Multi-Market Optimal Bidding for a Power Producer

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Outline

- Optimal bidding
- Uncertainty characterization
- Problem formulation
- Case study

Optimal bidding Objective

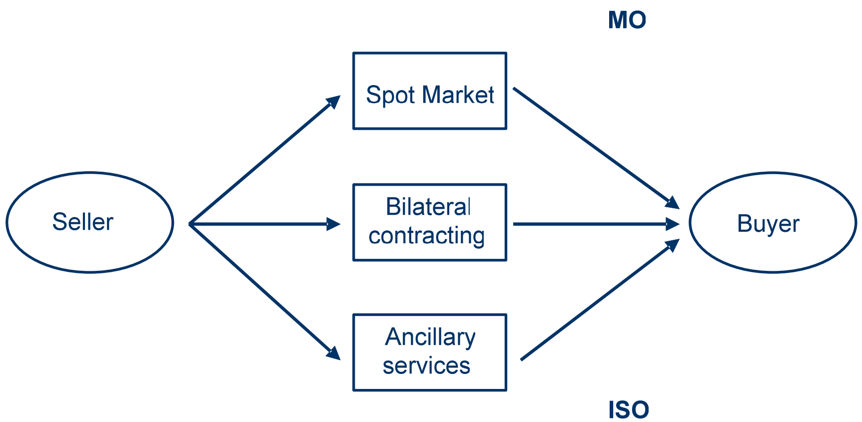
- FIND OUT Optimal bidding curves for the day-ahead market

TAKING INTO ACCOUNT:

- AGC market
- Balancing market

Electricity Markets

Background



Optimal bidding
Approach

Three stage stochastic programming

- ➢Day-ahead market
- ➢AGC market
- ➢Balancing market

Optimal bidding
Approach

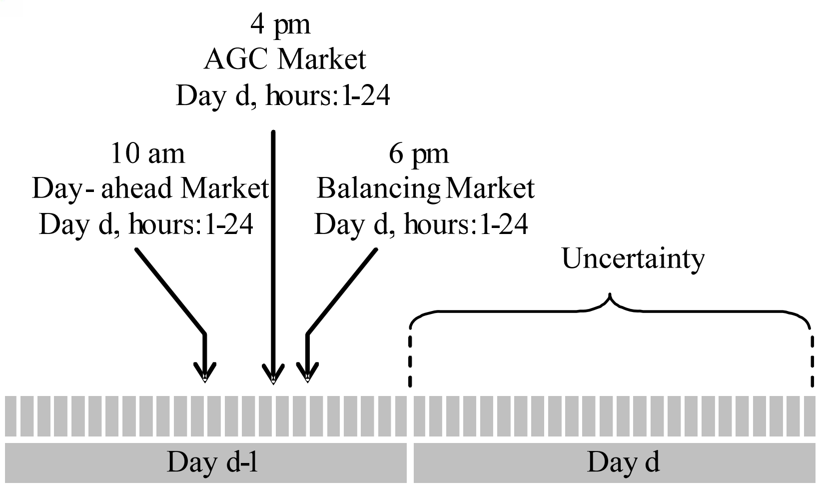
No market power:

- ➢Day-ahead market
- ➢AGC market

Market power:

- ➢Balancing market

Optimal bidding
Decision framework

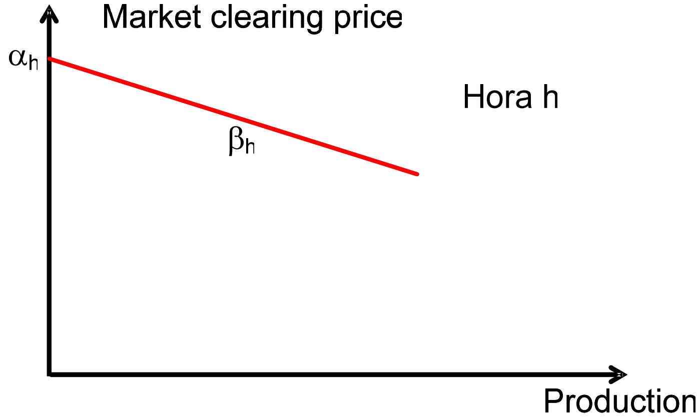


Uncertainty characterization
Random variables

- Day-ahead prices (24)
- AGC prices (24)
- Balancing market
  - ➢Intercepts (24)
  - ➢Slopes (24)

Uncertainty characterization
Random variables

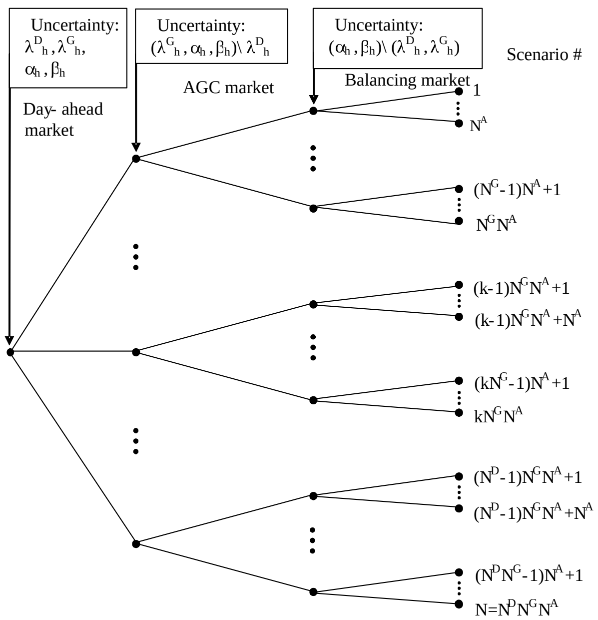
Balancing market (intercepts plus slopes)



Uncertainty characterization
Random variables

Variable	Weekdays
λ_h^D	ARIMA(1,0,1)(2,0,1)$_{24}$
λ_h^G	ARIMA(5,0,1)(1,0,0)$_{24}$
$\alpha_h - \lambda_h^D$	ARIMA(1,0,2)(1,0,1)$_{24}$
β_h	ARIMA(2,0,1)(1,0,1)$_{24}$

Uncertainty characterization. Scenario tree

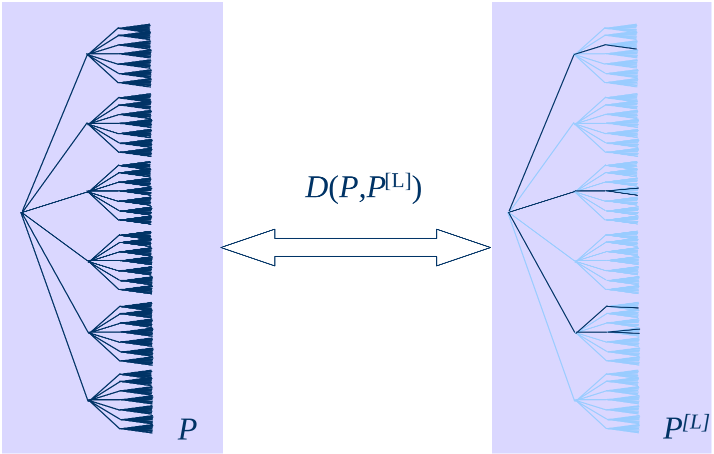


Uncertainty characterization
Scenario reduction

How to attain tractability?

Scenario reduction!

Uncertainty characterization
Scenario reduction



Strategy

- No optimal decisions
- Optimal offer curves

↓

- Decisions dependent on prices (on scenarios !)

Notation

p power (MW)

e energy (MWh)

t total energy (MWh)

R ramp limit (MW/h)

λ price (€/MWh)

C cost (€/MWh)

h time index

j unit index

k scenario index

PROBLEM FORMULATION
Day-ahead market

$$\text{Maximize}_{e^D_{jhk},\, t^D_{hk}}$$

Expected profit in the day ahead market plus expected profits in subsequent markets:

$$E_K\{\textstyle\sum_h (t^D_{hk}\lambda^D_{hk} - \sum_j C_j e^D_{jhk}) + \Psi^G_k(e^D_{jhk}, t^D_{hk})\}$$

Expected profit is subsequent markets

PROBLEM FORMULATION
Day-ahead market

Subject to:

Production limits (energy) per unit, hour and scenario:

$$e_{jhk}^{D} \le P_j^{max} \cdot 1 \qquad \forall j, \forall h, \forall k$$

$$e_{jhk}^{D} \ge P_j^{min} \cdot 1 \qquad \forall j, \forall h, \forall k$$

Energy production (all units) per hour & scenario:

$$t_{hk}^{D} = \sum_j e_{jhk}^{D} \qquad \forall h, \forall k$$

PROBLEM FORMULATION
Day-ahead market

Offer curves must be increasing over k (price scenarios):

$$e_{jhk}^{D} \le e_{jh\tilde{k}}^{D} \qquad \forall j, \forall h, \forall k, \tilde{k} : \lambda_{hk}^{D} \le \lambda_{h\tilde{k}}^{D}$$

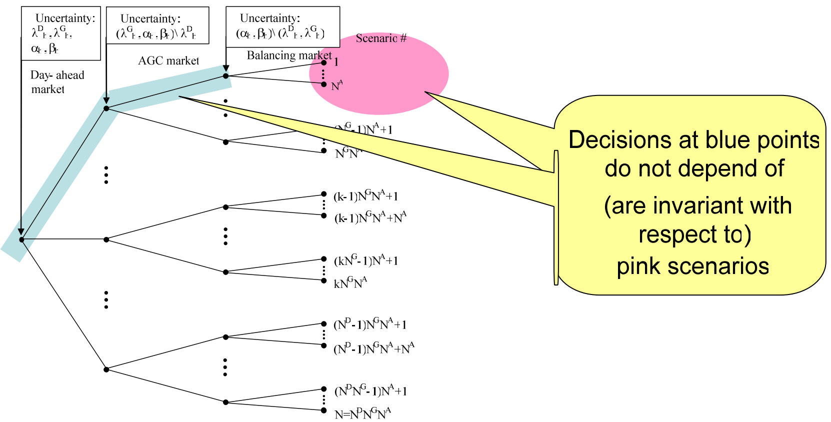
Partial non-anticipativity over price scenarios of day-ahead market: equal price, equal production

$$e_{jhk}^{D} = e_{jh\tilde{k}}^{D} \qquad \forall j, \forall h, \left(\forall k, \tilde{k} : \lambda_{hk}^{D} = \lambda_{h\tilde{k}}^{D}\right)$$

Production of unit j in hour h depends on price in that hour

PROBLEM FORMULATION
Day-ahead market

No anticipativity over balancing market price scenarios



PROBLEM FORMULATION
AGC market

$$\text{Maximize}_{p_{jhk}^{G}, p_{hk}^{G}, w_{jhk}}$$

Expected profit in AGC market plus expected profit in balancing market:

$$E_{K \backslash \lambda_{hk}^{D}} \left\{ \sum_h p_{hk}^{G} \lambda_{hk}^{G} + \Psi_k^{A}(e_{jhk}^{D}, t_{hk}^{D}, p_{jhk}^{G}, p_{hk}^{G}, w_{jhk}) \right\}$$

PROBLEM FORMULATION
AGC market

Subject to:

AGC contribution iff binary variables equal 1 (per unit, hour and scenario):

$$p^G_{jhk} \le w_{jhk} P^{AGC}_j \cdot 1 \; \forall j, \forall h, \forall k$$

Total power dedicated to AGC (per hour and scenario):

$$p^G_{hk} = \sum_j p^G_{jhk} \qquad \forall h, \forall k$$

PROBLEM FORMULATION
AGC market

Partial non-antivipativity over k (price scenario): equal price, equal production

$$p^G_{jhk} = p^G_{jh\tilde{k}} \qquad \forall j, \left(\forall h; \forall k, \tilde{k} : \lambda^D_{hk}, \lambda^D_{hk}\right)$$

$$\forall j,\; \forall h, \left(\forall k, \tilde{k} : \lambda^G_{hk} = \lambda^G_{h\tilde{k}}\right)$$

AGC power of unit j in hour h depends on price in that hour

Binary variable declaration:

$$w_{jhk} \in \{0,1\} \qquad \forall j, \forall h, \forall k$$

PROBLEM FORMULATION
Balancing market

$$\underset{p_{jhk}, e^A_{jhk}, t^A_{hk}}{\text{Maximize}}$$

Expected profit in balancing market:

$$E_{K\setminus(\lambda^D_{hk},\lambda^G_{hk})}\{\sum_h (t^A_{hk}\underbrace{(\alpha_{hk} + \beta_{hk} t^A_{hk})}_{\lambda^D_{hk}(\cdot)} - \sum_j C_j e^A_{jhk})\}$$

PROBLEM FORMULATION
Balancing market

Subject to:

Power capacity limits (per unit, hour and scenario):

$$p_{jhk} \le P^{max}_j \qquad p_{jhk} \ge P^{min}_j \qquad \forall j,h,k$$

Energy capacity limits (per unit, hour and scenario):

$$e^D_{jhk} + e^A_{jhk} + \tfrac{1}{2} p^G_{jhk} \cdot 1 \le P^{max}_j \cdot 1 \quad \forall j,h,k$$

$$e^D_{jhk} + e^A_{jhk} - \tfrac{1}{2} p^G_{jhk} \cdot 1 \ge P^{min}_j \cdot 1 \quad \forall j,h,k$$

PROBLEM FORMULATION
Balancing market

Energy and power relationship (linear change), per unit, hour and scenario:

$$e^{D}_{jhk} + e^{A}_{jhk} = \tfrac{1}{2}\left(p_{j(h-1)k} + p_{jhk}\right)\cdot 1 \qquad \forall j,h,k$$

If ramping no AGC and vice versa (per unit, hour and scenario):

$$p_{jhk} - p_{j(h-1)k} \le (1 - w_{jhk}) R^{up}_{j} \qquad \forall j,h,k$$

$$p_{j(h-1)k} - p_{jhk} \le (1 - w_{jhk}) R^{dw}_{j} \qquad \forall j,h,k$$

PROBLEM FORMULATION
Balancing market

Total energy in balancing market (all unit) (per hour and scenario):

$$t^{A}_{hk} = \sum_{j} e^{A}_{jhk} \qquad \forall h,k$$

Problem formulation
Program with recourse

$$\text{Maximize}_{e^{D}_{jhk}, t^{D}_{hk}, p^{G}_{jhk}, p^{G}_{hk}, w_{jhk}, p_{jhk}, e^{A}_{jhk}, t^{A}_{hk}}$$

$$\sum_{k}\Bigg[\sum_{h}\left(t^{D}_{hk}\lambda^{D}_{hk} - \sum_{j} C_j e^{D}_{jhk}\right)$$

Day-ahead market profit

$$+ \sum_{h} p^{G}_{hk}\lambda^{G}_{hk}$$

AGC market profit

$$+ \sum_{h}\left(t^{A}_{hk}\left(\alpha_{hk} + \beta_{hk} t^{A}_{hk}\right) - \sum_{j} C_j e^{A}_{jhk}\right)\Bigg]\pi_k$$

Balancing market profit

subject to:

Day-ahead market constrains

AGC market constrains

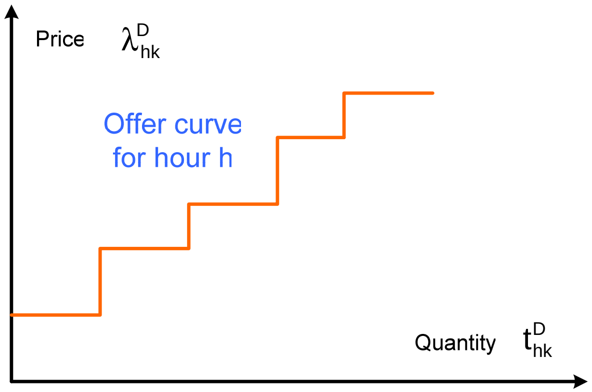
Balancing market constrains

Solution technique

Solution:

- CPLEX
- Coordinate descent: each unit optimized with others at fixed values. Iteration!

Solution: Offer curves



Solution quality

Quality:

- ➢VSS: Value of the Stochastic Solution
- ➢RP: Average value over scenarios of the day ahead profit evaluated with the *stochastic solution*
- ➢EEV: Average value over scenarios of the day ahead profit evaluated with the *deterministic solution* (random variables substituted by their respective expected values)
- ➢VSS = RP - EEV

Solution quality

Comparison among different approaches

Profit for actual prices:

- ➢EEM: Multi-market stochastic solution
- ➢DEM: Multi-market deterministic solution
- ➢DEU: Single-market deterministic solution

Case Study
(market of mainland Spain)

- Case 1: May 3-7, 2004 (Monday-Friday)
  - Low temperature
  - Low demand
  - Low prices
- Case 2: June 7-11, 2004 (Monday-Friday)
  - High temperatures
  - High demand
  - Low hydro production
  - High prices

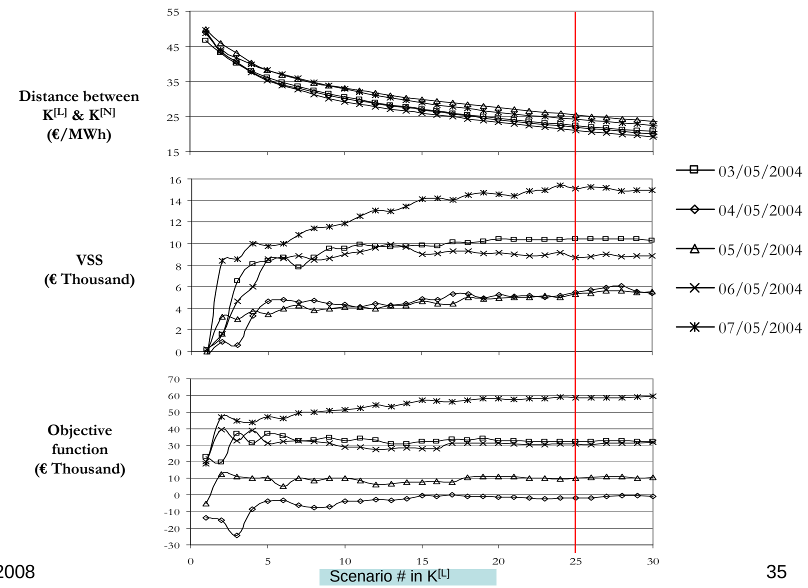
Case Study1: Production Company

	C_j^F	C_j	P_j^{max}	P_j^{min}	P_j^{AGC}	R_j^{up}	R_j^{dw}	P_{j0}
	€/h	€/MWh	MW	MW	MW	MW/h	MW/h	MW
Coal 1	**126.0**	**19.81**	**140**	**75**	**20**	**65**	**65**	**130**
Coal 2	**708.8**	**23.40**	**350**	**150**	**30**	**200**	**200**	**335**
CCGT 1	**1097.2**	**25.17**	**380**	**160**	**50**	**220**	**220**	**185**
CCGT 2	**992.8**	**25.51**	**390**	**180**	**50**	**210**	**210**	**205**
Coal 3	575.0	29.37	500	250	40	250	250	270
Fuel 1	1800	33.91	300	200	20	100	100	220
Fuel 2	91.5	37.91	50	25	0	25	25	25

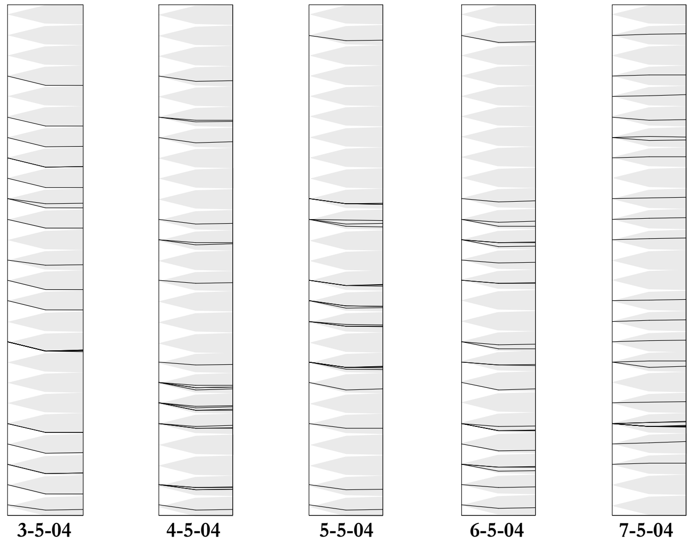
Case Study1. Uncertainty

Variable	Model
λ_h^D	ARIMA(1,0,1)(2,0,1)$_{24}$
λ_h^G	ARIMA(5,0,1)(1,0,1) $_{24}$
α_h	ARIMA(1,0,2)(1,0,1) $_{24}$
β_h	ARIMA(2,0,1)(1,0,1) $_{24}$

Case 1. Scenario Reduction



Case 1. Scenario Reduction



Case 1: Solution

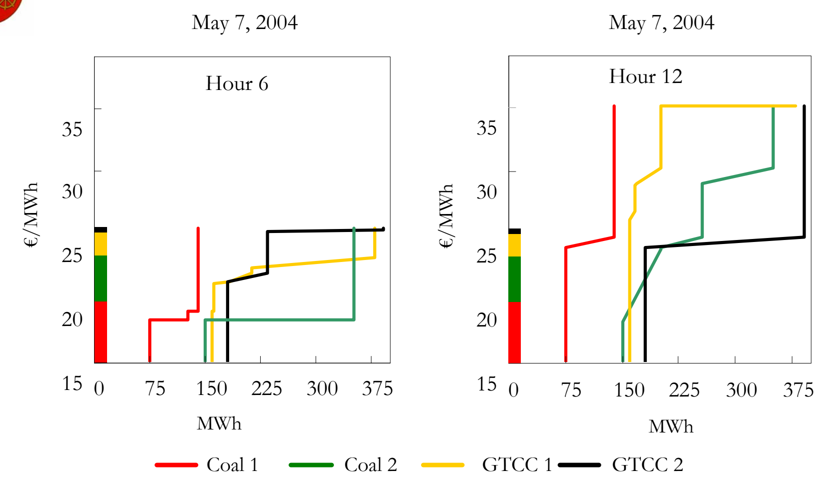
Coordinate Descent

	03-05-04	04-05-04	05-05-04	06-05-04	07-05-04
Iteration #	4	3	3	3	2
Result (€)	32654	-1878	10496	30690	58672
Error (€)	12	12	46	1	33
Error (%)	0.0	0.7	0.4	0.0	0.1
CPU time (s)	411	310	310	313	210

Direct Solution (CPLEX)

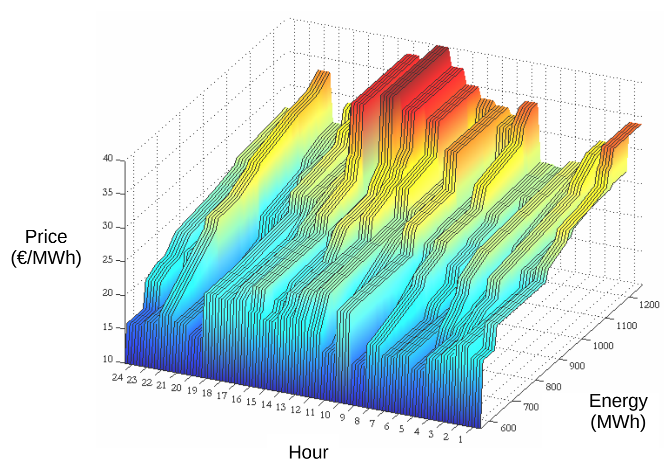
	03-05-04	04-05-04	05-05-04	06-05-04	07-05-04
Result (€)	32670	-1620	10662	30734	58737
Error (€)	535	619	532	687	673
Error (%)	1.6	38.2	5.0	2.2	1.1
CPU time (s)	411	310	310	313	210

Case1: Individual offers



Case1: Portfolio offers

May 7, 2004



Case 1: Solution Quality

VSS

Day	03-05-04	04-05-04	05-05-04	06-05-04	07-05-04	Total
RP (€)	32670	-1620	10662	30734	58737	131184
EEV (€)	27980	-6522	6904	25379	54252	107993
VSS (€)	**4690**	**4902**	**3758**	**5355**	**4486**	**23191**
VSS/RP (%)	**14**	**303**	**35**	**17**	**8**	**18**

Case 1: Solution Quality

Comparison among different approaches

Profit for actual prices:

- ➢EEM: Multi-market stochastic solution
- ➢DEM: Multi-market deterministic solution
- ➢DEU: Single-market deterministic solution

Case 1: Solution Quality

Comparison among different approaches

Day	03-05-04	04-05-04	05-05-04	06-05-04	07-05-04	Total
EEM (€)	6307	-924	35564	44658	83325	168929
DEM (€)	4126	-3889	30952	38932	80192	150312
DEU (€)	1873	-3764	32259	41953	79609	151929

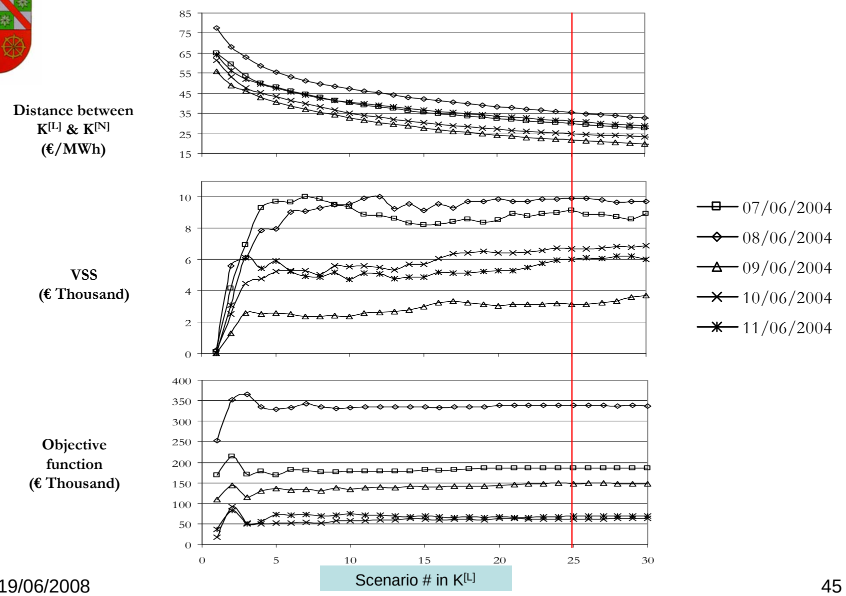
Case Study 2: Production Company

	C_j^F	C_j	P_j^{max}	P_j^{min}	P_j^{AGC}	R_j^{up}	R_j^{dw}	P_{j0}
	€/h	€/MWh	MW	MW	MW	MW/h	MW/h	MW
Coal 1	126.0	19.81	140	75	20	65	65	130
Coal 2	708.8	23.40	350	150	30	200	200	335
CCGT 1	1097.2	25.17	380	160	50	220	220	185
CCGT 2	992.8	25.51	390	180	50	210	210	205
Coal 3	575.0	29.37	500	250	40	250	250	270
Oil 1	1800	33.91	300	200	20	100	100	220
Oil 2	91.5	37.91	50	25	0	25	25	25

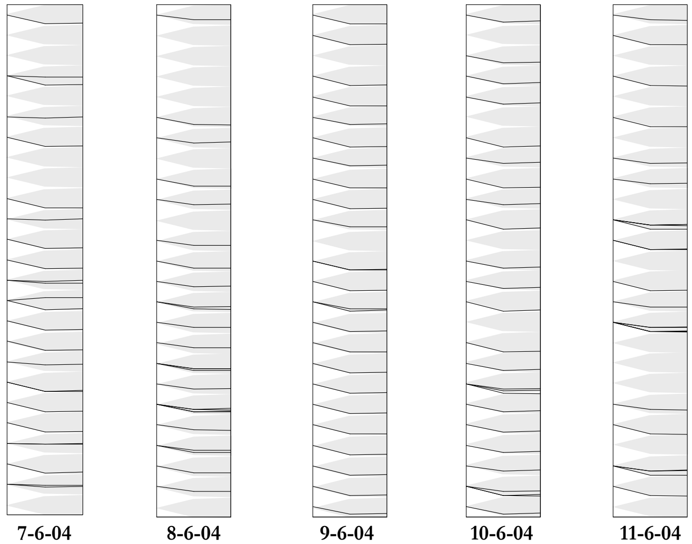
Case 2: Uncertainty

Variable	Model
λ_h^D	$ARIMA(1,0,1)(2,0,1)_{24}$
λ_h^G	$ARIMA(5,0,1)(1,0,1)_{24}$
α_h	$ARIMA(1,0,2)(1,0,1)_{24}$
β_h	$ARIMA(2,0,1)(1,0,1)_{24}$

Case 2: Scenario Reduction



Case 2: Scenario Reduction



Case 2: Solution

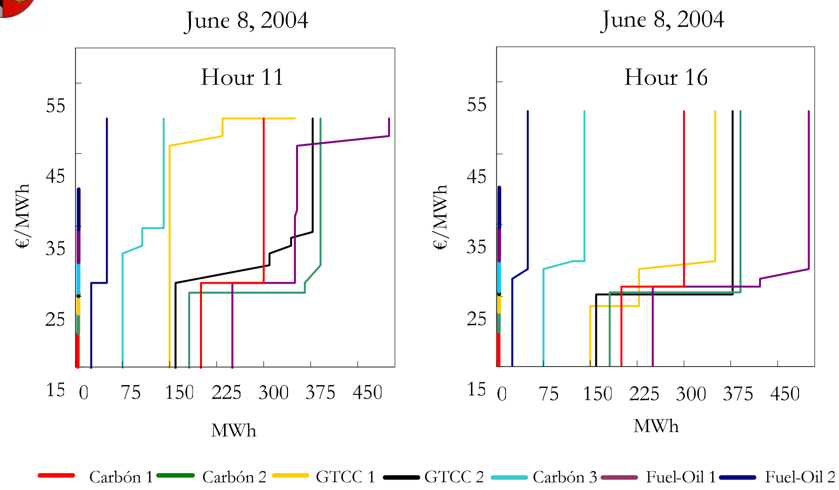
Coordinate Descent

	07-06-04	08-06-04	09-06-04	10-06-04	11-06-04
Iterations #	2	2	2	2	2
Result (€)	185525	338411	148240	61268	68445
Error (€)	31	54	94	36	46
Error (%)	0.02	0.02	0.06	0.06	0.07
CPU time (s)	315	315	316	319	319

Direct Solution (CPLEX)

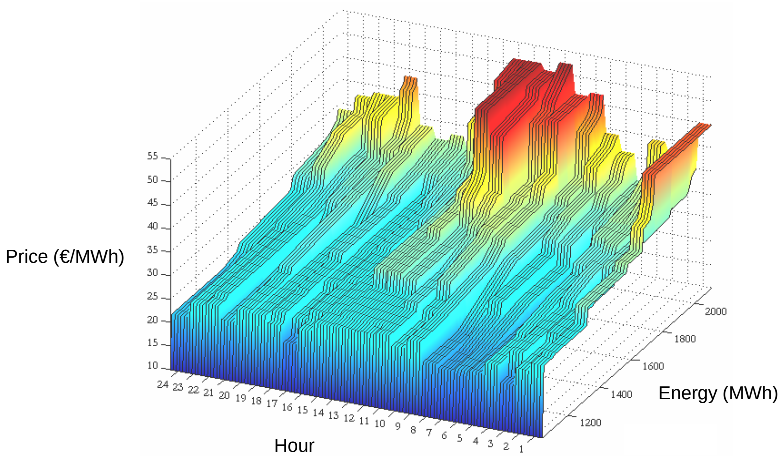
	07-06-04	08-06-04	09-06-04	10-06-04	11-06-04
Result (€)	185473	338274	148269	61205	68380
Error (€)	815	849	625	886	784
Error (%)	0.44	0.25	0.42	1.45	1.15
CPU time (s)	315	315	316	319	319

Case 2: Individual Offers



Case 2: Portfolio Offers

June 8, 2004



Case 2: Solution Quality

VSS

Day	07-06-04	08-06-04	09-06-04	10-06-04	11-06-04	Total
RP (€)	185473	338274	148269	61205	68380	801601
EEV (€)	180671	335105	145278	55890	64340	781284
VSS (€)	**4802**	**3169**	**2991**	**5315**	**4039**	**20317**
VSS/RP (%)	**3**	**1**	**2**	**9**	**6**	**3**

Case 2: Solution Quality

Comparison among different approaches

Day	07-06-04	08-06-04	09-06-04	10-06-04	11-06-04	Total
EEM (€)	618845	473392	148247	97228	387314	1725026
DEM (€)	605769	466852	151551	98983	385438	1708592
DEU (€)	607922	467459	151834	97670	388928	1713814

Further work

- Risk treatment
- One week span including forward contracting
- Unit on/off modeling

Simple Example
(by A. Delgadillo)

Example. Data

Unit data

	Variable cost	AGC power	Capacity	Minimum output	Ramp dawn limit	Ramp up limit
	(€/MWh)	MW	(MW)	(MW)	(MW/h)	(MW/h)
c1	20	15	140	75	65	65
c2	30	35	350	150	200	200

Example. Data

Price scenarios (€/MWh)

Low price scenario

Hour	Price spot	Price AGC	Price balancing	Slope balancing
1	10	15	20	-0.8
2	30	25	30	-0.8
3	20	15	20	-0.8

Example. Data

Price scenarios (€/MWh)

Medium price scenario

Hour	Price spot	Price AGC	Price balancing	Slope balancing
1	15	25	35	-0.5
2	45	40	40	-0.5
3	50	25	30	-0.5

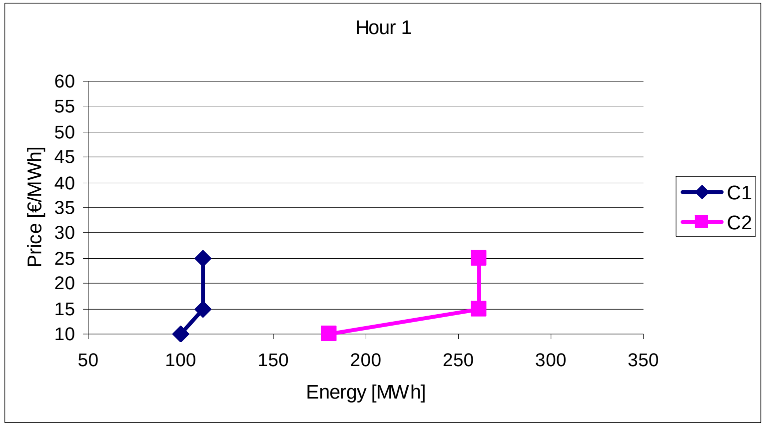
Example. Data

Price scenarios (€/MWh)

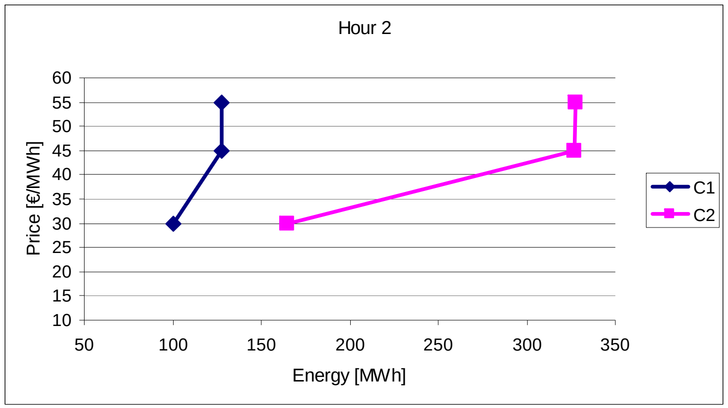
High price scenario

Hour	Price spot	Price AGC	Price balancing	Slope balancing
1	25	35	40	-0.3
2	55	45	55	-0.3
3	35	30	45	-0.3

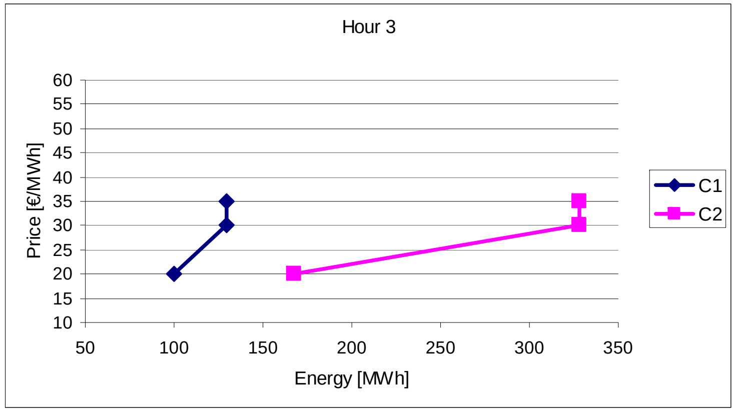
Example. Offers



Example. Offers



Example. Offers



Solution

Single market	
Spot profit	€ 3 791.66

Deterministic multi-market	
Total profit	€ 6 996.86
Spot profit	€ 2 996.45
AGC profit	€ 3 835.00
Adjustment profit	€ 175.42

Stochastic multi-market	
Total profit	€ 8 320.87
Spot profit	€ 5 044.40
AGC profit	€ 3 074.97
Adjustment profit	€ 201.50

VSS	€ 1 324.00
VSS/RP (€)	€ 15.91%

GAMS code

```
$title offering strategy

OPTION OPTCR=0.000,ITERLIM=50000;

SETS
H hour index /0*3/
J unit index /C1*C2/
E market index /D,G,A/
K scenario index /E1*E3/;

PARAMETER
PI(K)     probability of scenario K
/E1       0.33333
 E2       0.33333
 E3       0.33333/;
```


GAMS code

```
TABLE     CDATA(J,*) unit data
          C        PAGC     PMAX     PMIN     RDW      RUP
*         E/MWh    MW       MW       MW       MW/h     MW/h
C1        20       15       140      75       65       65
C2        30       35       350      150      200      200;
```


GAMS code

```
TABLE     VAR_EST(K,H,*) random variables

          PRI_D    PRI_G    ALFA_A   BETA_A
*Scenario 1
E1.0      0        0        0        0
E1.1      10       15       20       -0.8
E1.2      30       25       30       -0.8
E1.3      20       15       20       -0.8

*Scenario 2
E2.0      0        0        0        0
E2.1      15       25       35       -0.5
E2.2      45       40       40       -0.5
E2.3      30       25       30       -0.5

*Scenario 3
E3.0      0        0        0        0
E3.1      25       35       40       -0.3
E3.2      55       45       55       -0.3
E3.3      35       30       45       -0.3;
```

GAMS code

```
VARIABLES

FO             of
FO_DIA         spot of
FO_AGC         AGC of
FO_INTRA       balancing of
P(E,J,H,K)     power of unit J in hour H and market E
Q(E,J,H,K)     energy of unit J in hour H and market E
T(E,H,K)       total energy in market E
W(J,H,K)       1 if AGC during hour H;

POSITIVE VARIABLES P(E,J,H,K),Q(E,J,H,K),T(E,H,K);

BINARY VARIABLES W(J,H,K);
```


GAMS code

```
** Initial values

P.fx('D','C1','0',K)=100;
P.fx('D','C2','0',K)=200;
P.fx('G',J,'0',K)=0;
P.fx('A',J,'0',K)=0;

ALIAS(K,KP);
```


GAMS code

```
EQUATIONS
        BENEFICIO               of
        BENDIA                  pool profit
        BENAGC                  AGC profit
        BENINTRA                balancing profit
        MONOTO(J,H,K,KP)        increasing offers
        NOANTIDIA(J,H,K,KP)     pool no anticipativity
        NOANTIAGC(J,H,K,KP)     AGC no anticipativity
        ENERBAL(E,H,K)          energy equilibrium
        ENERPROM(E,J,H,K)       energy
        ENERMAX(J,H,K)          max energy
        ENERMIN(J,H,K)          min energy
        PMAX(J,H,K)             max power
        PMIN(J,H,K)             min power
        PAGC(J,H,K)             AGC constraint
        RAMPUP(J,H,K)           ramping up limit
        RAMPDW(J,H,K)           ramping down limit;
```


GAMS code

```
BENEFICIO..     FO =E= FO_DIA + FO_AGC + FO_INTRA;

BENDIA..        FO_DIA =E= SUM(K, ( SUM(H $(ord(H) GT 1),
                        T('D',H,K)*VAR_EST(K,H,'PRI_D') -
                SUM(J, CDATA(J,'C')*
                Q('D',J,H,K) )))*PI(K) );

BENAGC..        FO_AGC =E= SUM(K, (SUM(H $(ord(H) GT 1),
                        T('G',H,K)*VAR_EST(K,H,'PRI_G') ) )*PI(K) );

BENINTRA..      FO_INTRA =E= SUM(K, ( SUM(H $(ord(H) GT 1),
                        T('A',H,K)*(VAR_EST(K,H,'ALFA_A') +
                VAR_EST(K,H,'BETA_A')*T('A',H,K)) -
                SUM(J,CDATA(J,'C')*Q('A',J,H,K) ) ) )*PI(K) );
```

GAMS code

```
ENERBAL(E,H,K)$(ord(H) GT 1)..
        T(E,H,K) =E= SUM(J, Q(E,J,H,K));

ENERPROM(E,J,H,K)$(ord(H) GT 1)..
        Q(E,J,H,K) =E= 0.5 * (P(E,J,H-1,K) + P(E,J,H,K));

ENERMAX(J,H,K)$(ord(H) GT 1)..
        Q('D',J,H,K) + Q('A',J,H,K) + 0.5*Q('G',J,H,K) =L= CDATA(J,'PMAX');

ENERMIN(J,H,K)$(ord(H) GT 1)..
        Q('D',J,H,K) + Q('A',J,H,K) - 0.5*Q('G',J,H,K) =G= CDATA(J,'PMIN');

PMAX(J,H,K)$(ord(H) GT 1)..
        P('D',J,H,K) + P('A',J,H,K) =L= CDATA(J,'PMAX');

PMIN(J,H,K)$(ord(H) GT 1)..
        P('D',J,H,K) + P('A',J,H,K) =G= CDATA(J,'PMIN');
```


GAMS code

```
PAGC(J,H,K)$(ord(H) GT 1)..
        Q('G',J,H,K) =L= W(J,H,K)*CDATA(J,'PAGC');

RAMPUP(J,H,K)$(ord(H) GT 1)..
        P('D',J,H,K) + P('A',J,H,K) - (P('D',J,H-1,K) +
        P('A',J,H-1,K)) =L= (1-W(J,H,K))*CDATA(J,'RUP');

RAMPDW(J,H,K)$(ord(H) GT 1)..
        P('D',J,H-1,K) + P('A',J,H-1,K) - (P('D',J,H,K)+ P('A',J,H,K))
        =L= (1-W(J,H,K))*CDATA(J,'RDW');


MODEL ph /ALL/;
SOLVE ph USING MINLP MAXIMIZING FO;
```


Thanks for your attention!

GSEE: http://www.uclm.es/area/gsee/