

TOMA DE DECISIONES BAJO INCERTIDUMBRE EN MERCADOS ELÉCTRICOS

CLASE 4: “CIERRE DE MERCADOS ELÉCTRICOS CON INCERTIDUMBRE”

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DTU Electrical Engineering
Department of Electrical Engineering

Outline

- 1) Spot electricity markets
- 2) Challenges arising from the large-scale integration of RES
- 3) New market solutions
 - i. Energy and reserve capacity
 - ii. Stochastic market clearing

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Spot electricity markets

(Basic structure)



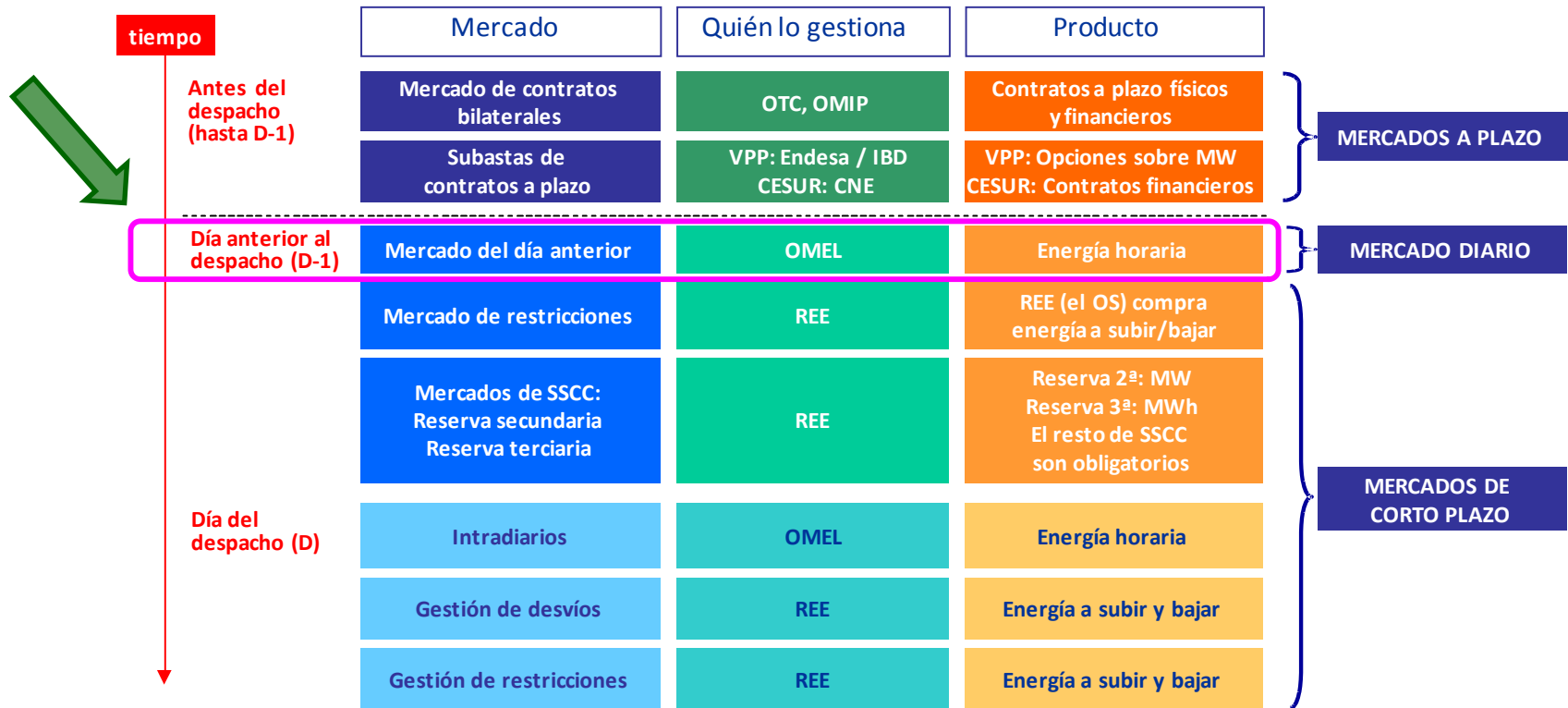
Spot markets

Spot electricity markets (Basic structure)

**Day-ahead
market**



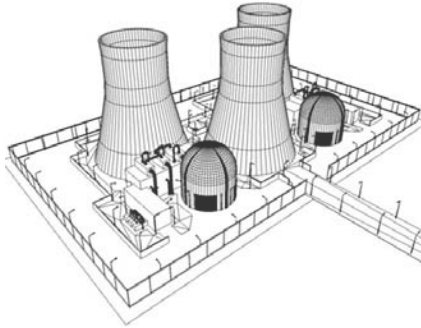
Spot electricity markets (Basic structure)



Day-ahead market

Spot electricity markets (Conventional vs. ?)

**Day-ahead
market**

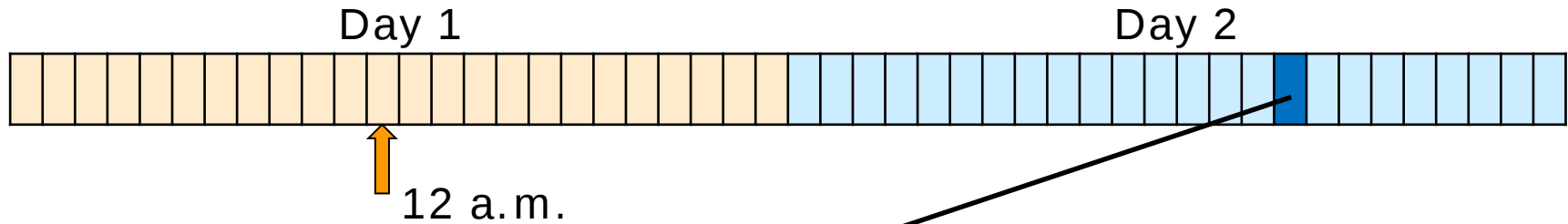


**Inflexible units
(need advance planning)**

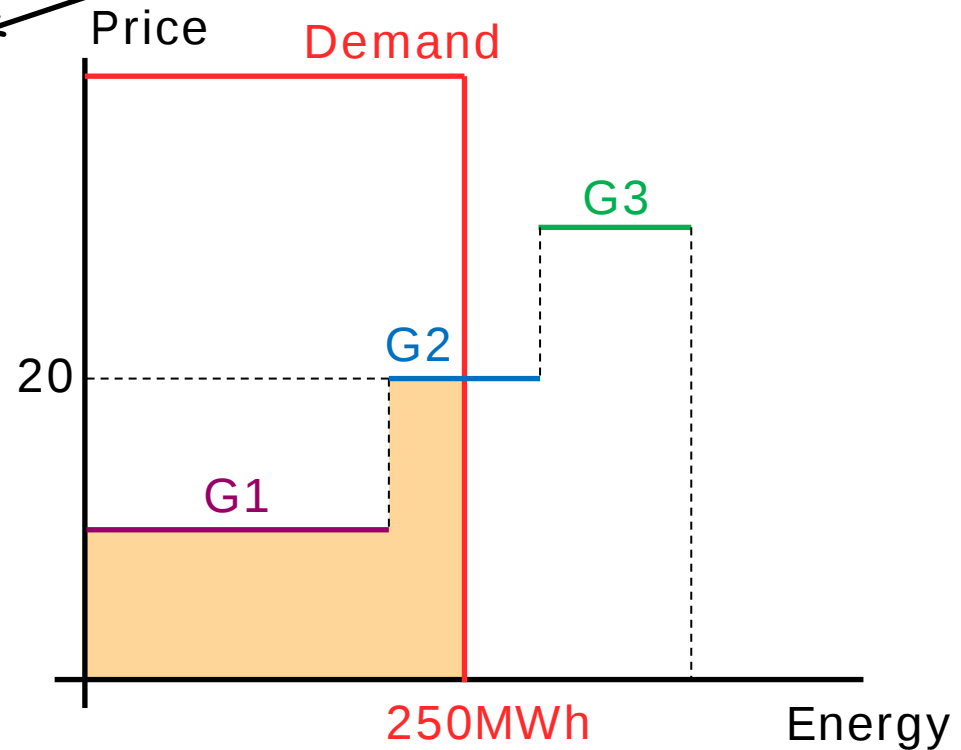
Outline

- 1) Spot electricity markets
- 2) Challenges arising from the large-scale integration of RES
- 3) New market solutions
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Challenges arising from RES (Day-ahead market)



4-5 P.M.			
UNIT	COST	OFFERS	DEMAND
G1	5	200@10	250 MWh
G2	15	100@20	
G3	25	100@30	

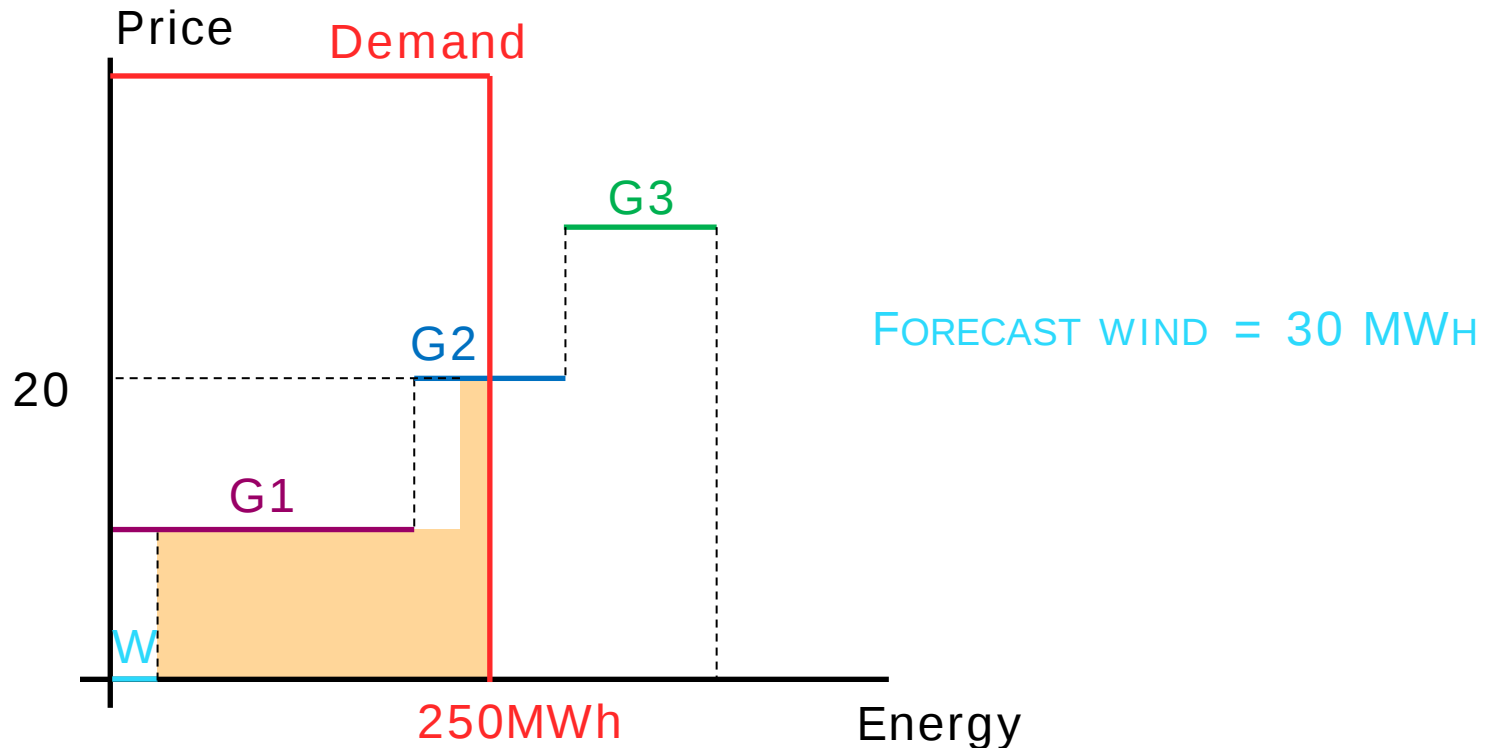


Challenges arising from RES (Day-ahead market)

$$\begin{array}{l}
 \text{Min } 10P_{G1} + 20P_{G2} + 30P_{G3} \\
 \text{s.t.} \\
 P_{G1} + P_{G2} + P_{G3} = 250 : \lambda_E \\
 0 \leq P_{G1} \leq 200 \\
 0 \leq P_{G2} \leq 100 \\
 0 \leq P_{G3} \leq 100
 \end{array}
 \left\{ \begin{array}{l} \rightarrow \end{array} \right.
 \left\{ \begin{array}{l}
 P_{G1}^* = 200 \text{ MW} \\
 P_{G2}^* = 50 \text{ MW} \\
 P_{G3}^* = 0 \text{ MW} \\
 \lambda_E^* = \$20 / \text{MWh}
 \end{array} \right.$$

Challenges arising from RES (Day-ahead market)

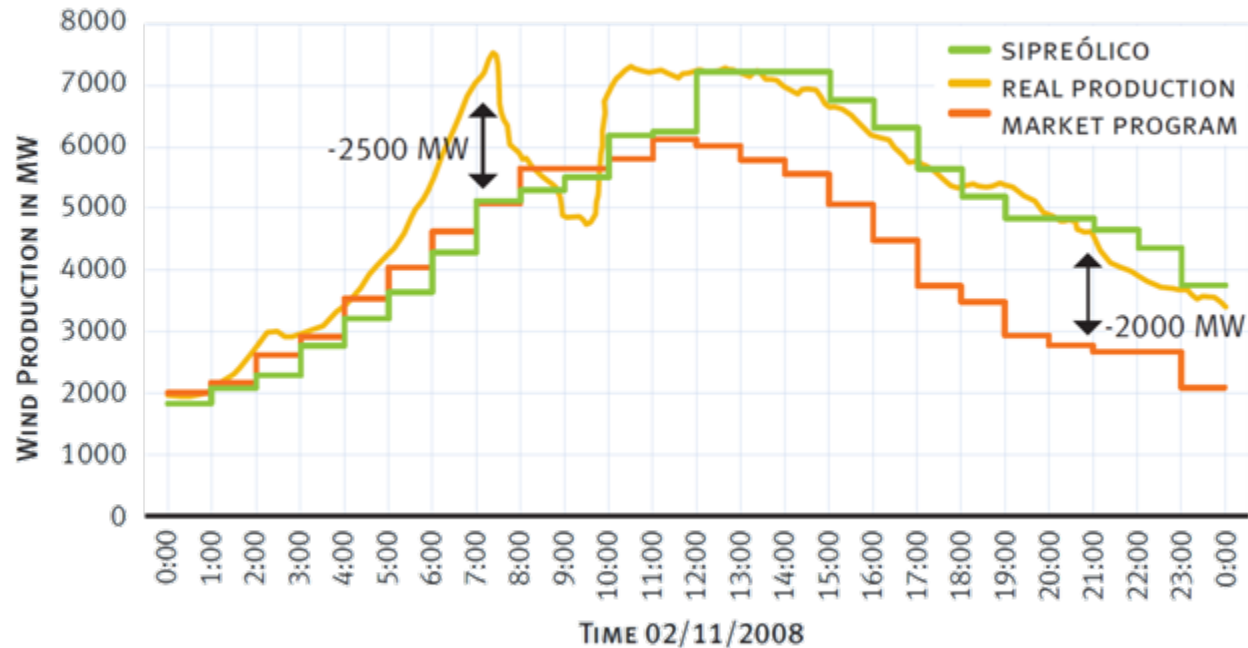
What if we have now wind power generation?



Challenges arising from RES (Day-ahead market)

So what?

FIGURE 16: WIND FORECAST ERROR IN SPAIN

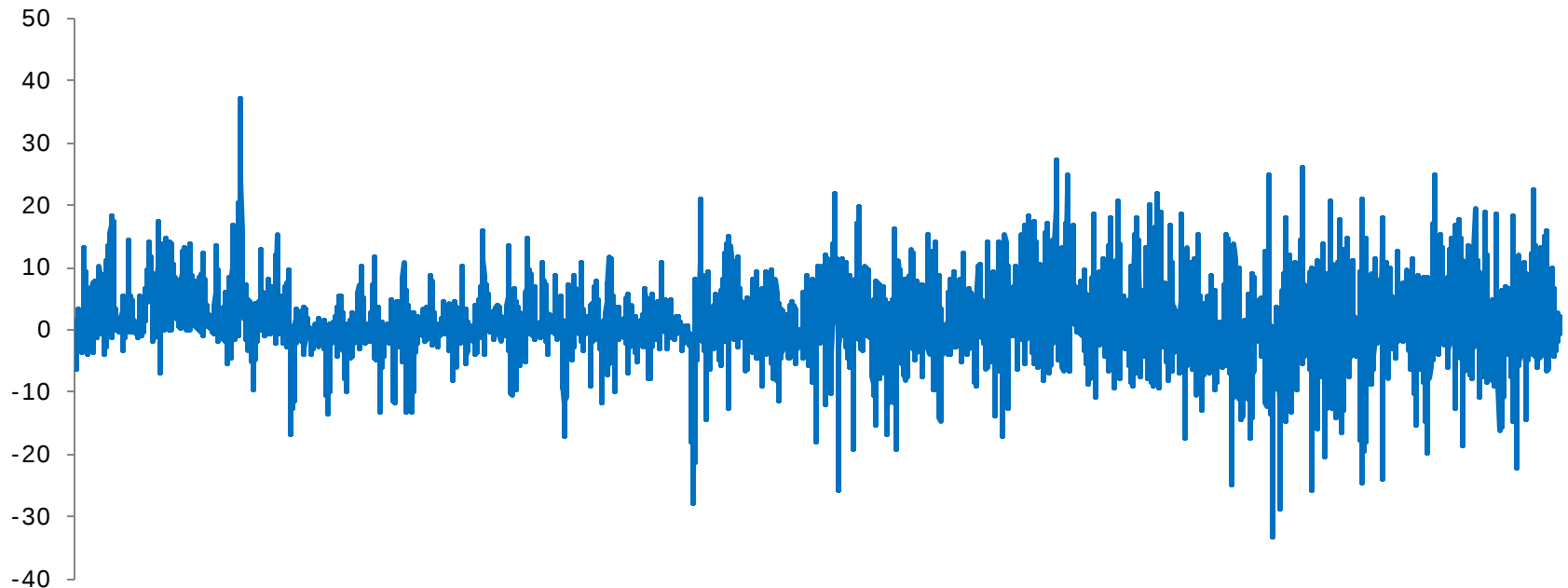


WIND CANNOT BE 100% PREDICTED 24-36 HOURS AHEAD!!

Challenges arising from RES (Day-ahead market)

So what?

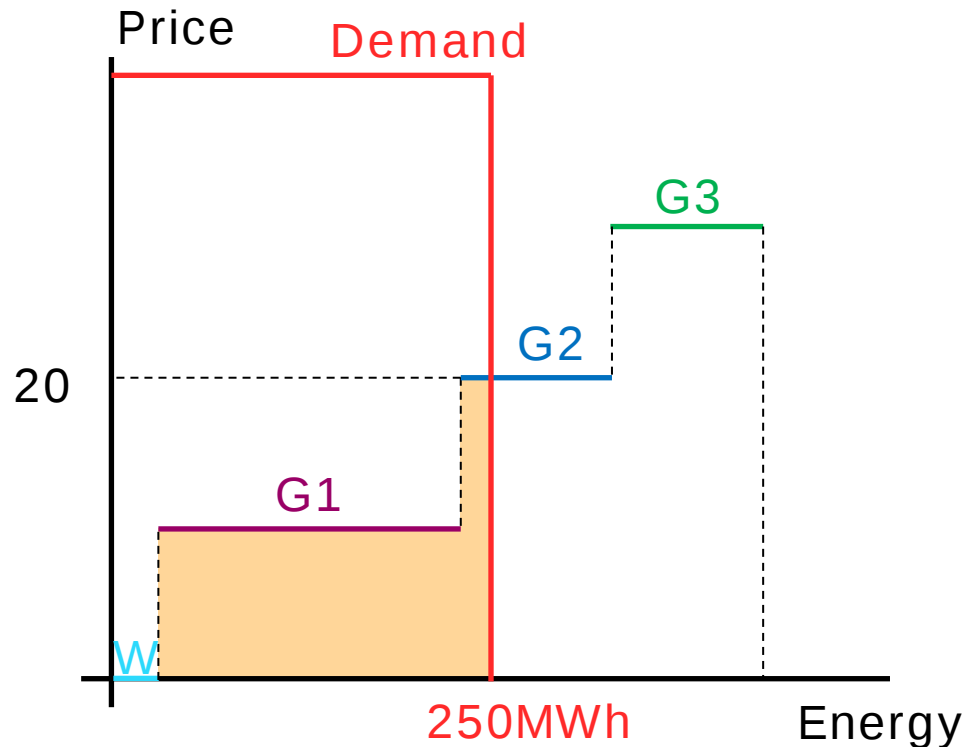
Forecast error at DK2 2011-2012 (%)



WIND CANNOT BE 100% PREDICTED 24-36 HOURS AHEAD!!

Challenges arising from RES (Day-ahead market)

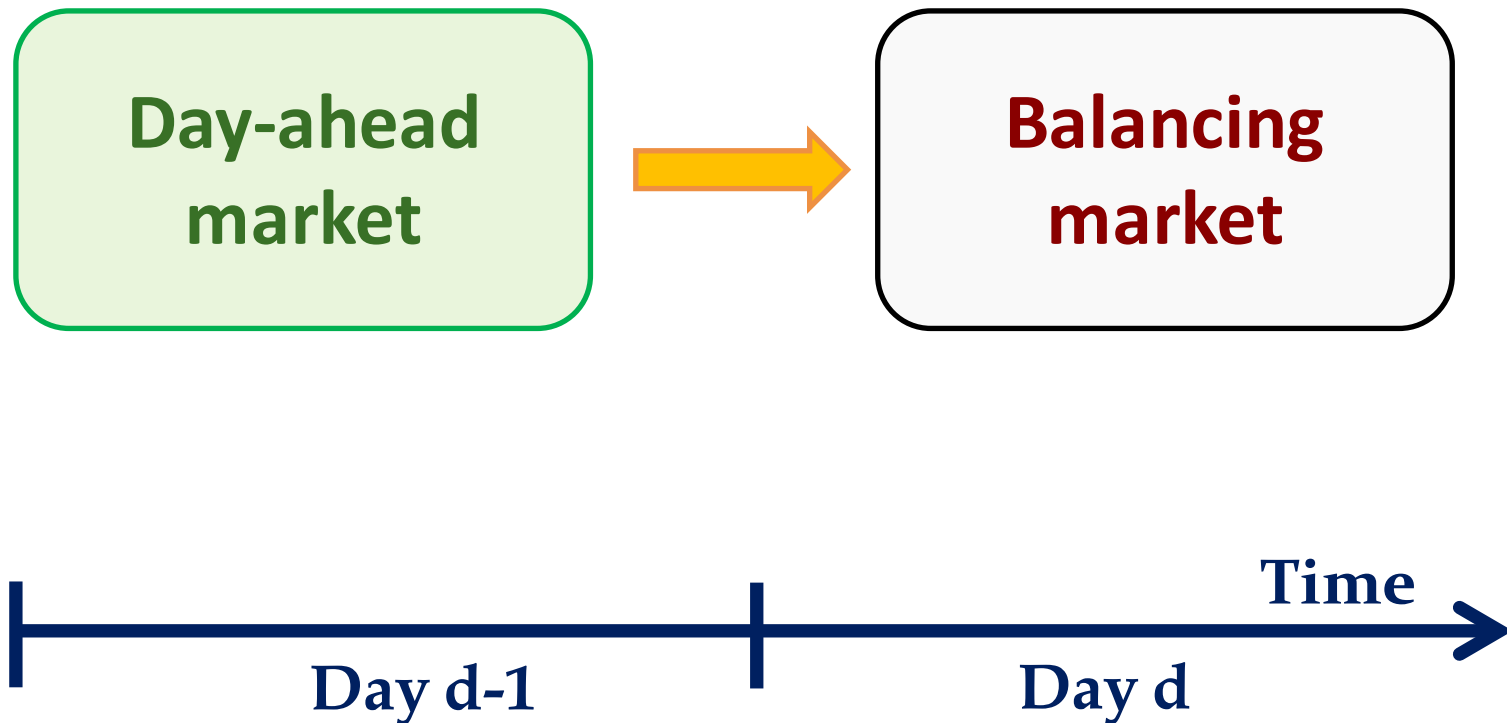
How do we deal with wind forecast errors?



NOWADAYS:
BALANCING MARKET

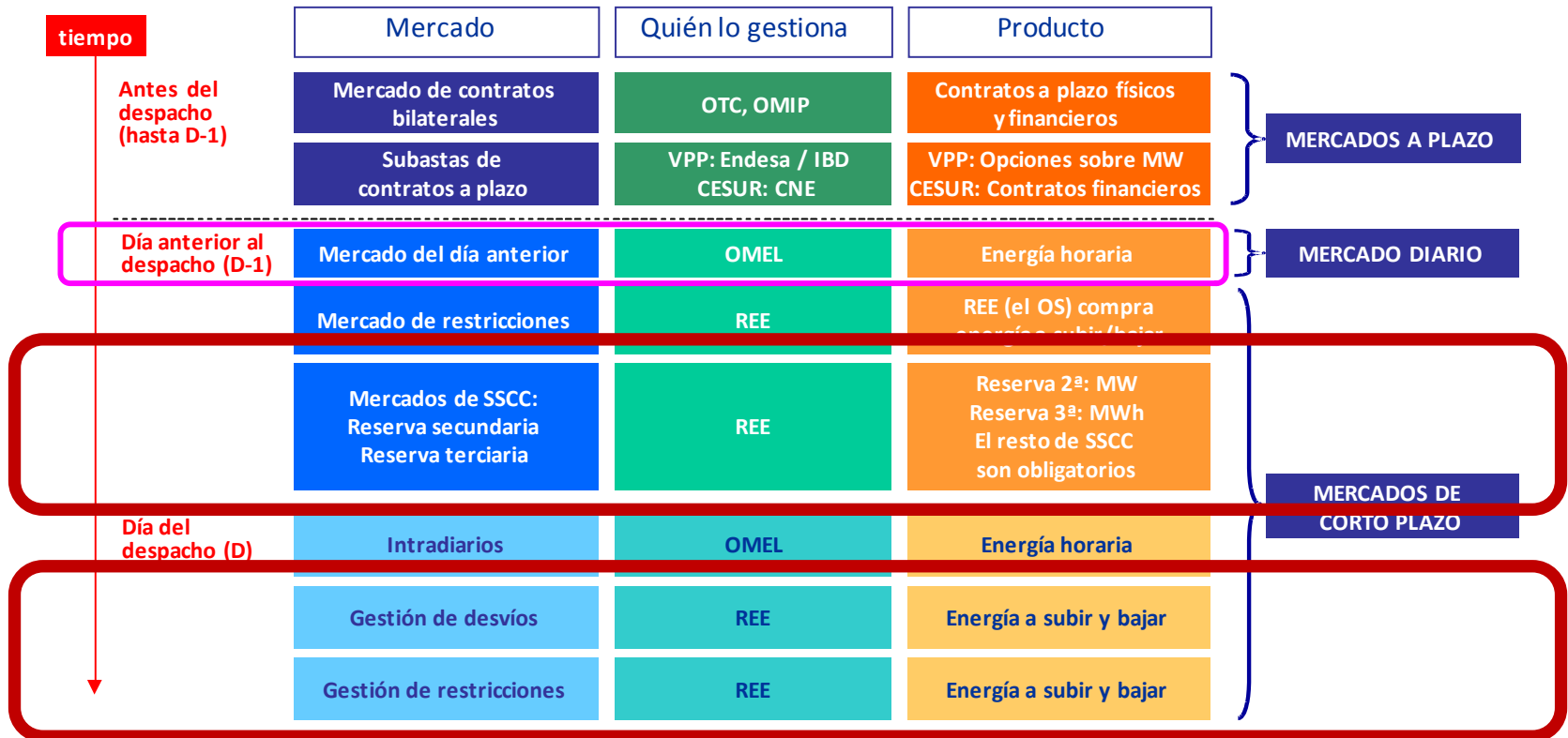
Spot electricity markets

(Basic structure)



Spot electricity markets

(Basic structure)

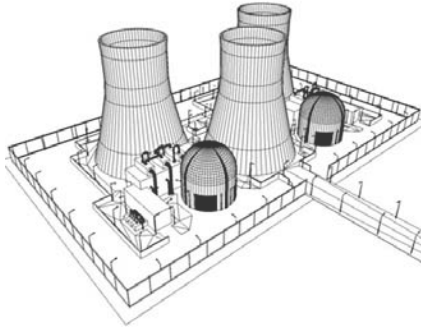


Balancing market



Spot electricity markets (Conventional vs. stochastic)

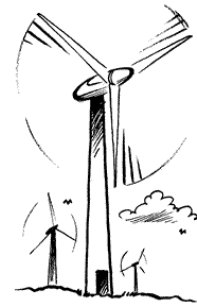
Day-ahead market



**Inflexible units
(need advance planning)**

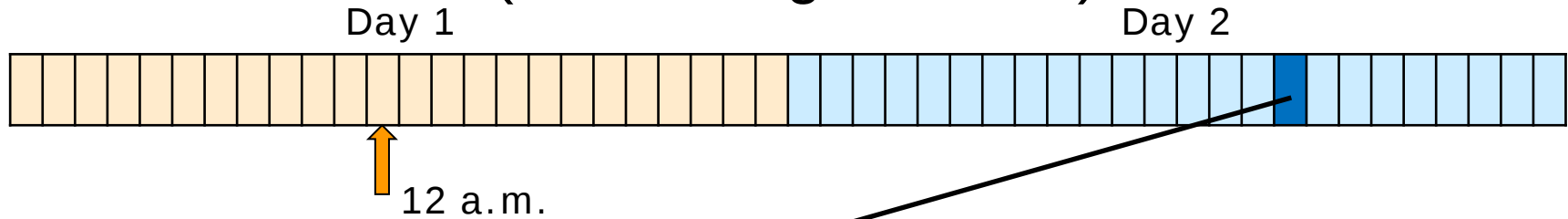


Balancing market



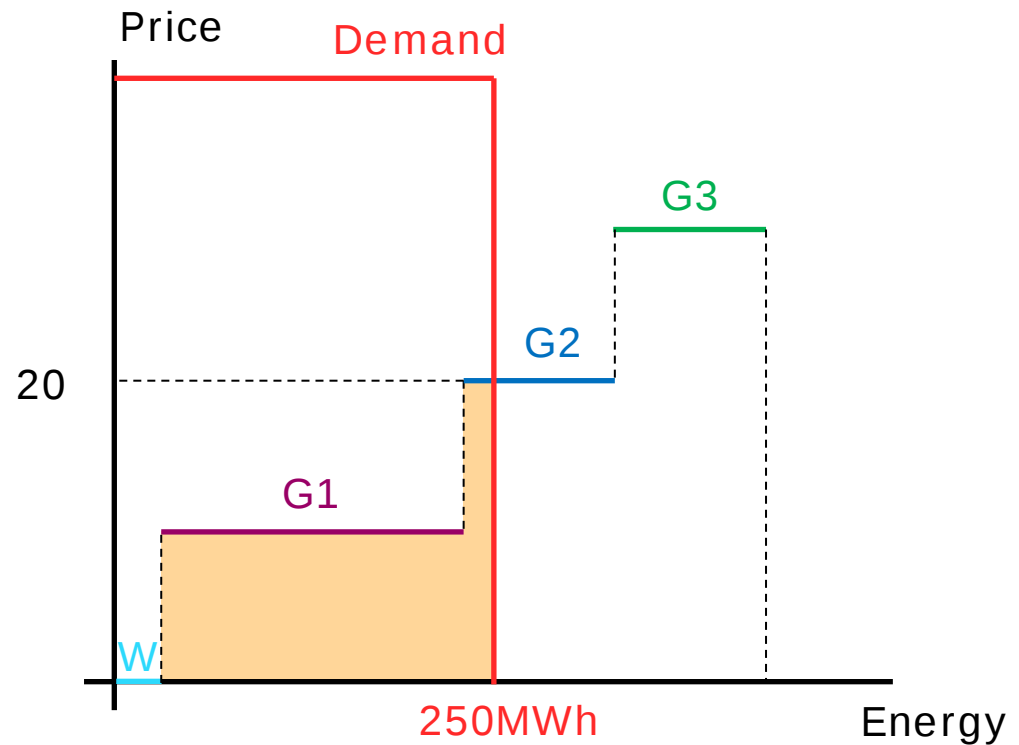
**Wind producers/consumers
(need balancing energy)**

Challenges arising from RES (Balancing market)

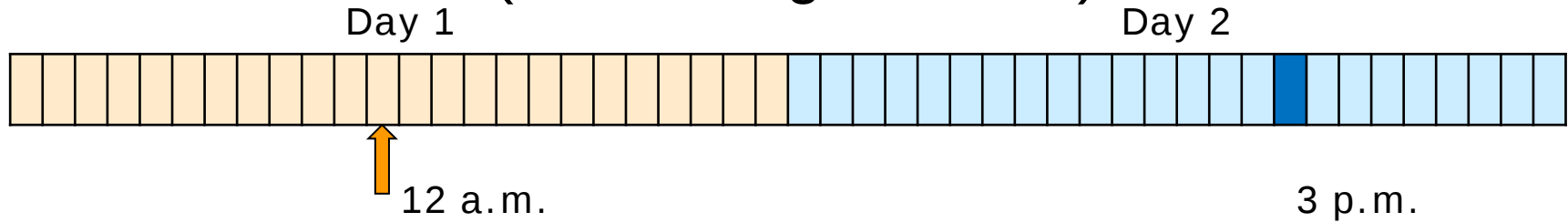


4-5 P.M.			
UNIT	COST	OFFERS	DEMAND
W	0	30@0	250 MWh
G1	5	200@10	
G2	15	100@20	
G3	25	100@30	

WIND FORECAST = 30 MWh

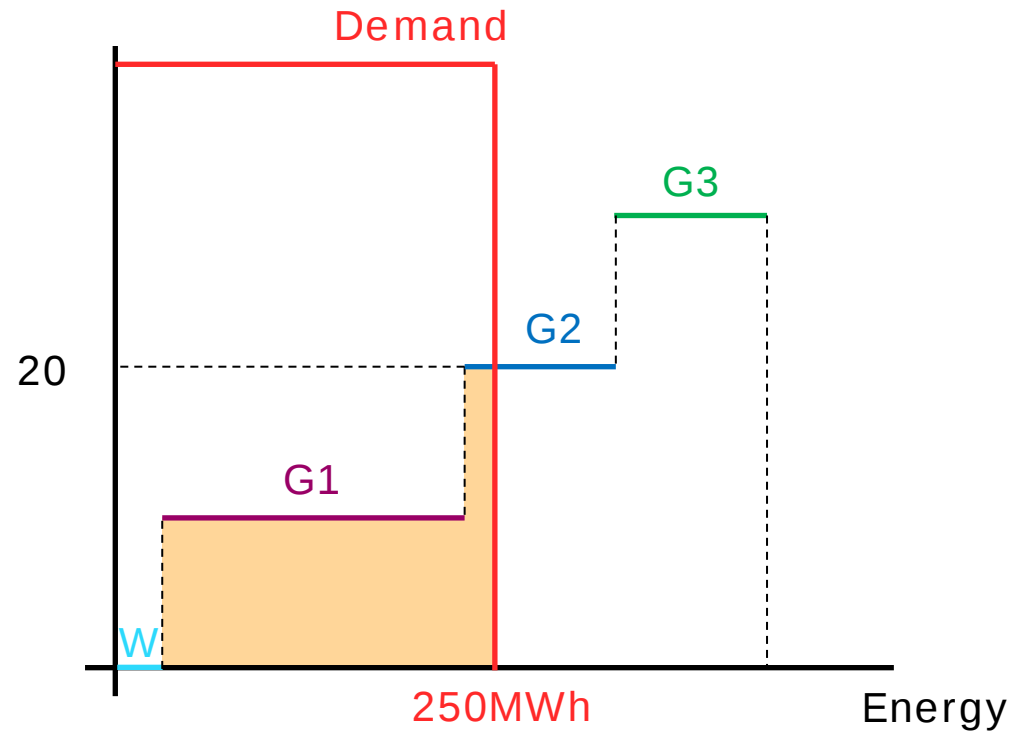


Challenges arising from RES (Balancing market)

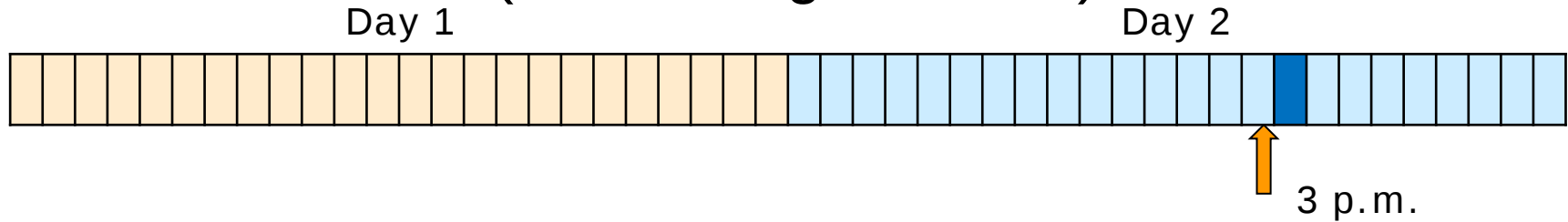


WIND POWER = 200 MWh

4-5 P.M.	
DA SCHEDULE	
UNIT	MWh
W	30
G1	200
G2	20
G3	-

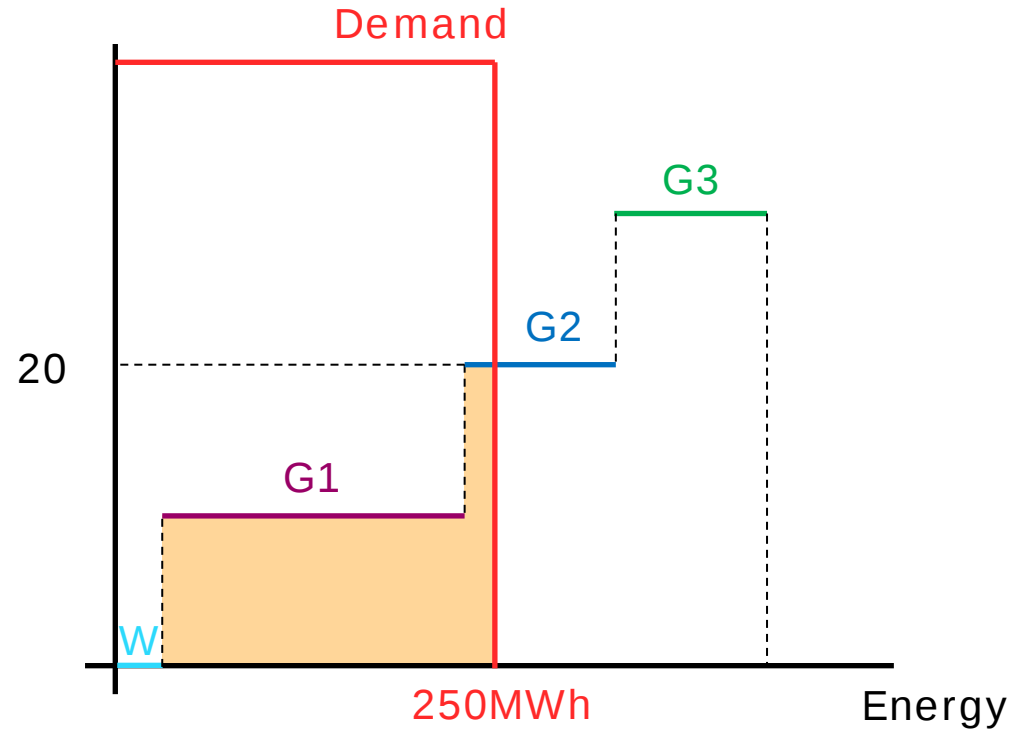


Challenges arising from RES (Balancing market)

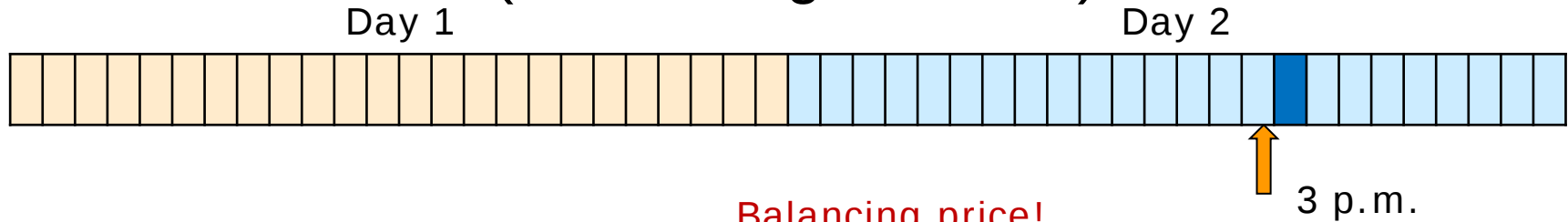


WIND POWER = 20 MW

4-5 P.M.			
DA SCHEDULE		BALANCING MARKET	
UNIT	MWh	UP	DOWN
W	30	-	-
G1	200	-	-
G2	20	10@25	-
G3	-	20@35	-



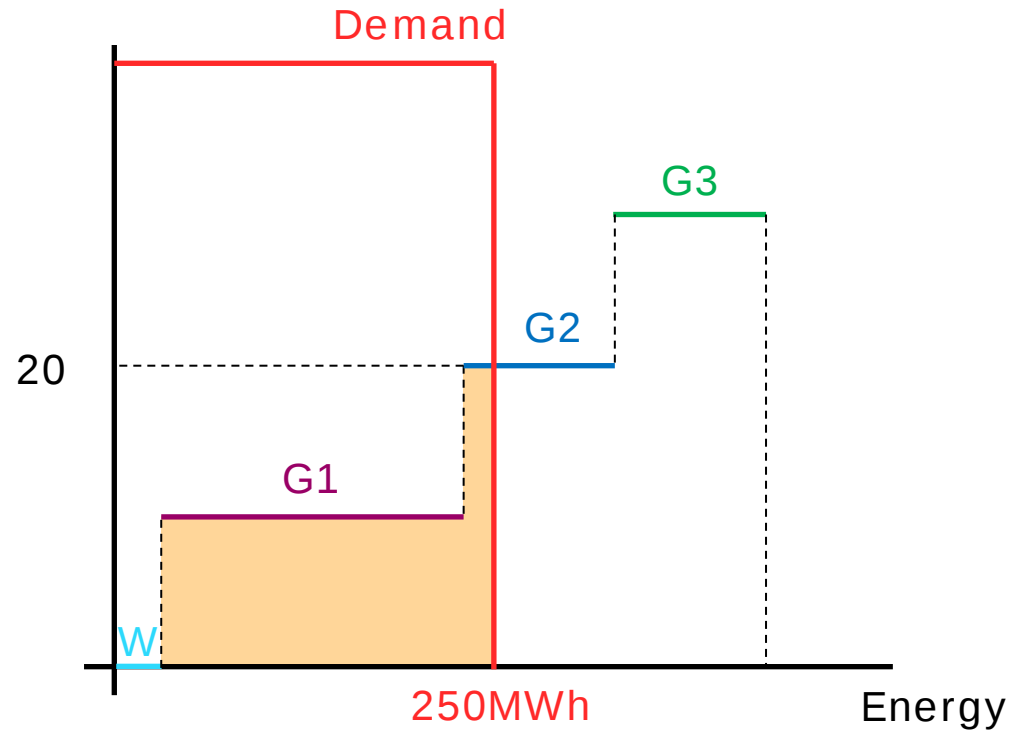
Challenges arising from RES (Balancing market)



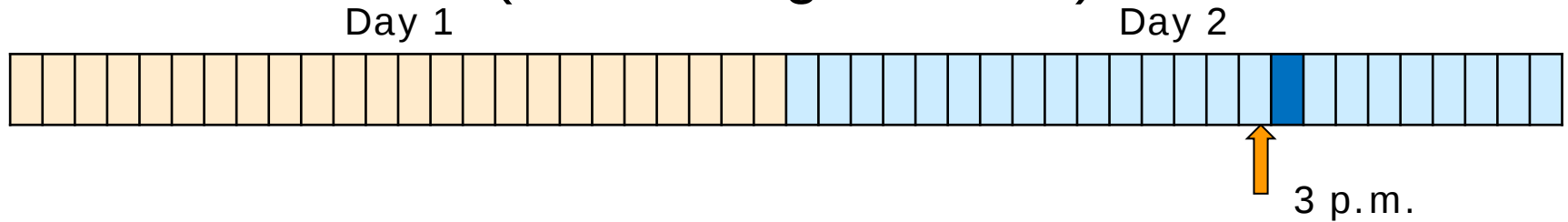
WIND POWER = 20 MW

4-5 P.M.			
DA SCHEDULE		BALANCING MARKET	
UNIT	MWh	UP	DOWN
W	30	-	-
G1	200	-	-
G2	20	10@25	-
G3	-	20@35	-

Balancing price!

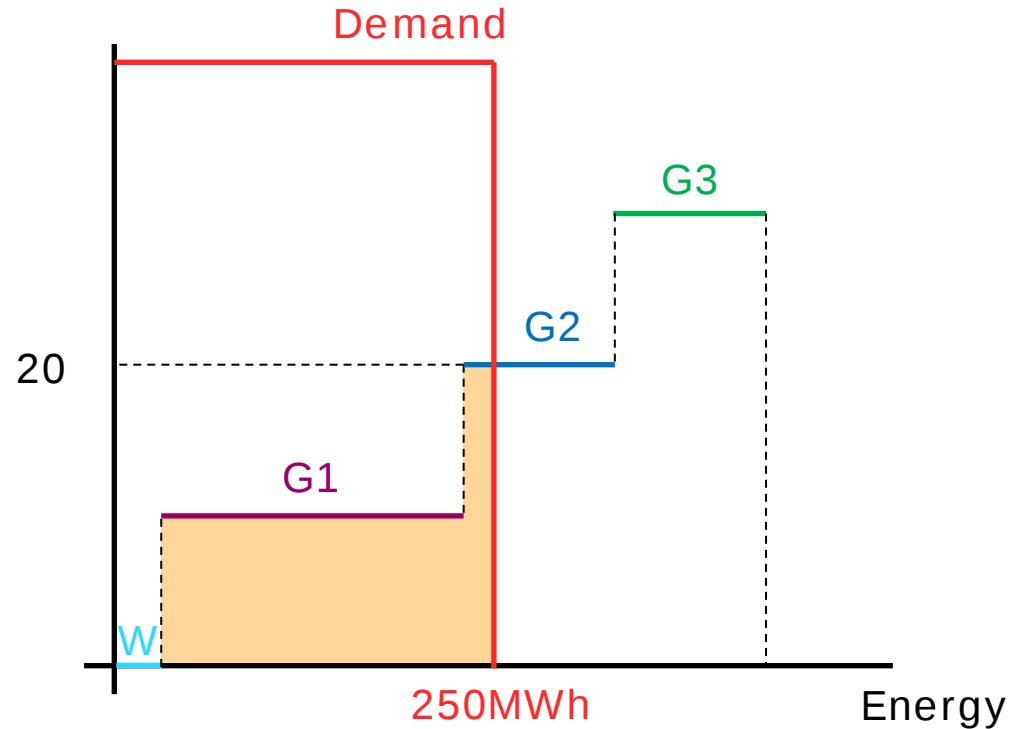


Challenges arising from RES (Balancing market)



WIND POWER = 20 MW

4-5 P.M.	
FINAL SCHEDULE	
UNIT	MWh
W	20
G1	200
G2	30
G3	-



Challenges arising from RES (Balancing market)

- LET'S CHECK THE PROFITS

4-5 P.M.				
UNIT	DA MARKET	B MARKET	FUEL COST	TOTAL
W				
G1				
G2				
G3				

Challenges arising from RES (Balancing market)

- LET'S CHECK THE PROFITS

4-5 P.M.				
UNIT	DA MARKET	B MARKET	FUEL COST	TOTAL
W	$20 \times 30 = 600$			
G1	$20 \times 200 = 4000$			
G2	$20 \times 20 = 400$			
G3	0			

Challenges arising from RES (Balancing market)

- LET'S CHECK THE PROFITS

4-5 P.M.				
UNIT	DA MARKET	B MARKET	FUEL COST	TOTAL
W	$20 \times 30 = 600$	$-25 \times 10 = -250$		
G1	$20 \times 200 = 4000$	0		
G2	$20 \times 20 = 400$	$25 \times 10 = 250$		
G3	0	0		

Challenges arising from RES (Balancing market)

- LET'S CHECK THE PROFITS

4-5 P.M.				
UNIT	DA MARKET	B MARKET	FUEL COST	TOTAL
W	$20 \times 30 = 600$	$-25 \times 10 = -250$	0	
G1	$20 \times 200 = 4000$	0	$5 \times 200 = 1000$	
G2	$20 \times 20 = 400$	$25 \times 10 = 250$	$15 \times 30 = 450$	
G3	0	0	0	

Challenges arising from RES (Balancing market)

- LET'S CHECK THE PROFITS

4-5 P.M.				
UNIT	DA MARKET	B MARKET	FUEL COST	TOTAL
W	$20 \times 30 = 600$	$-25 \times 10 = -250$	0	350
G1	$20 \times 200 = 4000$	0	$5 \times 200 = 1000$	3000
G2	$20 \times 20 = 400$	$25 \times 10 = 250$	$15 \times 30 = 450$	200
G3	0	0	0	0

Challenges arising from RES (Balancing market)

- LET'S CHECK THE PROFITS

4-5 P.M.				
UNIT	DA MARKET	B MARKET	FUEL COST	TOTAL
W	$20 \times 30 = 600$	$-25 \times 10 = -250$	0	350
G1	$20 \times 200 = 4000$	0	$5 \times 200 = 1000$	3000
G2	$20 \times 20 = 400$	$25 \times 10 = 250$	$15 \times 30 = 450$	200
G3	0	0	0	0


$(20-0) \times 20 = 400$
$(20-5) \times 200 = 3000$
$(20-15) \times 30 = 150$
0

Challenges arising from RES (Balancing market)

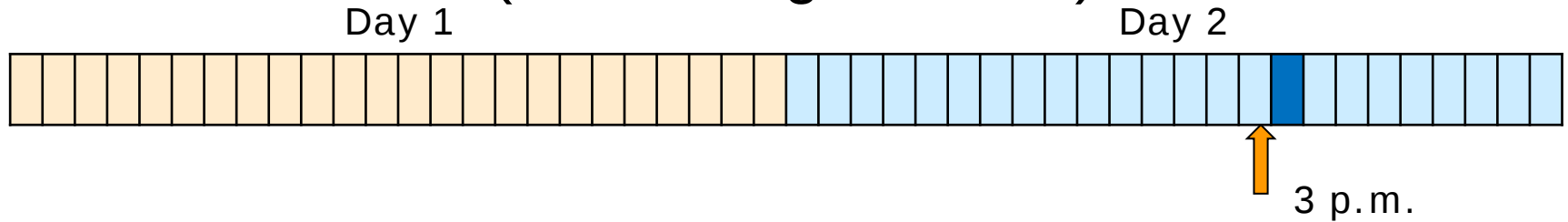
- LET'S CHECK THE PROFITS

4-5 P.M.				
UNIT	DA MARKET	B MARKET	FUEL COST	TOTAL
W	$20 \times 30 = 600$	$-25 \times 10 = -250$	0	350
G1	$20 \times 200 = 4000$	0	$5 \times 200 = 1000$	3000
G2	$20 \times 20 = 400$	$25 \times 10 = 250$	$15 \times 30 = 450$	200
G3	0	0	0	0


$(20 - 0) \times 20 = 400$
$(20 - 5) \times 200 = 3000$
$(20 - 15) \times 30 = 150$
0

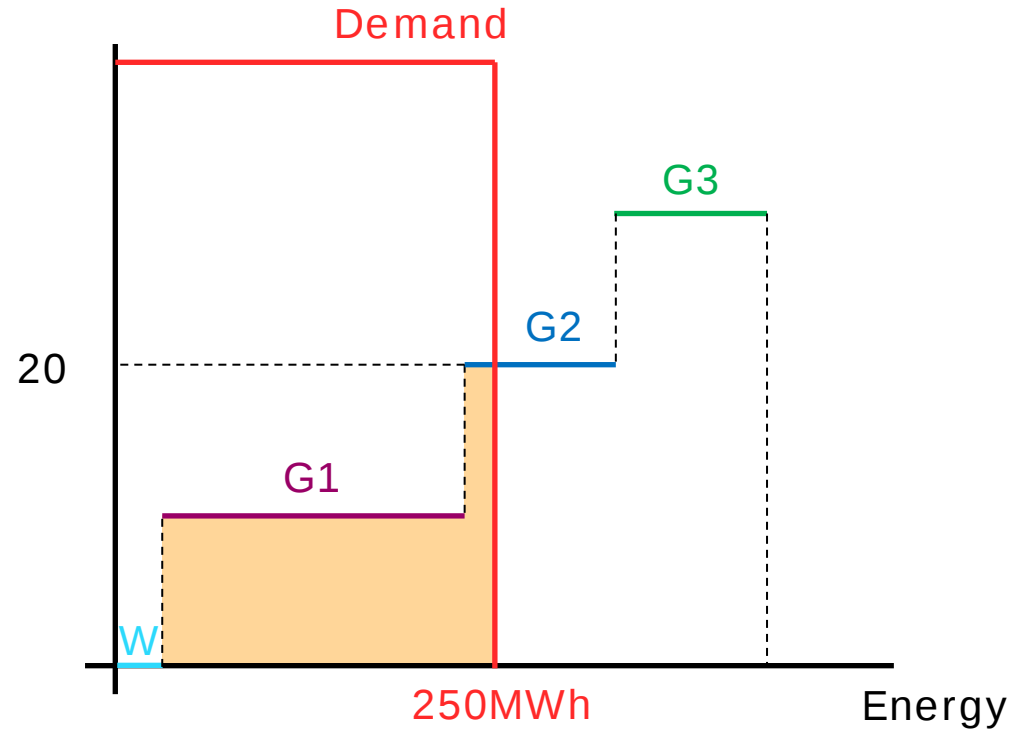
WIND PRODUCER INCURS IMBALANCE COST!!

Challenges arising from RES (Balancing market)



WIND POWER = 40 MW

4-5 P.M.			
DA SCHEDULE		BALANCING MARKET	
UNIT	MWh	UP	DOWN
W	30	-	-
G1	200	-	-
G2	20	10@25	10@15
G3	-	20@35	-



Challenges arising from RES (Balancing market)

Day 1

Day 2

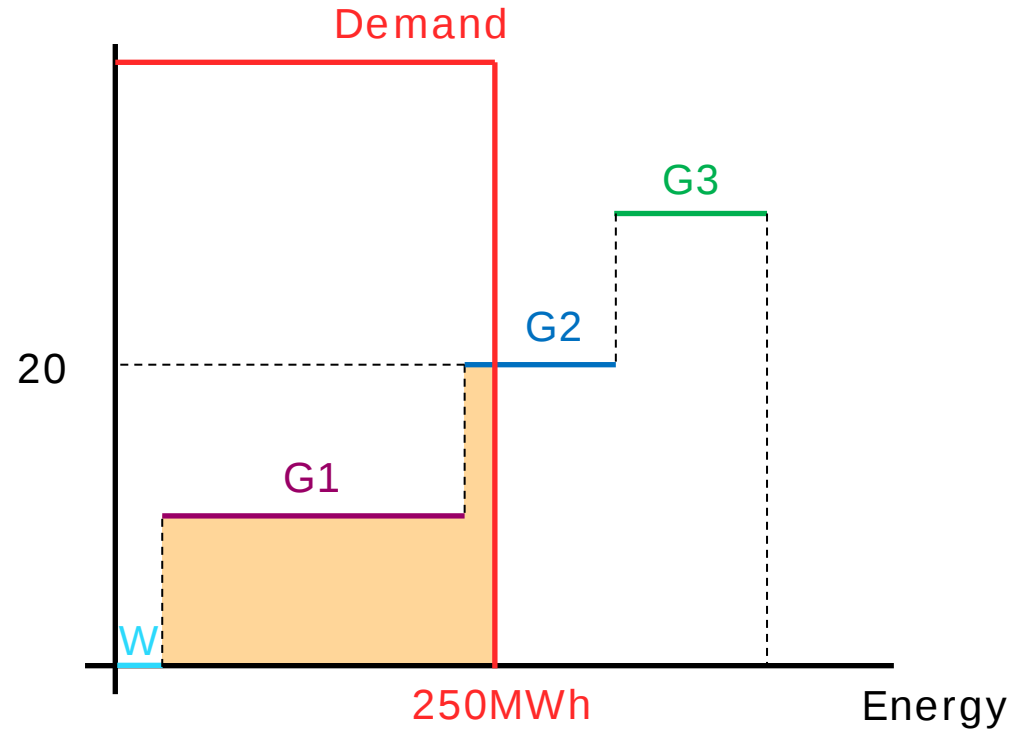


3 p.m.

Balancing price!

WIND POWER = 40 MW

4-5 P.M.			
DA SCHEDULE		BALANCING MARKET	
UNIT	MWh	UP	DOWN
W	30	-	-
G1	200	-	-
G2	20	10@25	10@15
G3	-	20@35	-



Challenges arising from RES (Balancing market)

- LET'S CHECK THE PROFITS

4-5 P.M.				
UNIT	DA MARKET	B MARKET	FUEL COST	TOTAL
W	$20 \times 30 = 600$	$15 \times 10 = 150$	0	750
G1	$20 \times 200 = 4000$	0	$5 \times 200 = 1000$	3000
G2	$20 \times 20 = 400$	$-15 \times 10 = 150$	$15 \times 10 = 150$	100
G3	0	0	0	0
L	$20 \times 250 = 5000$	0	-	5000


$(20 - 0) \times 40 = 800$
$(20 - 5) \times 200 = 3000$
$(20 - 15) \times 10 = 50$
0
$20 \times 250 = 5000$

Challenges arising from RES (Balancing market)

- LET'S CHECK THE PROFITS

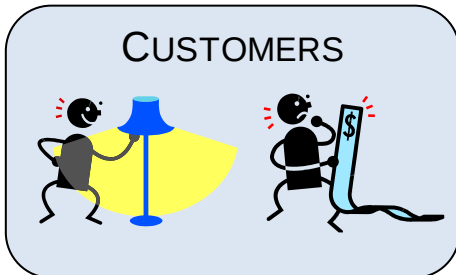
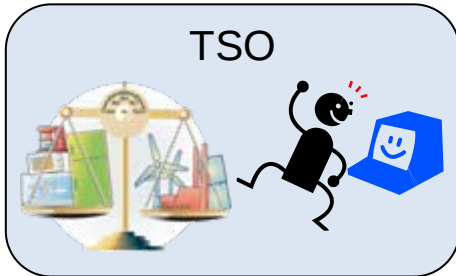
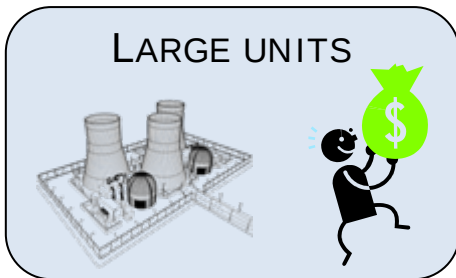
4-5 P.M.				
UNIT	DA MARKET	B MARKET	FUEL COST	TOTAL
W	$20 \times 30 = 600$	$15 \times 10 = 150$	0	750
G1	$20 \times 200 = 4000$	0	$5 \times 200 = 1000$	3000
G2	$20 \times 20 = 400$	$-15 \times 10 = 150$	$15 \times 10 = 150$	100
G3	0	0	0	0
L	$20 \times 250 = 5000$	0	-	5000


$(20-0) \times 40 = 800$
$(20-5) \times 200 = 3000$
$(20-15) \times 10 = 50$
0
$20 \times 250 = 5000$

WIND PRODUCER INCURS IMBALANCE COST!!

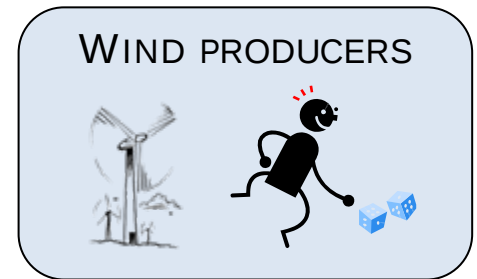
Challenges arising from RES

- IS THIS FAIR?
- IS IT NECESSARY TO CLEAR THE MARKET 24-36H AHEAD?



24-36H AHEAD

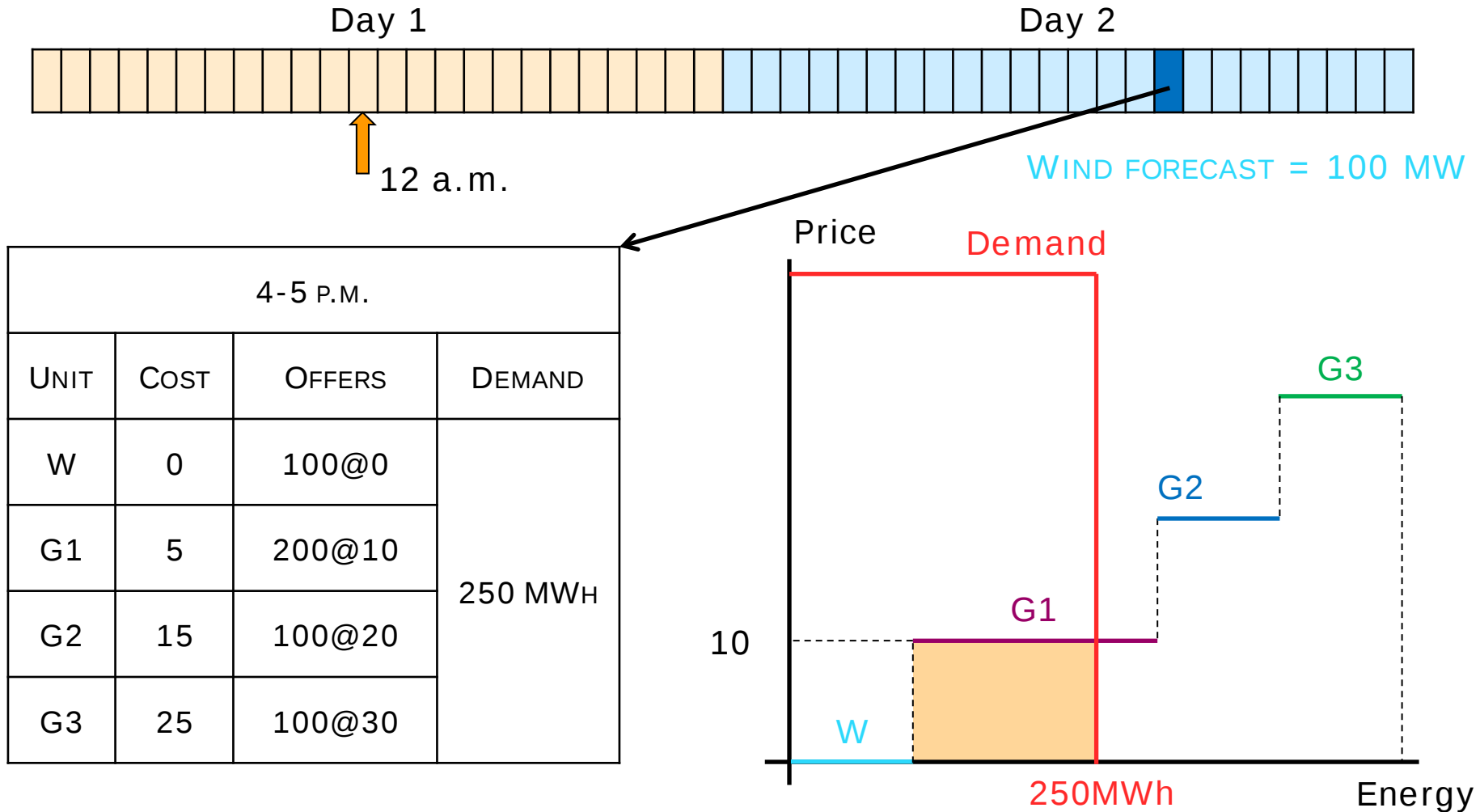
SHORTER HORIZON



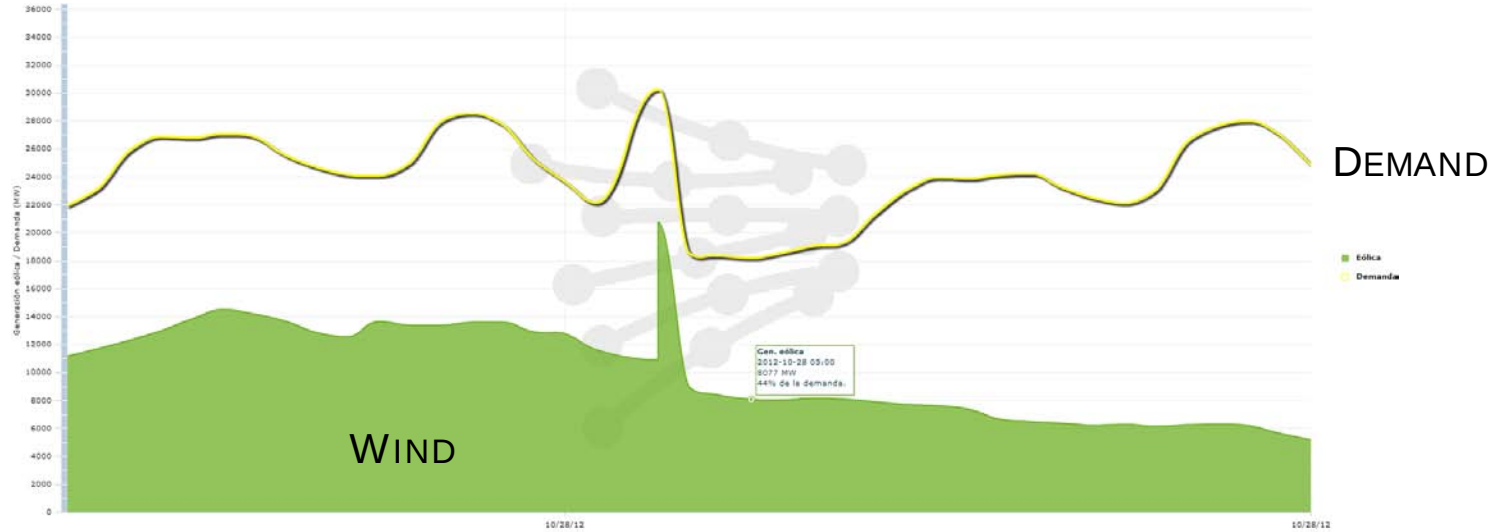
LOW VALUES OF WIND PENETRATION!!

Challenges arising from RES

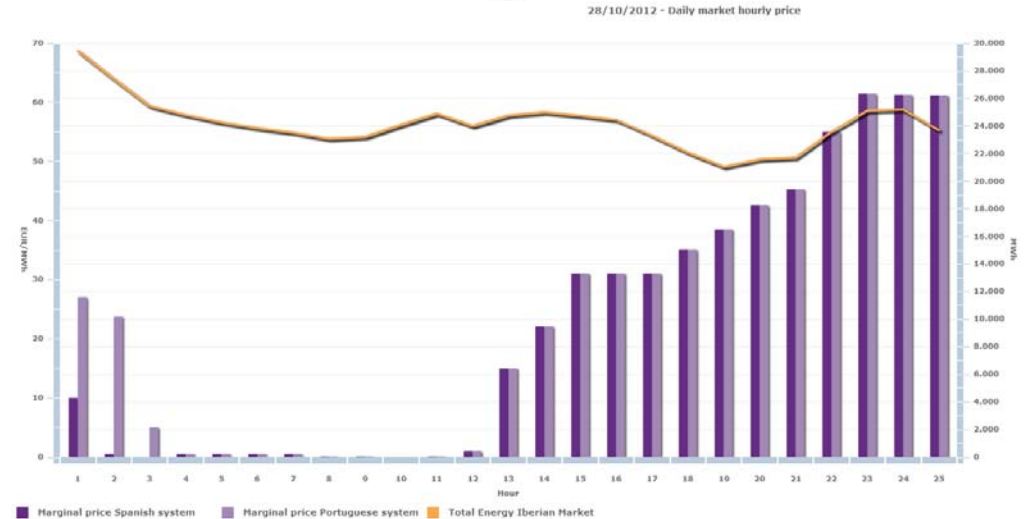
What would happen if wind capacity increases?



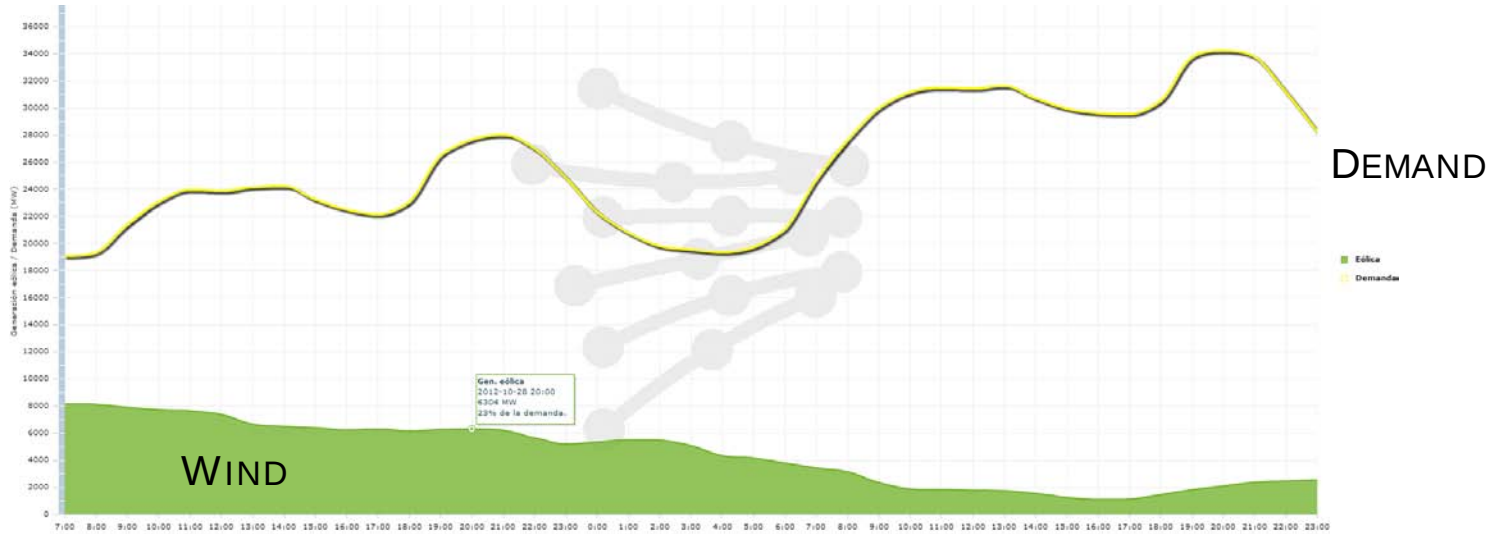
Challenges arising from RES



PRICES



Challenges arising from RES

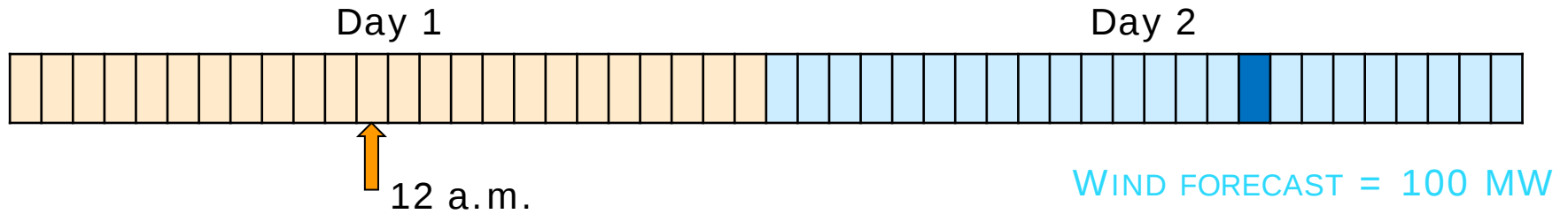


PRICES

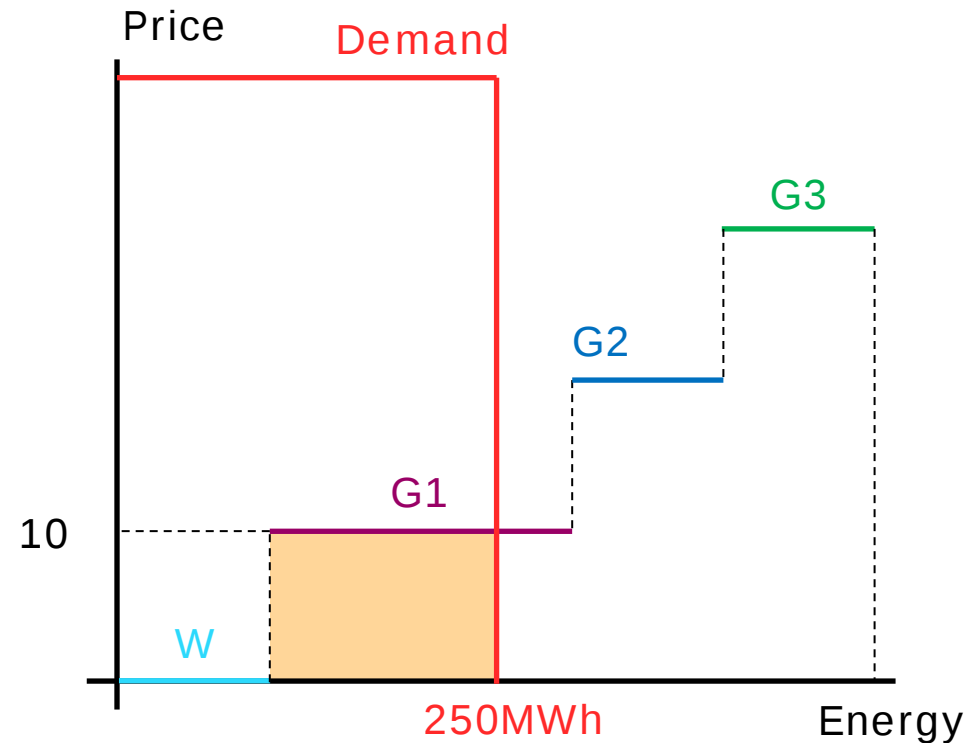


Challenges arising from RES

What would happen if wind capacity increases?

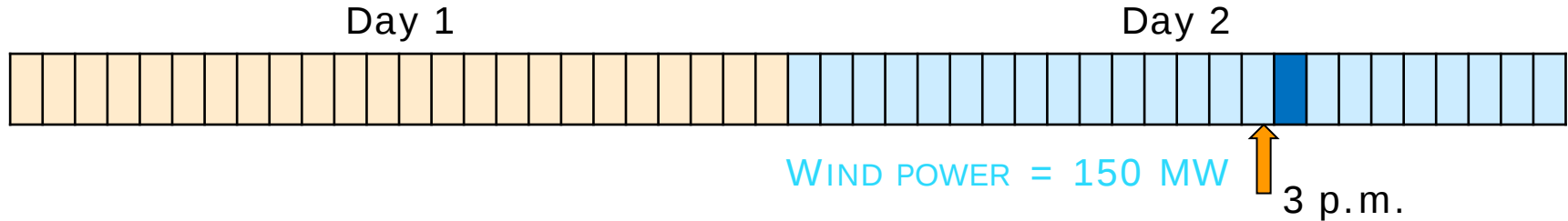


4-5 P.M.	
DA SCHEDULE	
UNIT	MW
W	100
G1	150
G2	-
G3	-

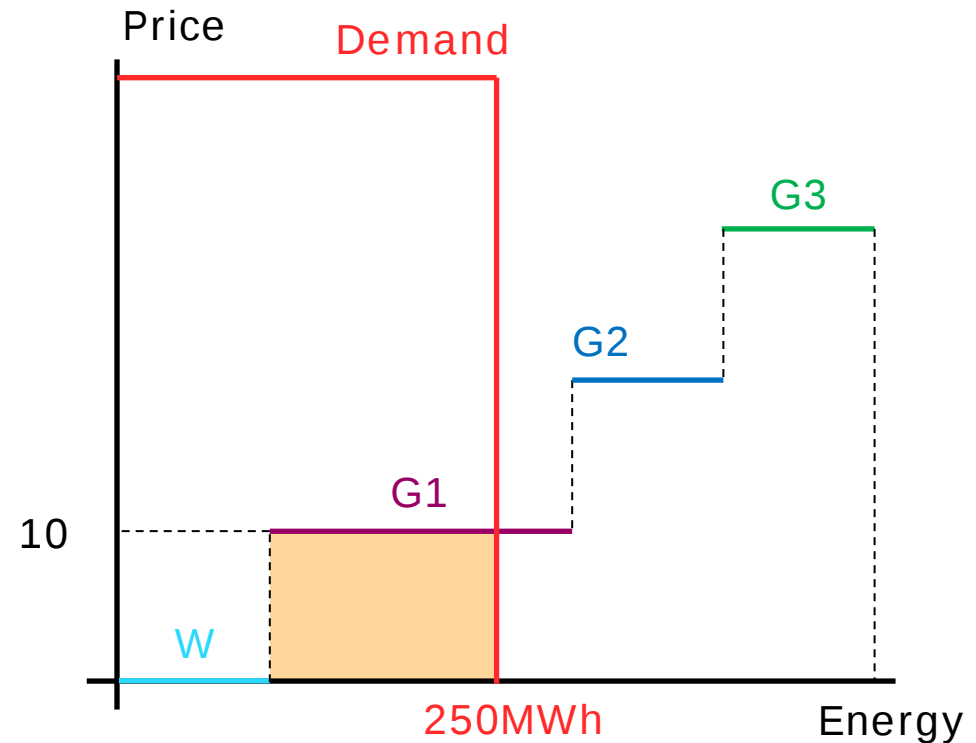


Challenges arising from RES

What would happen if wind capacity increases?

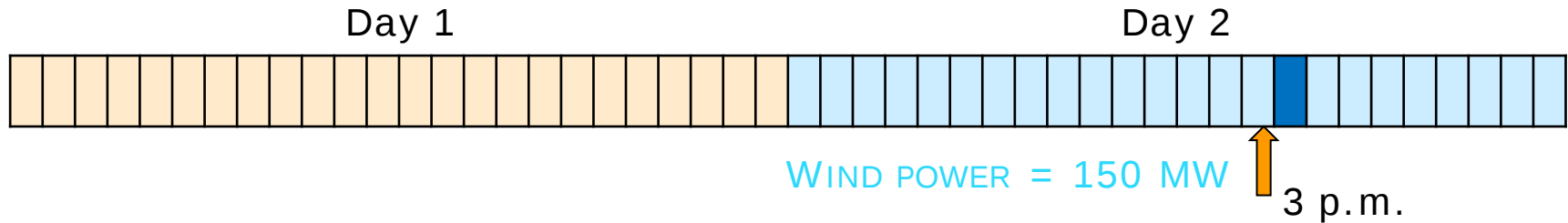


4-5 P.M.			
DA SCHEDULE		BALANCING MARKET	
UNIT	MW	UP	DOWN
W	100	-	-
G1	150	-	-
G2	-	10@25	10@15
G3	-	20@35	20@25



Challenges arising from RES

What would happen if wind capacity increases?



4-5 P.M.			
DA SCHEDULE		BALANCING MARKET	
UNIT	MW	UP	DOWN
W	100	-	-
G1	150	-	-
G2	-	10@25	10@15
G3	-	20@35	20@25

WIND 50MW
HIGHER THAN
EXPECTED

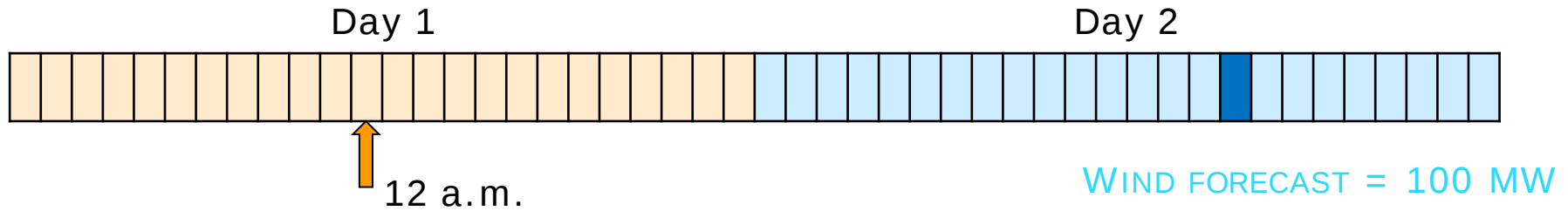
NONE DOWN
REGULATING
RESERVES



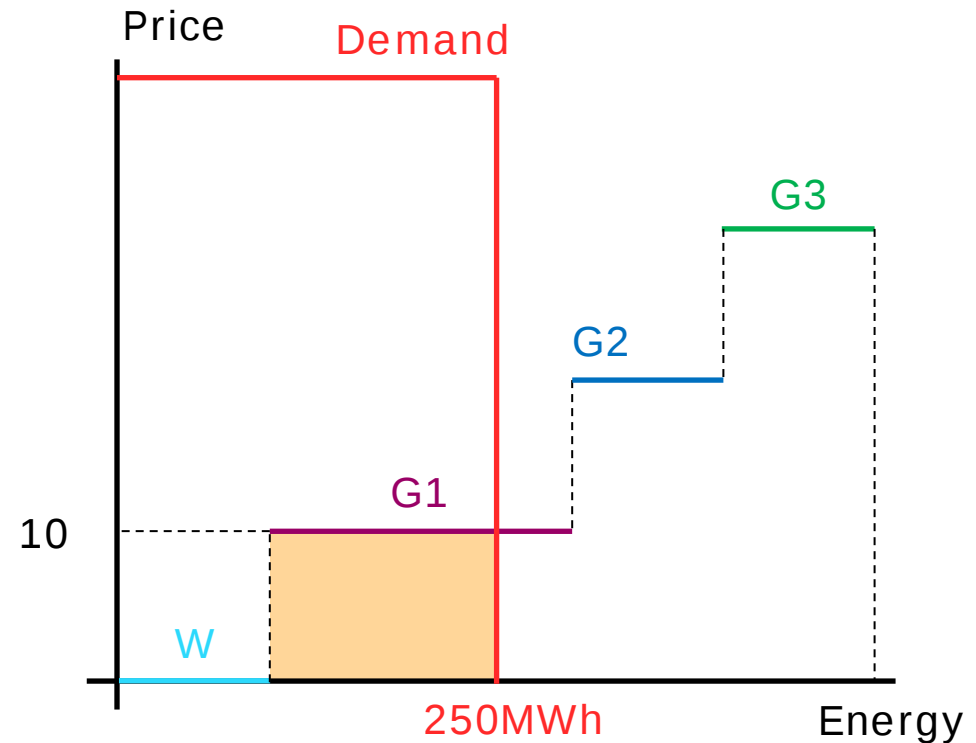
50MW OF WIND
SPILLAGE

Challenges arising from RES

What would happen if wind capacity increases?

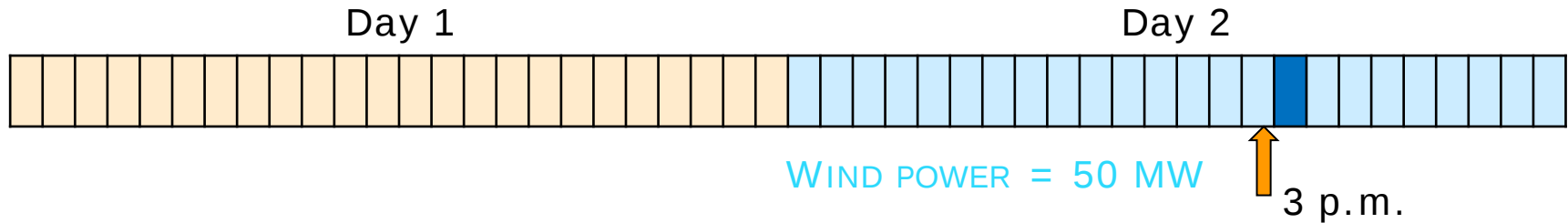


4-5 P.M.	
DA SCHEDULE	
UNIT	MW
W	100
G1	150
G2	-
G3	-



Challenges arising from RES

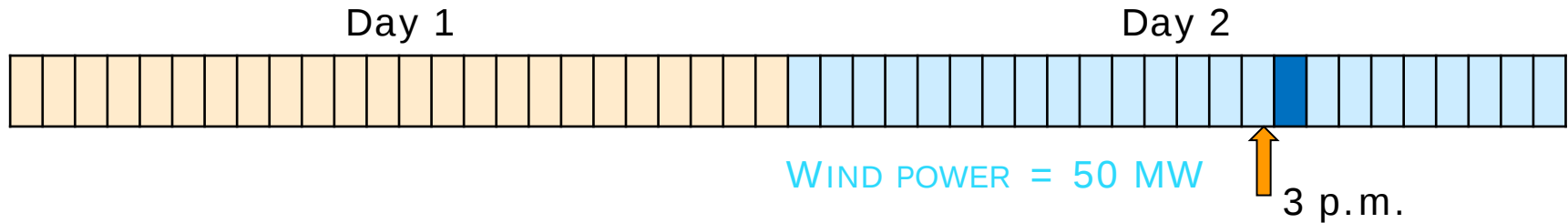
What would happen if wind capacity increases?



4-5 P.M.			
DA SCHEDULE		REGULATING MARKET	
UNIT	MW	UP	DOWN
W	100	-	-
G1	150	-	
G2	-	10@25	
G3	-	20@35	

Challenges arising from RES

What would happen if wind capacity increases?



4-5 P.M.			
DA SCHEDULE		REGULATING MARKET	
UNIT	MW	UP	DOWN
W	100	-	-
G1	150	-	
G2	-	10@25	
G3	-	20@35	

WIND 50MW
LOWER THAN
EXPECTED

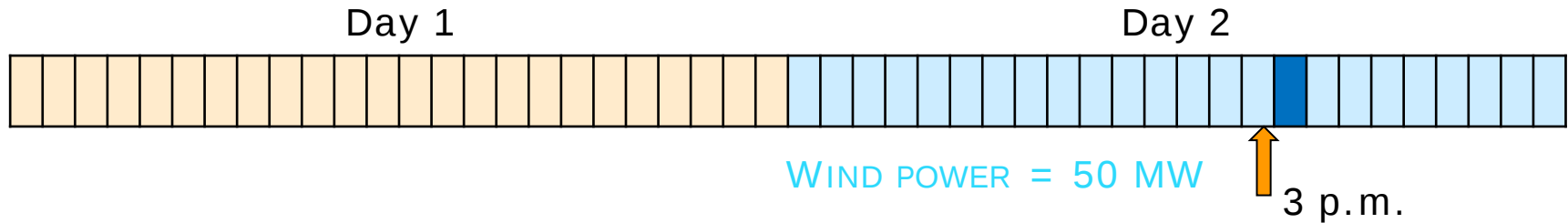
ONLY 30MW OF
UP REGULATING
RESERVES



20MW OF LOAD
SHEDDING

Challenges arising from RES

What would happen if wind capacity increases?



4-5 P.M.			
DA SCHEDULE		REGULATING MARKET	
UNIT	MW	UP	DOWN
W	100	-	-
G1	150	-	
G2	-	10@25	
G3	-	20@35	

WIND 50MW
LOWER THAN
EXPECTED

ONLY 30MW OF
UP REGULATING
RESERVES

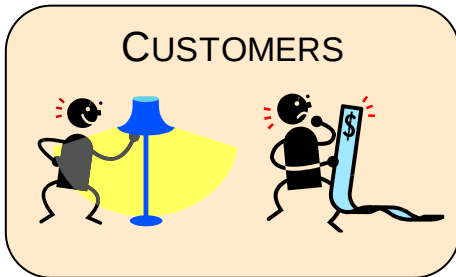
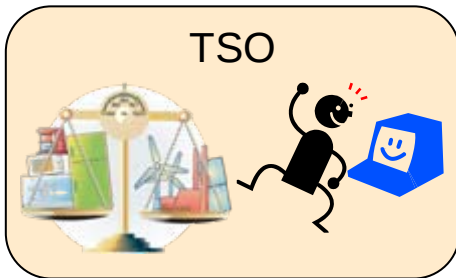
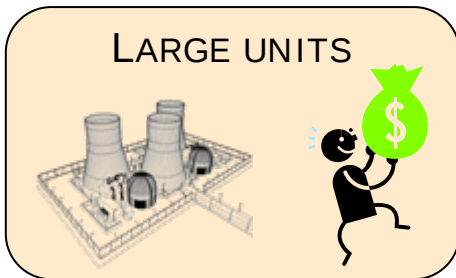


20MW OF LOAD
SHEDDING

Very costly!

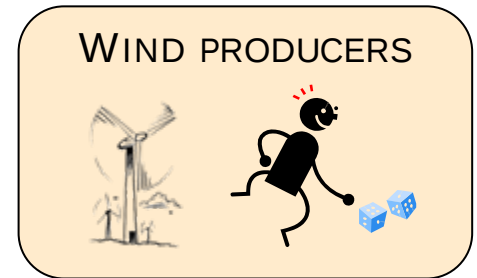
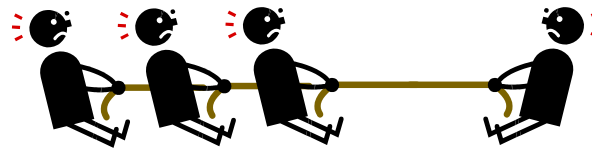
Challenges arising from RES

- LOW WIND POWER PENETRATION



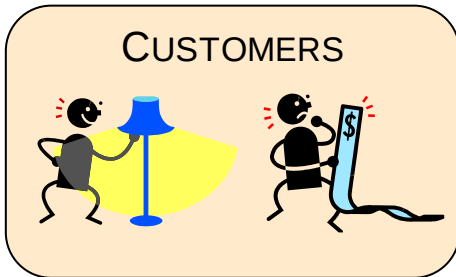
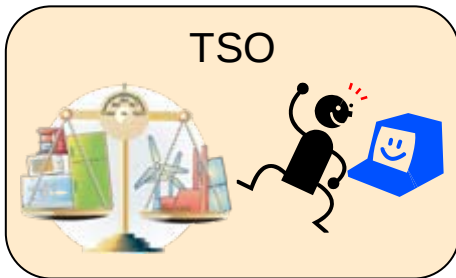
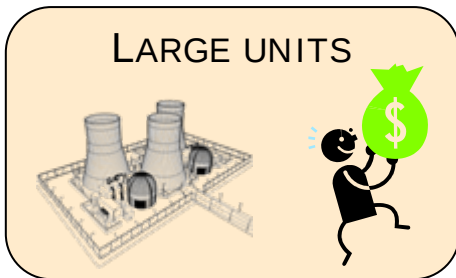
24-36H AHEAD

SHORTER HORIZON



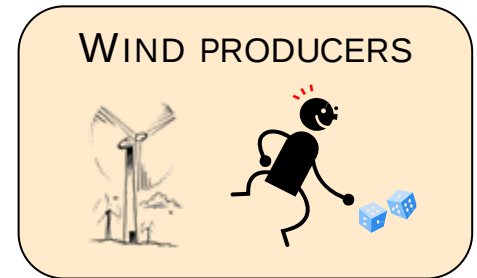
Challenges arising from RES

- HIGH WIND POWER PENETRATION



24-36H AHEAD

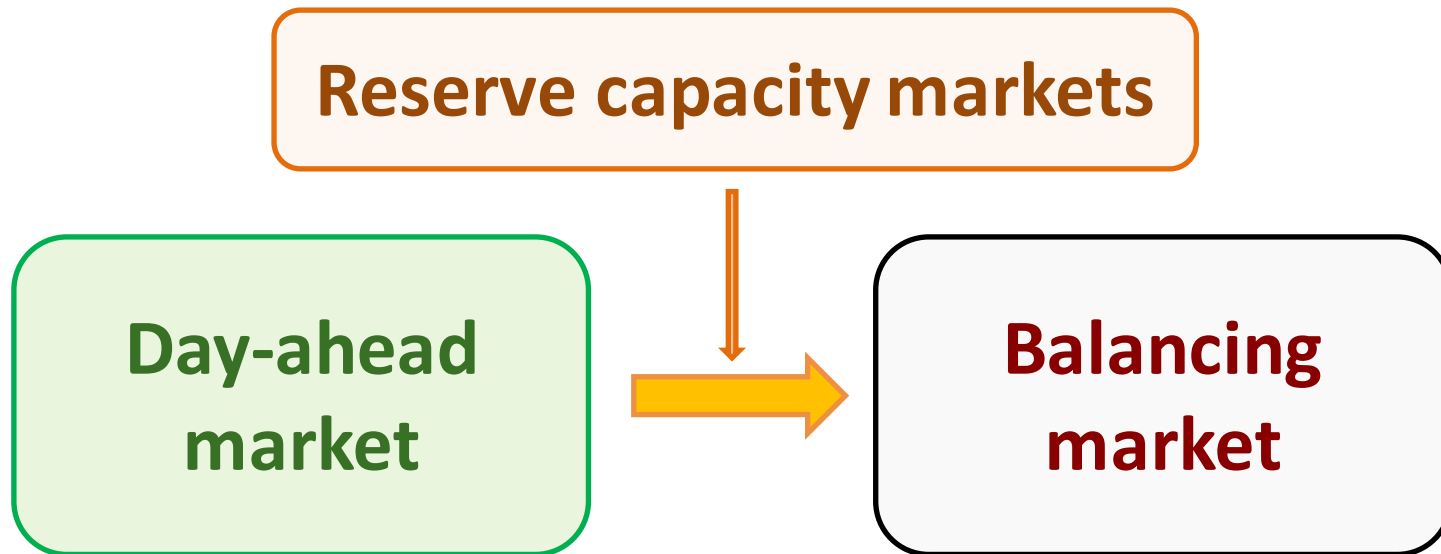
OTHER SOLUTIONS



Outline

- 1) Spot electricity markets
- 2) Challenges arising from the large-scale integration of RES
- 3) New market solutions
 - i. Energy and reserve capacity
 - ii. Stochastic market clearing

Reserve capacity markets



To guarantee enough balancing resources are available during the real-time operation of the power system

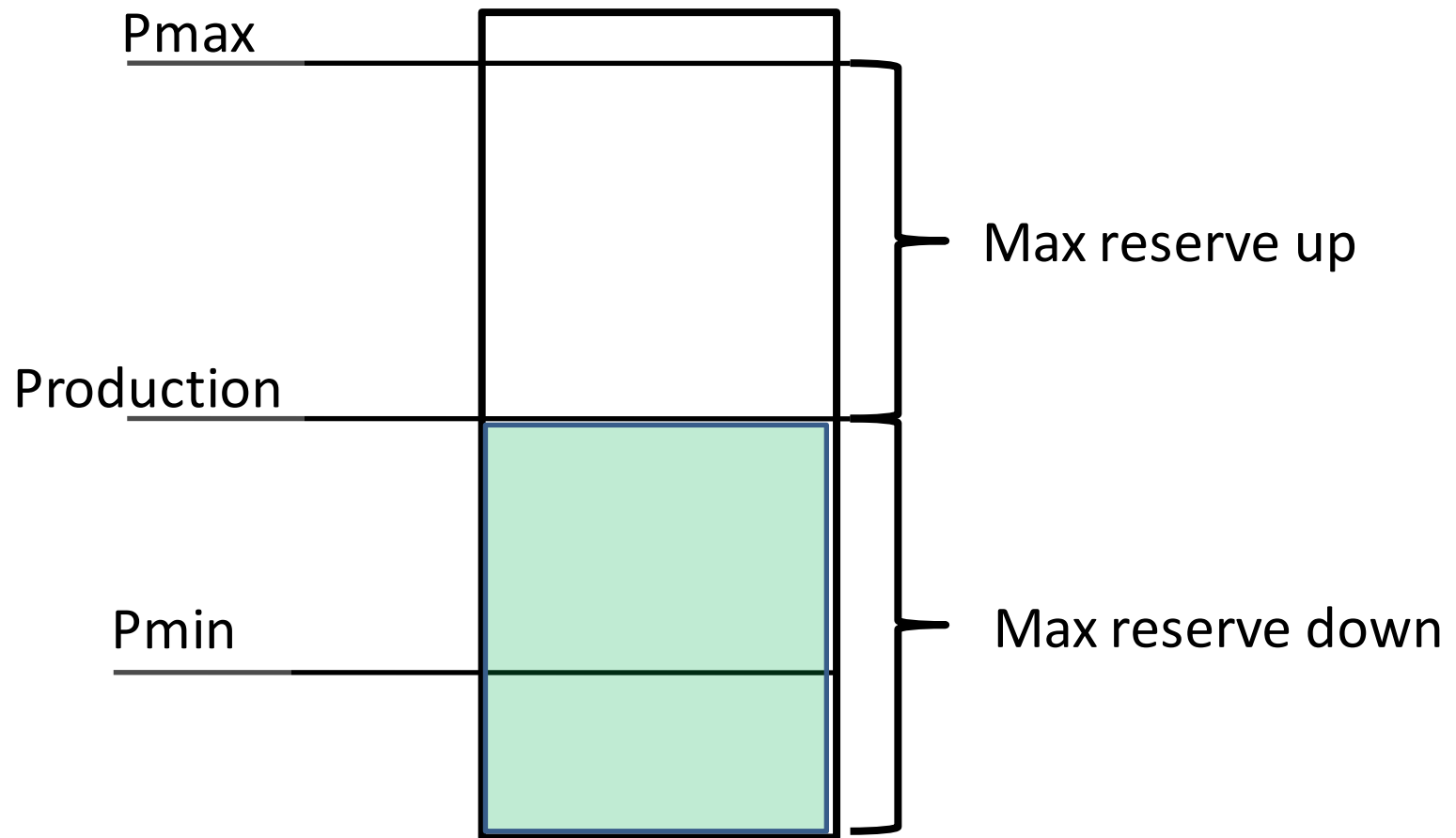
Reserve capacity markets

(Basic concepts)

- **Reserve capacity:** The capability of a power system above and below its current operating point to act in response of a disturbance within a specified time interval
- **Reserve deployment:** Collection of security corrective actions through which the reserve capacity is transformed into energy in the aftermath of a disturbance

Reserve capacity markets

(Basic concepts)



Reserve capacity markets

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- **Classification criteria:**
 - Spinning (synchronized)/non-spinning (not synchronized)
 - Activation time/purpose: Primary/Secondary/Tertiary
 - Purpose: contingency reserve/forecast errors/black-start
 - ...

Reserve capacity markets

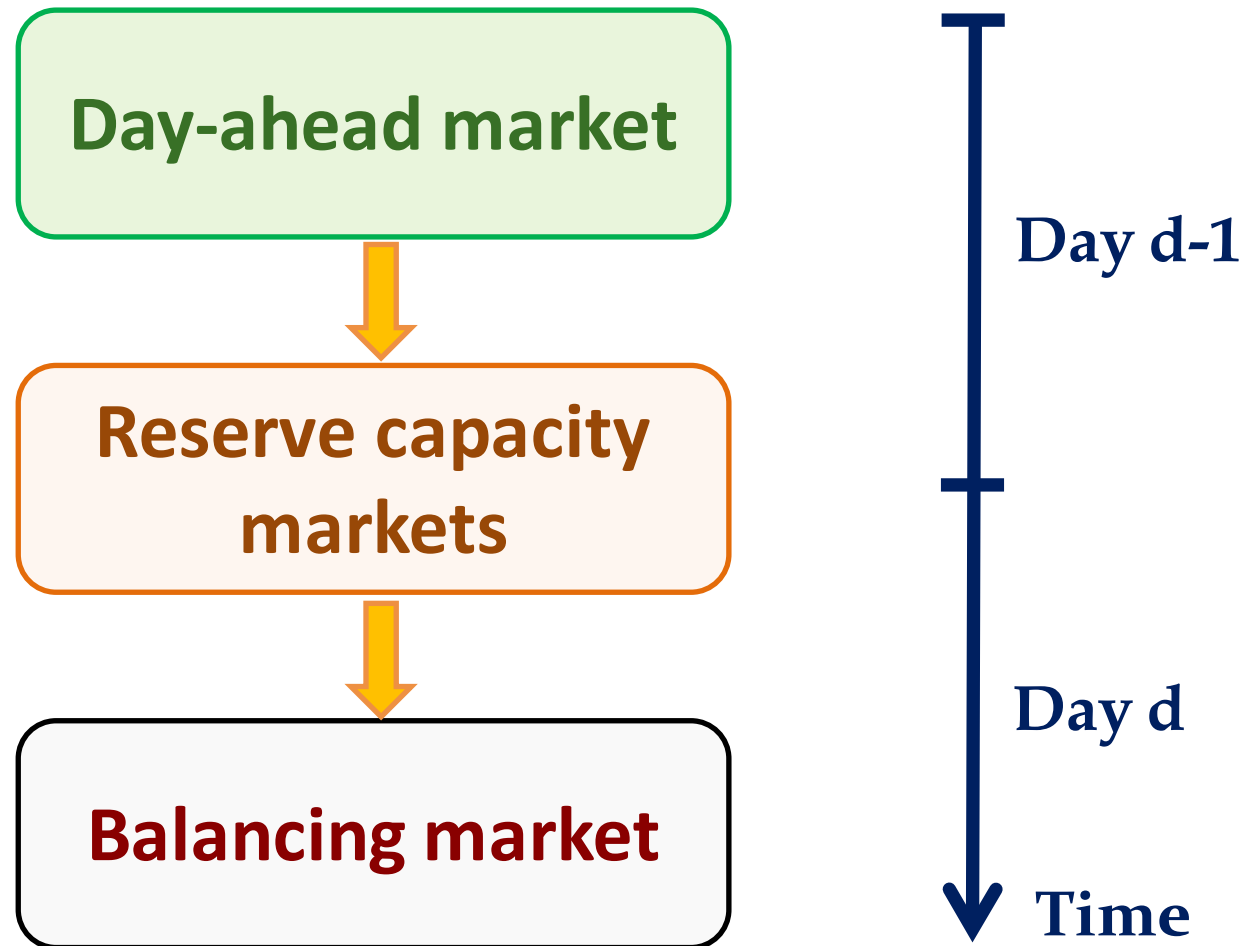
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 - ...

Terminology used in the Iberian
Electricity Market

Reserve capacity markets (Configurations)

**Sequential
set-up**



Reserve capacity markets

(Example: Sequential)

Data

- Producer A: 100MW & \$10/MWh
- Producer B: 100MW & \$30/MWh
- Net demand: 130MW

Reserve capacity markets

(Example: Sequential)

Data

Total system demand – Total wind power forecast

- Producer A: 100MW & \$10/MWh
- Producer B: 100MW & \$30/MWh
- Net demand: 130MW

Reserve capacity markets

(Example: Sequential)

Data

- Producer A: 100MW & \$10/MWh
- Producer B: 100MW & \$30/MWh
- Net demand: 130MW
- Reserve capacity requirement: 20MW
 - Producer A: free reserve capacity
 - Producer B: \$25/MW

Reserve capacity markets

(Example: Sequential)

Energy dispatch

$$\begin{array}{l} \text{Min } 10P_A + 30P_B \\ \text{s.t.} \\ P_A + P_B = 130 \\ 0 \leq P_A \leq 100 \\ 0 \leq P_B \leq 100 \end{array} \quad \longrightarrow \quad \begin{cases} P_A^* = 100 \text{ MW} \\ P_B^* = 30 \text{ MW} \\ \lambda_E^* = \$30 / \text{MWh} \end{cases}$$

Reserve capacity markets

(Example: Sequential)

Reserve dispatch

$$\begin{array}{l}
 \text{Min } 0R_A + 25R_B \\
 \text{s.t.} \\
 R_A + R_B = 20 \\
 0 \leq R_A \leq 100 - P_A^* \\
 0 \leq R_B \leq 100 - P_B^*
 \end{array}
 \left\{ \begin{array}{l} \rightarrow \end{array} \right.
 \left\{ \begin{array}{l}
 R_A^* = 0 \text{ MW} \\
 R_B^* = 20 \text{ MW} \\
 \lambda_R^* = \$25 / \text{MW}
 \end{array} \right.$$

Reserve capacity markets

(Example: Sequential)

Reserve dispatch

$$\begin{array}{l}
 \text{Min } 0R_A + 25R_B \\
 \text{s.t.} \\
 R_A + R_B = 20 \\
 0 \leq R_A \leq 100 - P_A^* \\
 0 \leq R_B \leq 100 - P_B^*
 \end{array}
 \quad \xrightarrow{\quad} \quad
 \begin{cases}
 R_A^* = 0 \text{ MW} \\
 R_B^* = 20 \text{ MW} \\
 \lambda_R^* = \$25 / \text{MW}
 \end{cases}$$

Inputs!

Reserve capacity markets

(Example: Sequential)

$$P_A^* = 100\text{MW} \quad P_B^* = 30\text{MW} \quad \lambda_E^* = \$30 / \text{MWh}$$

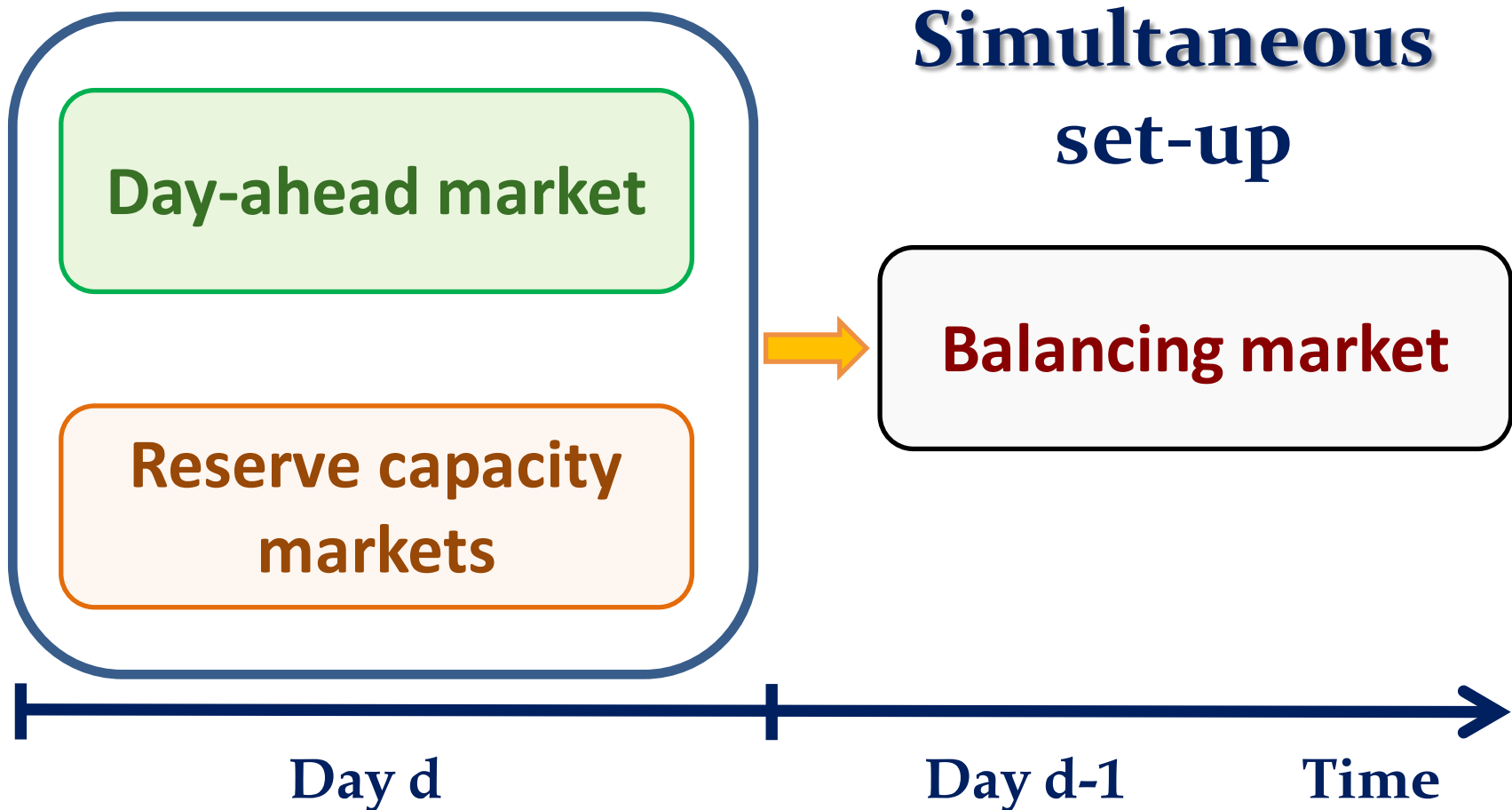
$$R_A^* = 0\text{MW} \quad R_B^* = 20\text{MW} \quad \lambda_R^* = \$25 / \text{MW}$$

$$\begin{aligned} \text{TC}^{\text{seq}} &= 10P_A^* + 30P_B^* + 0R_A^* + 25R_B^* = \\ &= 10 \cdot 100 + 30 \cdot 30 + 0 + 25 \cdot 20 = \$2400 \end{aligned}$$

$$\text{profit}_A^{\text{seq}} = (30 - 10)P_A^* + (25 - 0)R_A^* = \$2000$$

$$\text{profit}_B^{\text{seq}} = (30 - 30)P_B^* + (25 - 25)R_B^* = \$0$$

Reserve capacity markets (Configurations)



Reserve capacity markets

(Example: Simultaneous)

Data

- Producer A: 100MW & \$10/MWh
- Producer B: 100MW & \$30/MWh
- Net demand: 130MW
- Up-reserve capacity requirement: 20MW
 - Producer A: free reserve capacity
 - Producer B: \$25/MW

Reserve capacity markets

(Example: Simultaneous)

$$\begin{array}{l}
 \text{Min } 10P_A + 30P_B + \\
 \quad + 0R_A + 25R_B \\
 \text{s.t.} \\
 P_A + P_B = 130 \\
 R_A + R_B = 20 \\
 P_A + R_A \leq 100 \\
 P_B + R_B \leq 100 \\
 P_A \geq 0 \quad P_B \geq 0 \\
 R_A \geq 0 \quad R_B \geq 0
 \end{array}
 \quad \rightarrow \quad
 \begin{array}{l}
 P_A^* = 80\text{MW} \\
 R_A^* = 20\text{MW} \\
 P_B^* = 50\text{MW} \\
 R_B^* = 0\text{MW} \\
 \lambda_E^* = \$30 / \text{MWh} \\
 \lambda_R^* = \$20 / \text{MWh}
 \end{array}$$

Reserve capacity markets

(Example: Simultaneous)

$$P_A^* = 80\text{MW} \quad P_B^* = 50\text{MW} \quad \lambda_E^* = \$30 / \text{MWh}$$

$$R_A^* = 20\text{MW} \quad R_B^* = 0\text{MW} \quad \lambda_R^* = \$20 / \text{MW}$$

$$\begin{aligned} \text{TC}^{\text{sim}} &= 10P_A^* + 30P_B^* + 0R_A^* + 25R_B^* = \\ &= 10 \cdot 80 + 30 \cdot 50 + 0 \cdot 20 + 25 \cdot 0 = \$2300 \end{aligned}$$

$$\text{profit}_A^{\text{sim}} = (30 - 10)P_A^* + (20 - 0)R_A^* = \$2000$$

$$\text{profit}_B^{\text{sim}} = (30 - 30)P_B^* + (20 - 25)R_B^* = \$0$$

Reserve capacity markets

(Example: Comparison)

	Sequential		Simultaneous	
	Prod A	Prod B	Prod A	Prod B
Power	100MW	30MW	80MW	50MW
Reserve	0MW	20MW	20MW	0MW

	Sequential	Simultaneous
Energy price	\$30/MWh	\$30/MWh
Reserve price	\$25/MWh	\$20/MWh
Total Cost	\$2400	\$2300
Profit A	\$2000	\$2000
Profit B	\$0	\$0

Reserve capacity markets

(Example: Comparison)

	Sequential		Simultaneous	
	Prod A	Prod B	Prod A	Prod B
Power	100MW	30MW	80MW	50MW
Reserve	0MW	20MW	20MW	0MW

	Sequential	Simultaneous
Energy price	\$30/MWh	\$30/MWh
Reserve price	\$25/MWh	\$20/MWh
Total Cost	\$2400	\$2300
Profit A	\$2000	\$2000
Profit B	\$0	\$0

Reserve capacity markets

Is there a reserve capacity market in the Iberian Electricity Market?

Reserve capacity markets

Is there a reserve capacity market in the Iberian Electricity Market?

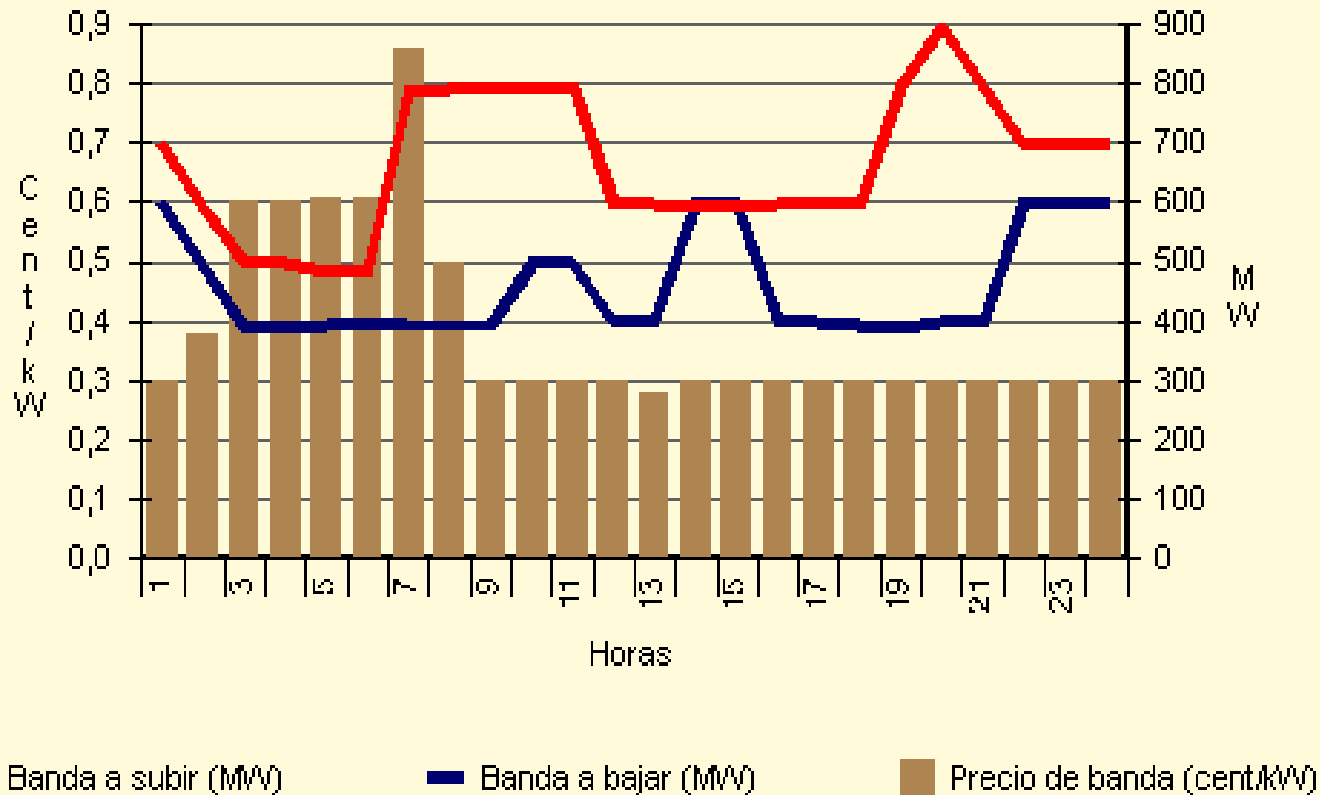
You should know ...

Reserve capacity markets



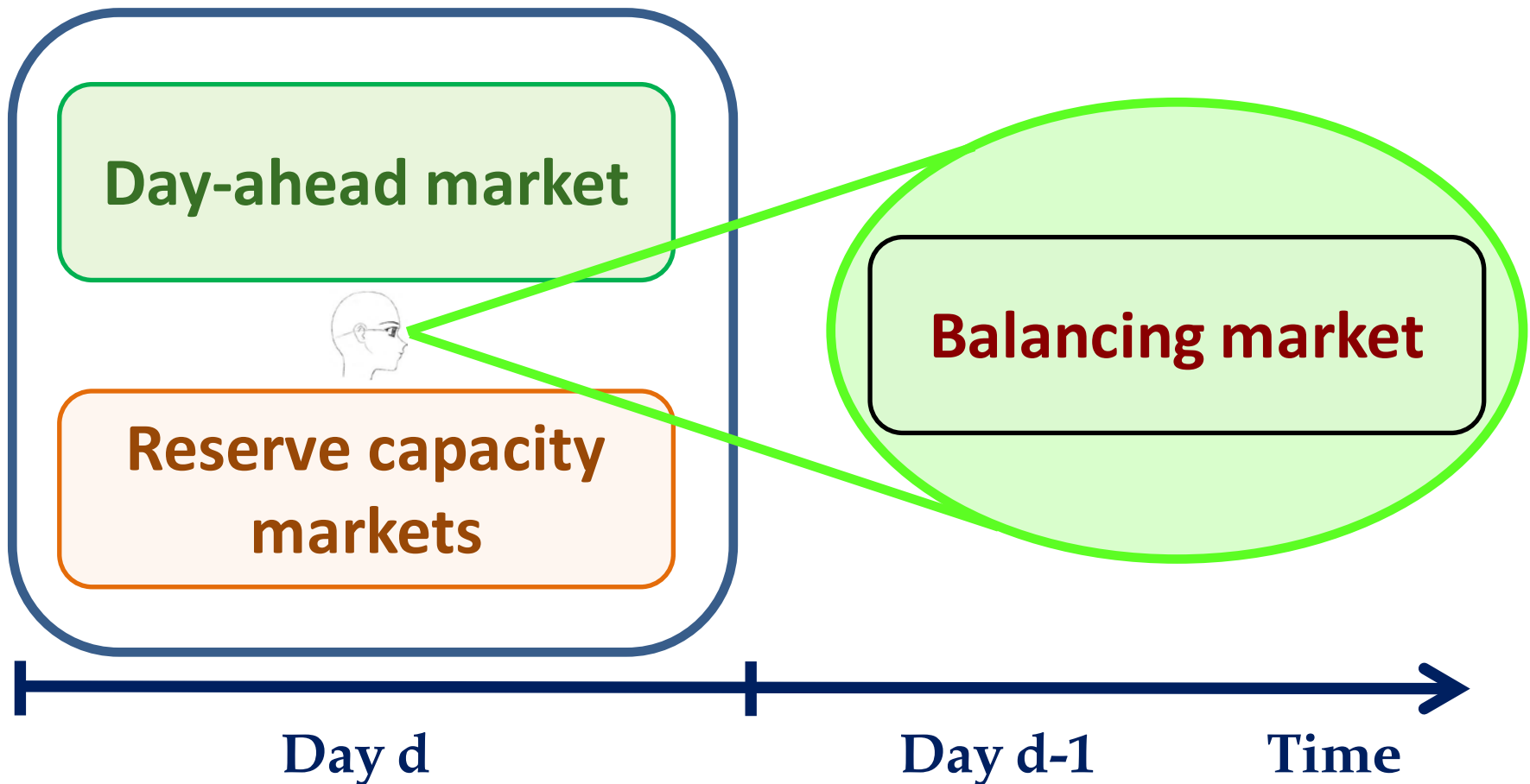
Reserve capacity markets

Precio de la banda de secundaria (cent/kW) - 05/03/2002



Stochastic market-clearing

(Basic idea)



Stochastic market-clearing

(Basic idea)

- Energy and reserve dispatches anticipate plausible balancing market outcomes
- The anticipation is based on a probabilistic description of uncertain factors
- Reserve requirements are *endogenously* estimated using a stochastic security metric: The expected load not served (ELNS)
- The cost of security is driven by the ELNS
- Minimization of the *expected* system cost

Stochastic market-clearing (Example)

Data

- Producer A: 100MW & \$10/MWh
- Producer B: 100MW & \$30/MWh
- Net demand: 130MW
- Up-reserve capacity requirement: 20MW
 - Producer A: free reserve capacity
 - Producer B: \$25/MW

Stochastic market-clearing (Example)

Data

- Producer A: 100MW & \$10/MWh
- Producer B: 100MW & \$30/MWh
- Net demand: 130MW → May unexpectedly increase up to 150 MW with a probability of 0.05
- ~~■ Up-reserve capacity requirement: 20MW~~
 - Producer A: free reserve capacity
 - Producer B: \$25/MW

Stochastic market-clearing (Example)

Three types of balancing actions ...

1. Producer A may increase its production from P_A to $P_A + r_A$ with $r_A \leq R_A$
2. Producer B may increase its production from P_B to $P_B + r_B$ with $r_B \leq R_B$
3. A part of the load increase, L^{shed} , may be simply not supplied at a cost of \$1000/MWh

Stochastic market-clearing (Example)

$$\begin{array}{l}
 \text{Min } 10P_A + 30P_B + \\
 \quad + 0R_A + 25R_B \\
 \quad + 0.05(10r_A + 30r_B + 1000L^{\text{shed}}) \\
 \text{s.t.} \\
 P_A + P_B = 130 \\
 r_A + r_B + L^{\text{shed}} = 20 \\
 P_A + R_A \leq 100 \\
 P_B + R_B \leq 100 \\
 r_A \leq R_A, \quad r_B \leq R_B \\
 P_A, P_B, R_A, R_B, r_A, r_B, L^{\text{shed}} \geq 0
 \end{array}
 \quad \Rightarrow \quad
 \begin{array}{l}
 P_A^* = 80\text{MW} \\
 R_A^* = 20\text{MW} \\
 P_B^* = 50\text{MW} \\
 R_B^* = 0\text{MW} \\
 r_A^* = 20\text{MW} \\
 r_B^* = 0 \\
 L^{\text{shed}} = 0
 \end{array}$$

Stochastic market-clearing (Example)

$$\begin{aligned} \text{Min } & 10P_A + 30P_B + \\ & + 0R_A + 25R_B \\ & + 0.05(10r_A + 30r_B + 1000L^{\text{shed}}) \end{aligned}$$

s.t.

$$P_A + P_B = 130$$

$$r_A + r_B + L^{\text{shed}} = 20$$

$$P_A + R_A \leq 100$$

$$P_B + R_B \leq 100$$

$$r_A \leq R_A, \quad r_B \leq R_B$$

$$P_A, P_B, R_A, R_B, r_A, r_B, L^{\text{shed}} \geq 0$$

Expected cost at the
balancing stage

$$P_A^* = 80\text{MW}$$

$$R_A^* = 20\text{MW}$$

$$P_B^* = 50\text{MW}$$

$$R_B^* = 0\text{MW}$$

$$r_A^* = 20\text{MW}$$

$$r_B^* = 0$$

$$L^{\text{shed}} = 0$$

Stochastic market-clearing (Example)

$$\begin{aligned}
 & \text{Min } 10P_A + 30P_B + \\
 & \quad + 0R_A + 25R_B \\
 & \quad + 0.05(10r_A + 30r_B + 1000L^{\text{shed}})
 \end{aligned}$$

Cost of the expected load not served

s.t.

$$\begin{aligned}
 P_A + P_B &= 130 \\
 r_A + r_B + L^{\text{shed}} &= 20 \\
 P_A + R_A &\leq 100 \\
 P_B + R_B &\leq 100 \\
 r_A &\leq R_A, \quad r_B \leq R_B \\
 P_A, P_B, R_A, R_B, r_A, r_B, L^{\text{shed}} &\geq 0
 \end{aligned}$$

→

$$\begin{aligned}
 P_A^* &= 80\text{MW} \\
 R_A^* &= 20\text{MW} \\
 P_B^* &= 50\text{MW} \\
 R_B^* &= 0\text{MW} \\
 r_A^* &= 20\text{MW} \\
 r_B^* &= 0 \\
 L^{\text{shed}} &= 0
 \end{aligned}$$

Stochastic market-clearing (Example)

$$\begin{aligned} \text{Min } & 10P_A + 30P_B + \\ & + 0R_A + 25R_B \\ & + 0.05(10r_A + 30r_B + 1000L^{\text{shed}}) \end{aligned}$$

s.t.

$$P_A + P_B = 130$$

$$r_A + r_B + L^{\text{shed}} = 20$$

$$P_A + R_A \leq 100$$

$$P_B + R_B \leq 100$$

$$r_A \leq R_A, \quad r_B \leq R_B$$

$$P_A, P_B, R_A, R_B, r_A, r_B, L^{\text{shed}} \geq 0$$



$$P_A^* = 80\text{MW}$$

$$R_A^* = 20\text{MW}$$

$$P_B^* = 50\text{MW}$$

$$R_B^* = 0\text{MW}$$

$$r_A^* = 20\text{MW}$$

$$r_B^* = 0$$

$$L^{\text{shed}} = 0$$

No reserve
determination constraint

Stochastic market-clearing (Example)

$$\begin{aligned} \text{Min } & 10P_A + 30P_B + \\ & + 0R_A + 25R_B \\ & + 0.05(10r_A + 30r_B + 1000L^{\text{shed}}) \end{aligned}$$

s.t.

$$P_A + P_B = 130$$

$$r_A + r_B + L^{\text{shed}} = 20$$

$$P_A + R_A \leq 100$$

$$P_B + R_B \leq 100$$

$$r_A \leq R_A, \quad r_B \leq R_B$$

$$P_A, P_B, R_A, R_B, r_A, r_B, L^{\text{shed}} \geq 0$$



$$P_A^* = 80\text{MW}$$

$$R_A^* = 20\text{MW}$$

$$P_B^* = 50\text{MW}$$

$$R_B^* = 0\text{MW}$$

$$r_A^* = 20\text{MW}$$

$$r_B^* = 0$$

$$L^{\text{shed}} = 0$$

Same solution as that of the
simultaneous set-up

Stochastic market-clearing (Example)

Data

- Producer A: 100MW & \$10/MWh
 - Producer B: 100MW & \$30/MWh
 - Net demand: 130MW → May unexpectedly increase up to 150 MW with a probability of 0.001
 - ~~Reserve capacity requirement: 20MW~~
- Producer A: free reserve capacity
 - Producer B: \$25/MW

Stochastic market-clearing (Example)

$$\begin{aligned} \text{Min } & 10P_A + 30P_B + \\ & + 0R_A + 25R_B \\ & + 0.001(10r_A + 30r_B + 1000L^{\text{shed}}) \end{aligned}$$

s.t.

$$P_A + P_B = 130$$

$$r_A + r_B + L^{\text{shed}} = 20$$

$$P_A + R_A \leq 100$$

$$P_B + R_B \leq 100$$

$$r_A \leq R_A, \quad r_B \leq R_B$$

$$P_A, P_B, R_A, R_B, r_A, r_B, L^{\text{shed}} \geq 0$$



$$P_A^* = 100\text{MW}$$

$$R_A^* = 0\text{MW}$$

$$P_B^* = 30\text{MW}$$

$$R_B^* = 0\text{MW}$$

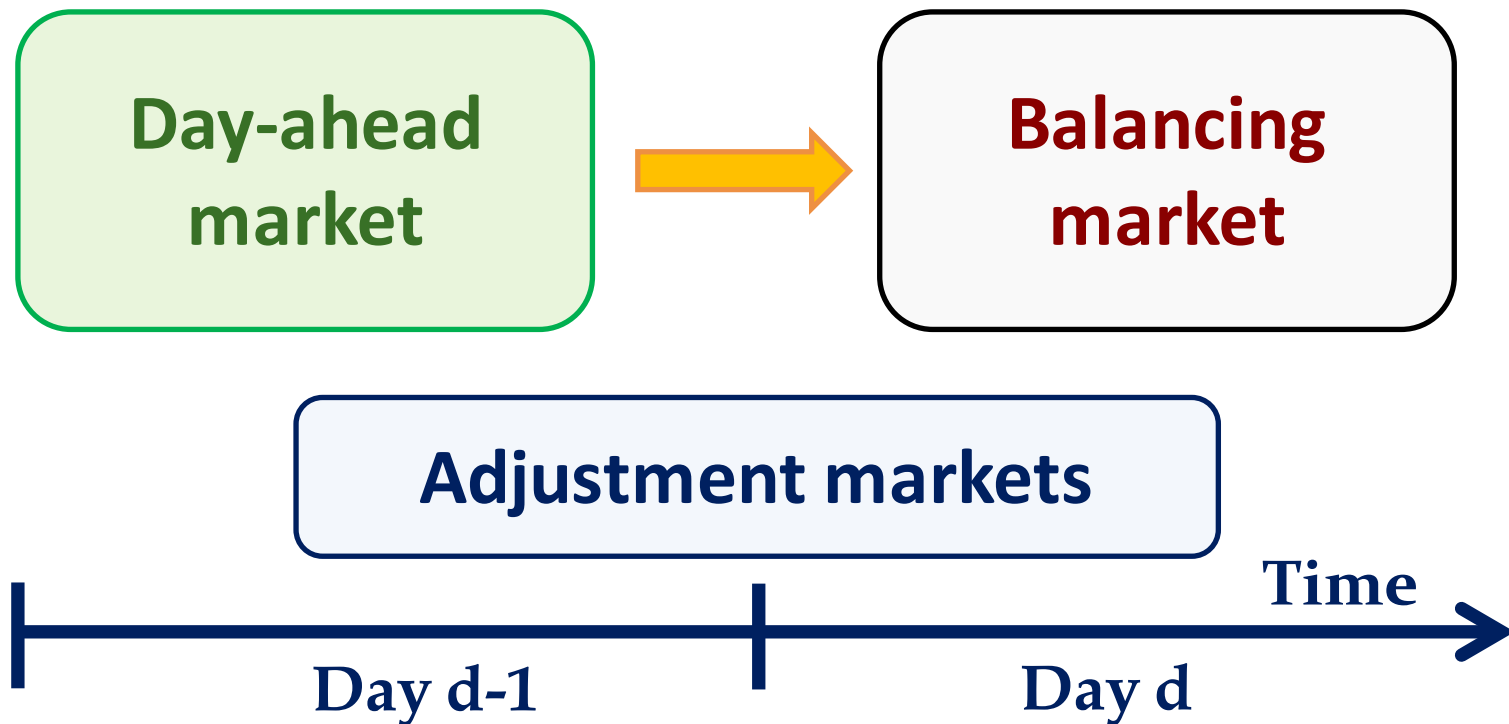
$$r_A^* = 0\text{MW}$$

$$r_B^* = 0$$

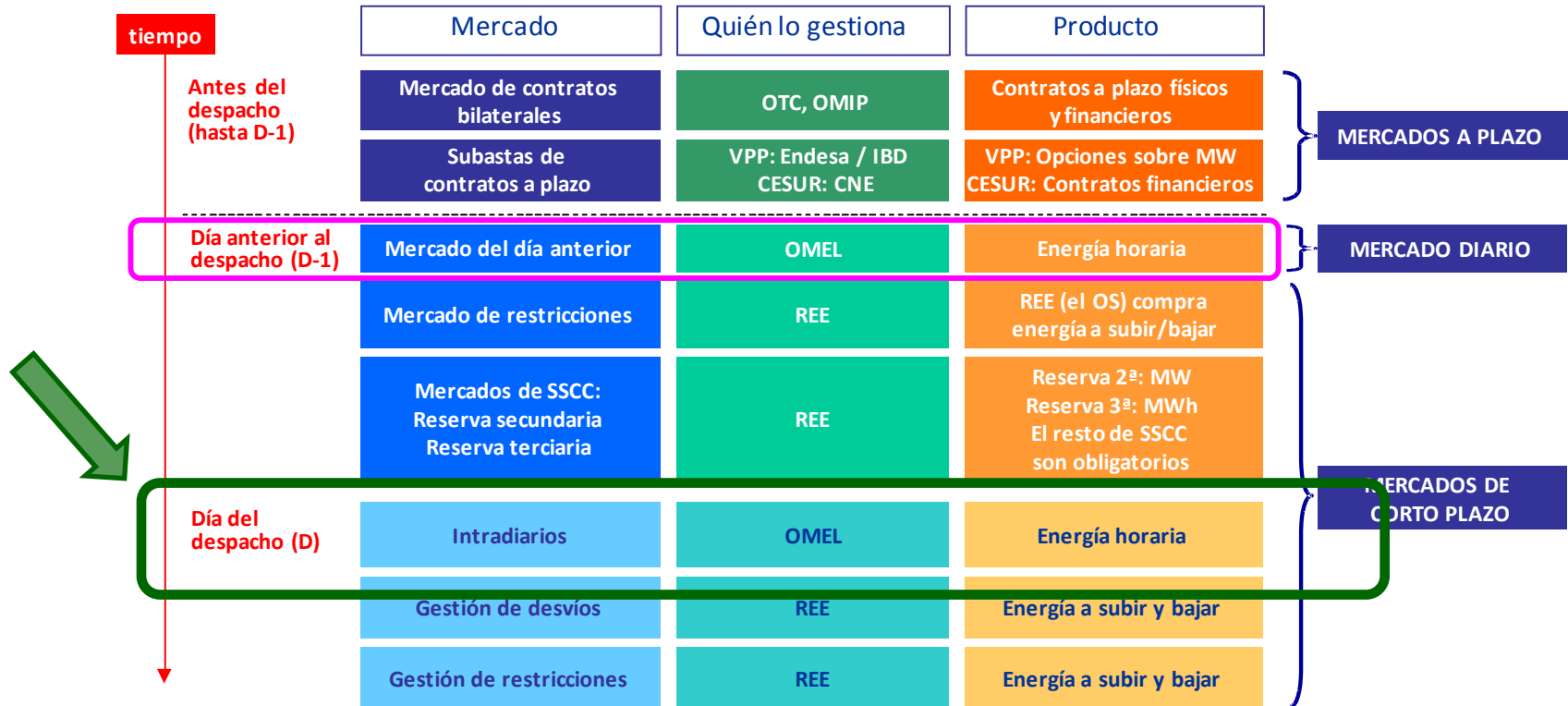
$$L^{\text{shed}} = 20$$

A different solution

Other market-design solutions (Adjustment Markets)



Other market-design solutions (Adjustment Markets)



Adjustment markets



To be continued...