$$

Operation variables for each year

- Commitment, startup and shutdown of thermal units

$$\text{Commitment, startup and shutdown} \quad \{0,1\} \quad UC^{\omega}_{ypst}, SU^{\omega}_{ypst}, SD^{\omega}_{ypst}$$

- Production of hydro and thermal units

$$\text{Production of a thermal or hydro unit} \quad [MW] \quad P^{\omega}_{ypsnt}, P^{\omega}_{ypsnh}$$

- Consumption of pumped storage hydro plants

$$\text{Consumption of a hydro plant} \quad [MW] \quad C^{\omega}_{ypsnh}$$

- Reservoir levels

$$\text{Reservoir level} \quad [hm^3] \quad R^{\omega}_{ypr}$$

- Non served energy and power

$$\text{Non served energy and power} \quad [MW] \quad ENS^{\omega}_{ypsn}, PNS^{\omega}_{yps}$$

Constraints: Operating power reserve

Committed output of thermal units

+ Maximum output of hydro plants

+ Non served power

≥ Demand

+ Operating reserve *for peak load level, subperiod, period, year and scenario*

nonlinear

$$\sum_{t}\left(\overline{p}_{t}+\sum_{z\leq y} IC_{zt}\right)UC^{\omega}_{ypst}+\sum_{h}\left(\overline{p}_{h}+\sum_{z\leq y} IC_{zh}\right)+PNS^{\omega}_{yps}\geq\left(D_{ps1}+O_{ps1}\right)I_{y}\qquad\forall\omega yps$$

Constraints: Generation and load balance

Generation of thermal units

+ Generation of storage hydro plants

– Consumption of pumped storage hydro plants

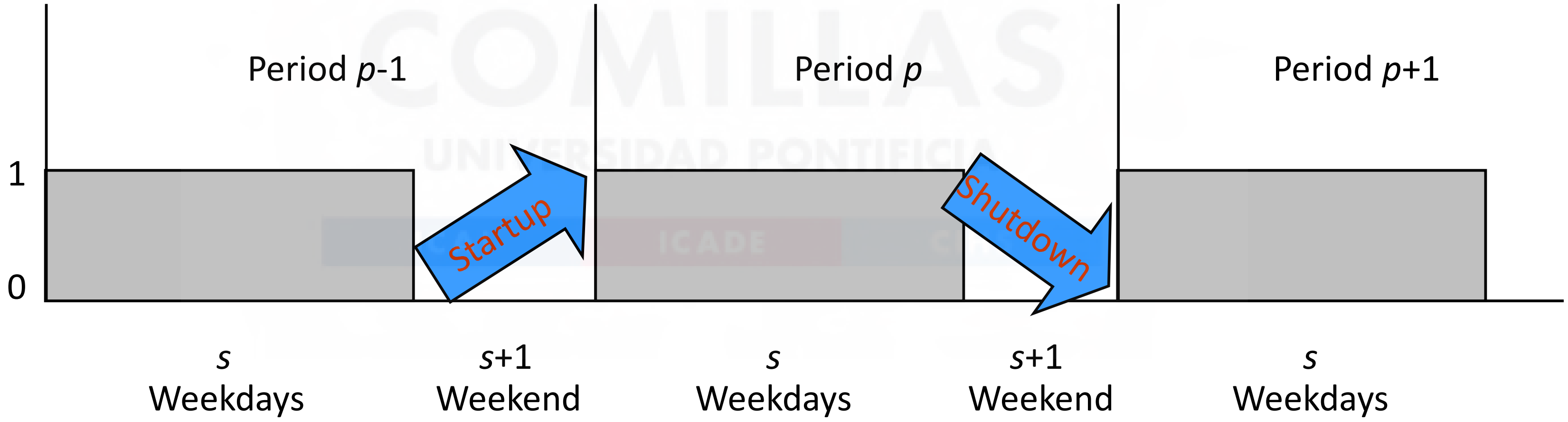
+ Non served energy

= Demand *for each load level, subperiod, period, year and scenario*

$$\sum_t P^{\omega}_{ypsnt} + \sum_h P^{\omega}_{ypsnh} - \sum_h C^{\omega}_{ypsnh} + ENS^{\omega}_{ypsn} = D_{psn} I_y \quad \forall \omega ypsn$$

Constraints: Commitment, startup and shutdown

- All the weekdays of the same month are similar (same for weekends)
- Commitment decision of a thermal unit
- Assumption: no startup between periods of consecutive years



Constraints: Commitment, startup and shutdown

- Startup of thermal units can only be made in the transition between consecutive weekend and weekdays

$$\begin{aligned}&\textit{Commitment of a thermal unit in a weekday}\\ &- \textit{Commitment of a thermal unit in the weekend of previous period}\\ &= \textit{Startup of a thermal unit in this weekday}\\ &- \textit{Startup of a thermal unit in this weekday}\end{aligned}$$

$$UC^{\omega}_{ypst} - UC^{\omega'}_{yp-1s+1t} = SU^{\omega}_{ypst} - SD^{\omega}_{ypst} \quad \forall \omega ypst \quad \omega' \in a(\omega)$$

- Shutdown only in the opposite transition

$$\begin{aligned}&\textit{Commitment of a thermal unit in a weekend}\\ &- \textit{Commitment of a thermal unit in the previous weekday}\\ &= \textit{Startup of a thermal unit in this weekend}\\ &- \textit{Shutdown of a thermal unit in this weekend}\end{aligned}$$

$$UC^{\omega}_{yps+1t} - UC^{\omega}_{ypst} = SU^{\omega}_{yps+1t} - SD^{\omega}_{yps+1t} \quad \forall \omega ypst$$

Constraints: Commitment and production

Production of a thermal unit
≥ Commitment of a thermal unit times the minimum output reduced by availability rate

Production of a thermal unit
≤ Commitment of a thermal unit times the maximum output reduced by availability rate

nonlinear　　　　　　　　　　　　　　　　nonlinear

$$UC^{\omega}_{ypst}\left(\overline{p}_t + \sum_{z\le y} IC_{zt}\right)\frac{\underline{p}_t}{\overline{p}_t}(1-q_t) \le P^{\omega}_{ypsnt} \le UC^{\omega}_{ypst}\left(\overline{p}_t + \sum_{z\le y} IC_{zt}\right)(1-q_t) \quad \forall \omega ypsnt$$

- If the thermal unit is committed ($UC^{\omega}_{ypst} = 1$) it can produce between its minimum and maximum output
- If the thermal unit is not committed ($UC^{\omega}_{ypst} = 0$) it can't produce

Constraints: Water balance for each reservoir

Reservoir volume at the beginning of the period

– Reservoir volume at the end of the period

+ Natural hydro inflows

– Spills from this reservoir

+ Spills from upstream reservoirs

+ Turbined water from upstream storage hydro plants

– Turbined and pumped water from this reservoir

+ Pumped water from upstream pumped hydro plants = 0 *for each reservoir, period, year and scenario*

$$R^{\omega'}_{yp-1r} - R^{\omega}_{ypr} + i^{\omega}_{pr} - S^{\omega}_{ypr} + \sum_{r' \in up(r)} S^{\omega}_{ypr'}$$

$$+ \sum_{\substack{sn \\ h \in up(r)}} d_{psn} P^{\omega}_{ypsnh} / c_h - \sum_{\substack{sn \\ h \in dw(r)}} d_{psn} P^{\omega}_{ypsnh} / c_h$$

$$+ \sum_{\substack{sn \\ h \in up(r)}} d_{psn} C^{\omega}_{ypsnh} \eta_h / c_h - \sum_{\substack{sn \\ h \in dw(r)}} d_{psn} C^{\omega}_{ypsnh} \eta_h / c_h = 0 \qquad \forall \omega y p r \quad \omega' \in a(\omega)$$

Constraints: Operation limits

Reservoir volumes between limits for each hydro reservoir

$$\underline{r}_r \leq R^{\omega}_{ypr} \leq \overline{r}_r \qquad \forall \omega y p r$$

$$R_{0r} = R^{\omega}_{yPr} = r'_r \quad \forall \omega y r$$

Operation power lower than existing + installed capacity

$$0 \leq P^{\omega}_{ypsnt} \leq \left(\overline{p}_t + \sum_{z \leq y} IC_{zt}\right)(1 - q_t) \quad \forall \omega ypsnt$$

$$0 \leq P^{\omega}_{ypsnh}, C^{\omega}_{ypsnh} \leq \left(\overline{p}_h + \sum_{z \leq y} IC_{zh}\right) \quad \forall \omega ypsnh$$

Commitment, startup and shutdown for each unit

$$UC^{\omega}_{ypst}, SU^{\omega}_{ypst}, SD^{\omega}_{ypst} \in \{0, 1\} \quad \forall \omega ypst$$

Constraints: Installed capacity limits

Installed capacity below limit for every year

$$0 \leq IC_{yt} \leq \overline{ic_t} \quad \forall yt$$

$$0 \leq IC_{yh} \leq \overline{ic_h} \quad \forall yh$$

Weighted-sum objective function

- Minimize
  - Investment costs

$$\sum_{yt} f_t' IC_{yt} + \sum_{yh} f_h' IC_{yh}$$

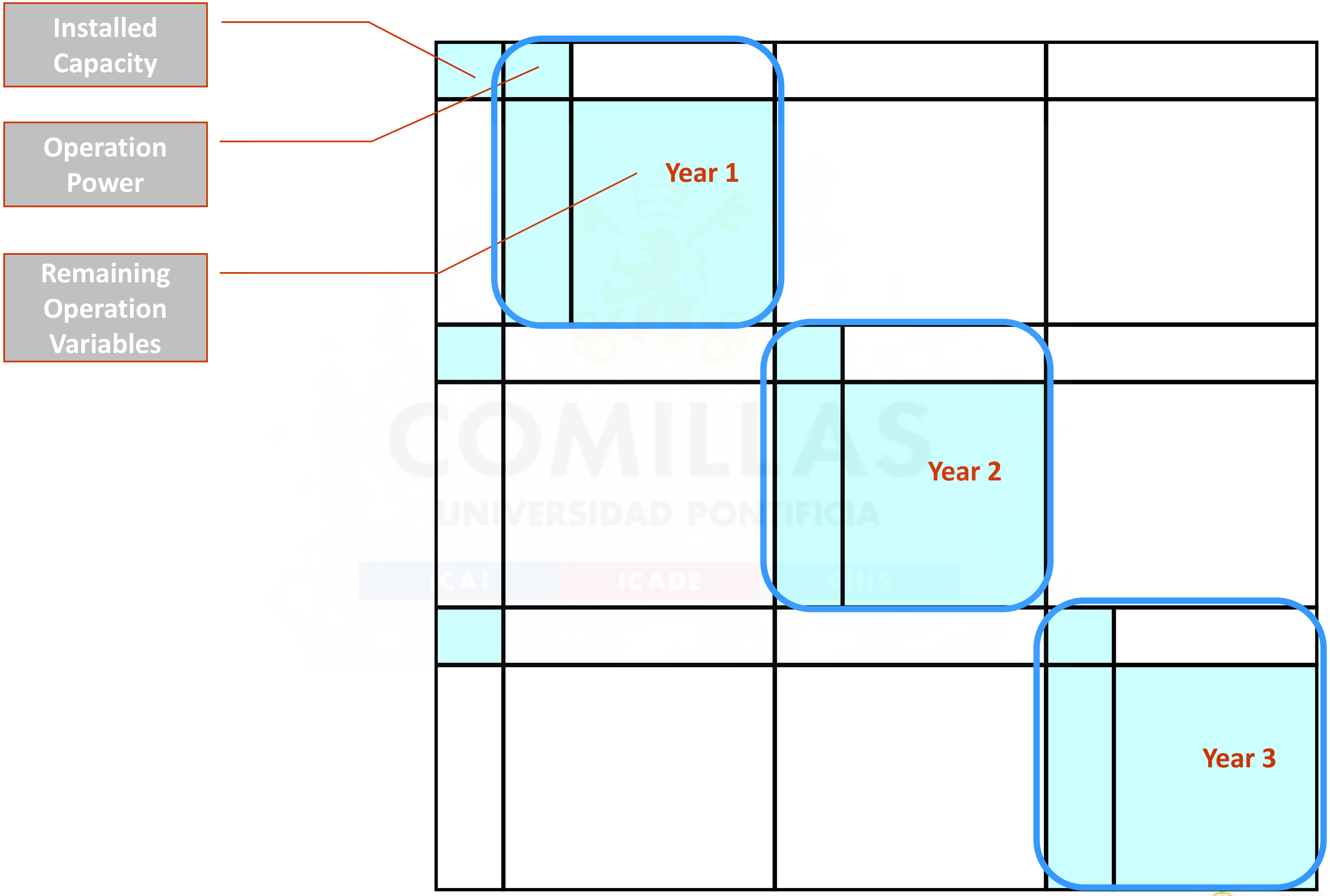
  - Expected thermal variable costs

$$\sum_{\omega ypst} p_p^\omega su_t SU_{ypst}^\omega + \sum_{\omega ypst} p_p^\omega sd_t SD_{ypst}^\omega + \sum_{\omega ypsnt} p_p^\omega d_{psn} f_t UC_{ypst}^\omega + \sum_{\omega ypsnt} p_p^\omega d_{psn} v_t P_{ypsnt}^\omega$$

  - Expected penalties introduced in the objective function for energy and power non served

$$\sum_{\omega ypsn} p_p^\omega d_{psn} v' ENS_{ypsn}^\omega + \sum_{\omega yps} p_p^\omega v'' PNS_{yps}^\omega$$

Structure of the constraint matrix of the optimization problem



1. Generation expansion planning
2. Simple GEP models
3. Modeling issues
4. Prototype GEP. Mathematical formulation
5. Prototype GEP. Computer implementation
6. Takeaways

5

Prototype GEP.

Computer implementation

StarGenLite_GEPM Long-Term Transmission Expansion Model (https://pascua.iit.comillas.edu/aramos/StarGenLite_GEPM.zip)

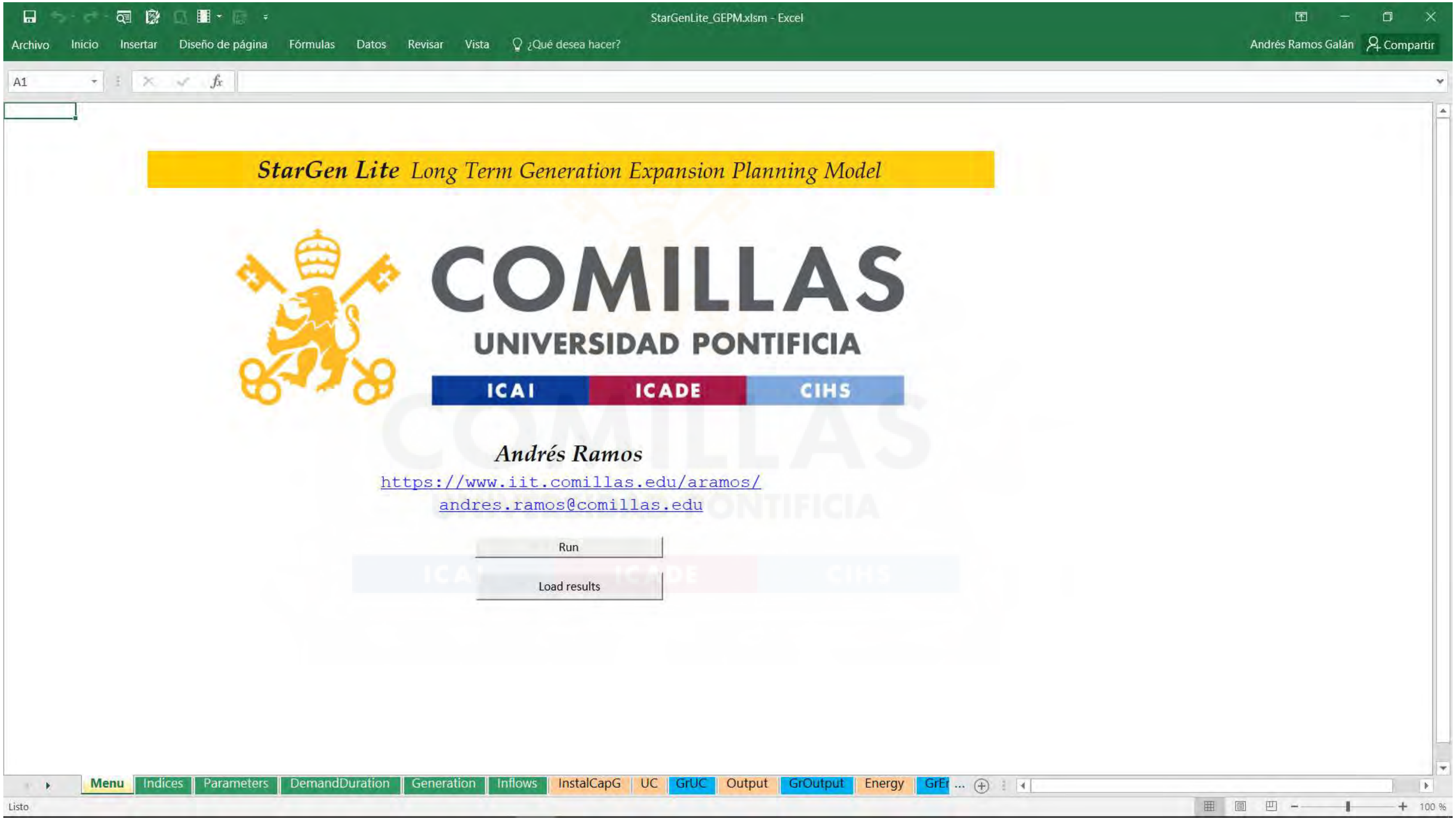
- Files
  - Microsoft Excel interface for input data and output results StarGenLite_GEPM.xlsm
  - GAMS file StarGenLite_GEPM.gms
- How to run it from Windows
  - Save the Excel workbook if data have changed
  - Run the model — Run
  - The model creates
    - tmp_StarGenLite_GEPM.xlsx with the output results
    - tmp_StarGenLite_GEPM.gdx with the output results
    - StarGenLite_GEPM.lst as the listing file of the GAMS execution
  - Load the results into the Excel interface — Load results

StarGenLite_GEPM Long-Term Transmission Expansion Model (https://pascua.iit.comillas.edu/aramos/StarGenLite_GEPM.zip)

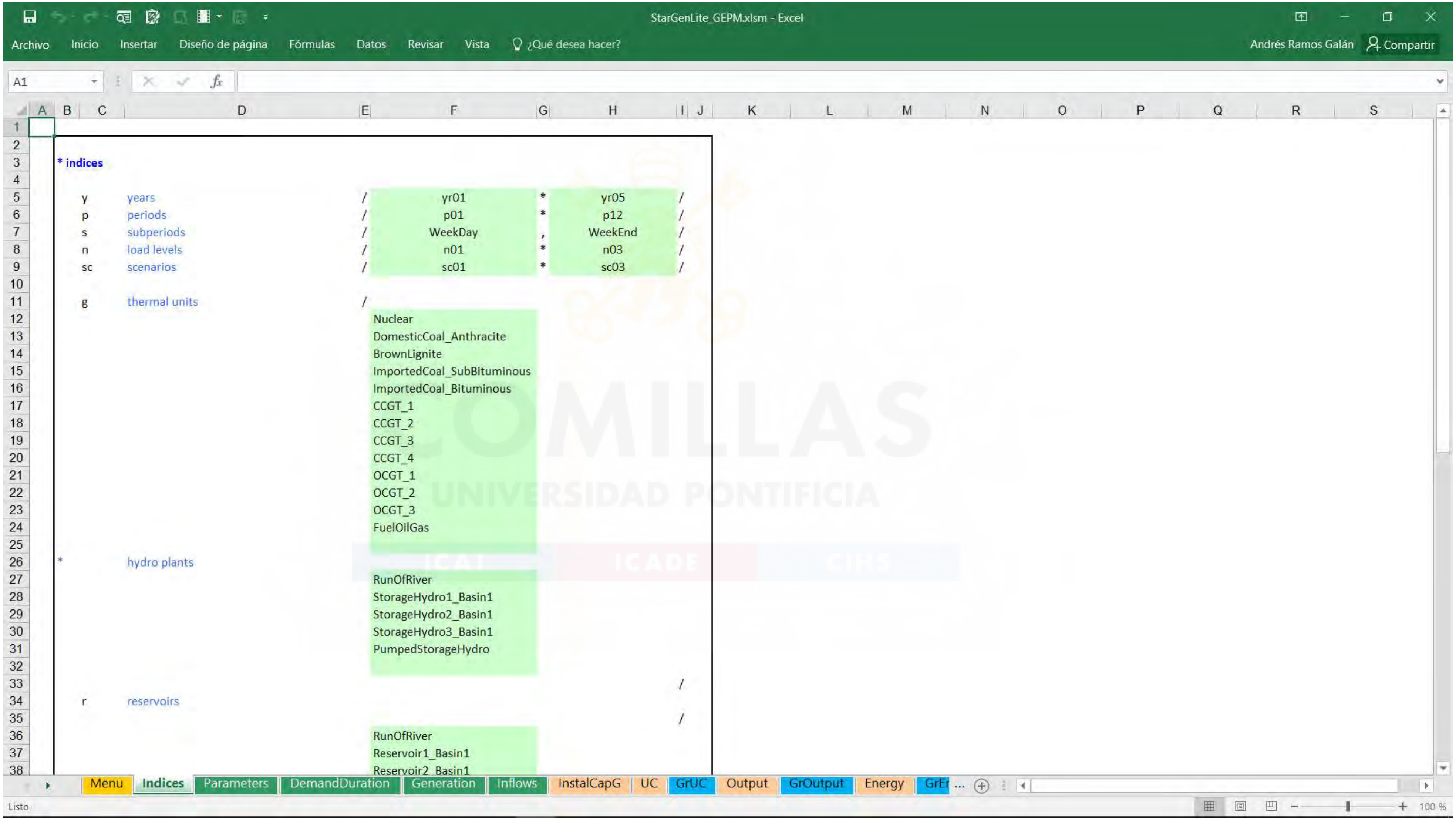
- Files
  - Text files for input data
  - GAMS file StarGenLite_GEPM.gms

- How to run it from MacOS
  - Run the model from GAMS Studio with these parameters
    - u1=StarGenLite_GEPM u2=1 u3=1
  - The model creates
    - tmp_StarGenLite_GEPM.gdx with the output results
    - StarGenLite_GEPM.lst as the listing file of the GAMS execution

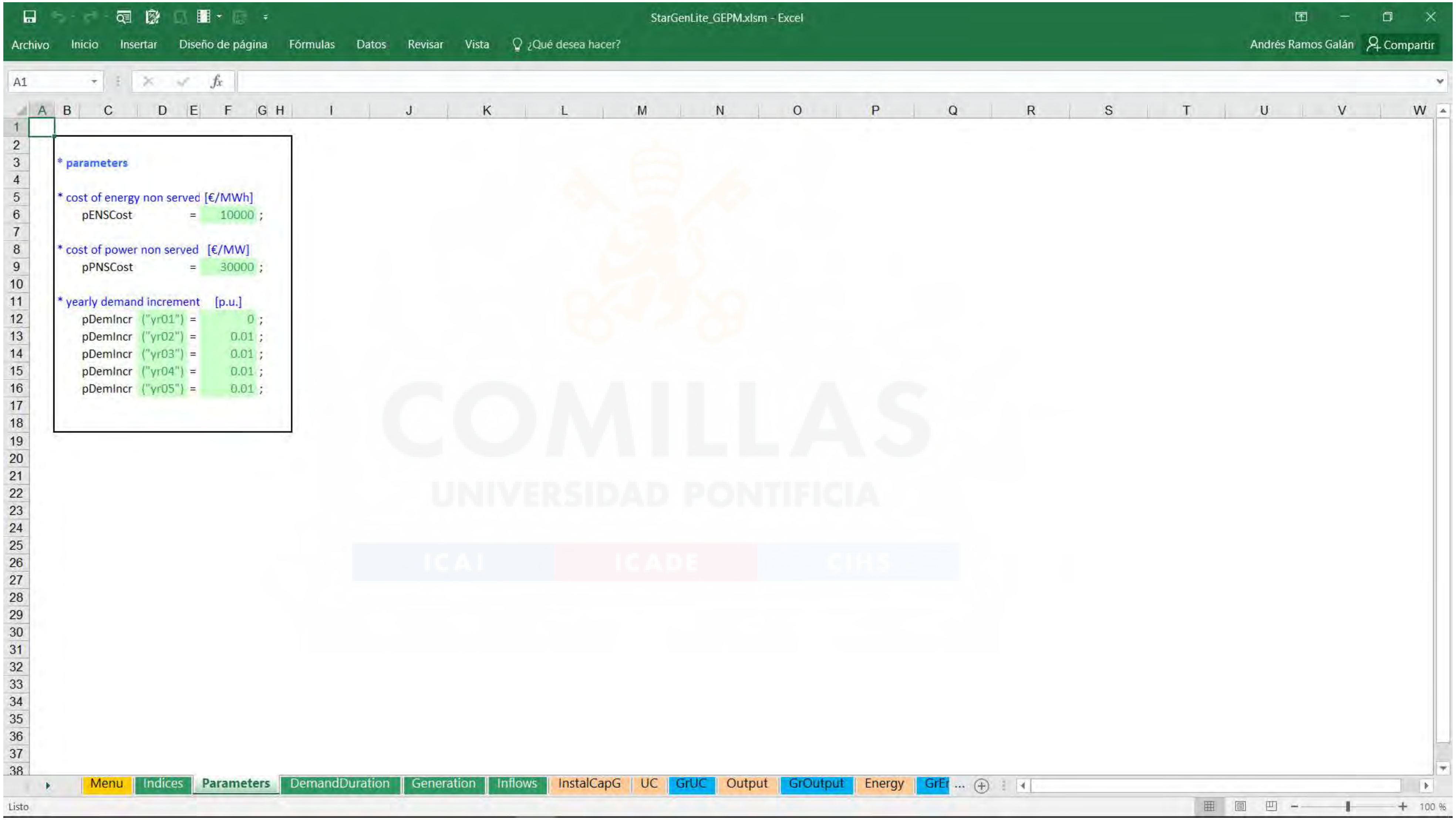
StarGen Lite Long-Term Stochastic Generation Expansion Model (https://pascua.iit.comillas.edu/aramos/StarGenLite_GEPM.zip)



Input Data. Indices



Input Data. Cost of energy or power non served. Demand growth

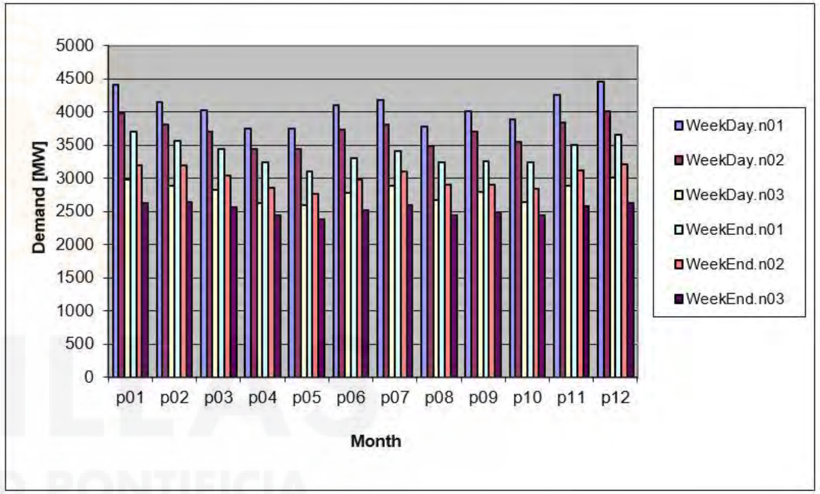


Input Data. Demand, operating reserve and duration

StarGenLite_GEPM.xlsm - Excel

* demand [MW]

	WeekDay.n01	WeekDay.n02	WeekDay.n03	WeekEnd.n01	WeekEnd.n02	WeekEnd.n03
sc01 . p01	4415	3983	2988	3697	3190	2619
sc01 . p02	4154	3817	2886	3561	3188	2644
sc01 . p03	4029	3703	2823	3442	3041	2572
sc01 . p04	3752	3448	2622	3242	2851	2436
sc01 . p05	3746	3443	2602	3109	2768	2385
sc01 . p06	4103	3729	2777	3301	2984	2512
sc01 . p07	4185	3819	2890	3413	3097	2599
sc01 . p08	3778	3493	2667	3238	2909	2448
sc01 . p09	4009	3706	2797	3256	2909	2488
sc01 . p10	3887	3557	2645	3242	2844	2443
sc01 . p11	4256	3845	2889	3503	3116	2586
sc01 . p12	4454	4005	3013	3660	3211	2619
sc02 . p01	4415	3983	2988	3697	3190	2619
sc02 . p02	4154	3817	2886	3561	3188	2644
sc02 . p03	4029	3703	2823	3442	3041	2572
sc02 . p04	3752	3448	2622	3242	2851	2436
sc02 . p05	3746	3443	2602	3109	2768	2385
sc02 . p06	4103	3729	2777	3301	2984	2512
sc02 . p07	4185	3819	2890	3413	3097	2599
sc02 . p08	3778	3493	2667	3238	2909	2448
sc02 . p09	4009	3706	2797	3256	2909	2488
sc02 . p10	3887	3557	2645	3242	2844	2443
sc02 . p11	4256	3845	2889	3503	3116	2586
sc02 . p12	4454	4005	3013	3660	3211	2619
sc03 . p01	4415	3983	2988	3697	3190	2619
sc03 . p02	4154	3817	2886	3561	3188	2644
sc03 . p03	4029	3703	2823	3442	3041	2572
sc03 . p04	3752	3448	2622	3242	2851	2436
sc03 . p05	3746	3443	2602	3109	2768	2385
sc03 . p06	4103	3729	2777	3301	2984	2512
sc03 . p07	4185	3819	2890	3413	3097	2599
sc03 . p08	3778	3493	2667	3238	2909	2448
sc03 . p09	4009	3706	2797	3256	2909	2488



Menu | Indices | Parameters | DemandDuration | Generation | Inflows | InstalCapG | UC | GrUC | Output | GrOutput | Energy | GrEr ...

Input Data. Thermal and hydro parameters

StarGenLite_GEPM.xlsm - Excel

* thermal generation

*	MaxProd [MW]	MinProd [MW]	FuelCost [€/Mcal]	SlopeVarCost [Mcal/MWh]	InterVarCost [Mcal/h]	OMVarCost [€/MWh]	StartupCost [Mcal]	EFOR [p.u.]	FixedCost [€/kW]	FxChargeRate [p.u.]	MxInstCpY [MW]	Aux
Nuclear	771.6	771.6	1.00	15				0.00	1500	0.05		15.00
DomesticCoal_Anthracite	588.0	235.2	0.02	2400		6		0.00	1000	0.10		48.00
BrownLignite	203.1	81.2	0.02	2300		6		0.00	1000	0.10		46.00
ImportedCoal_SubBituminous	150.4	60.2	0.02	2300		6		0.00	1000	0.10		46.00
ImportedCoal_Bituminous	194.4	77.8	0.02	2200		6		0.00	1000	0.10		44.00
CCGT_1	500.0	100.0	0.03	800		6		0.00	500	0.12	500.0	24.00
CCGT_2	500.0	100.0	0.03	900		4		0.00	500	0.12	500.0	27.00
CCGT_3	500.0	100.0	0.03	1000		4		0.00	500	0.12	500.0	30.00
CCGT_4	667.5	133.5	0.03	800		4		0.00	500	0.12	500.0	24.00
OCGT_1	400.0		0.03	2000		4		0.00	500	0.12	250.0	60.00
OCGT_2	400.0		0.03	2100		4		0.00	400	0.15	250.0	63.00
OCGT_3	400.0		0.03	2200		4		0.00	400	0.15	250.0	66.00
FuelOilGas	441.8		0.06	2000		3		0.00	1000	0.10		120.00

* hydro generation

*	MaxProd [MW]	MinProd [MW]	ProdFunct [kWh/m³]	Efficiency [p.u.]	MaxCons [MW]	FixedCost [€/kW]	FxChargeRate [p.u.]	MxInstCpY [MW]
RunOfRiver	150.0					2000	0.05	
StorageHydro1_Basin1	200.0		0.30			2000	0.05	
StorageHydro2_Basin1	200.0		0.30			2000	0.05	
StorageHydro3_Basin1	200.0		0.30			2000	0.05	
PumpedStorageHydro	200.0			0.70	200.0	2000	0.05	

* reservoir

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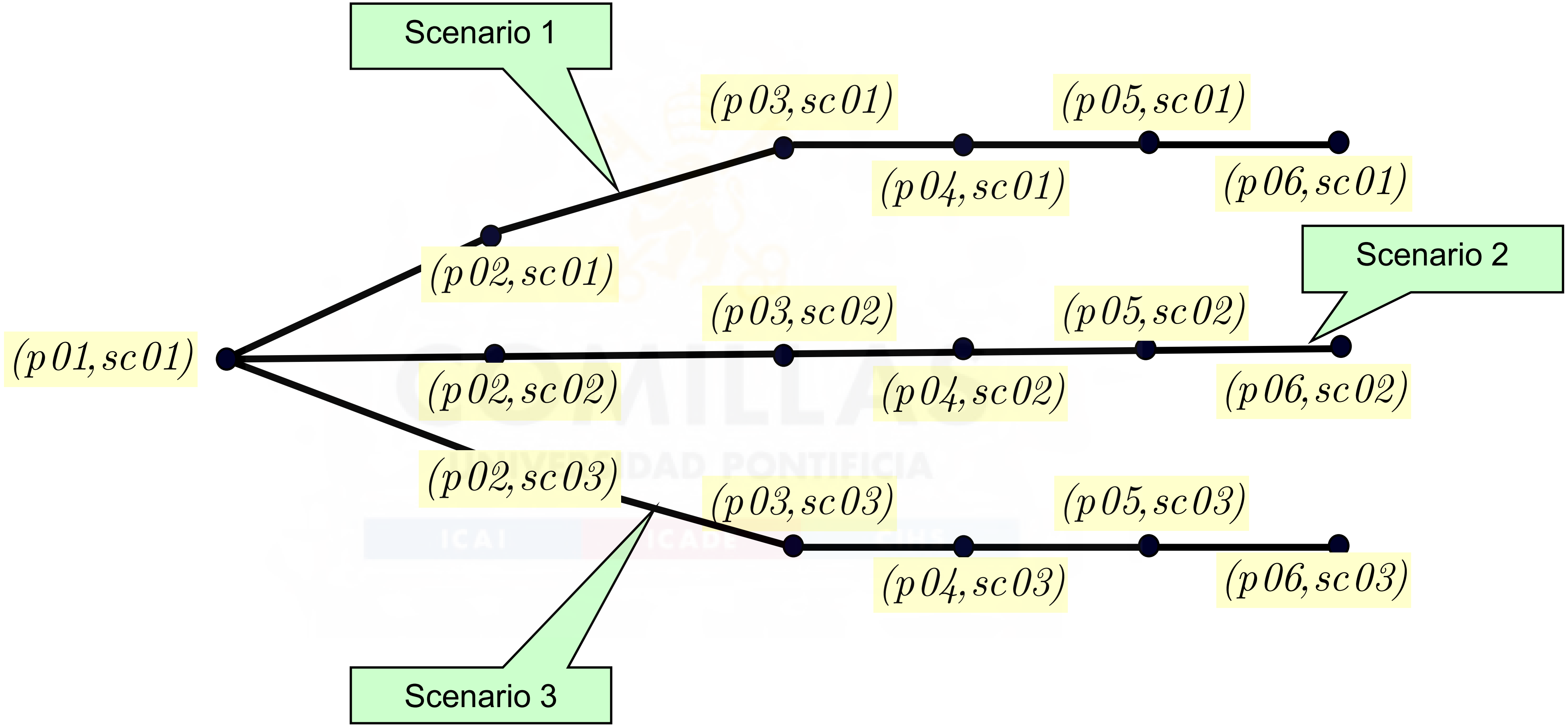
Scenario tree



Input Data. Inflows and scenario tree

StarGenLite_GEPM.xlsm - Excel

* natural hydro inflows [m³/s]

			p01	p02	p03	p04	p05	p06	p07	p08	p09	p10	p11	p12
	RunOfRiver	. sc01	40.0	40.0	40.0	35.0	30.0	20.0	20.0	20.0	30.0	35.0	40.0	40.0
	RunOfRiver	. sc02	40.0	38.0	38.0	33.3	28.5	19.0	19.0	19.0	28.5	33.3	38.0	38.0
	RunOfRiver	. sc03	40.0	42.0	42.0	36.8	31.5	21.0	21.0	21.0	31.5	36.8	42.0	42.0
*	RunOfRiver	. sc01	40.0	39.4	39.4	34.5	29.6	19.7	19.7	19.7	29.6	34.5	39.4	39.4
	Reservoir1_Basin1	. sc01	34.5	48.7	66.2	76.1	33.6	10.4	5.4	15.3	14.6	16.1	62.7	157.1
	Reservoir1_Basin1	. sc02	34.5	34.1	46.3	53.3	23.5	7.3	3.8	10.7	10.2	11.3	43.9	110.0
	Reservoir1_Basin1	. sc03	34.5	65.7	89.4	102.7	45.4	14.0	7.3	20.7	19.7	21.7	84.6	212.1
*	Reservoir1_Basin1	. sc01	34.5	44.6	60.6	69.6	30.7	9.5	4.9	14.0	13.4	14.7	57.4	143.7
	Reservoir2_Basin1	. sc01	28.8	6.9	11.9	4.4	16.6	4.6	5.3	8.8	6.1	10.7	36.3	60.0
	Reservoir2_Basin1	. sc02	28.8	5.2	8.9	3.3	12.5	3.5	4.0	6.6	4.6	8.0	27.2	45.0
	Reservoir2_Basin1	. sc03	28.8	9.7	16.7	6.2	23.2	6.4	7.4	12.3	8.5	15.0	50.8	84.0
*	Reservoir2_Basin1	. sc01	28.8	6.5	11.2	4.1	15.6	4.3	5.0	8.3	5.7	10.1	34.1	56.4
	Reservoir3_Basin1	. sc01	113.8	54.9	101.0	21.2	29.6	54.9	25.3	16.8	21.2	21.2	33.7	168.4
	Reservoir3_Basin1	. sc02	113.8	32.9	60.6	12.7	17.8	32.9	15.2	10.1	12.7	12.7	20.2	101.0
	Reservoir3_Basin1	. sc03	113.8	76.8	141.4	29.7	41.5	76.8	35.4	23.6	29.7	29.7	47.1	235.7
*	Reservoir3_Basin1	. sc01	113.8	48.3	88.9	18.7	26.1	48.3	22.2	14.8	18.7	18.7	29.6	148.1

* scenario tree

	Ancestor	stPeri	Prob
sc01	-1	1	0.500
sc02	1	1	0.400
sc03	1	1	0.100

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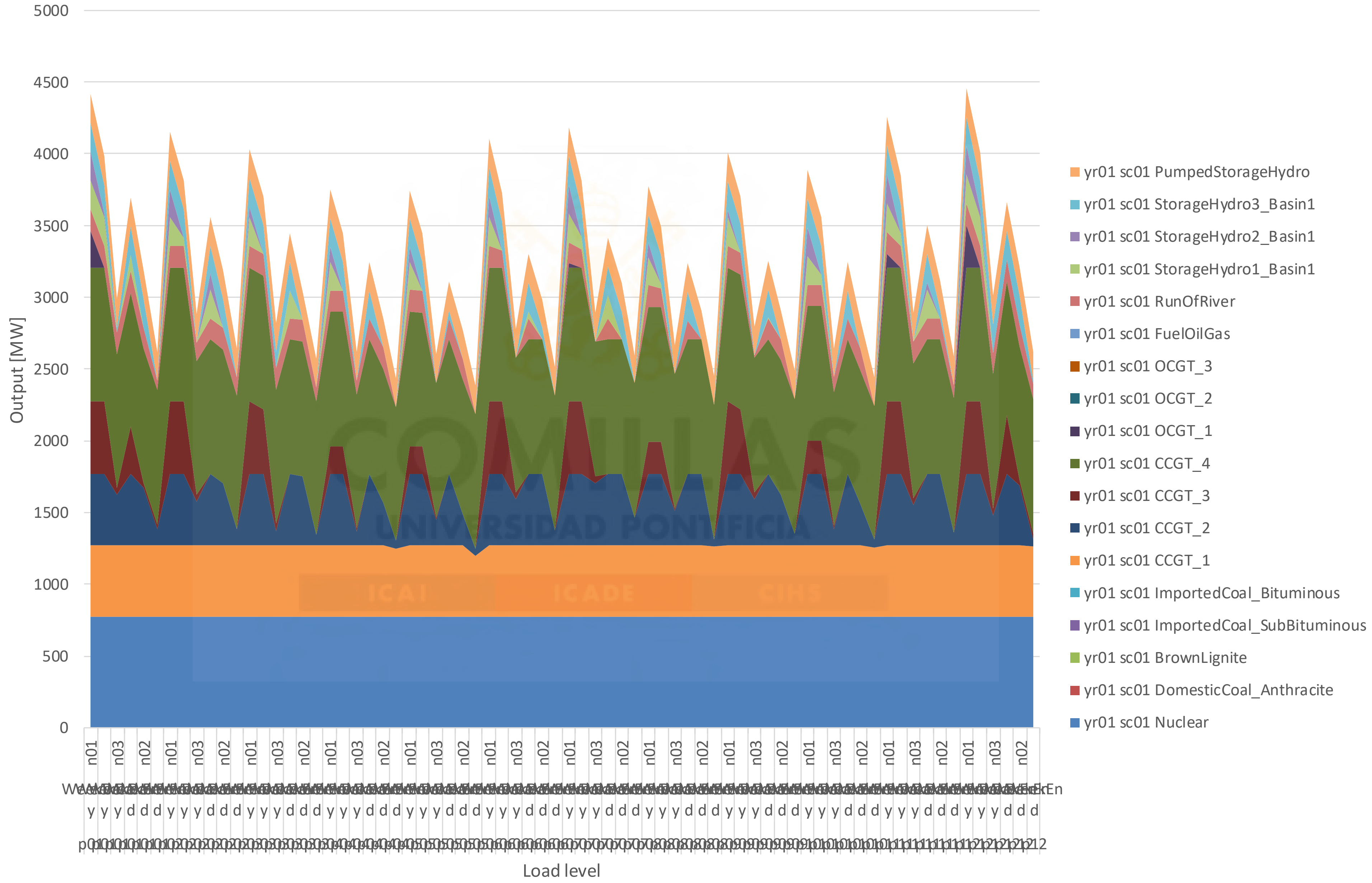
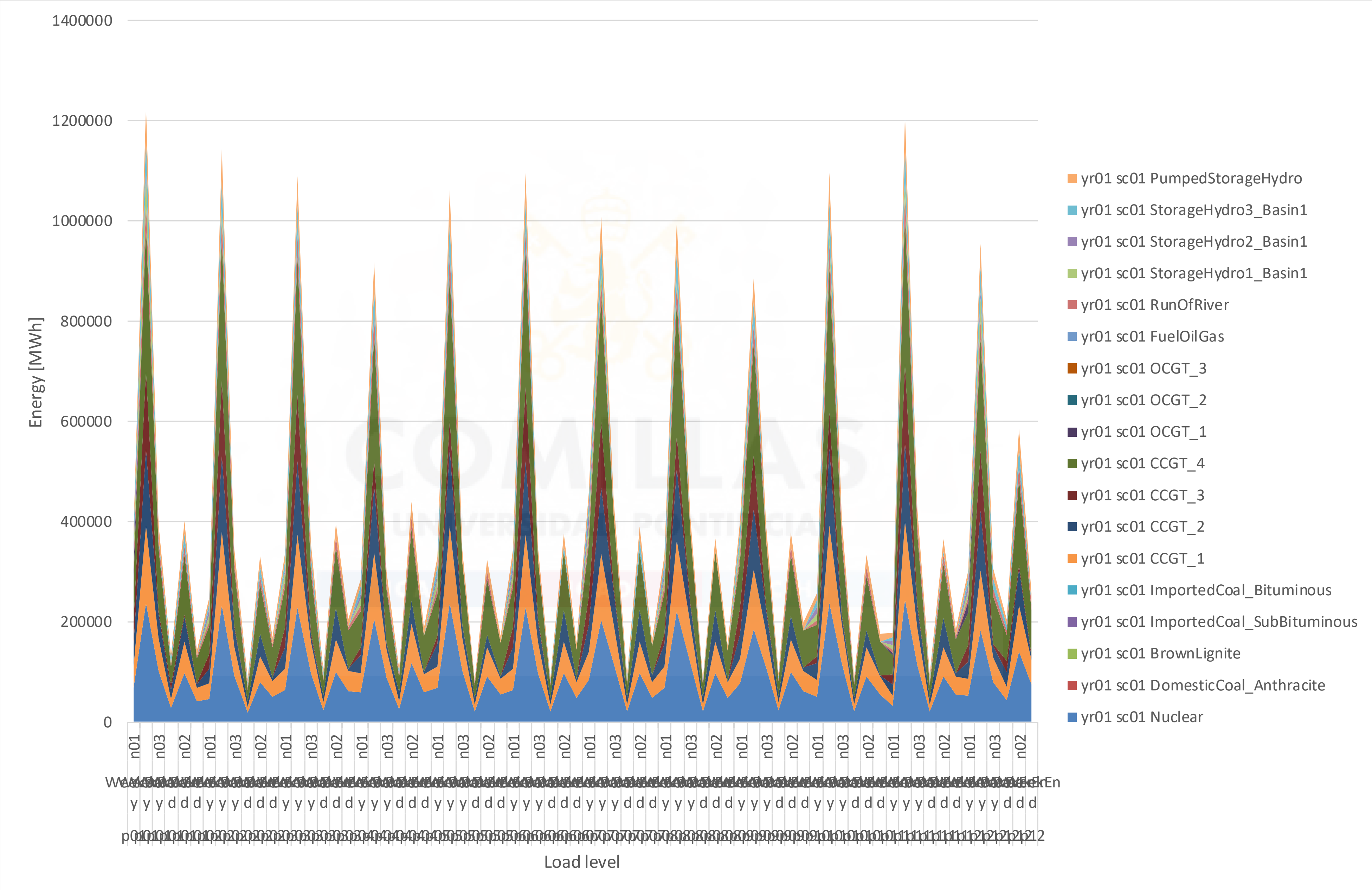
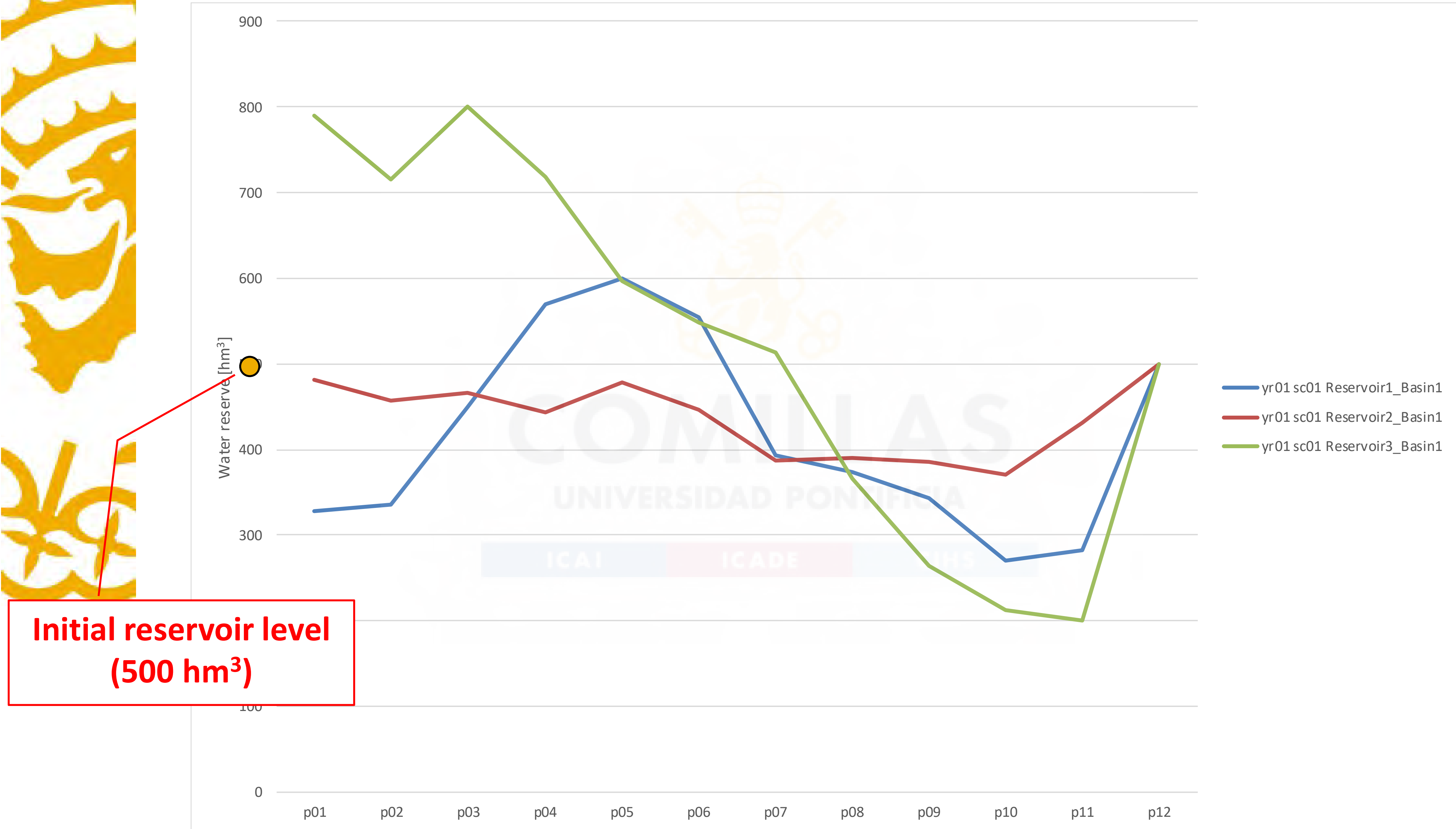
Output Data. Production for year 1



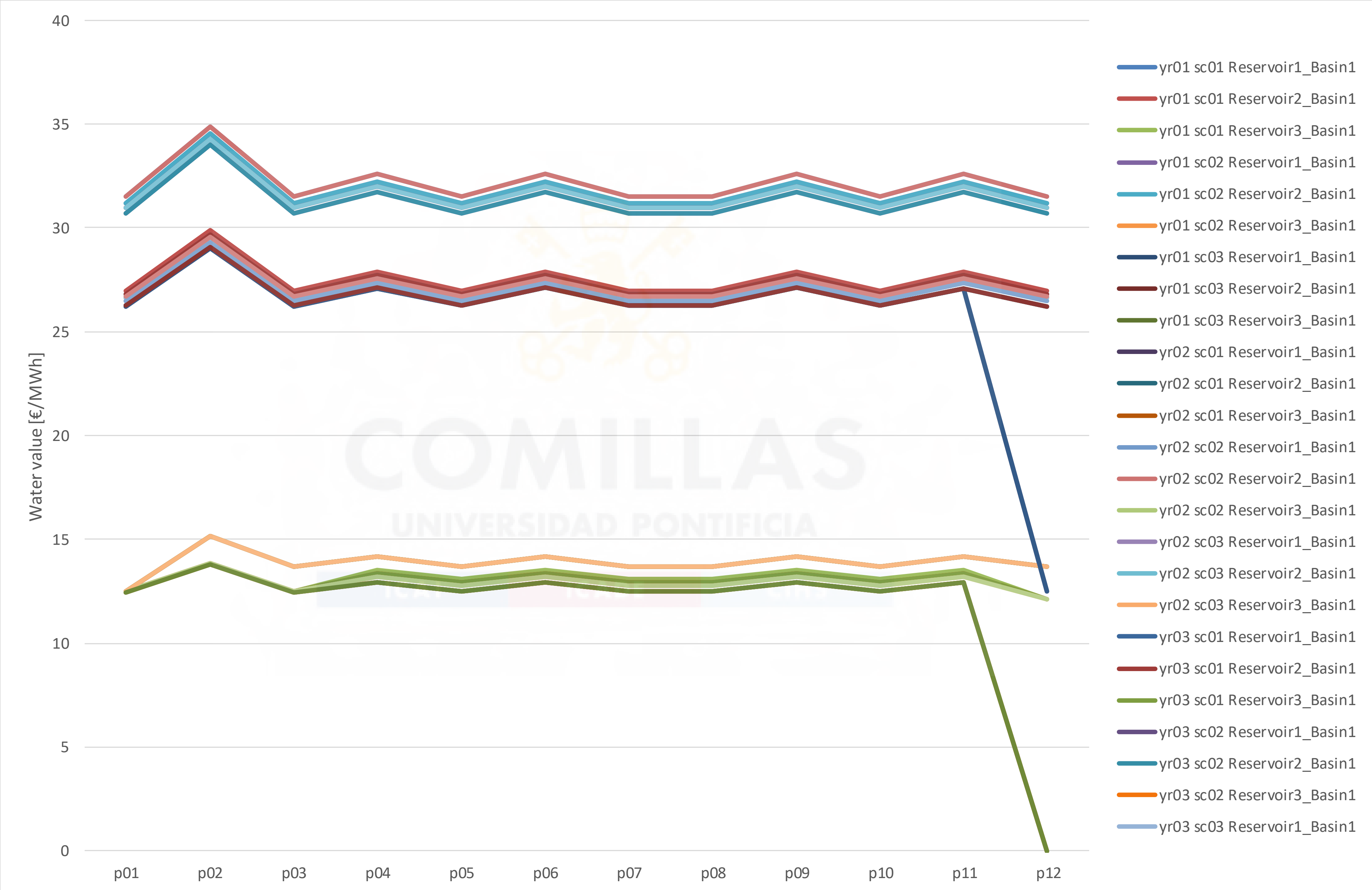
Output Data. Energy for year 1



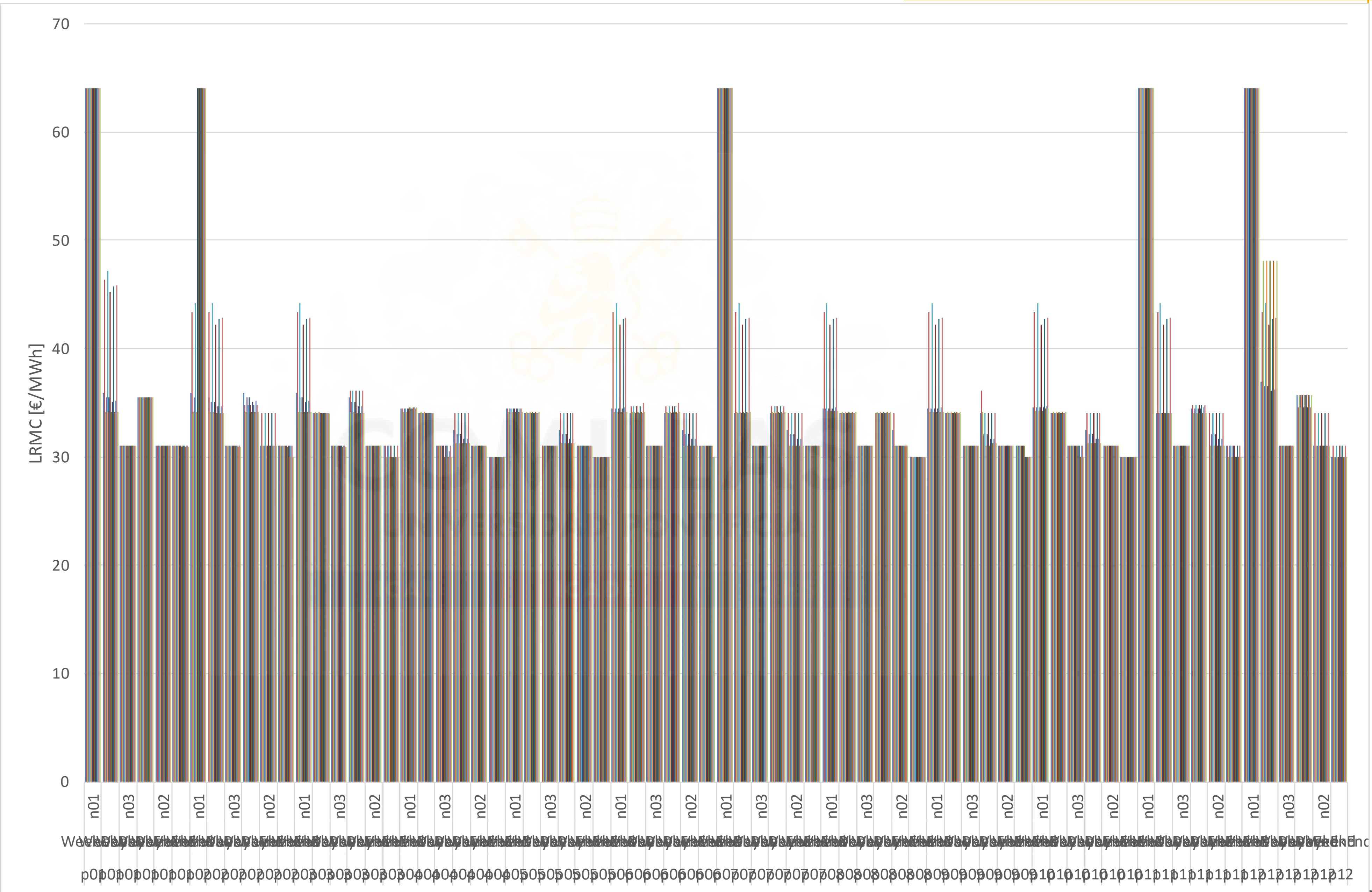
Output Data. Reservoir level for year 1



Output Data. Water value for year 1



Output Data. Long Run Marginal Cost for year 1



If GEP model is solved with binary investment decisions no marginal impact of those decisions is taken into account

1. Generation expansion planning
2. Simple GEP models
3. Modeling issues
4. Prototype GEP. Mathematical formulation
5. Prototype GEP. Computer implementation
6. Takeaways

6

Takeaways

Task assignment

- Include the environmental (carbon) costs into the objective function
- Include either:
  - A constraint stating a yearly cap to the total CO2 emissions of generation expansion problem in a hydro scenario o in an average year
  - A lower bound reserve margin
  - Wind generation and some minimum target for this generation. Include Renewable Portfolio Standards (RPS) in the model
- Make a sensitivity analysis with respect to the most important parameters:
  - Investment cost of each technology
  - Discount rate

Takeaways

- Generation expansion planning is an extremely complex problem
- Uncertainty representation plays a major role
- Real models representing this problem may become very difficult
- There exists a set of solving techniques to address this problem, it is interesting to make use of various of them
- Use of mathematical models improves decision process

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