Universidad Carlos III de Madrid

Research group REDES

Research on wind integration in electricity markets

Presented by Julio Usaola

Research subjects. REDES.

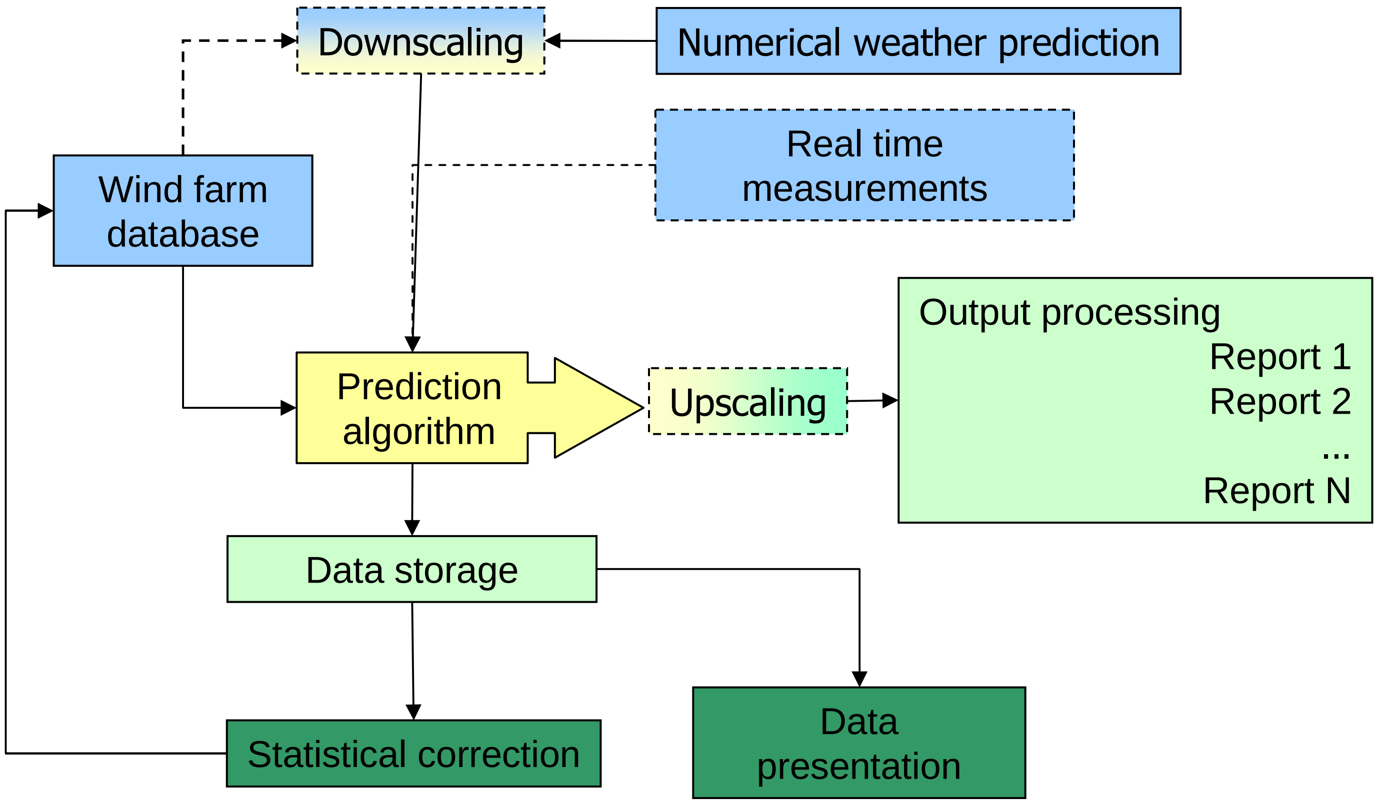
- **Transmission grid cost allocation methods.**
- **Modelling of uncertainty of wind power prediction.**
- **Stochastic power flows with high penetration of wind power.**
- **Trading modelling. Optimal bidding strategies for wind farms considering uncertainties.**
- **Hydro-wind coordination with storage. Stochastic optimization tools to set the optimal day-ahead scheduling.**
- **Optimization of Wind Dispatching Centres operation**

ANEMOS.PLUS

Presentation index

- **Introduction. Short term wind power prediction.**
- **Participation of wind energy in the electricity markets.**
- **Hydro wind coordination.**
- **Optimization of Wind Dispatching Centres operation.**

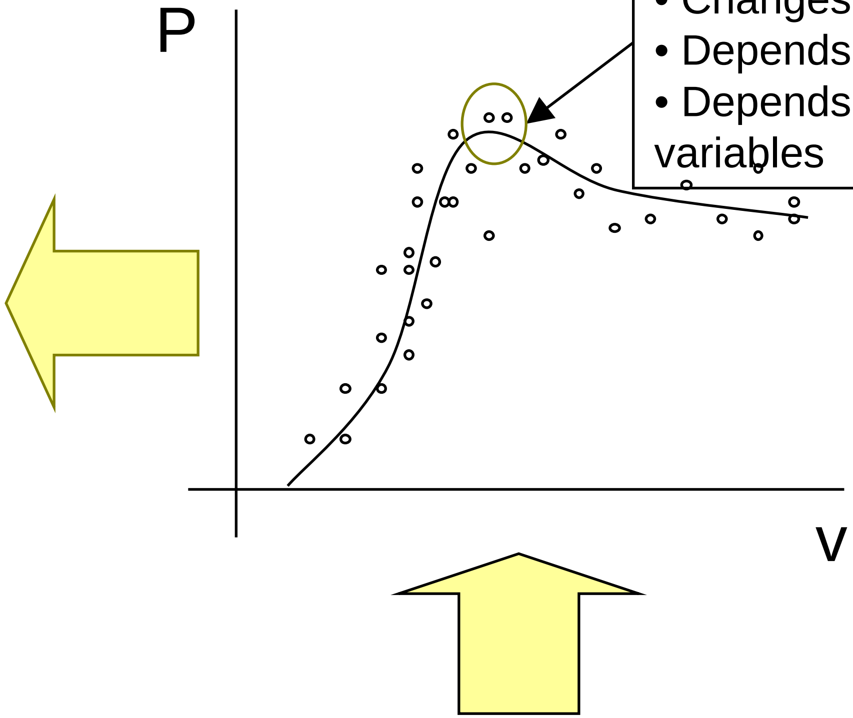
Outline of a short term prediction program



How predictions are done

Wind farm P-v curve

- Changes with time.
- Depends on wind direction.
- Depends on changing meteorological variables



Predicted power

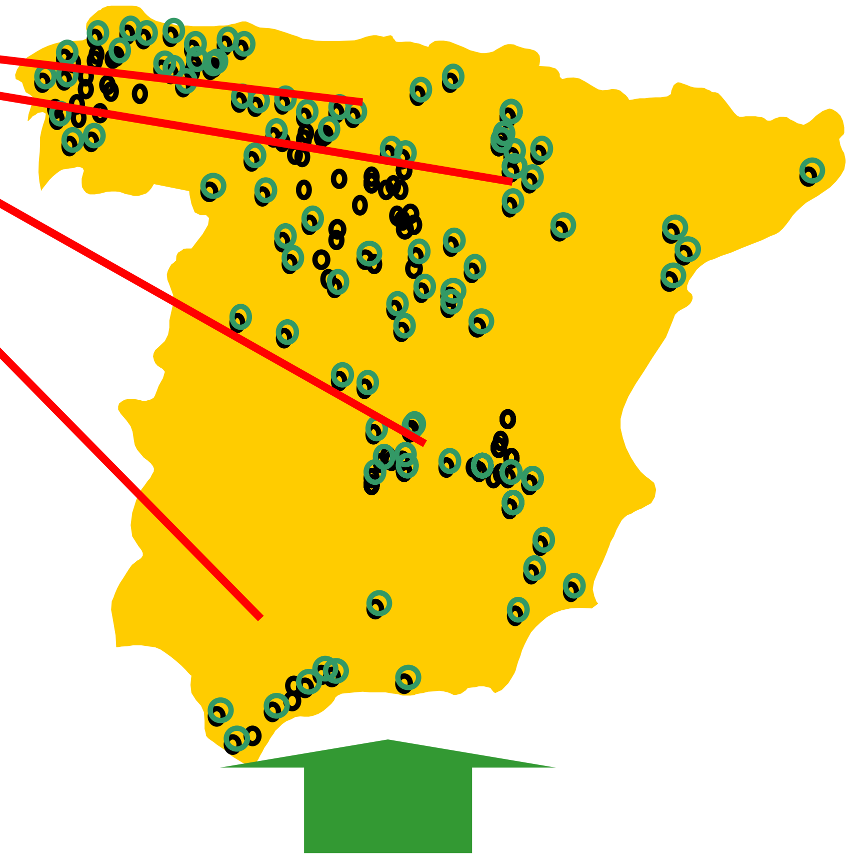
Wind forecast

Short term wind power prediction. SIPREÓLICO. REE-UC3M

Real time data

Numerical weather predictions

Red Eléctrica de España

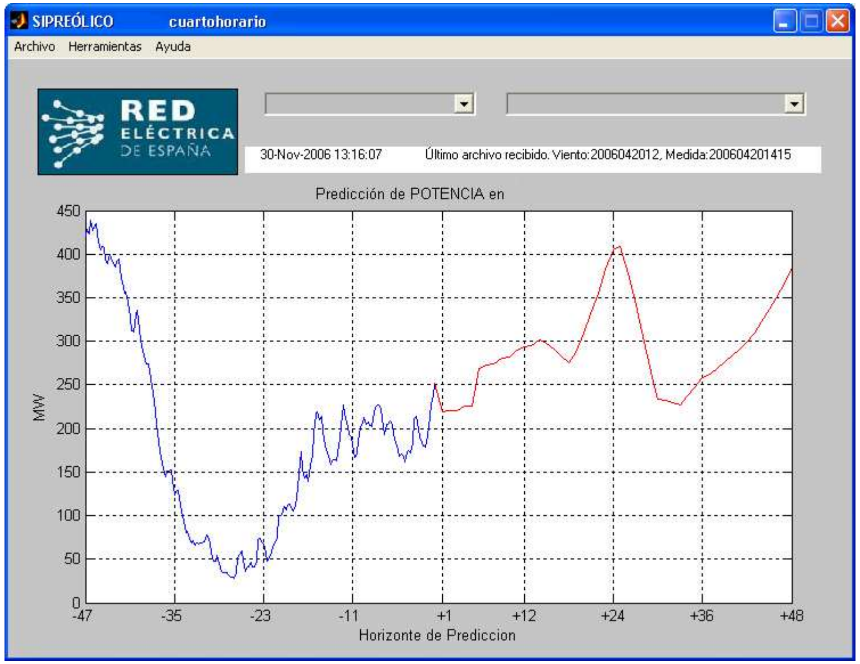


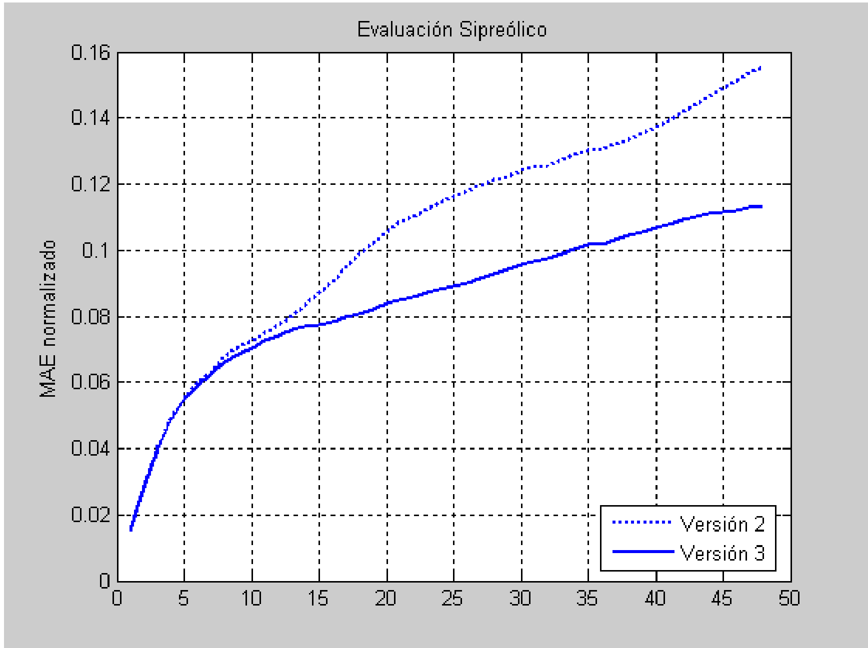
System operation

Main features

- **Working in REE since 2002.**
- **Runs on MATLAB in a PC. Statistical model.**
- **Inputs:**
  - **Predictions of wind speed and direction from National Weather Service.**
  - **Database of wind farms**
  - **Real time measures of the 85% of the Spanish wind production.**
- **Output:**
  - **Predictions of hourly average production of all Spanish peninsular wind farms (more than 14000 MW).**
  - **Issued each 15 min.**

Prediction and accuracy





$$NMAE_k = \frac{1}{Rated\ power} \frac{1}{N} \sum_{t=1}^{N} \left| e(t+k|t) \right|$$

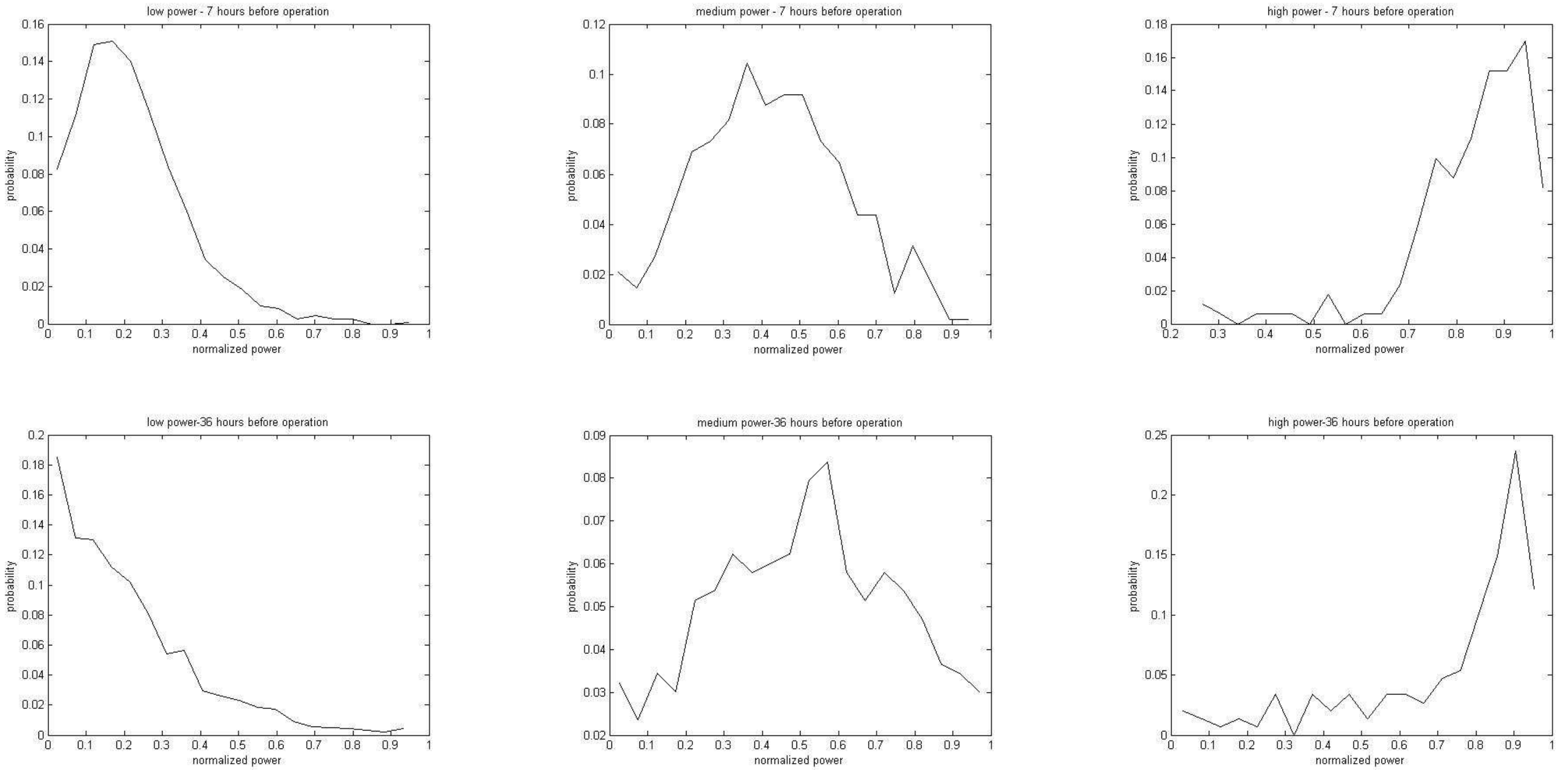
Uncertainty of prediction.

- **Important to fully apply the capabilities of short term wind power prediction.**
- **Under study.**
- **Depends on:**
  - **Wind farm characteristics.**
  - **Time delay between prediction and real time**
  - **Level of production.**
  - **Correlation between wind farms.**

Uncertainty of prediction. PDFs

k=7

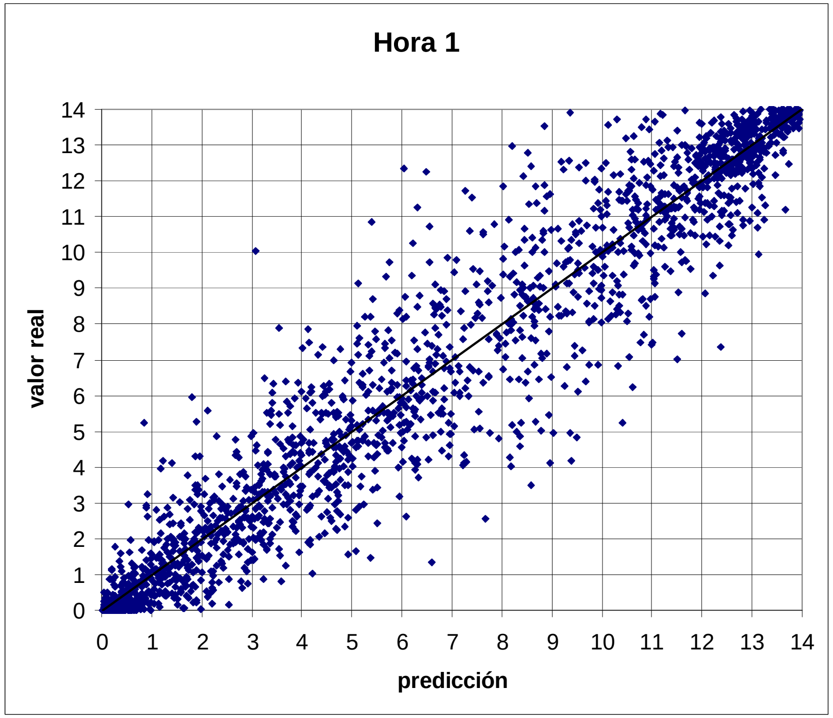
k=36

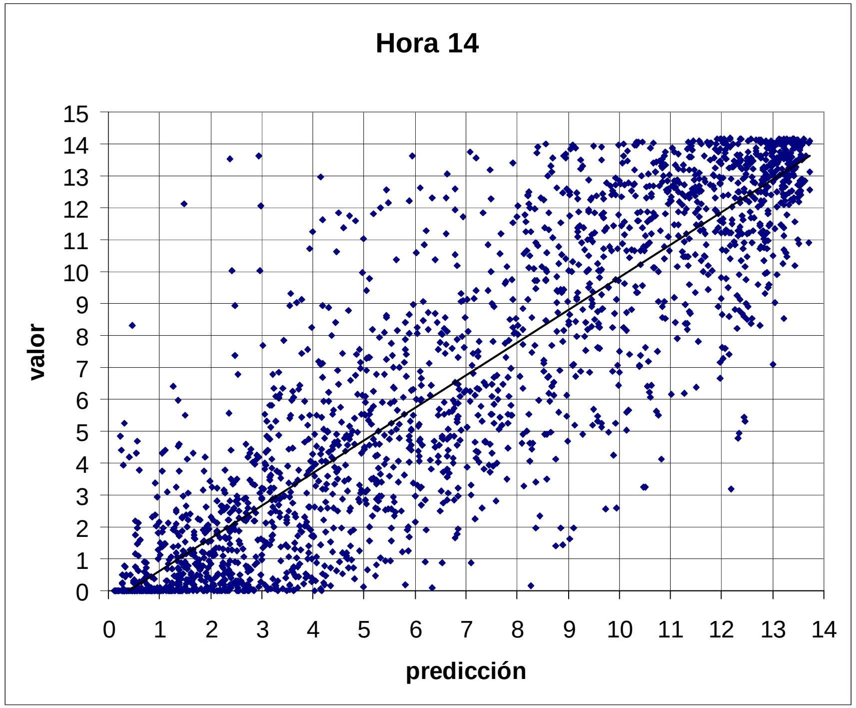


Low power predicted Medium power predicted High power predicted

From frequency distribution of predictions obtained empirically

Increasing variance with time horizon





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Market participation of wind energy

- Bids presented to the daily market.
- Updated in the intradaily market

Revenue = Daily market + Exchanges in the intradaily market + Cost of deviation

Cost of deviation = -Sell price x deviation   Pgen > Pdeclared

Buy price x deviation   Pgen < Pdeclared

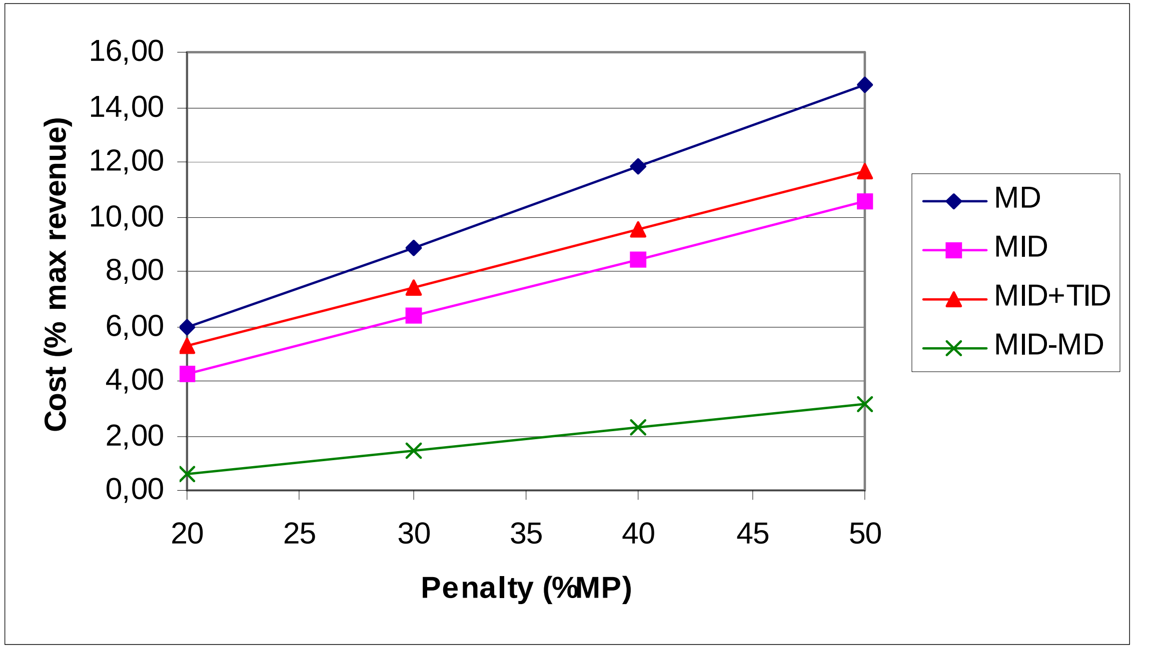
Buy price > Marginal price > Sell price

		DAY D-1												
	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Daily	x													
ID1											x			
ID2														
ID3														
ID4														
ID5														
ID6														

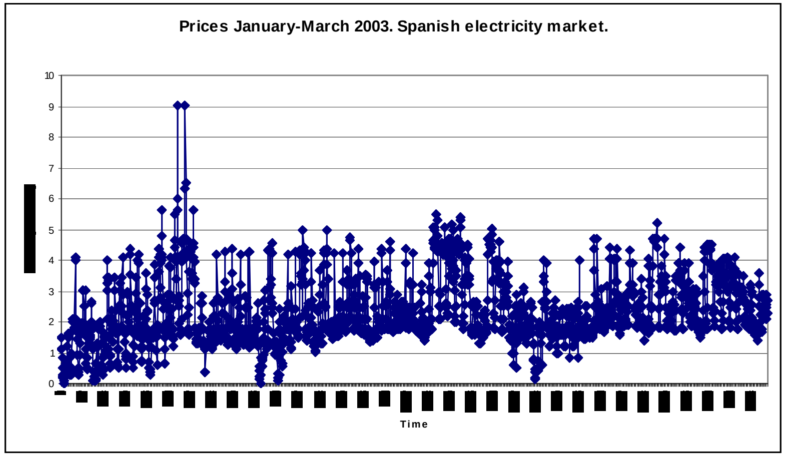
	DAY D																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Daily	13			16	17			20	21			24	25			28	29			32	33			36
	10	10	10	10																				
ID1	3			6	14	14	14	14																
ID2		x			3			6	18	18	18	18												
ID3						x			3			6	22	22	22	22								
ID4										x			3			6	26	26	26	26				
ID5														x			3			6	30	30	30	30
ID6																		x			3			6

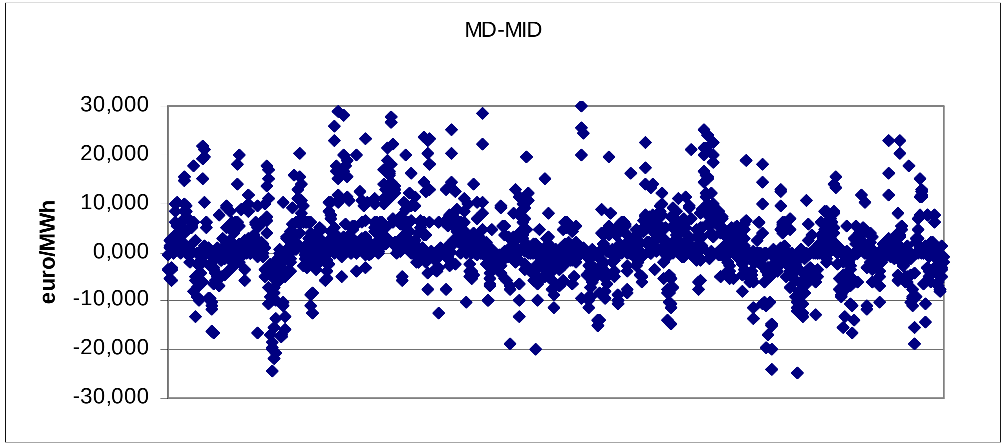
Example of revenues

Total time of study: 3 months
Capacity factor: 44.5%
Rated power: 15MW
6 ID markets of 4 hours.



Prices in the Spanish market.





Average price: 2.3235 c€/kWh

Mean: -0,342 €/MWh   Std. dev: 7,254 €/MWh

	Av. €/MWh	Volat	Penalty 0,2	0,3	0,4	0,5
2003	23,54	45,89	0,943	0,914	0,886	0,857
2005	48,11	36,14	0,941	0,911	0,882	0,852
2005(2)	54,53	29,29	0,939	0,908	0,878	0,847

Different prices series in 2005

Revenue received in p.u. of the maximum revenue

Premiums included. Spanish market.

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Analysis of a wind farm's revenue in the British and Spanish markets

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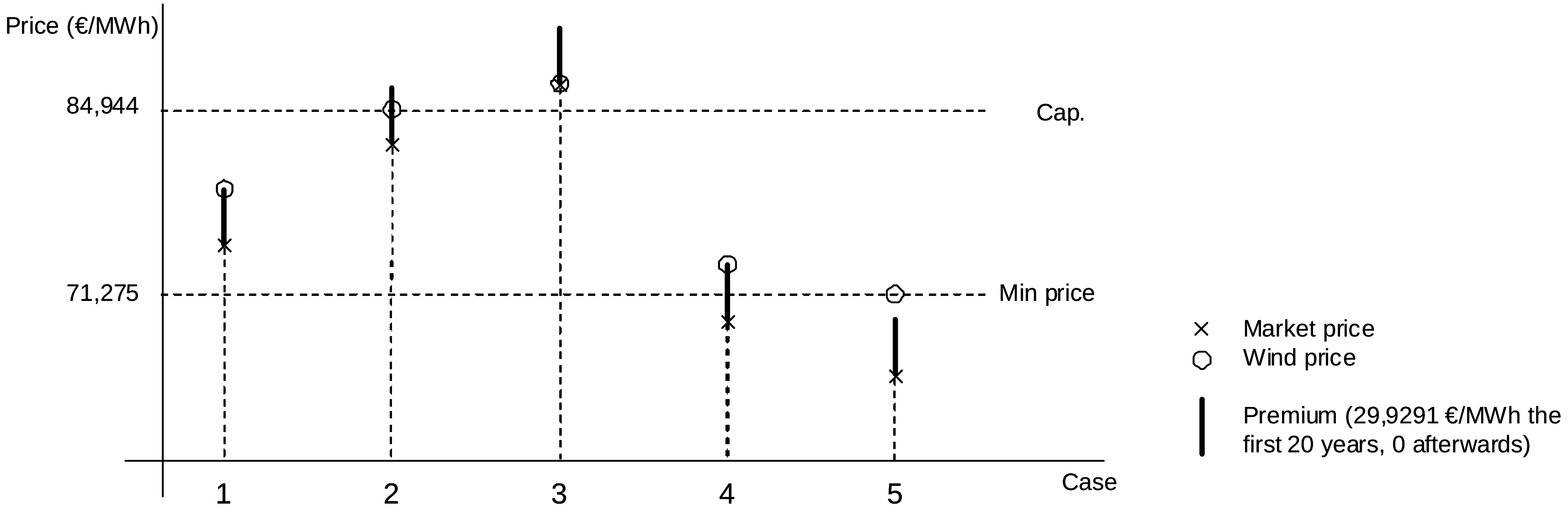
- **Cost of imbalance: 26.6% of MP**
- **Incentives considered (year 2004)**

$$IC_{SP} = \sum_{t=1}^{t=T} \left(E_t^{act}\right) \cdot \lambda^{ref} \cdot \left(\gamma + \varphi\right)$$

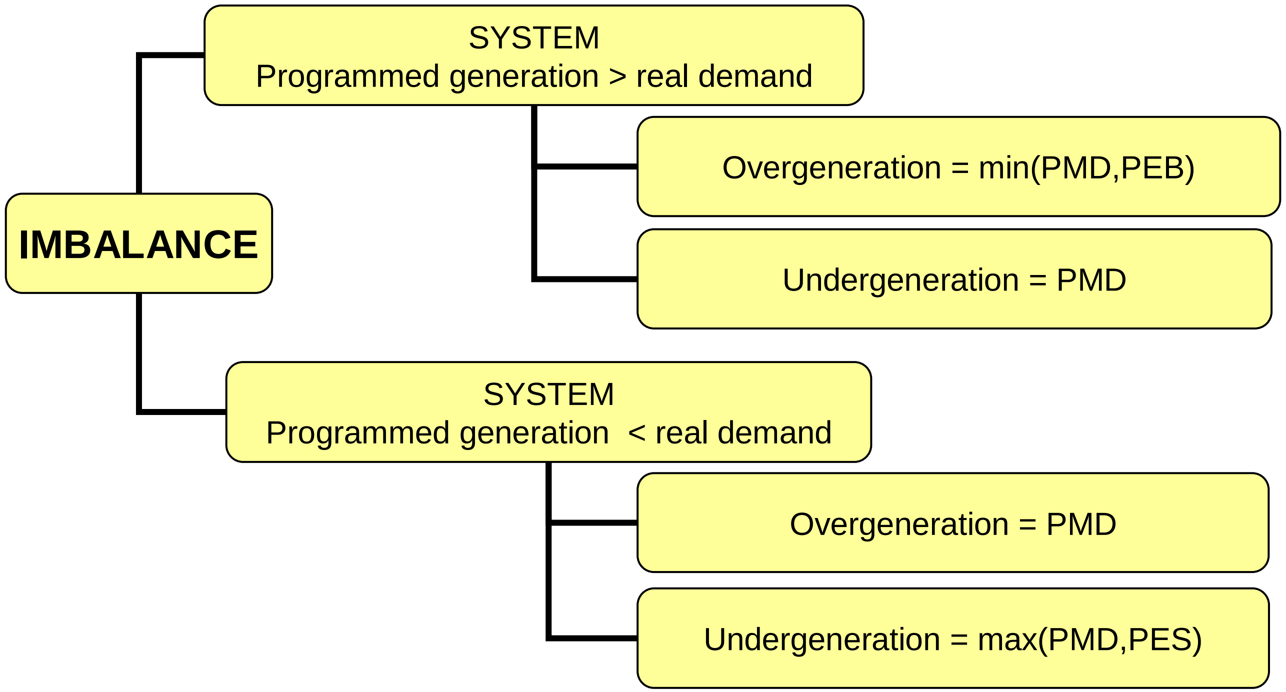
$$CI_{SP} = \sum_{t=1}^{t=T} \left(E_t^{act}\right) \cdot \lambda^{cc}$$

Spain. New incentive system.



NB: figures for 2007

Imbalance cost. New Spanish rules.



Premiums included. UK market

Revenues

$$TP_{UK} = IG_{UK} + OIM_{UK} + IC_{UK}$$

Imbalances

$$IG_{UK} = \sum_{t=1}^{t=T} E_t^{traded} \cdot \lambda_t^{ref}$$

$$OIM_{UK} = \sum_{t=1}^{t=T} E_t \cdot \lambda_t^{pen}$$

$$E_t = E_t^{act} - E_t^{traded}$$

$$E_t > 0 \quad \lambda_t^{pen} = ssp_t$$

$$E_t < 0 \quad \lambda_t^{pen} = sbp_t$$

Premium

$$IC_{UK} = \sum_{t=1}^{t=T} E_t^{act} \cdot \lambda^{ROC}$$

Data

Wind power production: 3rd of January 2003 and 29th March 2003

Market data: 3rd of January 2006 and 29th March 2006

Table 2
ROC income and total revenue for different ROC prices

ROCs price (€/MWh)	ROC income (IC) (€)	Total revenue (TP) (€)	
		forecasting	persistence
47.25	646450	1195212	1195744
54	738800	1287562	1288094
60.75	831150	1379912	1380444
68	**923500**	**1472262**	**1472794**
74.25	1015850	1564612	1565144
81	1108200	1656962	1657494
87.75	1200550	1749312	1749844

Results for Spain

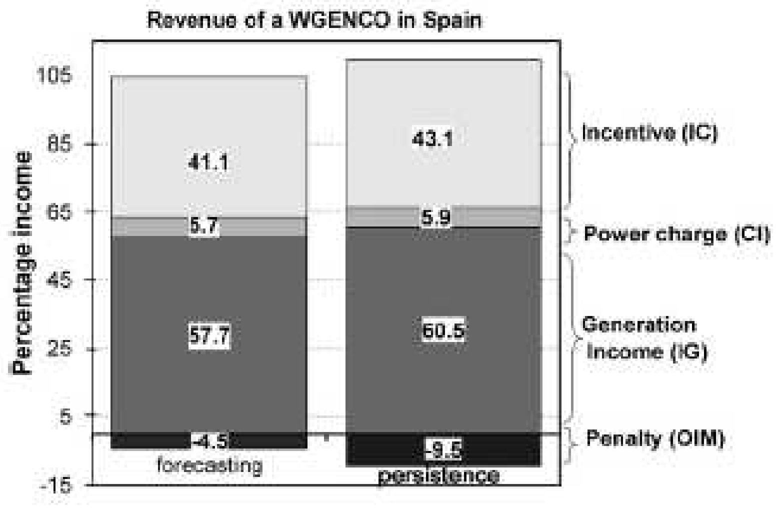


Fig. 3. Revenue for a WGENCO in the Spanish market considering offers only in the daily market.

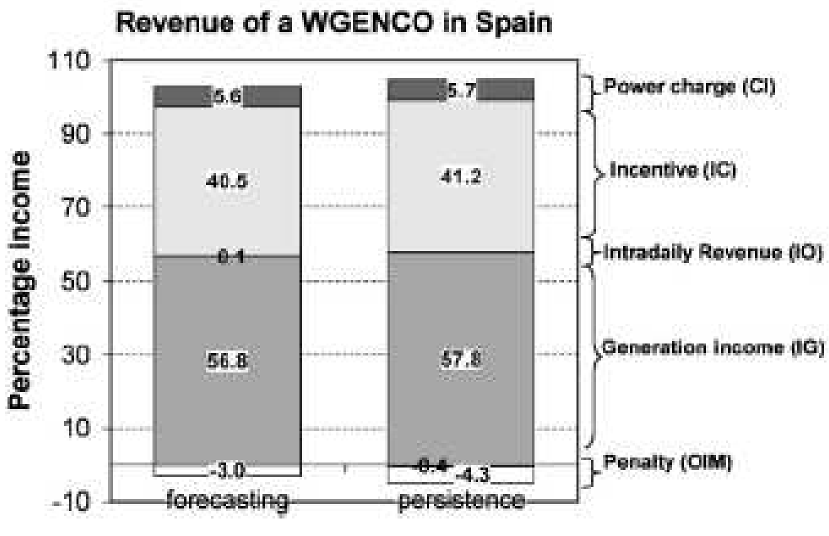


Fig. 4. Revenue for a WGENCO in the Spanish market considering offers in the daily and intra-daily markets.

Results for UK

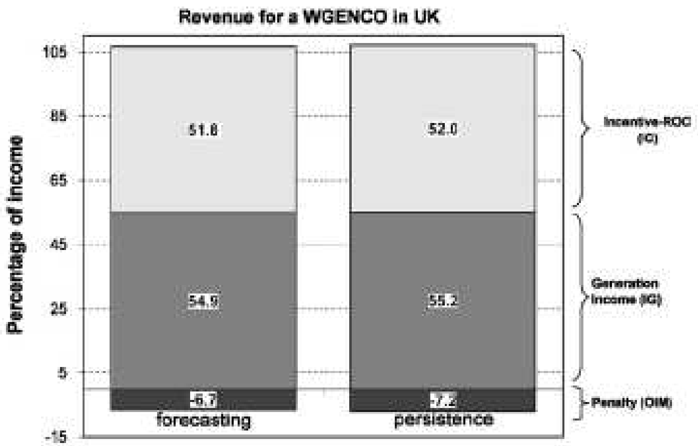


Fig. 5. Revenue for a WGENCO in the British market.

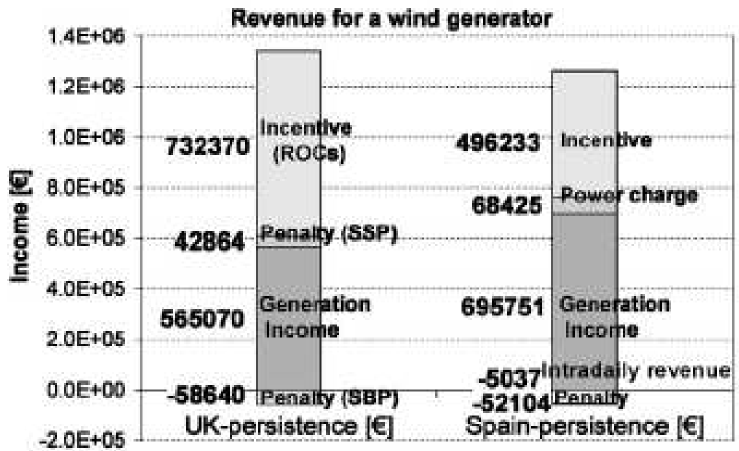
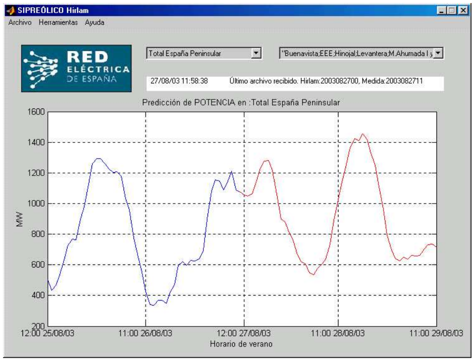
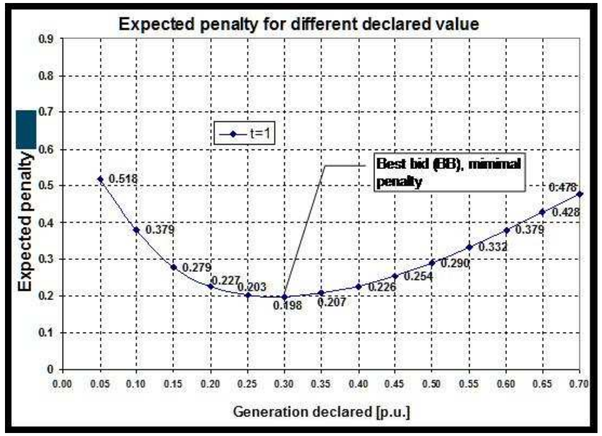


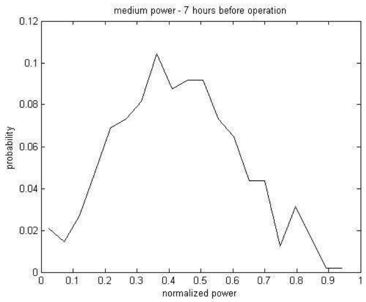
Fig. 6. Revenue comparison between the British and Spanish cases.

Wind power bids considering uncertainty.





Wind power prediction



Uncertainty

Optimal bid

$$\max_{P_{last}} \sum_{j=1}^{j=N} \left\{ R\left(P_{last}, P_{gen,j}\right) \cdot \rho\left(P_{gen,j} \middle| P_{pred}(\Delta t)\right) \right\}$$

Example. Data and assumptions

- **Data:**
  - Wind power production data from a wind farm of 14 MW.
  - Predictions generated by SIPREÓLICO.
  - Uncertainty of these predictions.
  - Prices from the Spanish electricity market
- **Strategy:**
  - Bids presented to the daily market
  - Bids updated in the intraday market
- **Different assumptions:**
  - OPTIMAL: Uncertainties.
  - BEST PREDICTION: Most accurate.
  - NO INTRADAY: No updating

Predictions' uncertainty. Example. Overall results

Maximum revenue

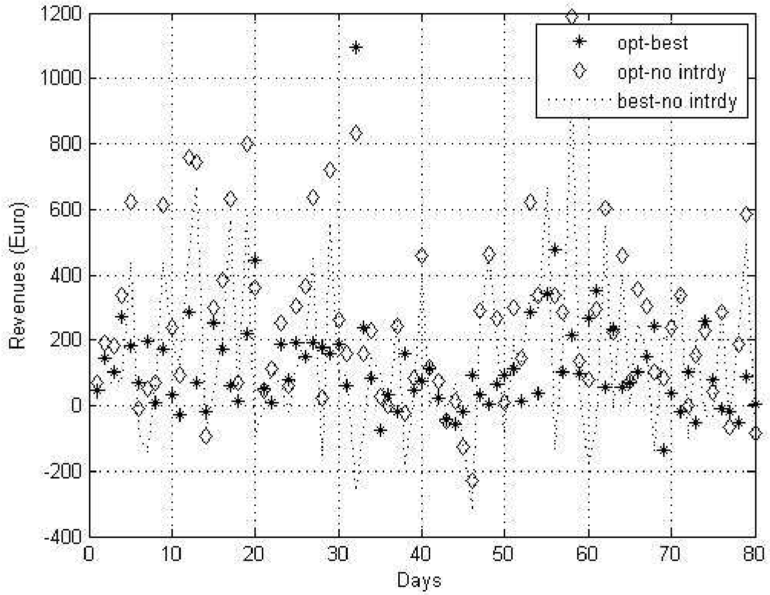
Minimum error

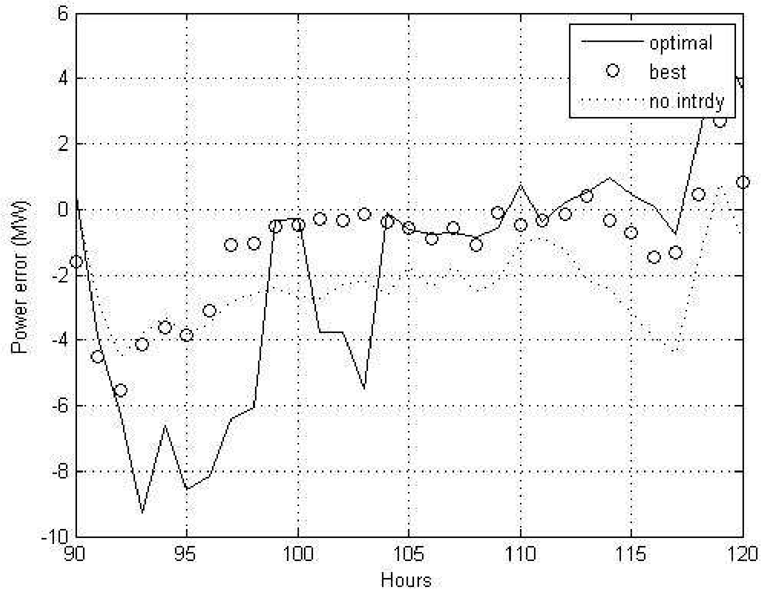
BP/SP=1.5/0.5	OPTIMAL	BEST PREDICTION	NO INTRADAY
Revenues (€)	290 112	280 500	269 046
Error (MW)	-0.3661	0.1412	0.1619
Absolute error(MW)	1.8722	1.4132	2.0198

Buy/Sell prices	1.5/0.5	1/1	0.5/1.5
Optimal	290 112	348 834	467 178
Best prediction	280 500	311 751	343 002
No intraday	269 046	313 039	357 032

Different Buy/sell prices

Example. Overall results





Difference between revenues

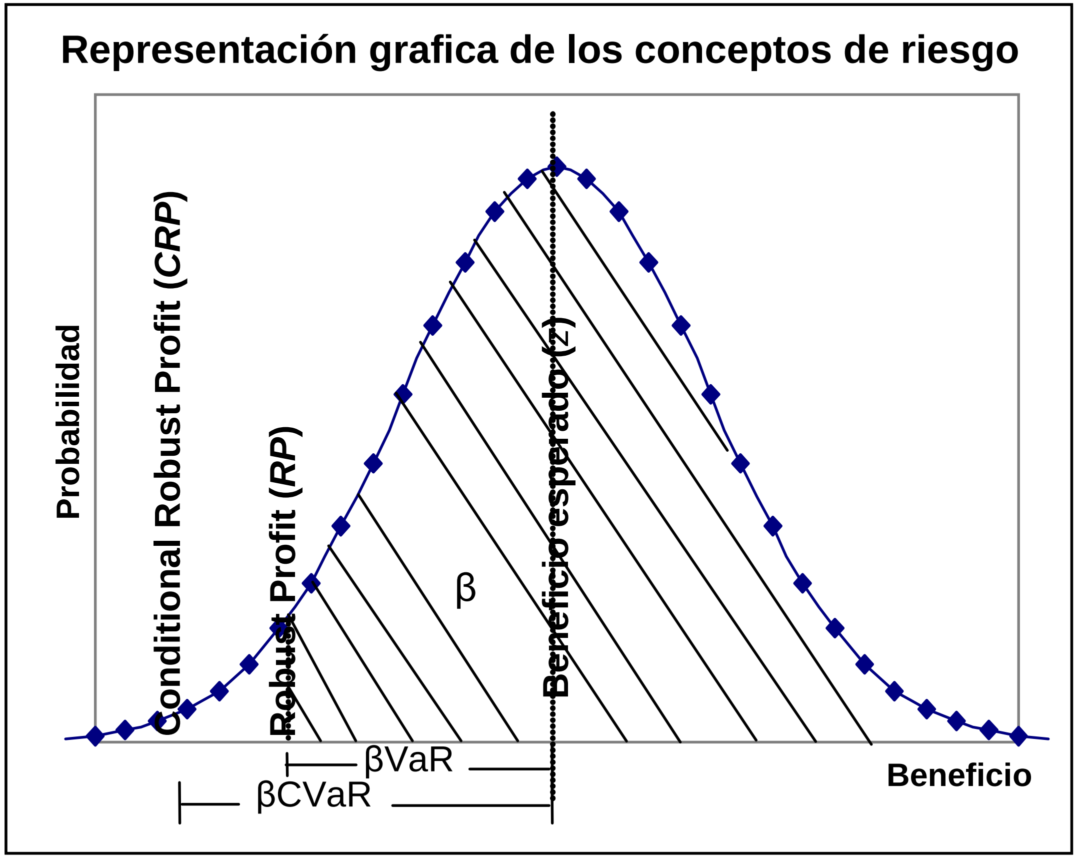
Power error

Sources of uncertainty

- **Wind power predictions.**
- **Uncertainty of prices.**
- **Uncertainty of deviations' cost.**

Work in progress…

Risk analysis.



Risk analysis. Results. Summary

Period of 44 days

	maximum penalty	real penalty
min VaR	0,958	224,729
min CVaR	0,668	527,777
min variance	0,615	366,374
min mean value	0,990	202,228

Maximum hourly penalty p.u.

Minimum accumulated penalty p.u.

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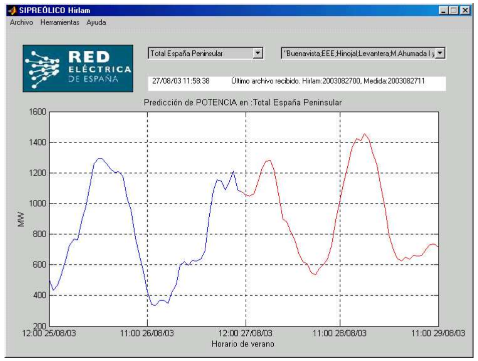
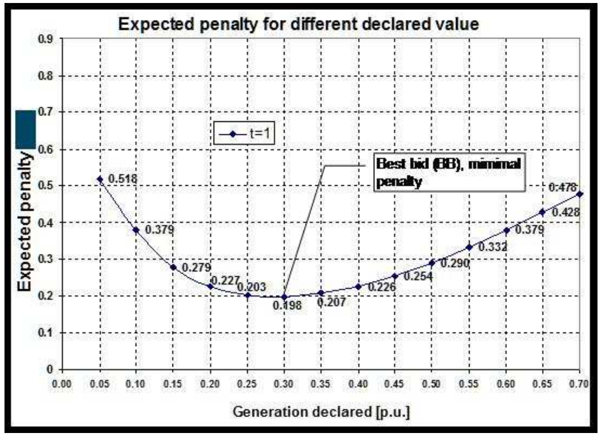
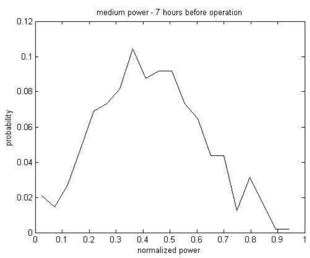
Hidro-wind bids to the electricity markets





Optimal bid

Wind power prediction



Uncertainty

+

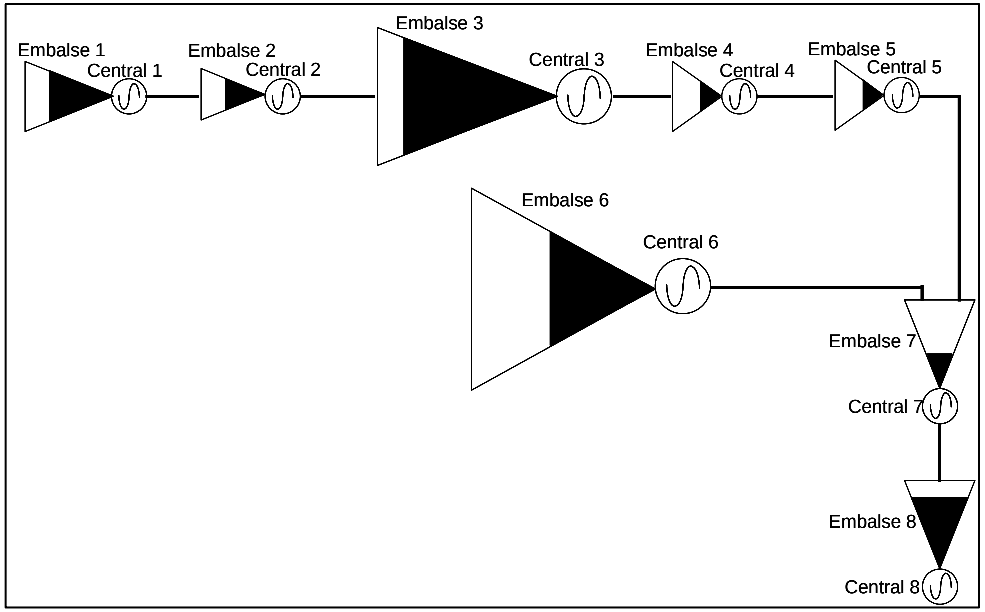
Strategies considered

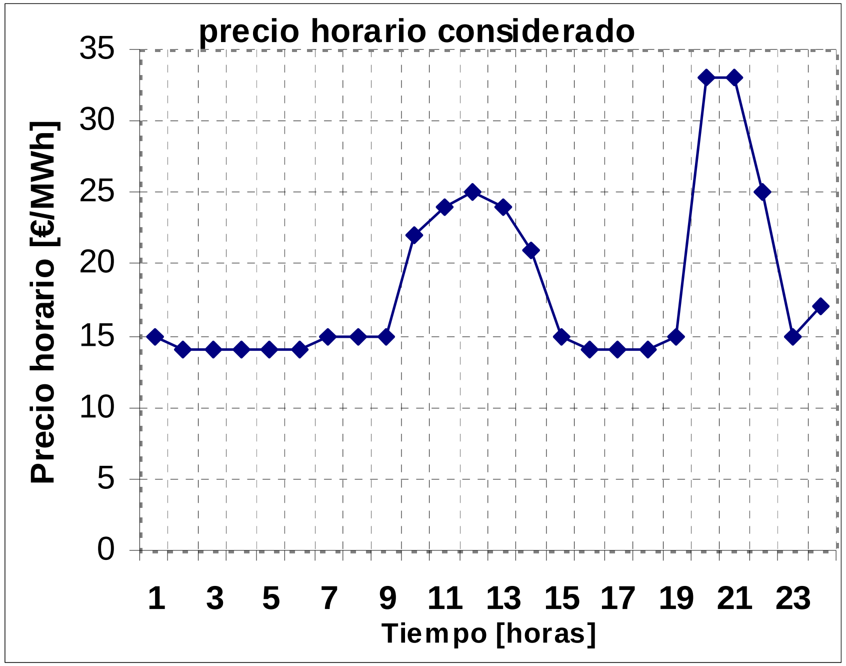
- **Optimal joint operation: hydro and wind bid separately, and hydro covers wind deviations, if profitable.**
- **Optimal joint bid: hydro and wind generation present an update to a previous bid.**

Hydro model. Optimization problem.

- **Objective function: maximum revenue (with water price)**
- **Constraints:**
  - **Maximum and minimum volume.**
  - **Water discharge along the period.**
  - **Water balance.**
  - **Logical constraints.**
  - **…**
- **Piecewise linear performance curve for the hydro unit.**

Hydro model. Example.





Data from: "Self Scheduling of Hydro Producer in a Pool-Based Electricity Marked", ***IEEE Transactions on power systems*****, Vol. 17, No.4, November 2002.**

Hydro model. Optimization problem.

$$IHE = \sum_{t=1}^{t=T} \left\{ \sum_{i=1}^{i=I} \left(\lambda_t \cdot ph_{t,i} - ca_i \cdot y_{t,i} \right) \right\}$$

Objective functions

$$BHE = \sum_{t=1}^{t=T} \left\{ \sum_{i=1}^{i=I} \left\{ \lambda_t \cdot p_{t,i} - ca_i \cdot y_{t,i} + Q_i \right\} \right\} \qquad Q_i = \sum_{j=1}^{j=I} \left\{ \frac{x_{T,i}}{M} \cdot \overline{m}_j \cdot \gamma \right\} \qquad \forall i \in I, \forall j \in \Theta$$

$$x_{t,i} = x_{t-1,i} + W_{t,i} + M \sum_{j \in \Omega i} \sum_{l=1}^{l=L} \left[u_{t-\tau ij,j,l} + s_{t-\tau ij,l} \right] - M \cdot \sum_{l=1}^{l=L} \left[u_{t,i,l} + s_{t,i,l} \right] \; \forall i \in I, \; \forall t \in T$$

Some constraints…

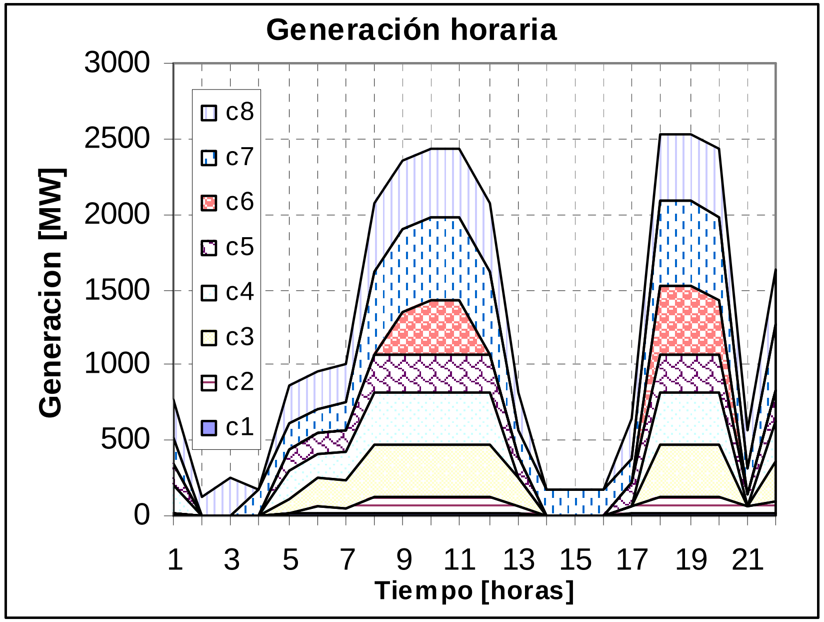
$$min \left\{ \underline{U}_i, \underline{U}_{i,t}^{ext} \right\} \leq \sum_{l=1}^{l=L} u_{t,i,l} \leq max \left\{ \overline{U}_i, \overline{U}_{i,t}^{ext} \right\} \; \forall i \in I, \forall t \in T, \forall l \in L$$

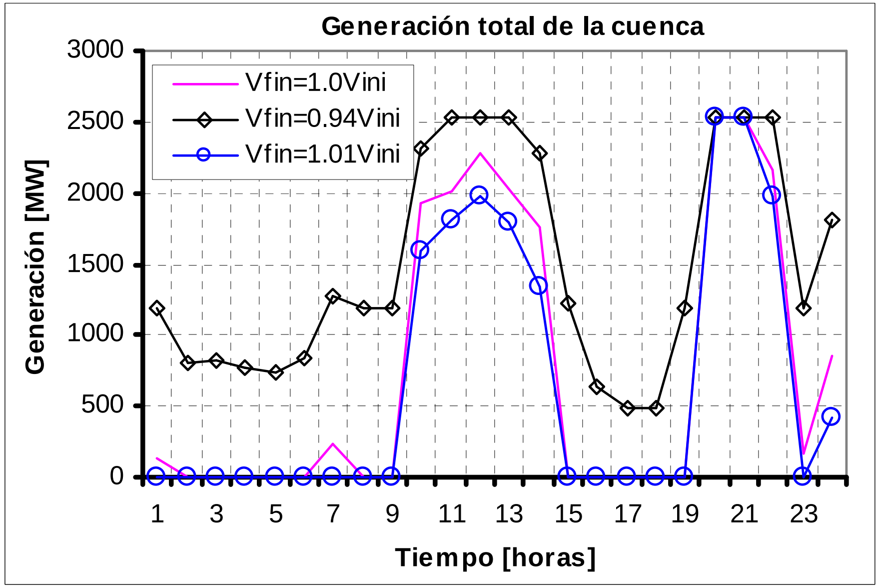
$$x_{24,i} = x_{obj,i} \quad \forall i \in I$$

…

Hydro model. Example. Results.

- **Problem solved using Matlab/Gams/Cplex**
- **Results for**
  - **Water volume.**
  - **Water future shade price.**





Optimal hydro wind operation. Assumptions.

- Hydro and wind have prepared bids to the market separatedly.
- Hydro units try to minimize deviations from wind, only if profitable for both. Future water price is taken into account.
- Decision is taken short time before operation (1 hour): wind production is known accurately.
- Routines programed in GAMS. Moderate size of the problem.

Optimal hydro wind operation. Problem settings.

$$\max\ IO\_HE_t = \{IH_t + IE_t - P_t\}$$

$$IH_t = \sum_{i \in I} \left[\lambda_t \cdot ph_{t,i} + Q_i\right]$$ Hydro revenues

$$IE_t = pe_t \cdot \lambda_t$$ Wind revenues

Penalties:

$$P_t = |R_t| \cdot \psi_t$$

$$R_t = \sum_{i=1}^{i=I} \{ph_{t,i}\} + pe_t - \sum_{i=1}^{i=I} \{ph_{t,i}^{prog}\} - pe_t^{prog}$$

$$\psi_t = \psi_{t,undergeneration} \quad if \quad R_t < 0$$

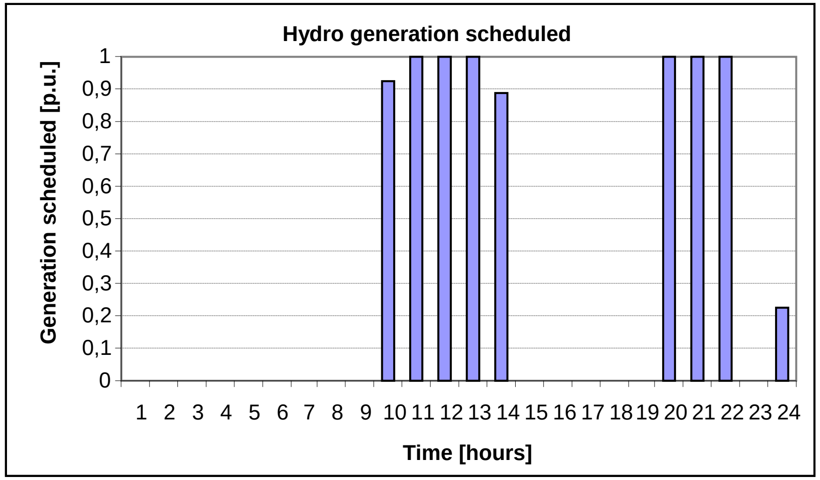
$$\psi_t = \psi_{t,overgeneracion} \quad if \quad R_t \geq 0$$

Optimal hydro wind operation. Results

- **Benefits from joint operation: reduction between 25% and 45% of the deviation cost.**
- **Sometimes hydro cannot change its production:**
  - **Maximum hydro production and wind undergeneration**
  - **Minimum (zero) production and wind overgeneration**

Hydro wind operation. Results

Problem solved using Gams/Cplex.



$$\psi_{t,overgen} = \eta_{over} \cdot \lambda_t$$

$$\psi_{t,undergen} = \eta_{under} \cdot \lambda_t$$

$$\eta_{over} = \eta_{under} = 0{,}1$$

	Generation imbalance	
	over	under
Base case [MWh]	35,72	39,69
Joint operation [MWh]	29,71	34,98
Reduction [MWh]	6,01	4,72
Reduction [%]	16,83	11,88

	Power imbalances [MW]											
	h1	h2	h3	h4	h5	h6	h7	h8	h9	h10	h11	h12
Wind generation	4,082	7,448	-0,372	3,098	2,335	5,123	1,533	0,440	0,475	2,177	1,045	-0,058
Joint operation	4,082	7,448	-0,372	3,098	2,335	5,123	1,533	0,440	0,475	0,000	0,000	-0,058
	h13	h14	h15	h16	h17	h18	h19	h20	h21	h22	h23	h24
Wind generation	-0,101	-1,364	2,566	-0,982	2,608	-0,664	-8,071	-14,698	-2,112	2,789	-8,021	-3,251
Joint operation	0,000	0,000	2,566	-0,982	2,608	-0,664	-8,071	-14,698	-2,112	0,000	-8,021	0,000

Hydro-wind joint bids. Optimization problem

- **Joint bid of hydro and wind generation.**
- **Stochastic optimization problem. Great dimension.**
- **Maximization of revenues. Takes into account wind prediction uncertainty.**
- **Programed in GAMS.**

- **Results:**
  - **The deviations are smaller if their cost is high.**
  - **Results are better than with deterministic optimization.**
  - **Benefits depend on the deviation price**

Hydro-wind joint bids. Optimization problem

$$\max IEP\_HE = \sum_{w=1}^{w=N}\sum_{t=1}^{t=T}\rho_w \left\{IEH_{t,w} + IE_{t,w} - P_{t,w}\right\}$$

Objective function

$$IHE_{t,w} = \sum_{i=1}^{i=I}\left\{\lambda_t \cdot ph_{i,t,w} - ca_i \cdot y_{t,i,w} + Q_{i,w}\right\} \qquad \forall t \in T,\ \forall w \in N$$

$$ph_{i,t,w} = \sum_{l=1}^{l=L} u_{i,t,l,w}\rho_{i,l} \quad \forall i \in I, \forall t \in T, \forall w \in N$$

Constraints

$$y_{t,y,w} - z_{t,i,w} = \mu_{t,i,w} - \mu_{t-1,i,w} \qquad \forall i \in I, \forall t \in T, \forall w \in N$$

Optimal hydro-wind bid. Example

Time		PDF 1	PDF 2	PDF 3	Expectad value (MW)	Expected imbalance: undergeneration	Expected imbalance: overgeneration
hour 1	power(MW)	230	200	190	207	6,90	6,90
	probab.	0,3	0,5	0,2			
hour 2	power(MW)	250	235	220	236,5	5,40	5,40
	probab.	0,4	0,3	0,3			
hour 3	power(MW)	230	220	200	215	5,25	5,25
	probab.	0,2	0,45	0,35			
hour 4	power(MW)	210	190	175	196	6,30	6,30
	probab.	0,45	0,35	0,2			
hour 5	power(MW)	190	180	170	184	3,00	3,00
	probab.	0,5	0,4	0,1			
				TOTAL	1038,5	26,85	26,85
						53,70	

- A period of 5 hours and three scenarios, i.e. 245 total scenarios.
- Wind farm of 250 MW.

Optimal hydro-wind bid. Example. Results

$$\psi_{t,undergeneration} = \eta \cdot \lambda_t \qquad \psi_{t,overgeneration} = \eta \cdot \lambda_t$$

		÷										
	Penalty	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1
Optimal	Overgeneration (MW)	-	2	2	2	2	2	2	0	0	0	0
	Undergeneration (MW)	-	8	0	0	0	0	0	0	0	0	0
	Overgeneration cost (€)	-	9,6	19,2	28,8	38,4	48	57,6	0	0	0	0
	Undergeneration cost (€)	-	40,2	0	0	0	0	0	0	0	0	0
	Total imbalance cost (€)	-	49,8	19,2	28,8	38,4	48	57,6	0	0	0	0
Expected value	Overgeneration (MW)	-	5,25	5,25	5,25	5,25	5,25	5,25	5,25	5,25	5,25	5,25
	Undergeneration (MW)	-	8,25	3	3	3	3	3	3	3	3	3
	Overgeneration cost (€)	-	25,2	50,4	75,6	100,8	126	151,2	176,4	201,6	226,8	252
	Undergeneration cost (€)	-	45	39,6	59,38	79,17	98,96	118,75	138,54	158,33	178,13	197,92
	Total imbalance cost (€)	-	70,2	90	135	180	224,96	269,95	314,94	359,93	404,93	449,92

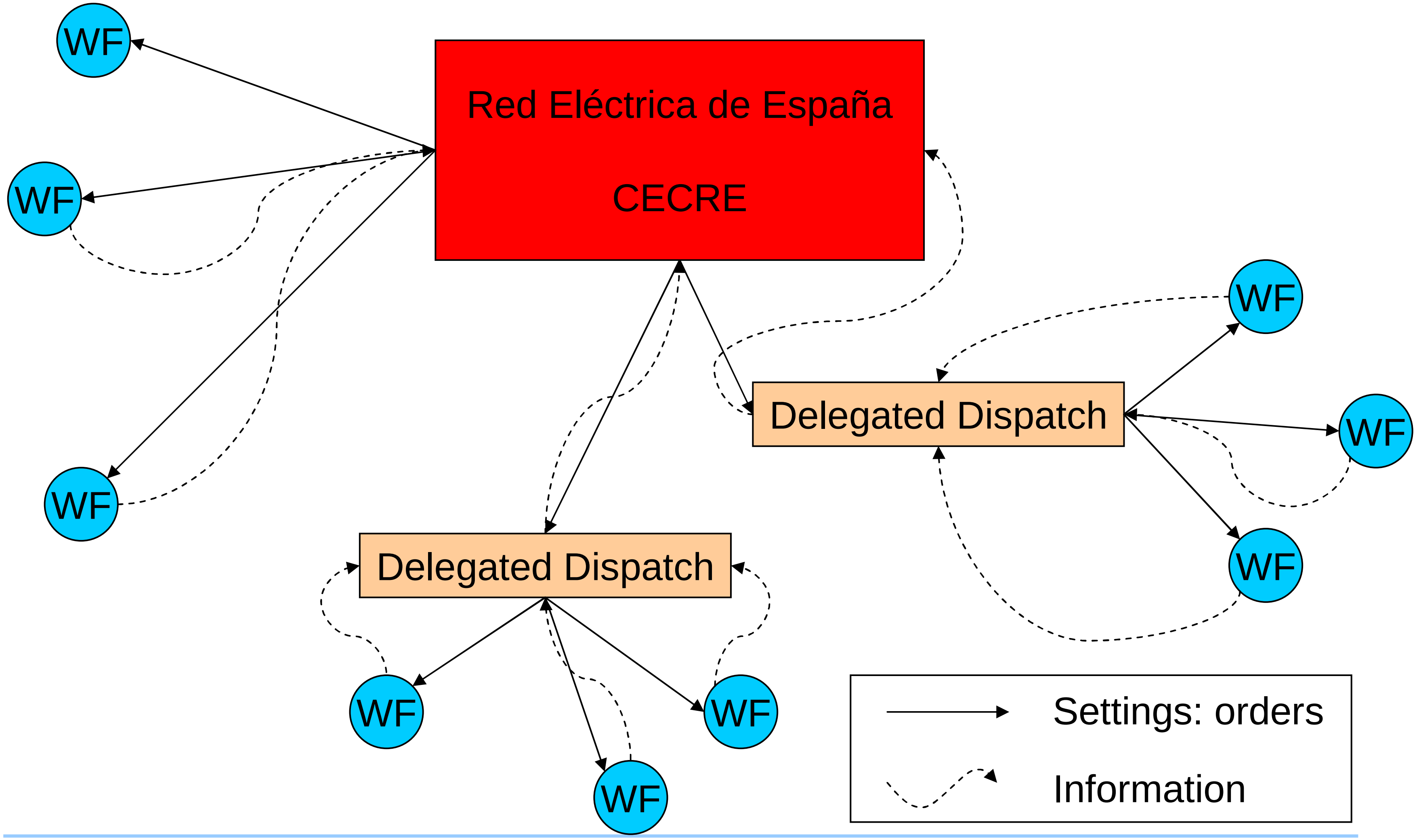
Future research lines

- **Uncertainty of prices.**
- **Uncertainty of deviations’ cost.**
- **Pumping and storage.**
- **Improvement of the optimization process.**

Presentation index

- Introduction. Research subjects.
- Short term wind power prediction.
- Participation of wind energy in the electricity markets.
- Hydro wind coordination.
- **Optimization of Wind Dispatching Centres operation.**

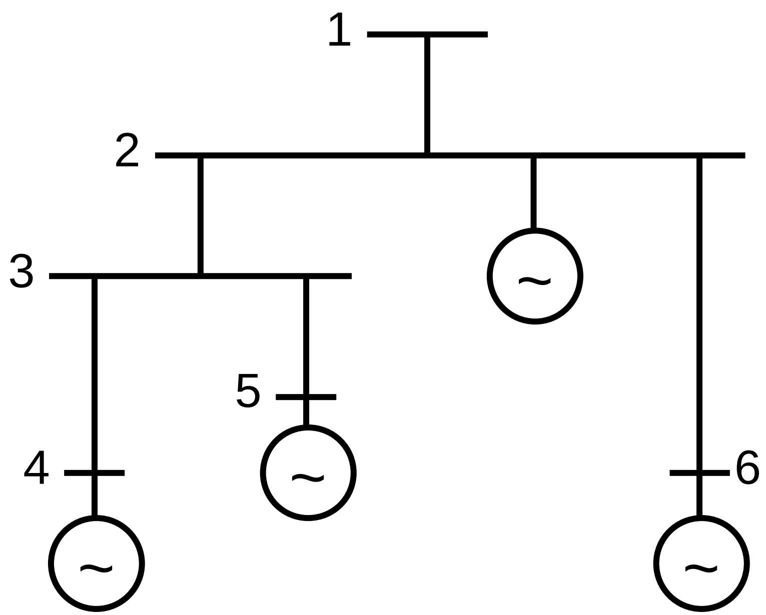
Wind energy and Delegated Dispatches



Alternatives for the Optimal Allocation of the Reductions

- **Three alternatives for the optimal allocation of the reductions required by the SO are considered:**
  - **proportional reduction,**
  - **with controllability prices**
  - **with controllability and interruptive prices.**
- **Tested in a Spanish test system.**

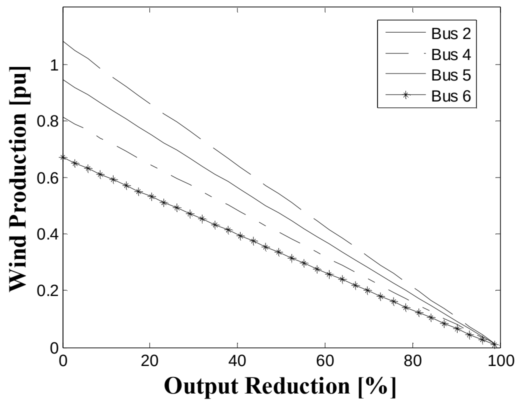
Alternatives for the Optimal Allocation of the Reductions – Test Case

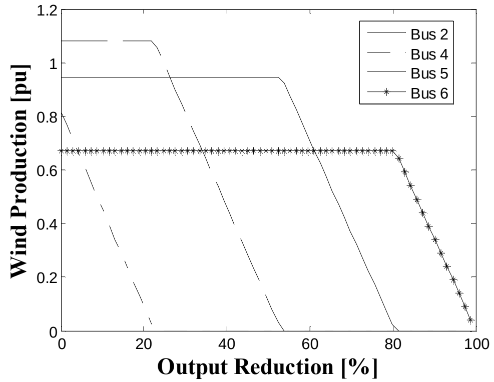


- **6 buses and 4 wind parks.**
- **Bus 1 is the output bus (connection with the transmission system)**

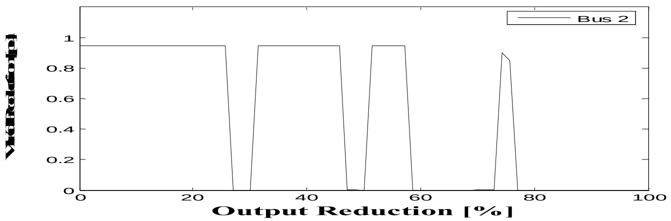
Optimal Allocation of the Reductions

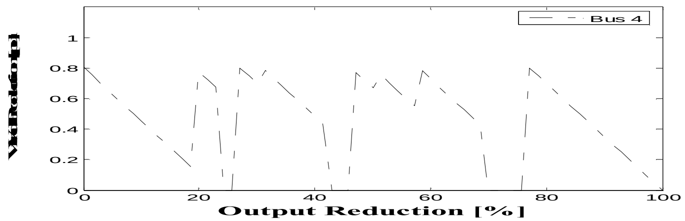
Proportional



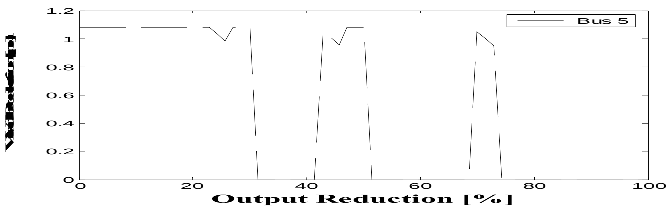


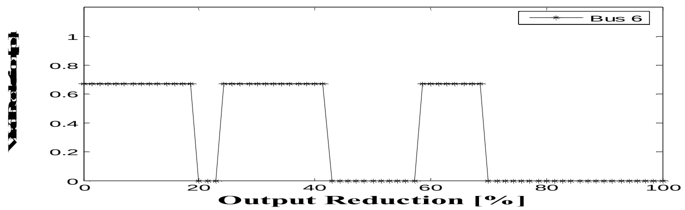
With controlability prices.





Controlability and interrumpibility prices.





Optimization process

$$\min \sum_{j=1}^{m} cp_j \cdot CR_j$$

s.t.

$$CR_j = P_{Gj}^{av} - S_{Gj} \cdot \cos\varphi_j$$

$$S_{Gi} \cdot \cos\varphi_i + P_{Gi}^{NC} - P_{Di} - P(V,\alpha) = 0$$

$$S_{Gi} \cdot \sin\varphi_i + Q_{Gi}^{NC} - Q_{Di} - Q(V,\alpha) = 0$$

$$P_{out} \le P_{out}^{Max}$$

$$\alpha_{sk} = 0$$

$$0.0 \le CR_j \le P_{Gj}^{av}$$

$$S_{Gj} \cdot \cos\varphi_j \ge 0.0$$

$$\cos\varphi_i \ge \cos\varphi_i^{\min}$$

$$V_i^{\min} \le V_i \le V_i^{\max}$$

$$T_{ik}^{\min} \le T_{ik} \le T_{ik}^{\max} \quad i \ne k$$

$$i,k = 1 \ldots n \qquad j = 1 \ldots m$$

With controlability prices.

$$\min \sum_{j=1}^{m} \left(cp_j \cdot CR_j + ip_j \cdot IR_j \cdot P_{Gj}^{av} \right)$$

s.t.

$$\sum_{j=1}^{m} P_{Gj} = P_{out}^{Max}$$

$$P_{Gj} + CR_j = P_{Gj}^{av} \cdot (1 - IR_j)$$

$$IR_j + \frac{CR_j}{P_{Gj}^{av}} \le 1.0$$

$$[P_{Gi}] = [B] \cdot [\varphi_i]$$

$$i = 1 \ldots n$$

$$j = 1 \ldots m$$

Controlability and interrumpibility prices.

Reserves in Spain