Electricity Markets and Stochastic Producers

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Tutorial 3: Electricity markets for renewable based energy systems
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Outline

- Electricity markets: basic concepts
- Electricity markets & uncertainty
- Electricity markets & investment

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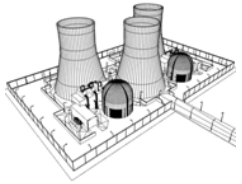
- Electricity markets: basic concepts
- Electricity markets & uncertainty
- Electricity markets & investment

What is a market?

- People need certain products

- People can produce such products



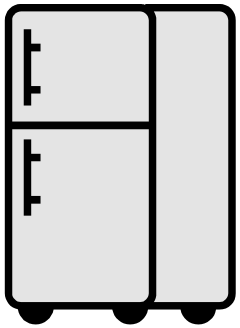
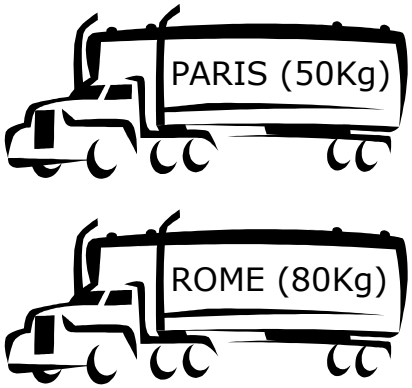
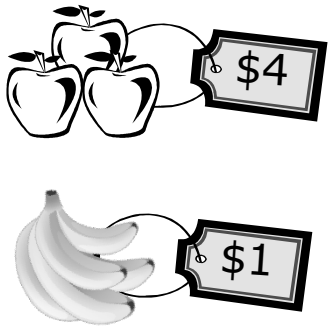
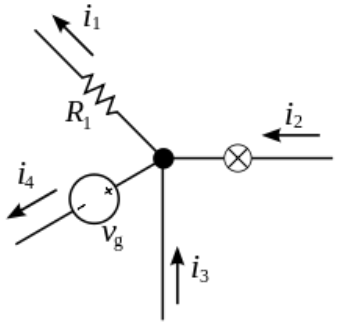
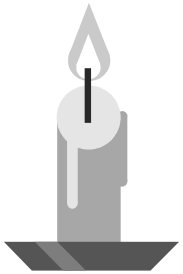
- Place to trade the products

nordpool spot

What is a market?

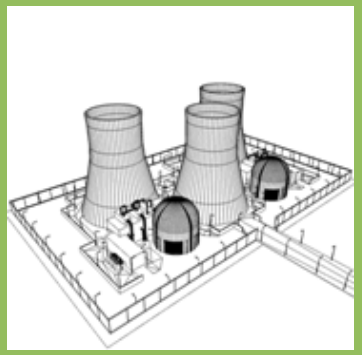
- A market is any structure that allows buyers and sellers to **exchange** any type of goods, services and information.
- Goods or services are exchange for **money**.
- Market participants consist of all the **buyers** and **sellers** of a good who influence its price.
- The market facilitates trade and enables the distribution and **allocation of resources** in a society.
- Markets allow any tradable item to be evaluated and **priced**.

Why is electricity different?

Product	Stored	Transportation	Demand
			
			

Electricity market

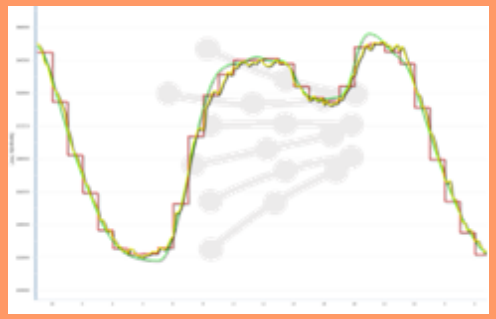
- We need to know the characteristics of the players:



Large fuel-based units (economy of scale)

Technical constraints (required a schedule)

Far from consumption centers (transmission)



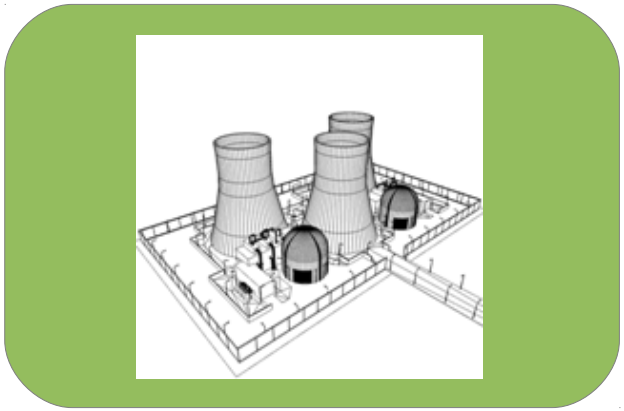
Demand level easily forecast

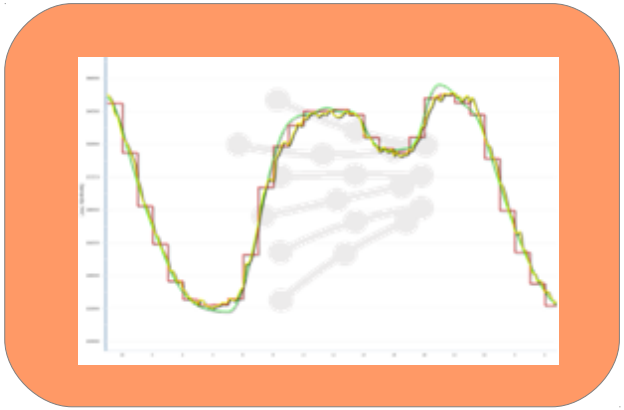
Known daily, weekly, and yearly patterns

High inflexibility

Day-ahead electricity market

- We need to know the characteristics of the players:





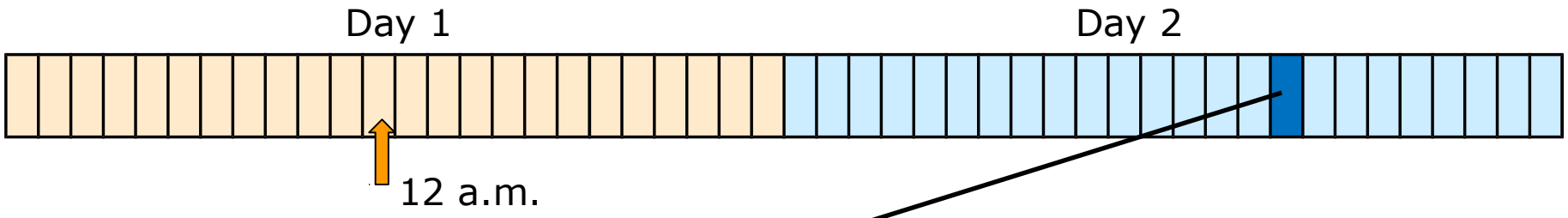
Day-ahead market

Power producers submit offers to sell electricity for the next 24 hours

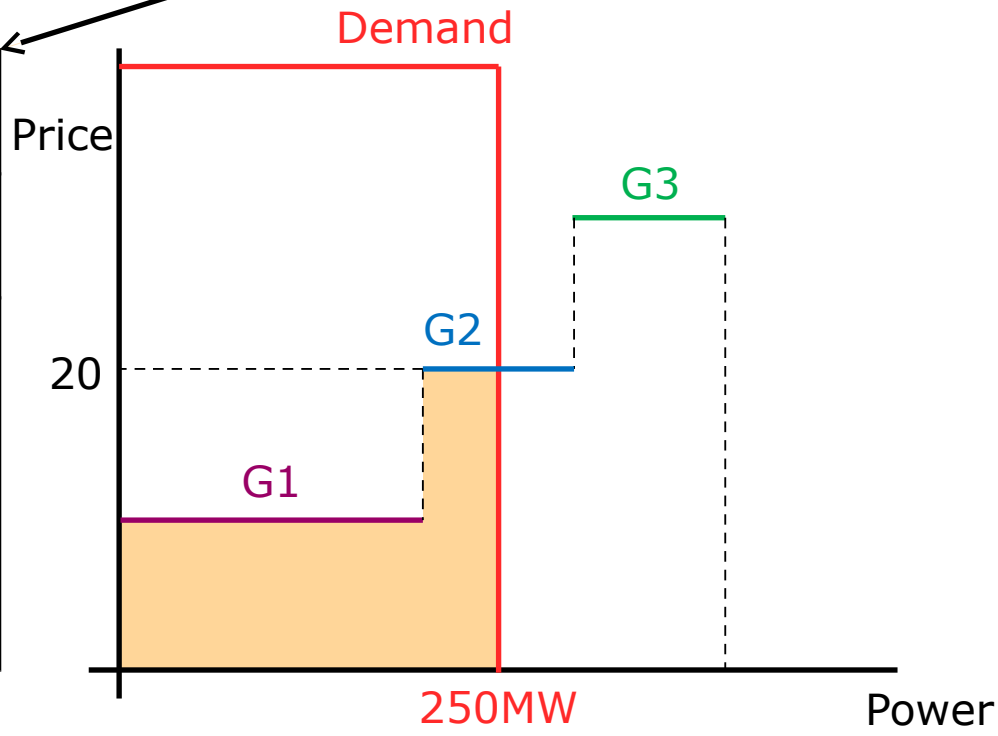
The demand for the next day is forecast

The cheapest offers are accepted up to the forecast demand

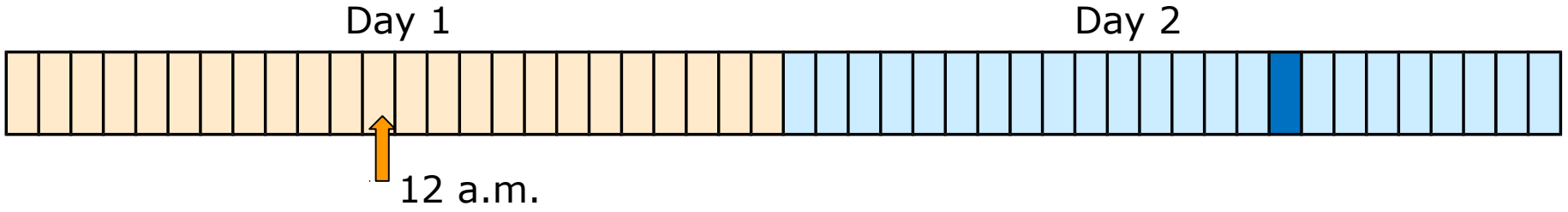
Day-ahead electricity market



4-5 p.m.			
Unit	Cost	Offers	Demand
G1	5	200@10	250 MW
G2	15	100@20	
G3	25	100@30	



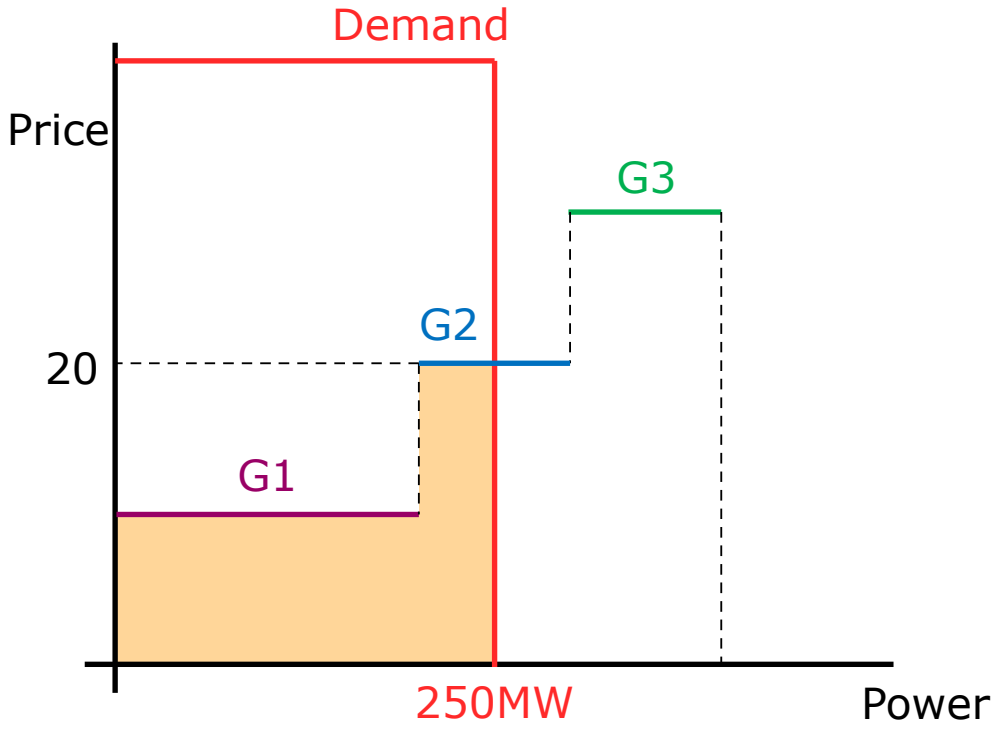
Day-ahead electricity market



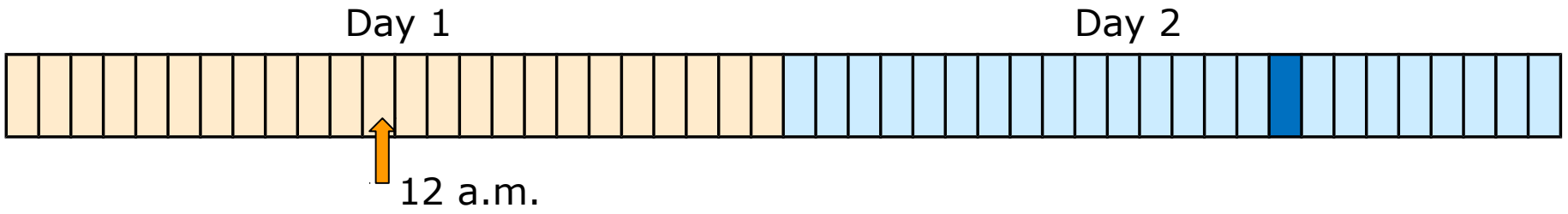
$$\underset{p_G}{\text{Minimize}} \quad \mathcal{C}^{\mathrm{D}}\left(p_G\right)$$

$$\text{s.t.} \quad h^{\mathrm{D}}\left(p_G\right) - l = 0 : \lambda^{\mathrm{D}}$$

$$g^{\mathrm{D}}\left(p_G\right) \leq 0$$



Day-ahead electricity market

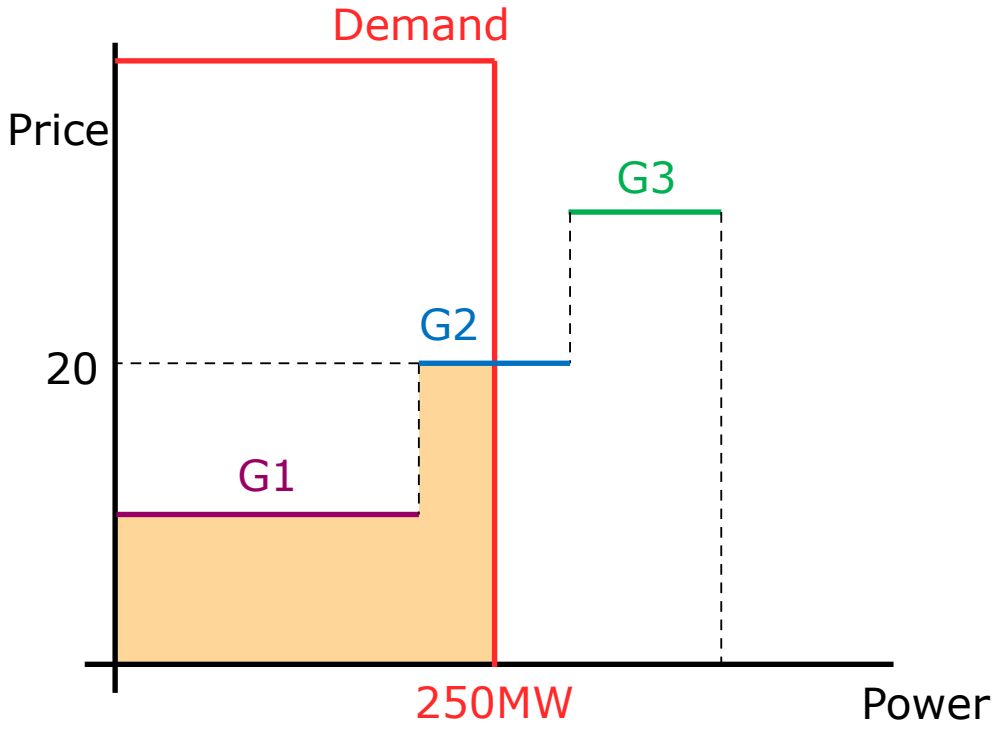


Demand = 250x20 = 5000$

G1 = 20x200 = 4000$

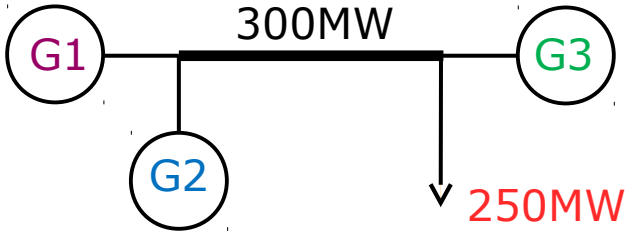
G2 = 20x50 = 1000$

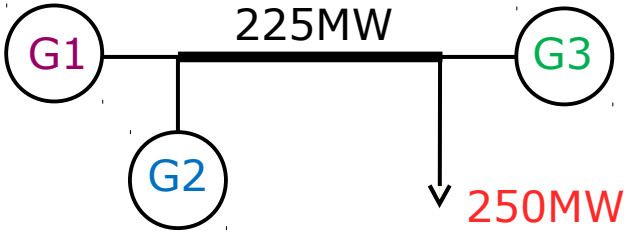
This is called marginal pricing

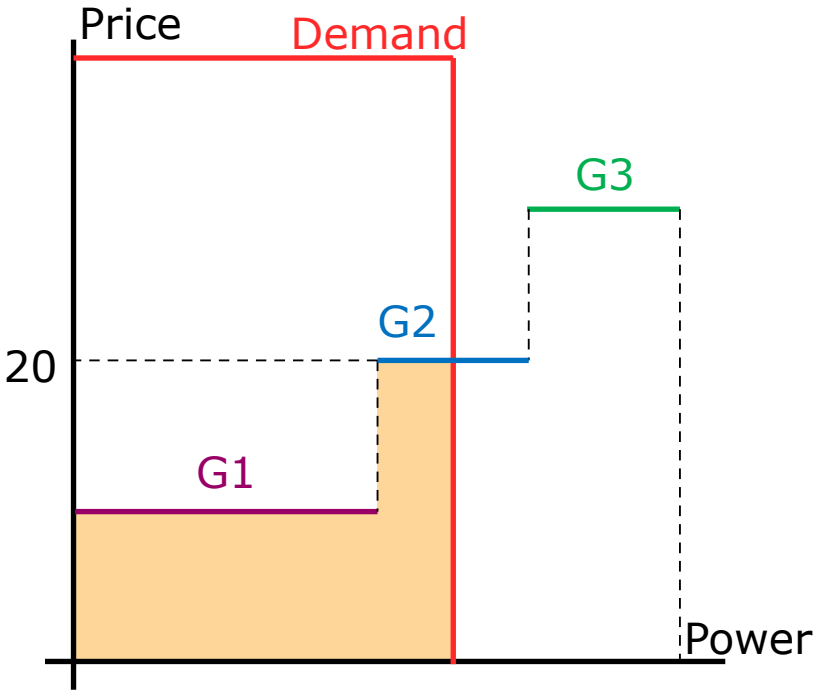


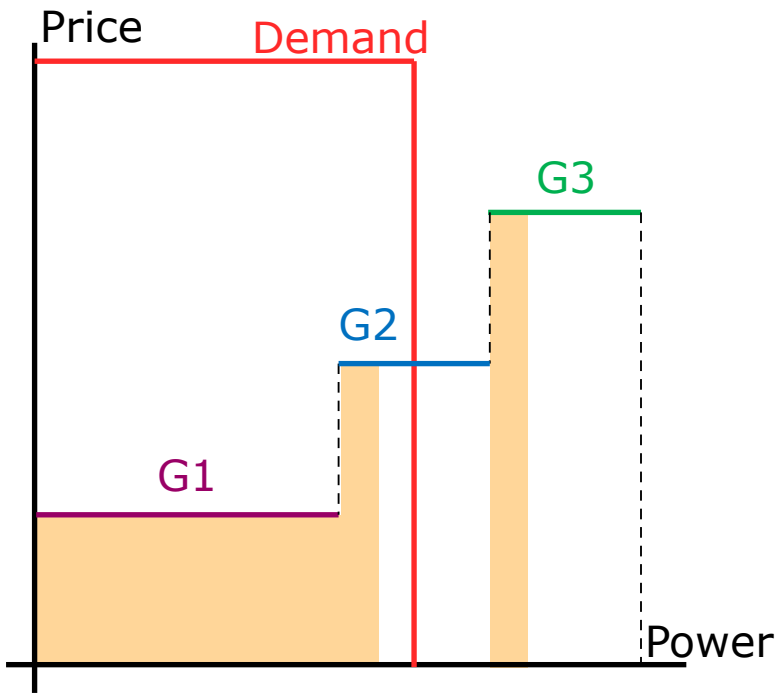
Day-ahead electricity market

- What about the network?









Day-ahead electricity market

- What about the network?

What should be the price?

Bus 1 = 20 $/MWh

Bus 2 = 30 $/MWh

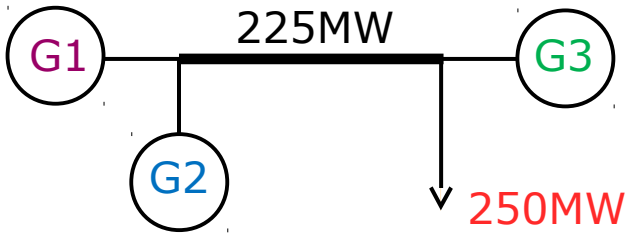
Demand = 250x30 = 7500$

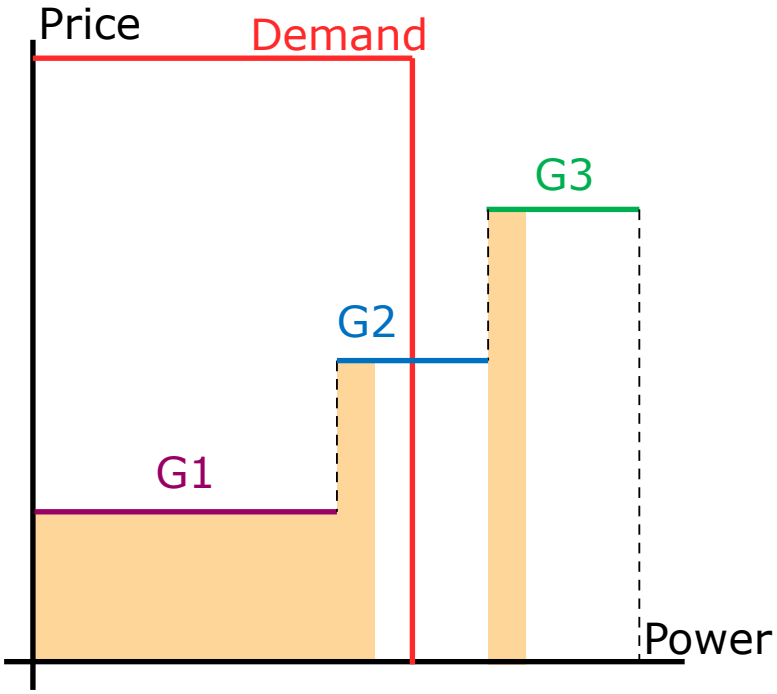
G1 = 20x200 = 4000$

G2 = 20x25 = 500$

G3 = 30x25 = 750$

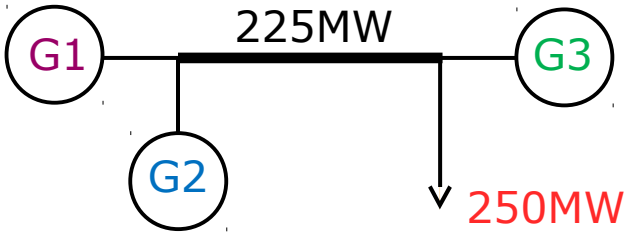
2250$ extra!!





Day-ahead electricity market

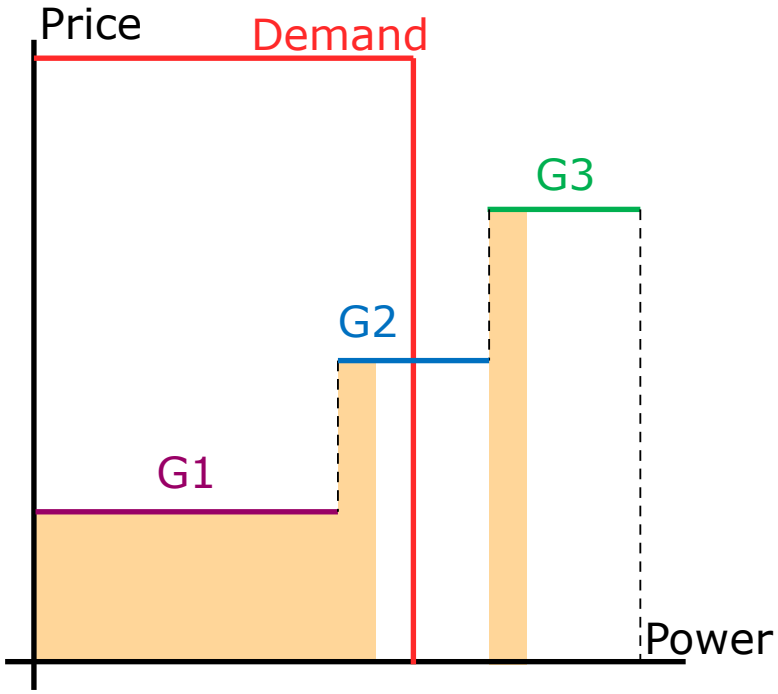
- What about the network?



$$\underset{p_G,\delta^0}{\text{Minimize}} \quad \mathcal{C}^{\mathrm{D}}\left(p_G\right)$$

$$\text{s.t.} \quad h^{\mathrm{D}}\left(p_G,\delta^0\right) - l = 0 : \lambda^{\mathrm{D}}$$

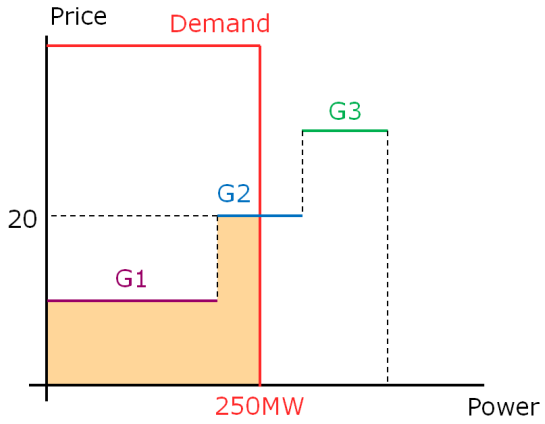
$$g^{\mathrm{D}}\left(p_G,\delta^0\right) \leq 0$$

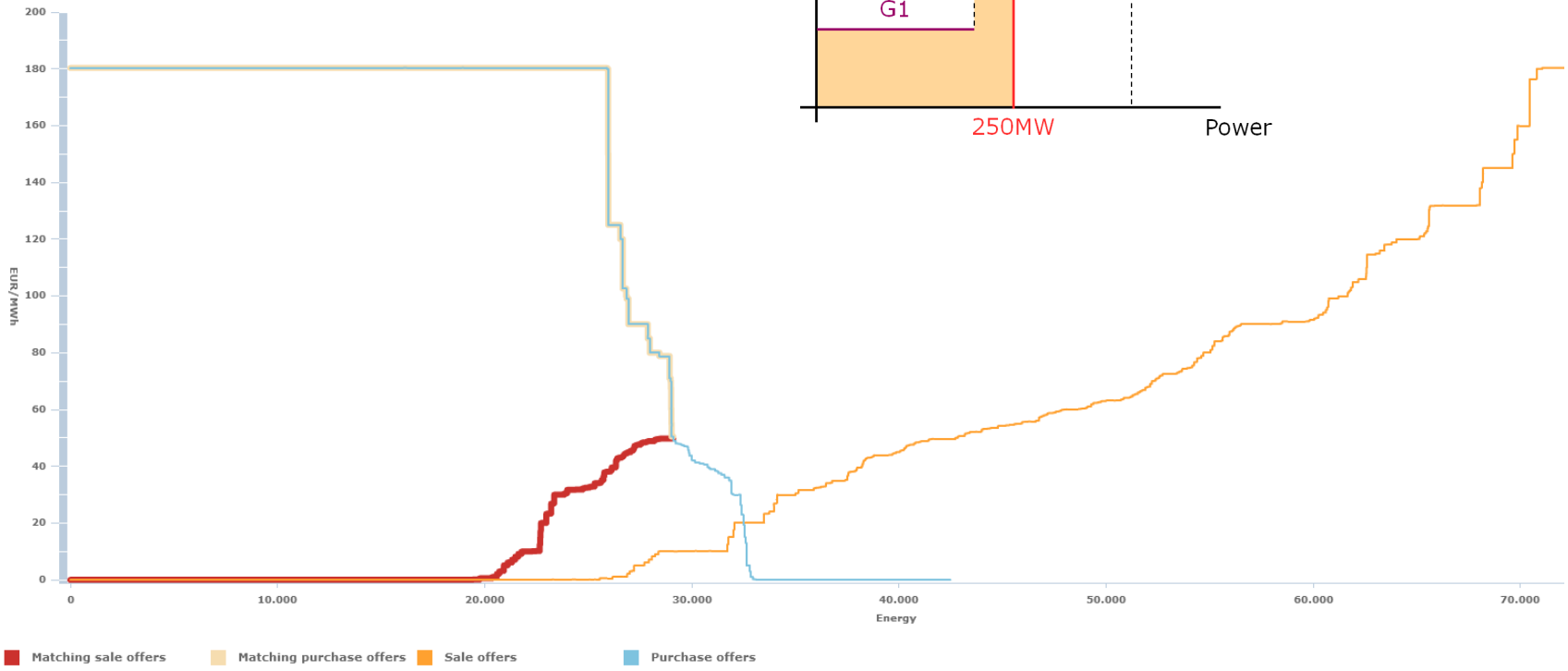


Day-ahead electricity market

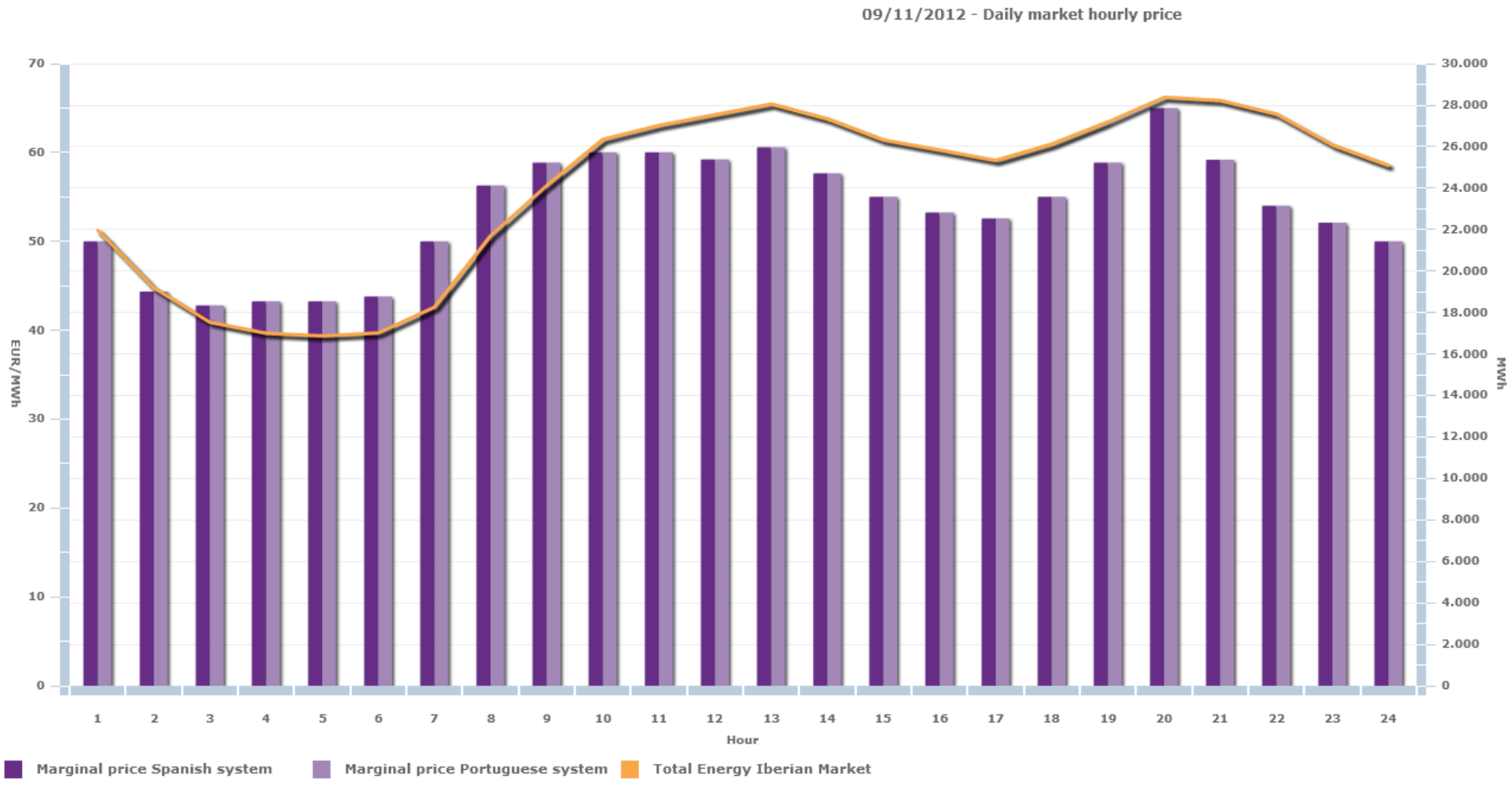
- Large and inflexible units
- Predictable demand
- Day-ahead electricity market
- Generating unit schedules determined 24h ahead
- Electricity price equal to the marginal cost
- Locational marginal prices if the network is congested

Day-ahead electricity market

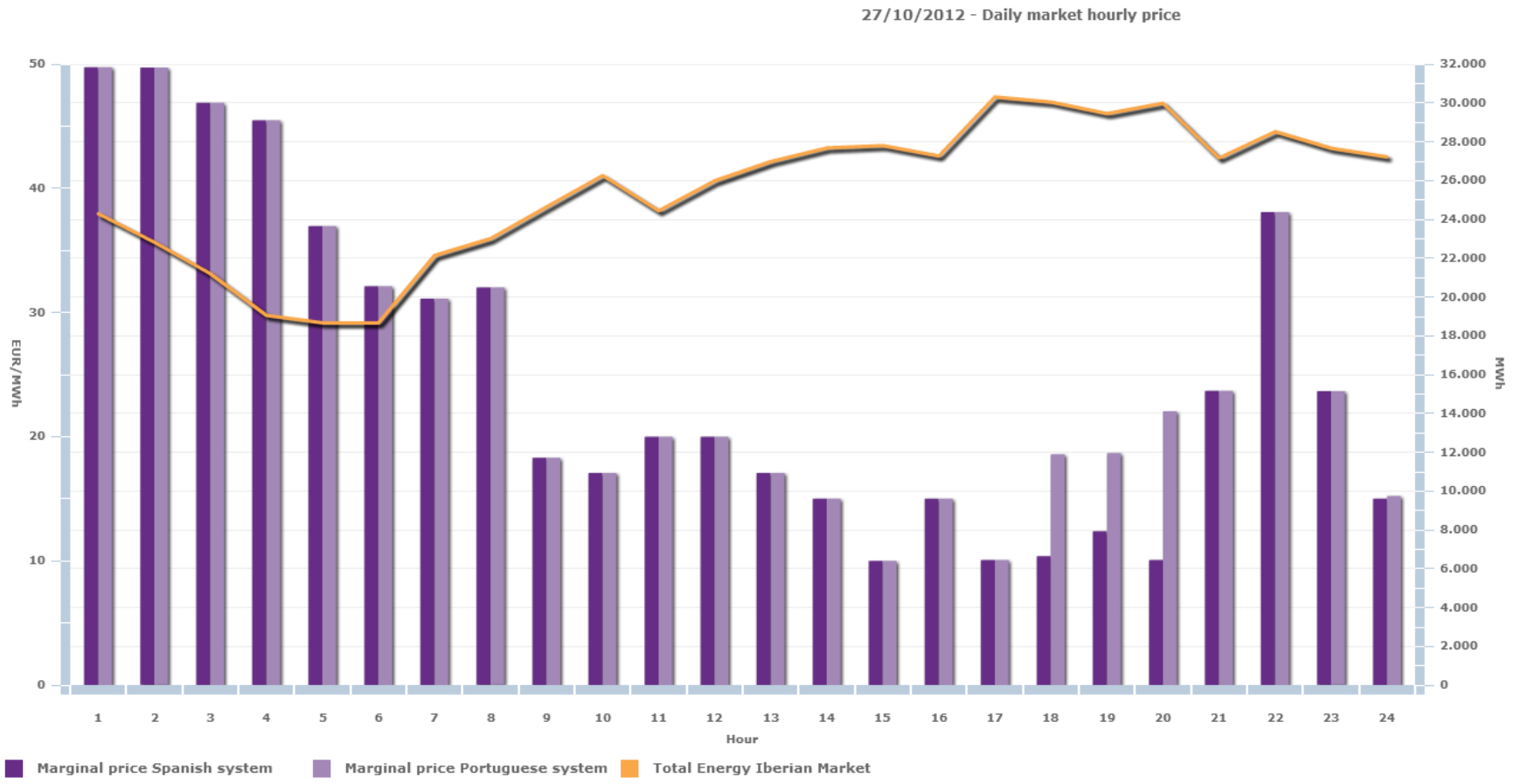




Day-ahead electricity market



Day-ahead electricity market



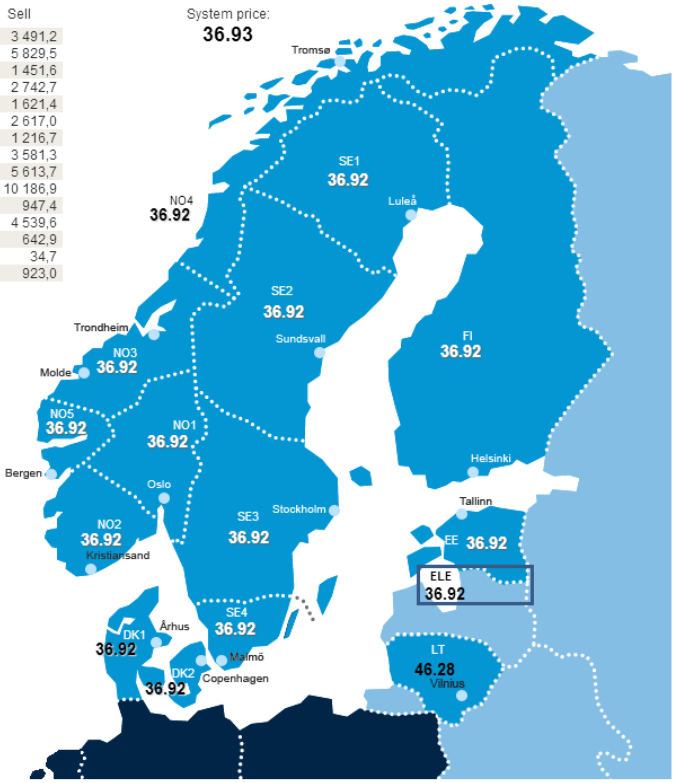
Day-ahead electricity market

01-11-2012 Resolution 10 - 11 Currency EUR Capacities ITVC Flow ITVC Area Prices

Elspot volumes

	Buy	Sell
NO1	5 241,4	3 491,2
NO2	4 405,9	5 829,5
NO3	2 430,0	1 451,6
NO4	2 218,5	2 742,7
NO5	1 715,8	1 621,4
DK1	3 083,2	2 617,0
DK2	1 720,9	1 216,7
SE1	1 270,6	3 581,3
SE2	1 675,2	5 613,7
SE3	10 732,2	10 186,9
SE4	3 100,5	947,4
FI	6 112,6	4 539,6
EE	333,4	642,9
ELE	476,4	34,7
LT	923,0	923,0

System price: **36.93**

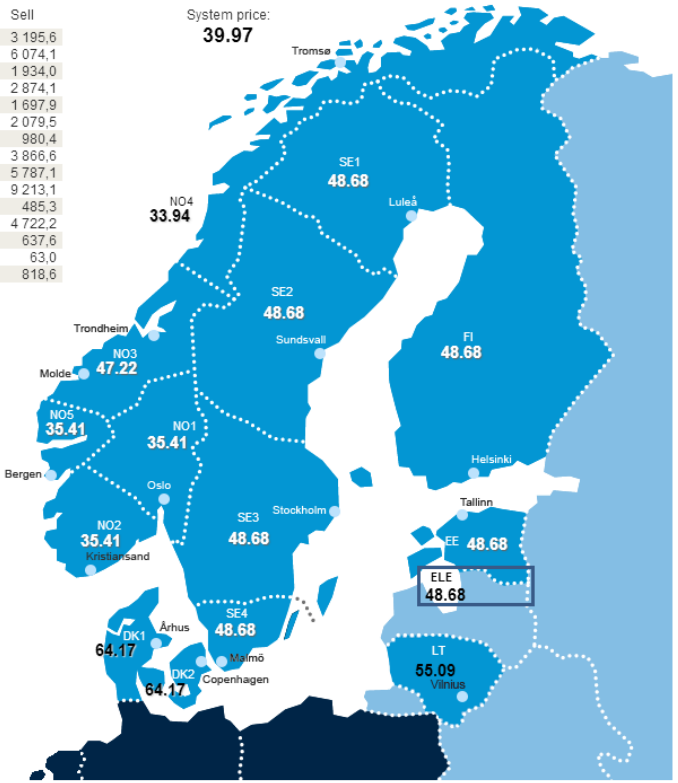


10-10-2012 Resolution 18 - 19 Currency EUR Capacities ITVC Flow ITVC Area Prices

Elspot volumes

	Buy	Sell
NO1	4 141,1	3 195,6
NO2	3 876,6	6 074,1
NO3	2 134,0	1 934,0
NO4	1 824,1	2 874,1
NO5	1 419,9	1 697,9
DK1	3 439,5	2 079,5
DK2	2 280,4	980,4
SE1	1 206,4	3 866,6
SE2	1 709,4	5 787,1
SE3	10 524,0	9 213,1
SE4	3 968,4	485,3
FI	6 436,9	4 722,2
EE	315,7	637,6
ELE	334,1	63,0
LT	818,6	818,6

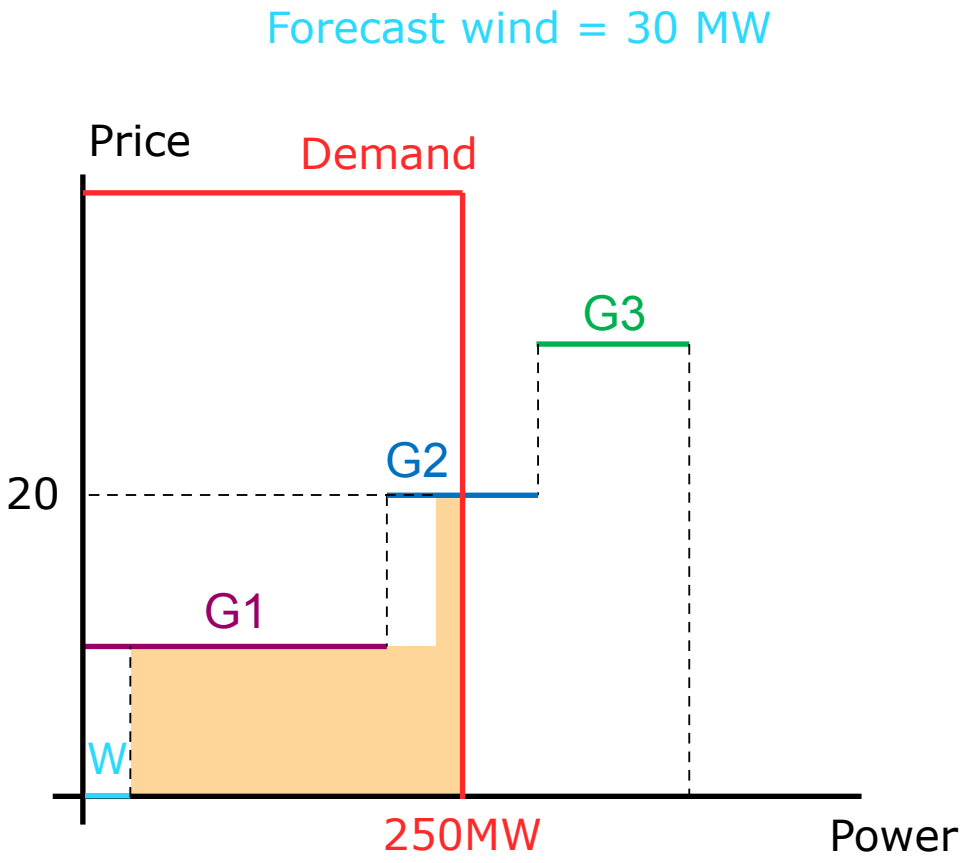
System price: **39.97**



Day-ahead electricity market

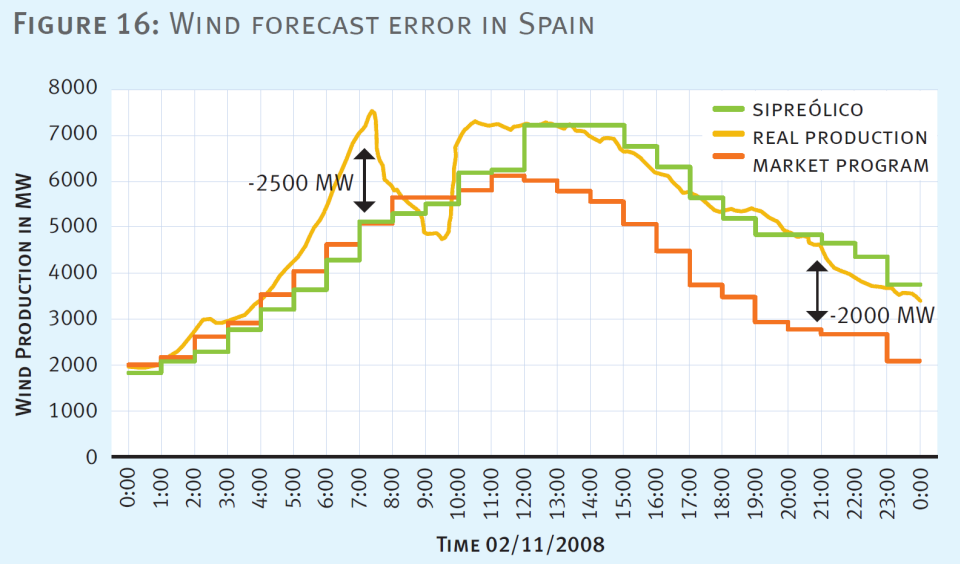
- What about the wind?

$$\begin{aligned}
\underset{p_G, p_W, \delta^0}{\text{Minimize}} \quad & \mathcal{C}^{\mathrm{D}}\left(p_G, p_W\right) \\
\text{s.t.} \quad & h^{\mathrm{D}}\left(p_G, p_W, \delta^0\right) - l = 0 : \lambda^{\mathrm{D}} \\
& g^{\mathrm{D}}\left(p_G, \delta^0\right) \leq 0 \\
& p_W \leq \widehat{W}
\end{aligned}$$



Day-ahead electricity market

- What about the wind?

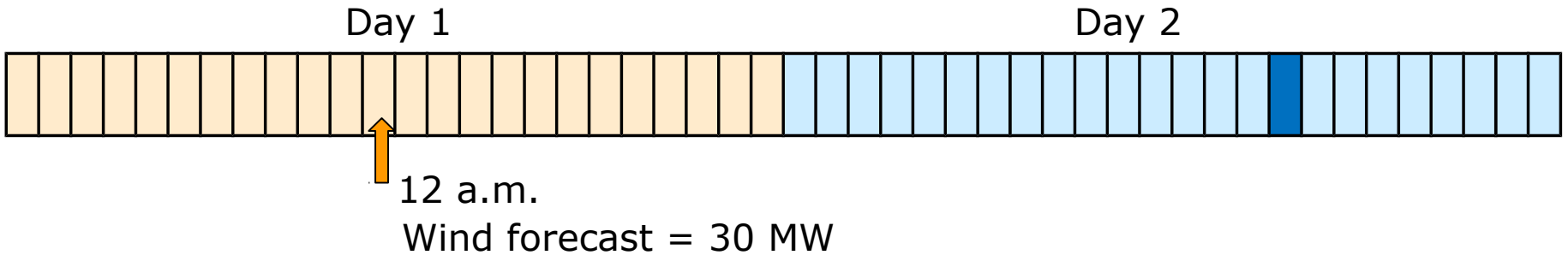


Wind cannot be predicted 24-36 hours ahead!!

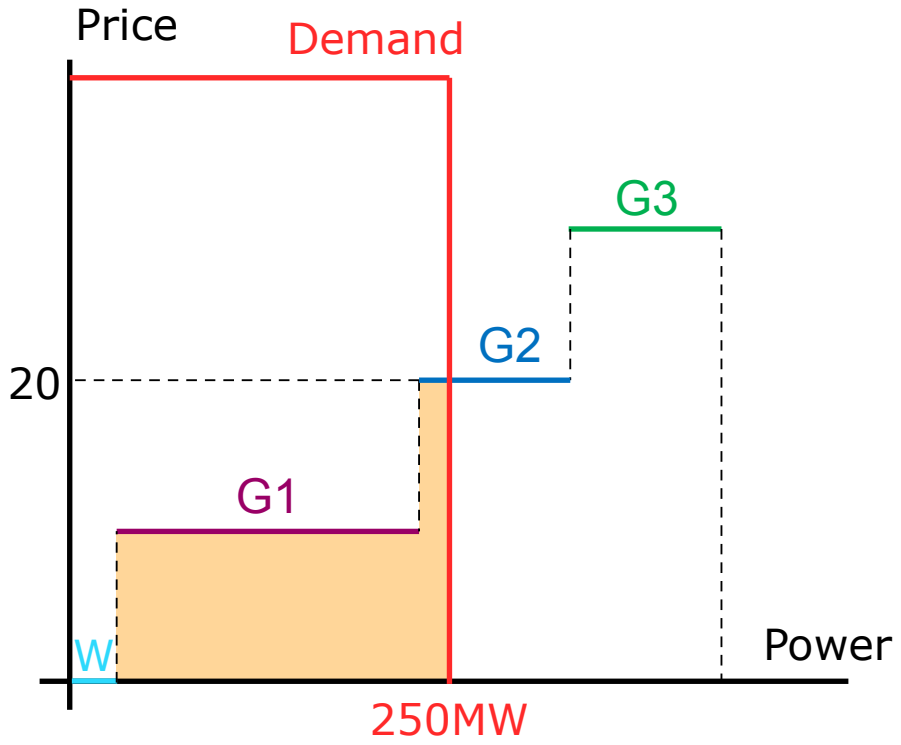
How do we deal with wind forecast errors?

Nowadays: balancing market

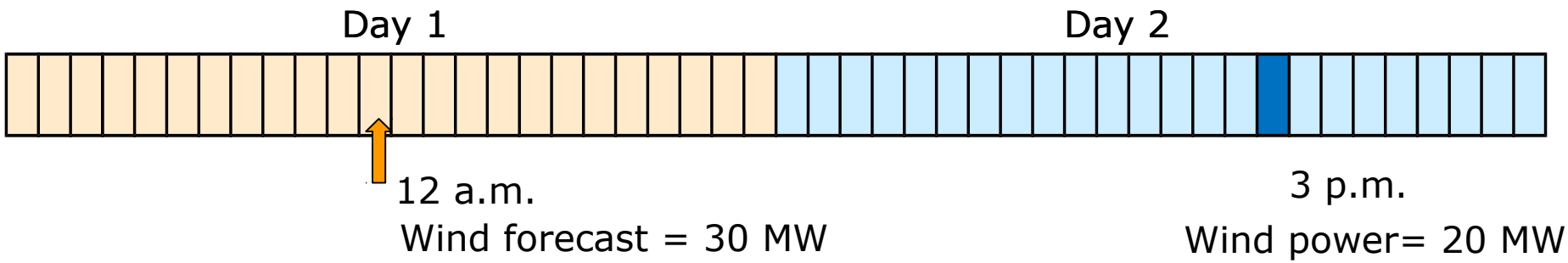
Balancing electricity market



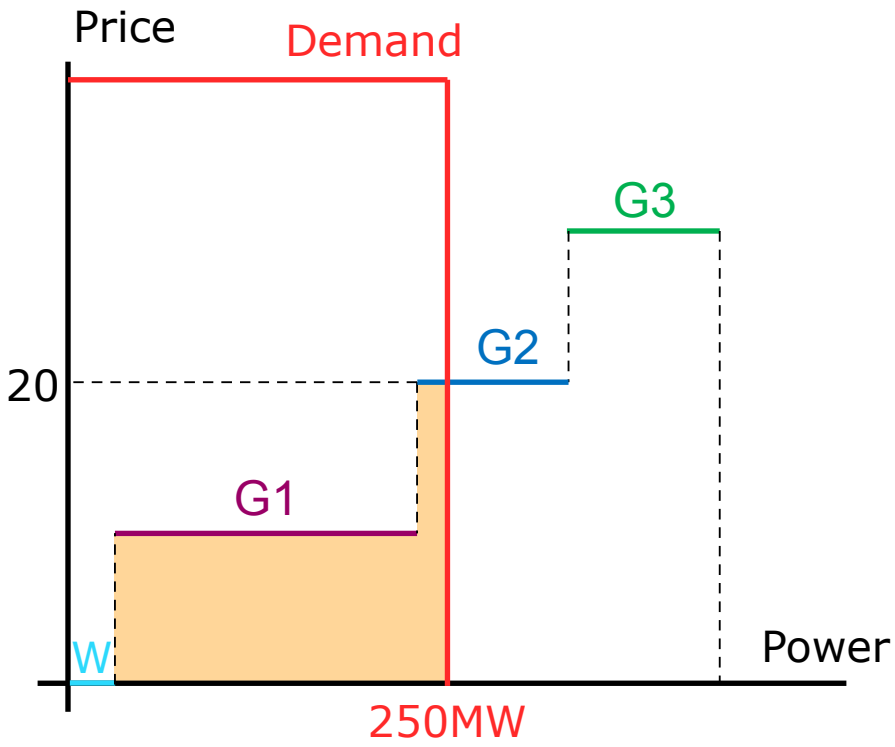
4-5 p.m.			
Unit	Cost	Offers	Demand
W	0	30@0	250 MW
G1	5	200@10	
G2	15	100@20	
G3	25	100@30	



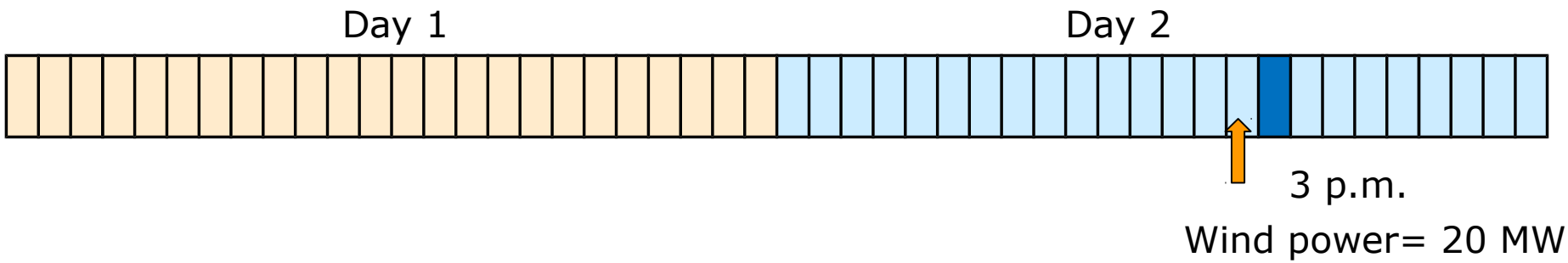
Balancing electricity market



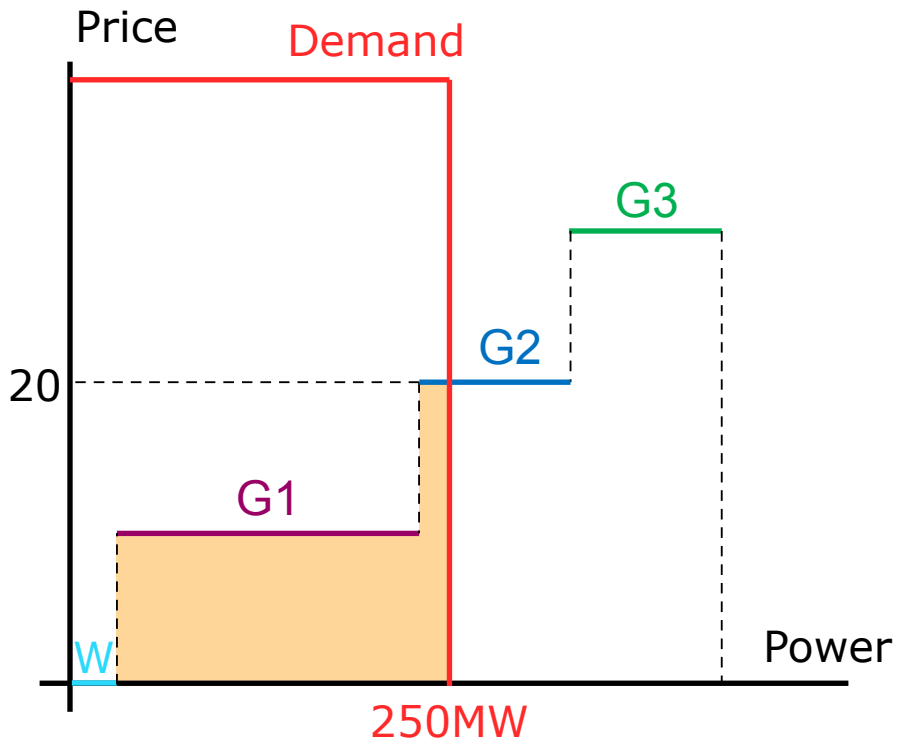
4-5 p.m.	
DA Schedule	
Unit	MW
W	30
G1	200
G2	20
G3	-



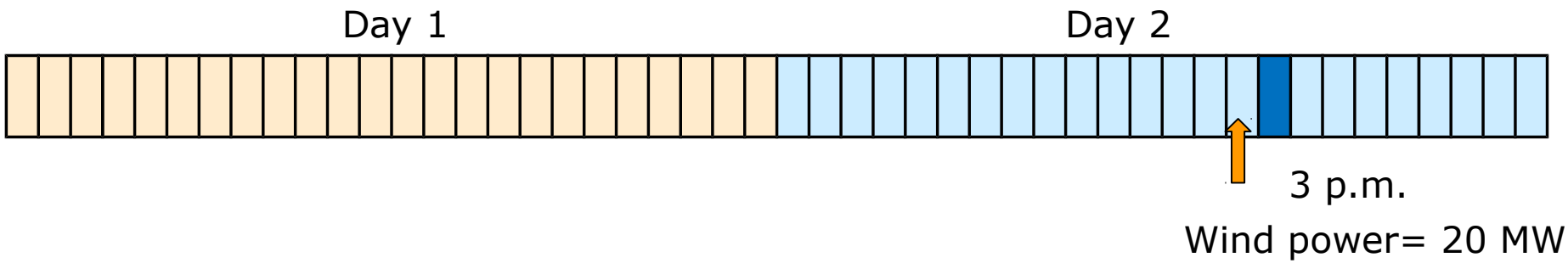
Balancing electricity market



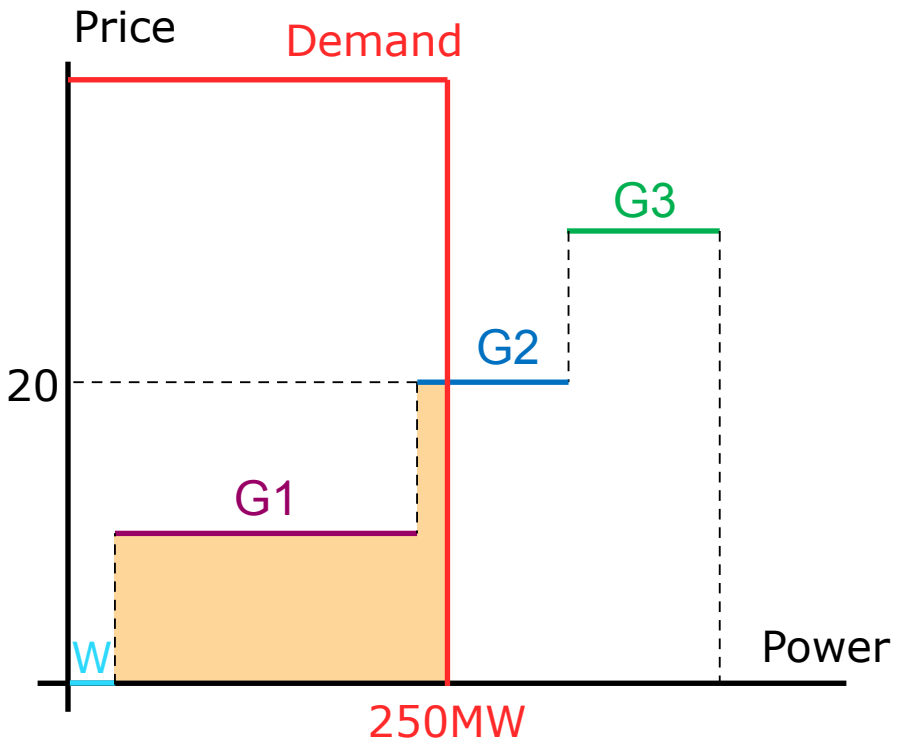
4-5 p.m.			
DA Schedule		Balancing market	
Unit	MW	UP	DOWN
W	30	-	-
G1	200	-	
G2	20	10@25	
G3	-	20@35	



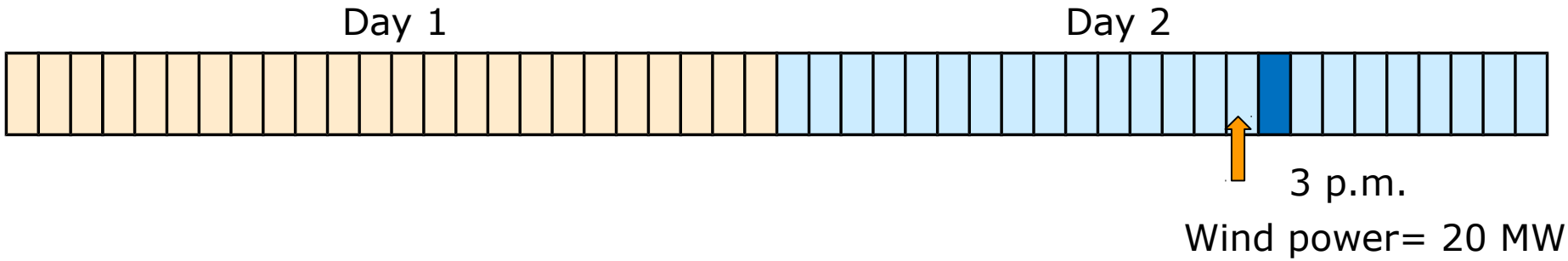
Balancing electricity market



4-5 p.m.			
DA Schedule		Balancing market	
Unit	MW	UP	DOWN
W	30	-	-
G1	200	-	
G2	20	10@25	
G3	-	20@35	



Balancing electricity market



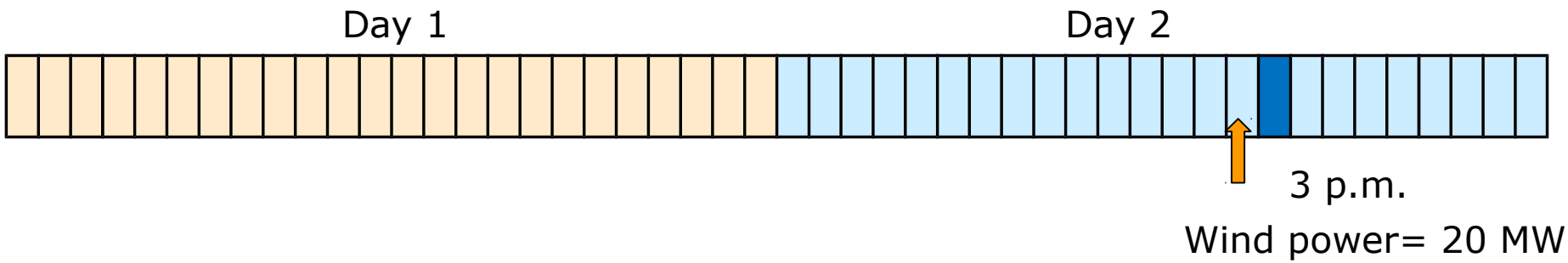
4-5 p.m.			
DA Schedule		Balancing market	
Unit	MW	UP	DOWN
W	30	-	-
G1	200	-	
G2	20	10@25	
G3	-	20@35	

$$\underset{y_{\omega'},\delta_{\omega'}}{\text{Minimize}} \quad \mathcal{C}^{\mathrm{B}}\left(y_{\omega'}\right)$$

$$\text{s.t.} \quad h^{\mathrm{B}}\left(y_{\omega'},\delta_{\omega'},\delta^{0*}\right)+W_{\omega'}-p_W^*=0:\lambda_{\omega'}^{\mathrm{B}}$$

$$g^{\mathrm{B}}\left(y_{\omega'},\delta_{\omega'},p_G^*;W_{\omega'}\right)\leq 0$$

Balancing electricity market



4-5 p.m.	
DA Schedule	
Unit	MW
W	20
G1	200
G2	30
G3	-

Balancing electricity market

- Let’s check the profits

4-5 p.m.				
Unit	DA market	B market	Fuel cost	Total
W	20x30=600	-25x10=-250	0	350
G1	20x200=4000	0	5x200=1000	3000
G2	20x20=400	25x10=250	15x30=450	200
G3	0	0	0	0


(20-0)x20=400
(20-5)x200=3000
(20-15)x30=150
0

Balancing electricity market

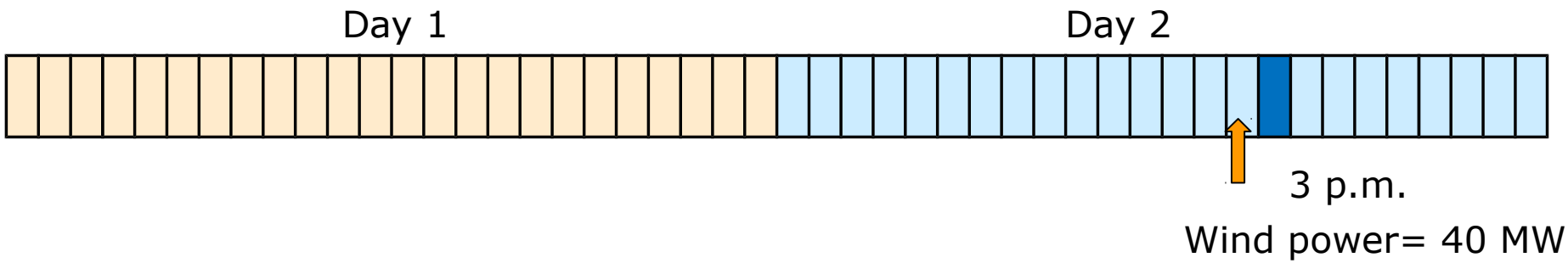
- Let's check the profits

4-5 p.m.				
Unit	DA market	B market	Fuel cost	Total
W	20x30=600	-25x10=-250	0	350
G1	20x200=4000	0	5x200=1000	3000
G2	20x20=400	25x10=250	15x30=450	200
G3	0	0	0	0

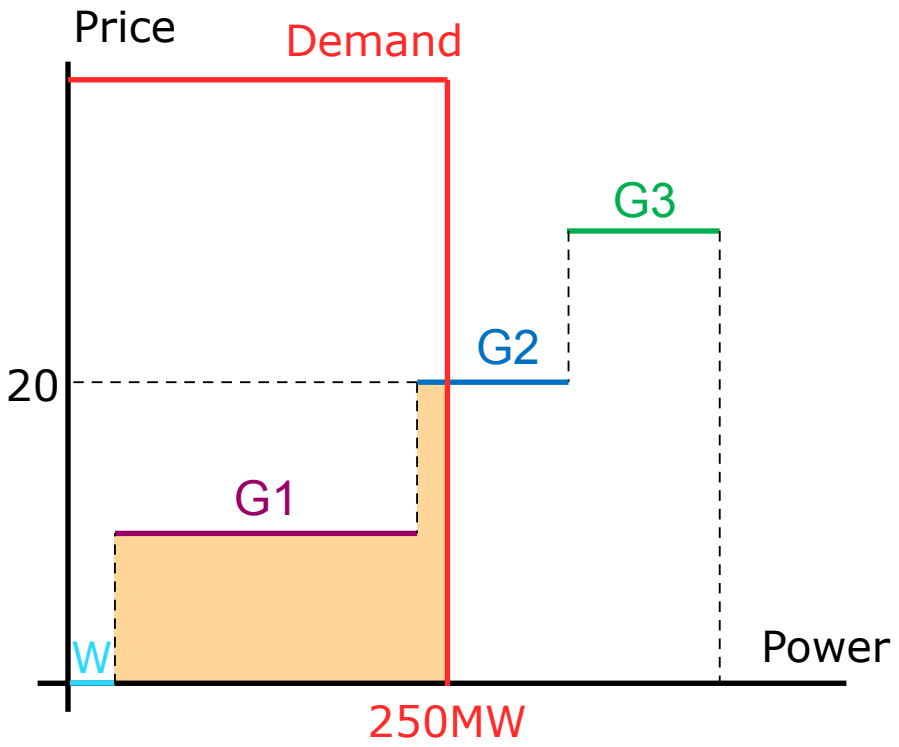

(20-0)x20=400
(20-5)x200=3000
(20-15)x30=150
0

Wind producers are paying for forecast errors!!

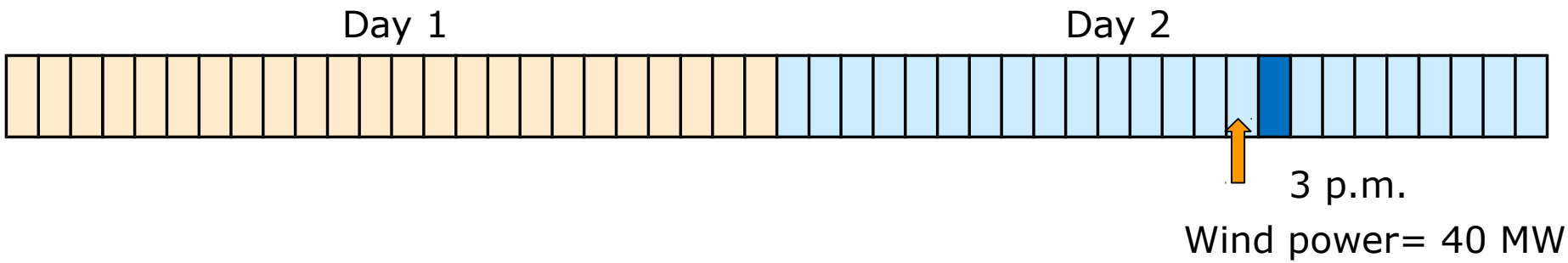
Balancing electricity market



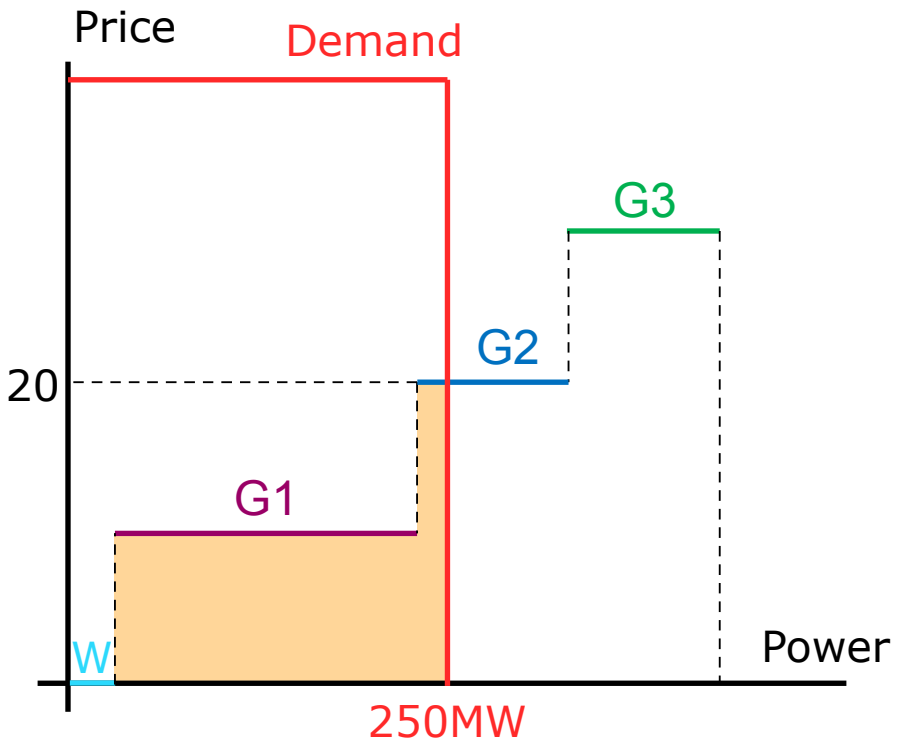
4-5 p.m.			
DA Schedule		Balancing market	
Unit	MW	UP	DOWN
W	30	-	-
G1	200	-	-
G2	20	10@25	10@15
G3	-	20@35	-



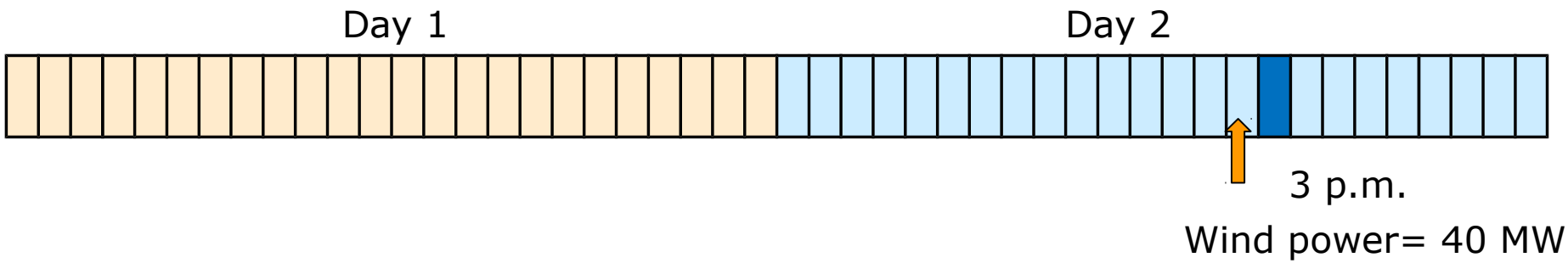
Balancing electricity market



4-5 p.m.			
DA Schedule		Balancing market	
Unit	MW	UP	DOWN
W	30	-	-
G1	200	-	-
G2	20	10@25	10@15
G3	-	20@35	-



Balancing electricity market



4-5 p.m.	
DA Schedule	
Unit	MW
W	40
G1	200
G2	10
G3	-

Balancing electricity market

- Let’s check the profits

4-5 p.m.				
Unit	DA market	B market	Fuel cost	Total
W	20x30=600	15x10=150	0	750
G1	20x200=4000	0	5x200=1000	3000
G2	20x20=400	-15x10=150	15x10=150	100
G3	0	0	0	0
L	20x250=5000	0	-	5000


(20-0)x40=800
(20-5)x200=3000
(20-15)x10=50
0
20x250=5000

Balancing electricity market

- Let's check the profits

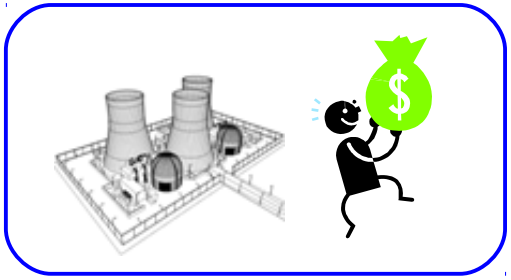
4-5 p.m.				
Unit	DA market	B market	Fuel cost	Total
W	20x30=600	15x10=150	0	750
G1	20x200=4000	0	5x200=1000	3000
G2	20x20=400	-15x10=150	15x10=150	100
G3	0	0	0	0
L	20x250=5000	0	-	5000

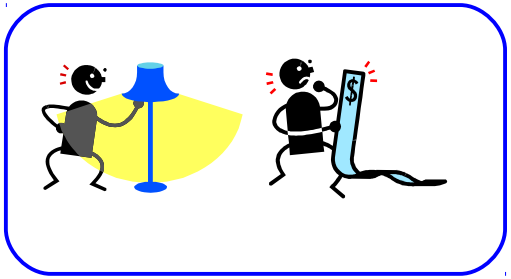

(20-0)x40=800
(20-5)x200=3000
(20-15)x10=50
0
20x250=5000

Wind producers are paying for forecast errors!!

Balancing electricity market

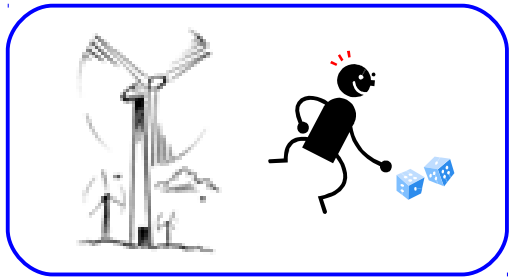
- Is this fair?
- Is it necessary to clear the market 24-36h ahead?





24-36h ahead

Shorter horizon

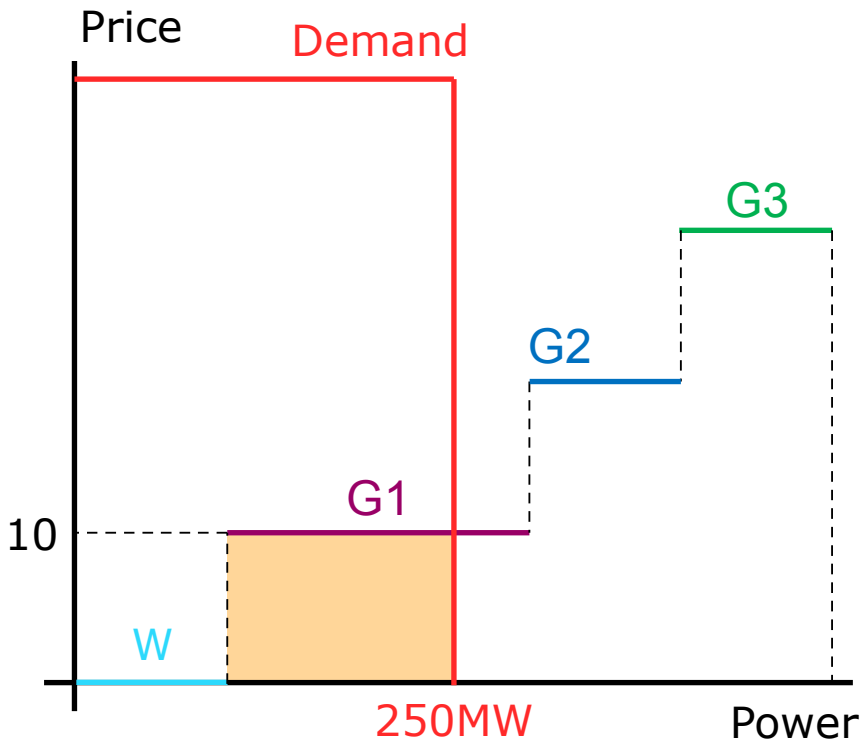


Low values of wind penetration!!

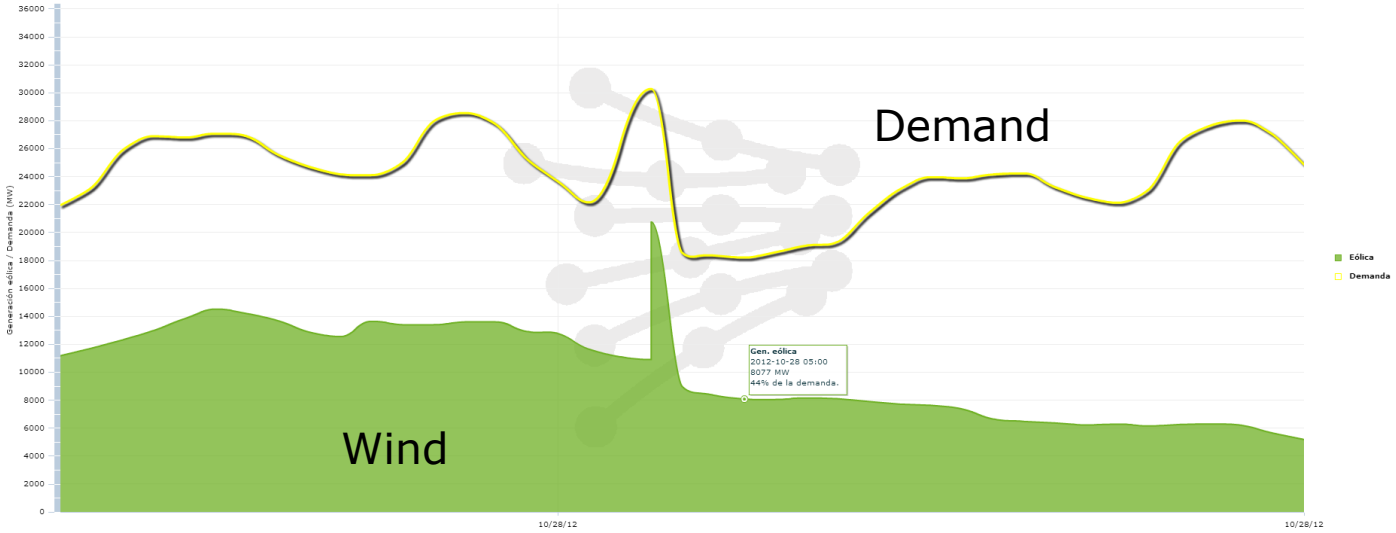
Balancing electricity market

- What would happen if wind capacity increases?
- Wind forecast = 100 MW

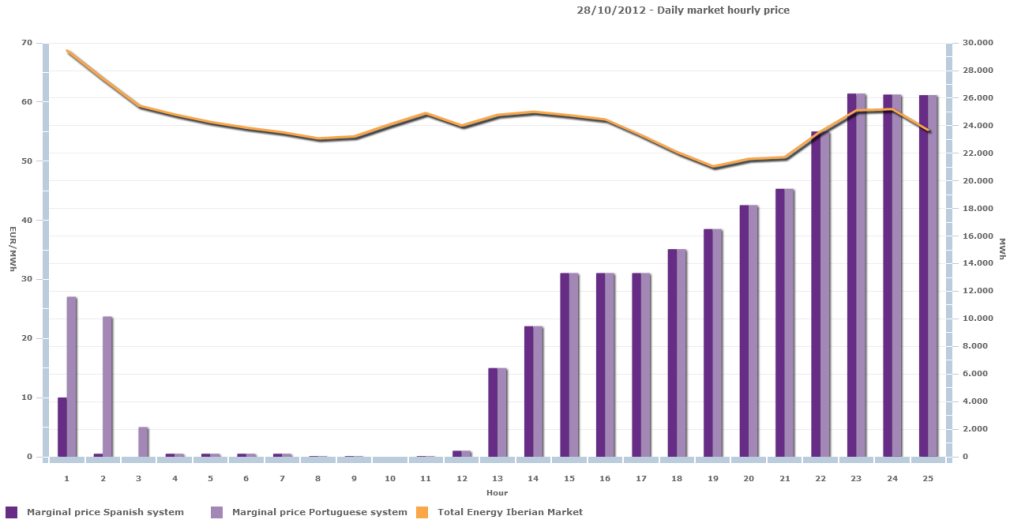
4-5 p.m.			
Unit	Cost	Offers	Demand
W	0	100@0	250 MW
G1	5	200@10	
G2	15	100@20	
G3	25	100@30	



Balancing electricity market

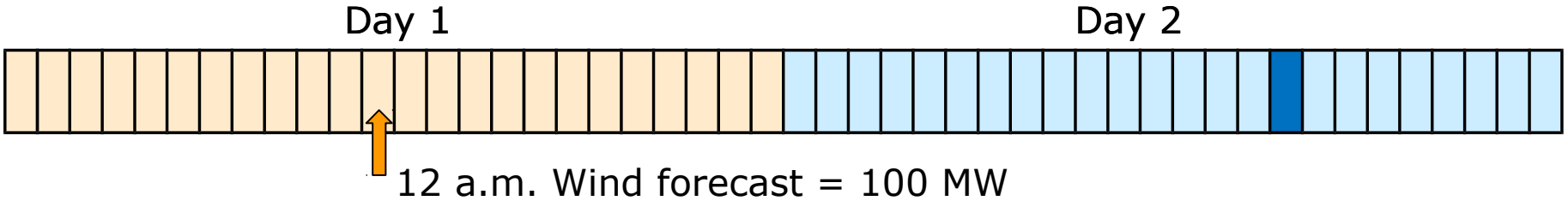


Prices

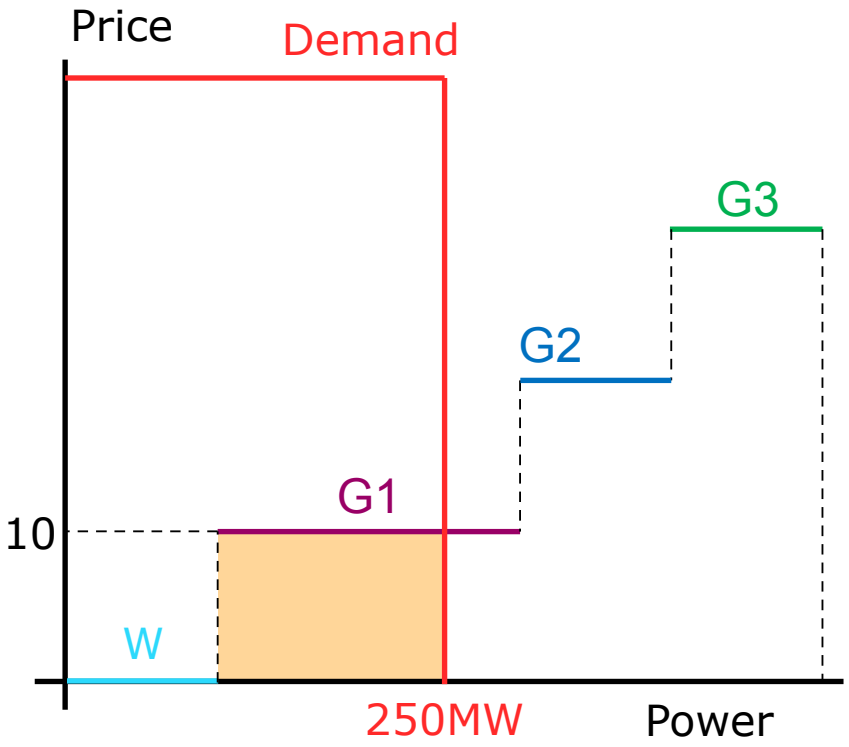


Balancing electricity market

- What would happen if wind capacity increases?

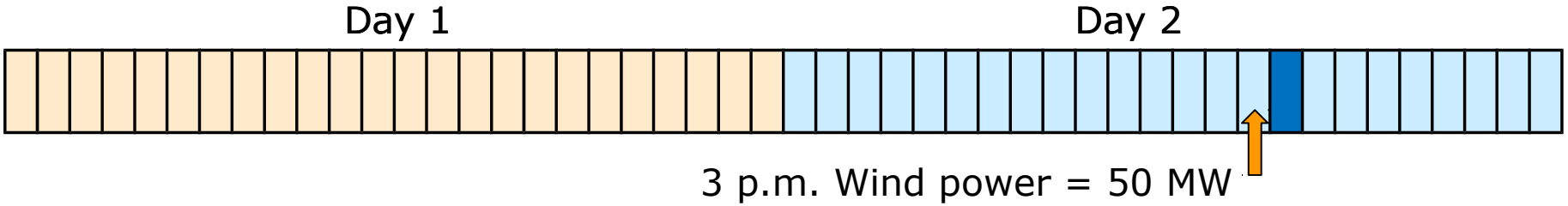


4-5 p.m.	
DA Schedule	
Unit	MW
W	100
G1	150
G2	-
G3	-

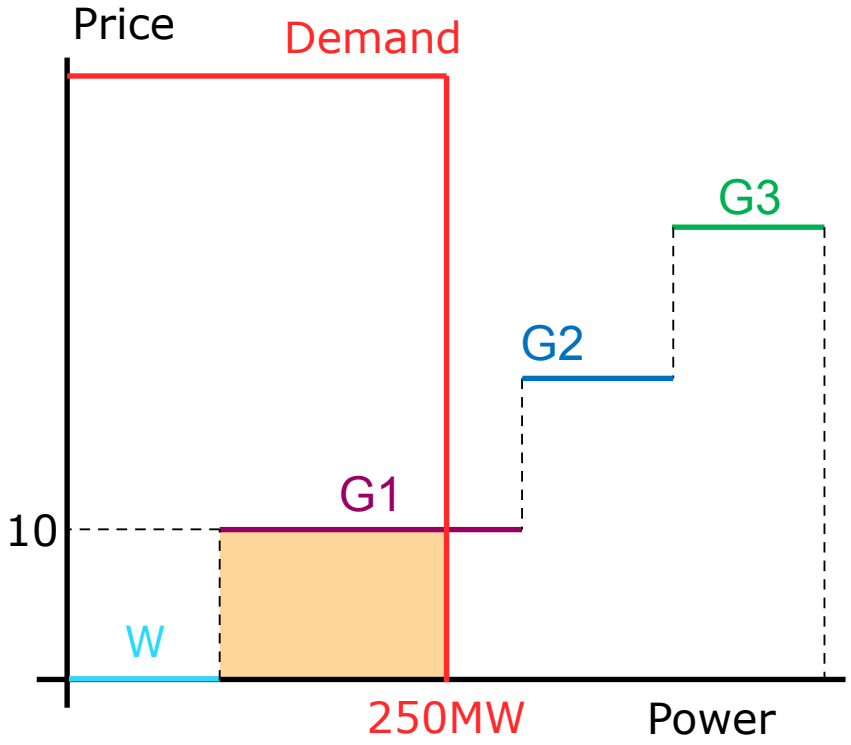


Balancing electricity market

- What would happen if wind capacity increases?

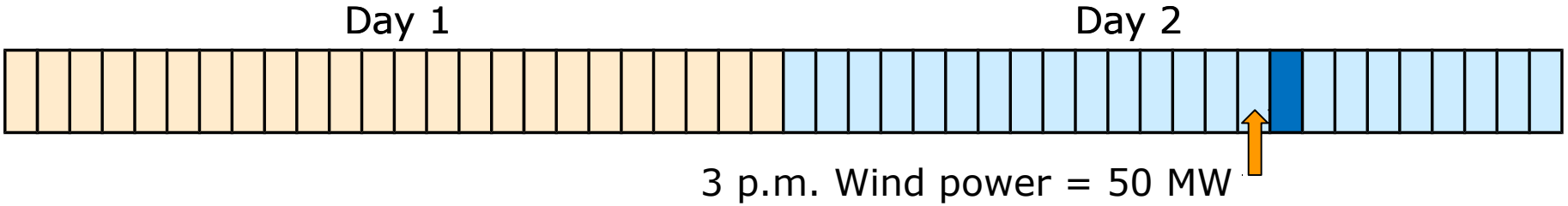


4-5 p.m.			
DA Schedule		Regulating market	
Unit	MW	UP	DOWN
W	100	-	-
G1	150	-	
G2	-	10@25	
G3	-	20@35	



Balancing electricity market

- What would happen if wind capacity increases?



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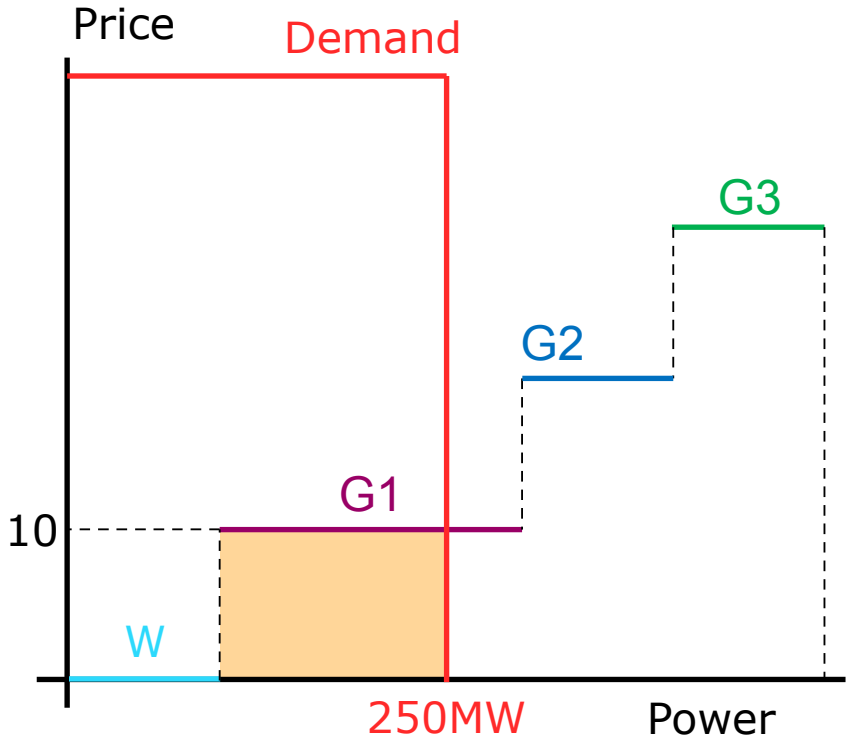
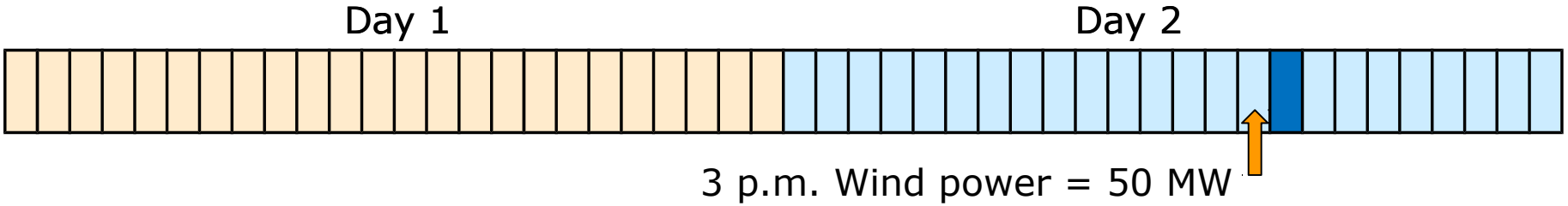
DA Schedule		Regulating market	
Unit	MW	UP	DOWN
W	100	-	-
G1	150	-	
G2	-	10@25	
G3	-	20@35	



Balancing electricity market

- 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	

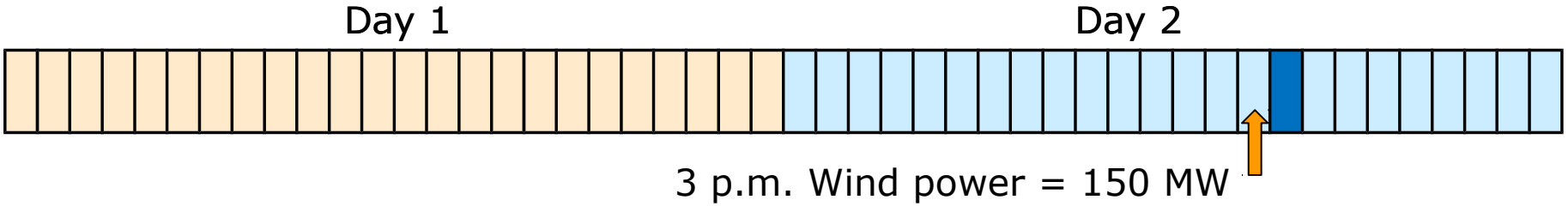
Wind 50MW lower than expected

Only 30MW up power

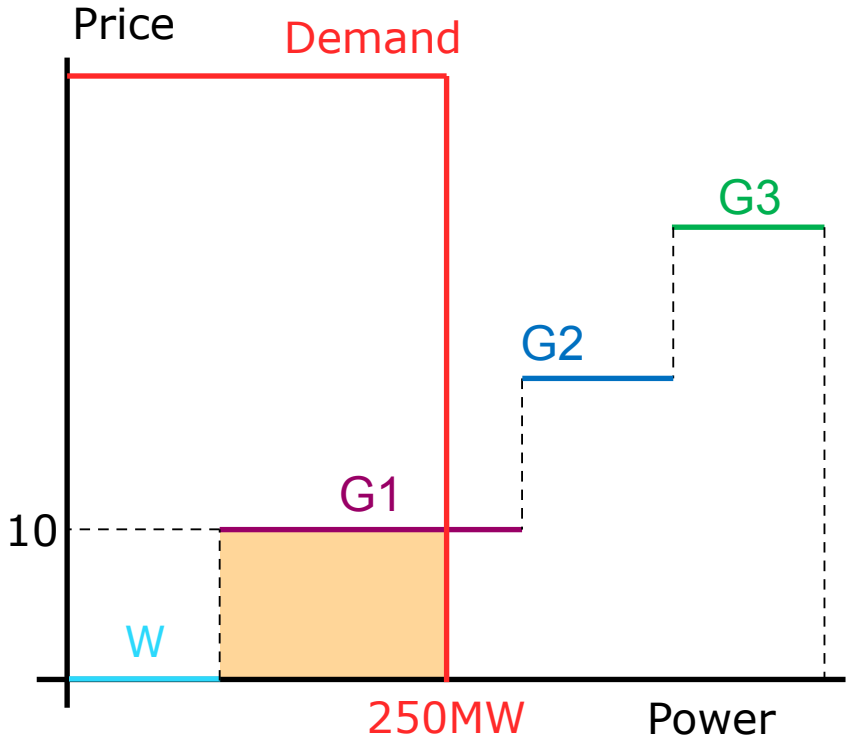
20MW of load shedding

Balancing electricity market

- What would happen if wind capacity increases?

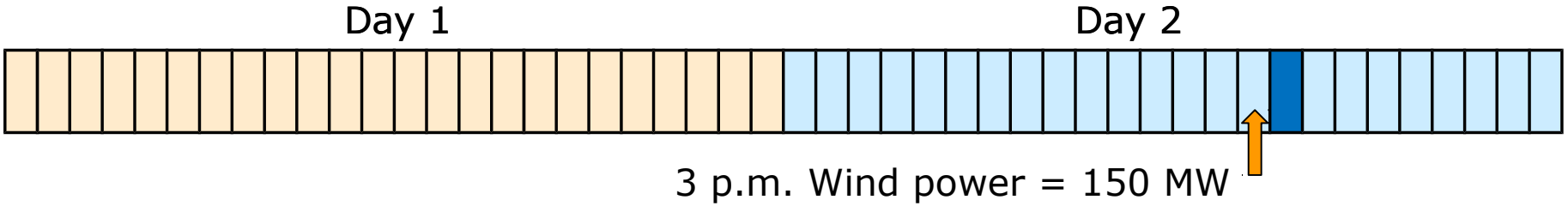


4-5 p.m.			
DA Schedule		Regulating market	
Unit	MW	UP	DOWN
W	100	-	-
G1	150	-	-
G2	-	10@25	10@15
G3	-	20@35	20@25



Balancing electricity market

- 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	10@15
G3	-	20@35	20@25

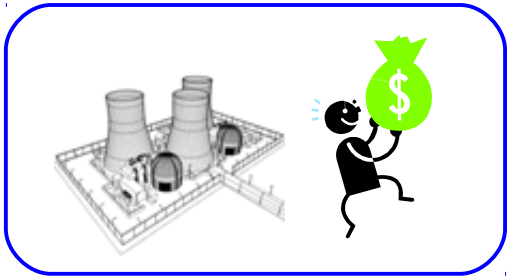
Wind 50MW higher than expected

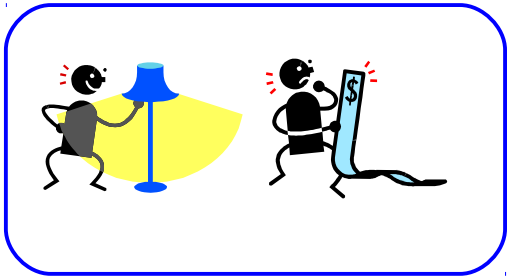
None down power

50MW of wind spillage

Balancing electricity market

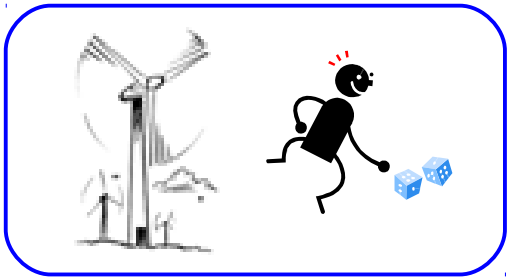
- Low wind power penetration





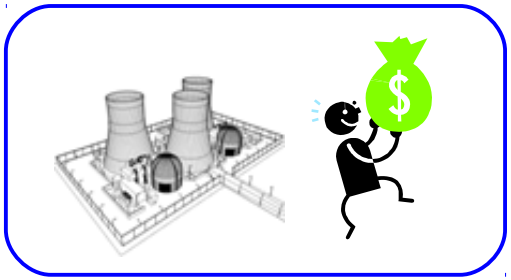
24-36h ahead

Shorter horizon

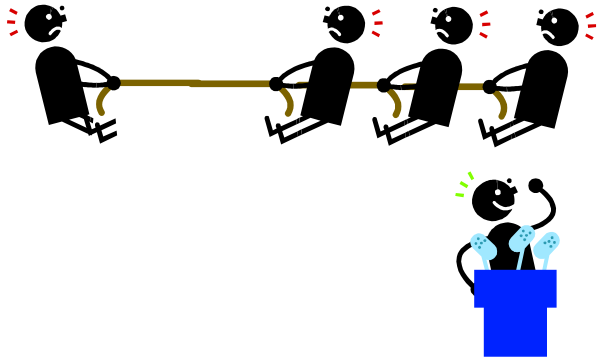


Balancing electricity market

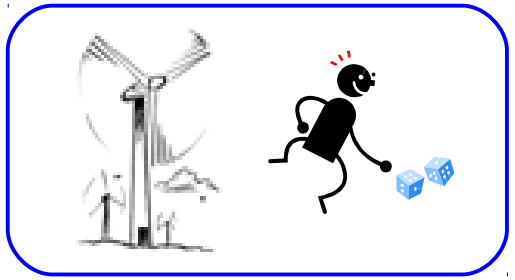
- High wind power penetration

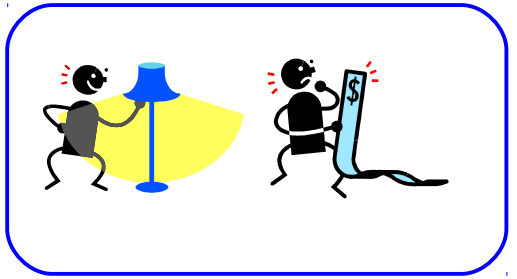


24-36h ahead

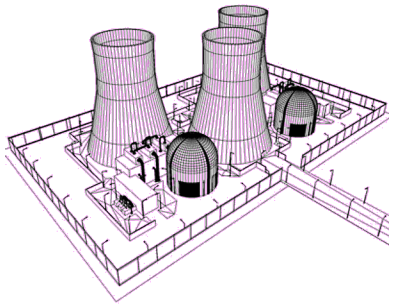


Shorter horizon





Electricity market: basic concepts



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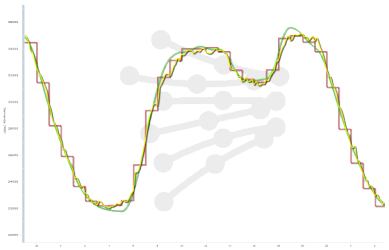

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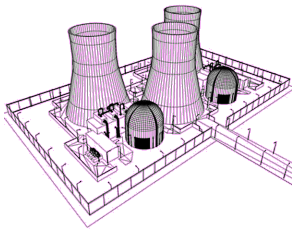
Day-ahead market

Balancing



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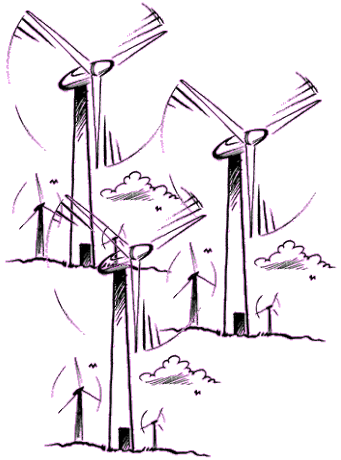

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Day-ahead market

Balancing

Outline

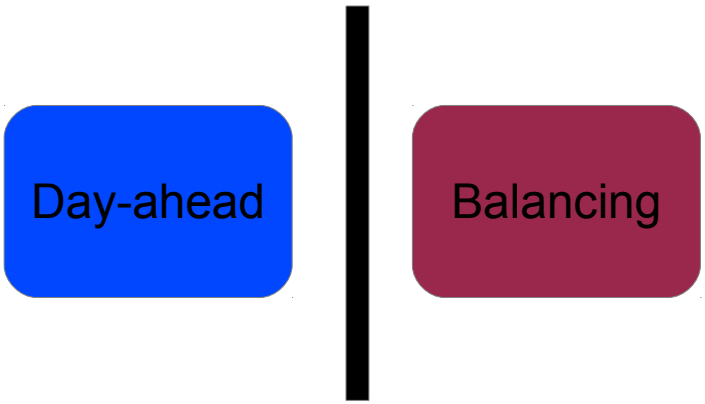
- Electricity markets: basic concepts
- Electricity markets & uncertainty
- Electricity markets & investment

Market design solutions

- Coordination between day-ahead and balancing

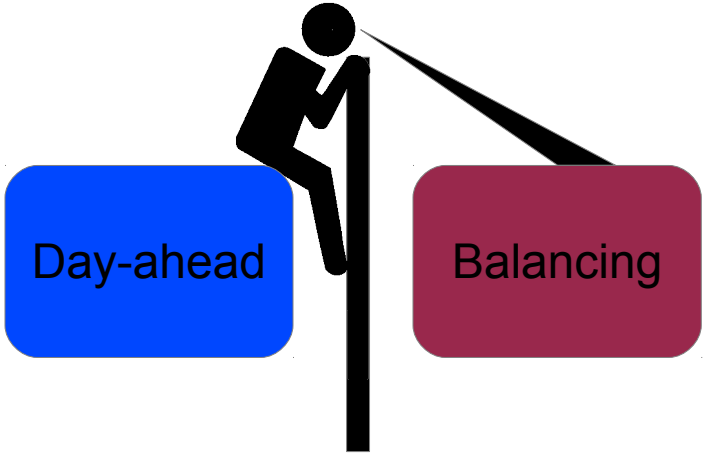
Conventional MC

Day-ahead dispatch compute disregarding balancing operation



Stochastic MC

Day-ahead dispatch takes into account balancing operation



Market design solutions

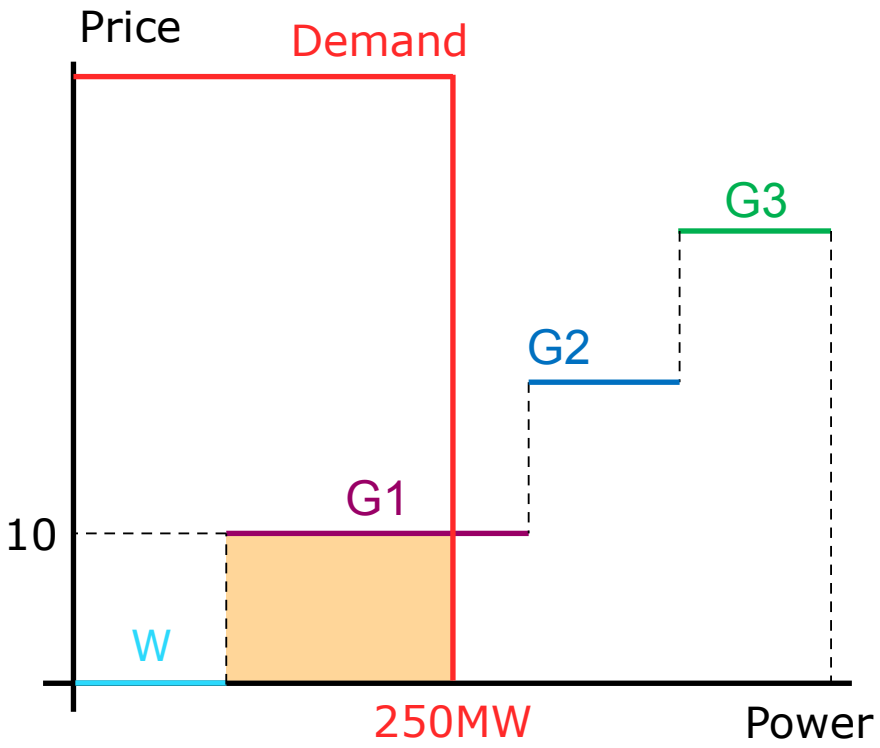
- Coordination between day-ahead and balancing

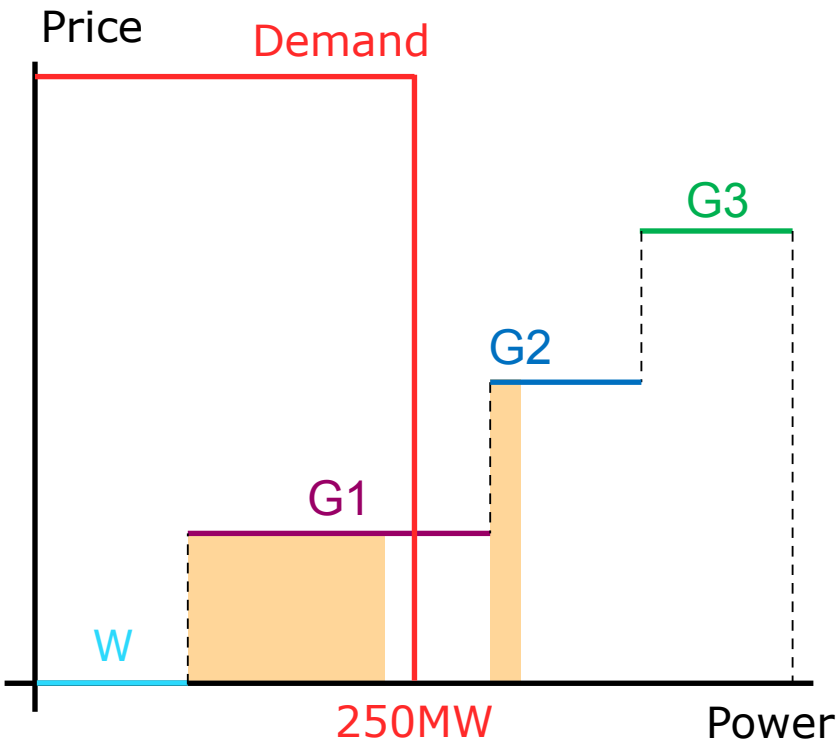
Conv MC

Forecast=100 MW

Wind(30%)=130 MW

Stoc MC





Market design solutions

- Coordination between day-ahead and balancing

Conv MC

$$\underset{p_G, p_W, \delta^0}{\text{Minimize}} \quad \mathcal{C}^{\mathrm{D}}\left(p_G, p_W\right)$$

$$\text{s.t.} \quad h^{\mathrm{D}}\left(p_G, p_W, \delta^0\right) - l = 0 : \lambda^{\mathrm{D}}$$

$$g^{\mathrm{D}}\left(p_G, \delta^0\right) \leq 0$$

$$p_W \leq \widehat{W}$$

$$\underset{y_{\omega'}, \delta_{\omega'}}{\text{Minimize}} \quad \mathcal{C}^{\mathrm{B}}\left(y_{\omega'}\right)$$

$$\text{s.t.} \quad h^{\mathrm{B}}\left(y_{\omega'}, \delta_{\omega'}, \delta^{0*}\right) + W_{\omega'} - p_W^* = 0 : \lambda^{\mathrm{B}}_{\omega'}$$

$$g^{\mathrm{B}}\left(y_{\omega'}, \delta_{\omega'}, p_G^*; W_{\omega'}\right) \leq 0$$

Stoc MC

$$\underset{p_G, p_W, \delta^0; y_\omega, \delta_\omega, \forall\omega}{\text{Minimize}} \quad \mathcal{C}^{\mathrm{D}}\left(p_G, p_W\right) + \mathbb{E}_\omega\left[\mathcal{C}^{\mathrm{B}}\left(y_\omega\right)\right]$$

$$\text{s.t.} \quad h^{\mathrm{D}}\left(p_G, p_W, \delta^0\right) - l = 0 : \lambda^{\mathrm{D}}$$

$$g^{\mathrm{D}}\left(p_G, \delta^0\right) \leq 0$$

$$p_W \leq \overline{W}$$

$$h^{\mathrm{B}}\left(y_\omega, \delta_\omega, \delta^0\right) + W_\omega - p_W = 0\,, \quad \forall\omega \in \Omega$$

$$g^{\mathrm{B}}\left(y_\omega, \delta_\omega, p_G; W_\omega\right) \leq 0\,, \quad \forall\omega \in \Omega$$

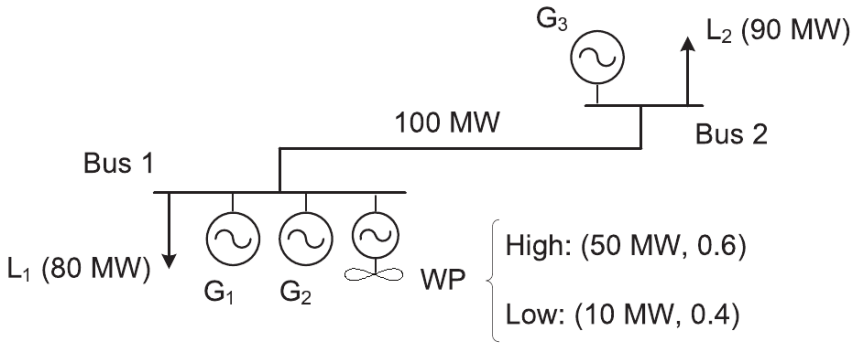
$$\underset{y_{\omega'}, \delta_{\omega'}}{\text{Minimize}} \quad \mathcal{C}^{\mathrm{B}}\left(y_{\omega'}\right)$$

$$\text{s.t.} \quad h^{\mathrm{B}}\left(y_{\omega'}, \delta_{\omega'}, \delta^{0*}\right) + W_{\omega'} - p_W^* = 0 : \lambda^{\mathrm{B}}_{\omega'}$$

$$g^{\mathrm{B}}\left(y_{\omega'}, \delta_{\omega'}, p_G^*; W_{\omega'}\right) \leq 0$$

Market design solutions

- Coordination between day-ahead and balancing



Expensive but flexible

Cheaper than G1 but inflexible

Unit	G1	G2	G3
Pmax (MW)	100	110	50
C ($/MWh)	35	30	10
C_up ($/MWh)	40	-	-
C_do ($/MWh)	34	-	-
P_up (MW)	20	0	0
P_do (MW)	40	0	0

Market design solutions

- Coordination between day-ahead and balancing

Conv MC **Stoc MC**

Agent	Day-ahead
G1	0
G2	86
G3	50
WP	34

Rest of the units dispatched following least-cost merit order

Wind dispatched to its expected production

Market design solutions

- Coordination between day-ahead and balancing

Conv MC

Agent	Day-ahead
G1	0
G2	86
G3	50
WP	34

Rest of the units dispatched following least-cost merit order

Wind dispatched to its expected production

Stoc MC

Agent	Day-ahead
G1	40
G2	70
G3	50
WP	10

G1 dispatched out-of-merit

Wind dispatched below its expected production

Market design solutions

- Coordination between day-ahead and balancing

Conv MC

Agent	Day-ahead	Balancing	
		High	Low
G1	0		
G2	86		
G3	50		
WP	34		

Stoc MC

Agent	Day-ahead	Balancing	
		High	Low
G1	40		
G2	70		
G3	50		
WP	10		

Market design solutions

- Coordination between day-ahead and balancing

Conv MC

Agent	Day-ahead	Balancing	
		High	Low
G1	0	0	
G2	86	0	
G3	50	0	
WP	34	16	

Stoc MC

Agent	Day-ahead	Balancing	
		High	Low
G1	40		
G2	70		
G3	50		
WP	10		

Market design solutions

- Coordination between day-ahead and balancing

Conv MC

Agent	Day-ahead	Balancing	
		High	Low
G1	0	0	
G2	86	0	
G3	50	0	
WP	34	16	

Stoc MC

Agent	Day-ahead	Balancing	
		High	Low
G1	40	-40	
G2	70	0	
G3	50	0	
WP	10	0	

Market design solutions

- Coordination between day-ahead and balancing

Conv MC

Agent	Day-ahead	Balancing	
		High	Low
G1	0	0	20
G2	86	0	0
G3	50	0	0
WP	34	16	0

Stoc MC

Agent	Day-ahead	Balancing	
		High	Low
G1	40	-40	0
G2	70	0	0
G3	50	0	0
WP	10	0	0

Market design solutions

- Coordination between day-ahead and balancing

Conv MC

Agent	Day-ahead	Balancing	
		High	Low
G1	0	0	20
G2	86	0	0
G3	50	0	0
WP	34	16	0

Day-ahead cost	3080
Balancing cost	320
Load curtailment	320
Total	**3720**

Stoc MC

Agent	Day-ahead	Balancing	
		High	Low
G1	40	-40	0
G2	70	0	0
G3	50	0	0
WP	10	0	0

Day-ahead cost	4000
Balancing cost	-816
Load curtailment	0
Total	**3184**

Market design solutions

- Coordination between day-ahead and balancing

Conv MC

Agent	Expected	Per-scenario	
		High	Low
G1	1320	0	3300
G2	0	0	0
G3	1000	1000	1000
WP	-900	1020	-3780

Stoc MC

Agent	Expected	Per-scenario	
		High	Low
G1	24	174	-200
G2	0	0	0
G3	1000	1000	1000
WP	916	1326	300

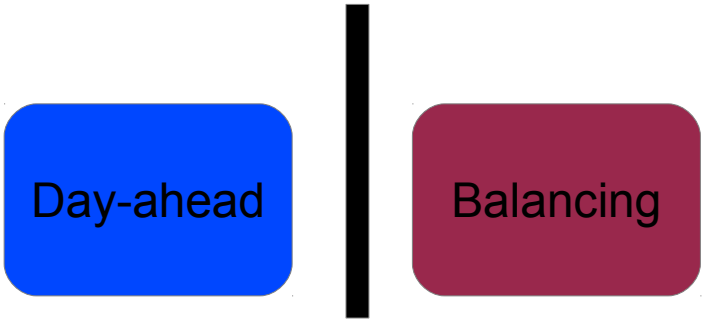
Higher profit of wind producers under Stoc MC

Flexible units may incur losses under Stoc MC

Market design solutions

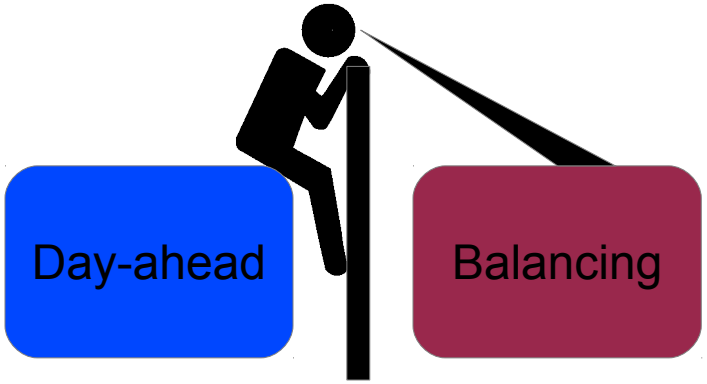
- Coordination between day-ahead and balancing

Conv MC



- DA dispatch: cheaper go first
- Balancing operation not included
- Minimizes day-ahead cost
- Higher imbalance cost
- All units obtain profits

Stoc MC

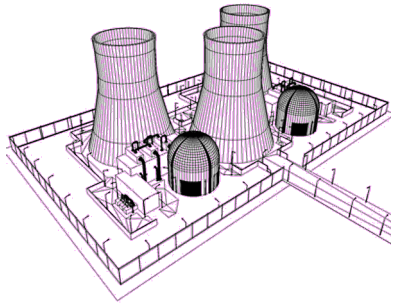


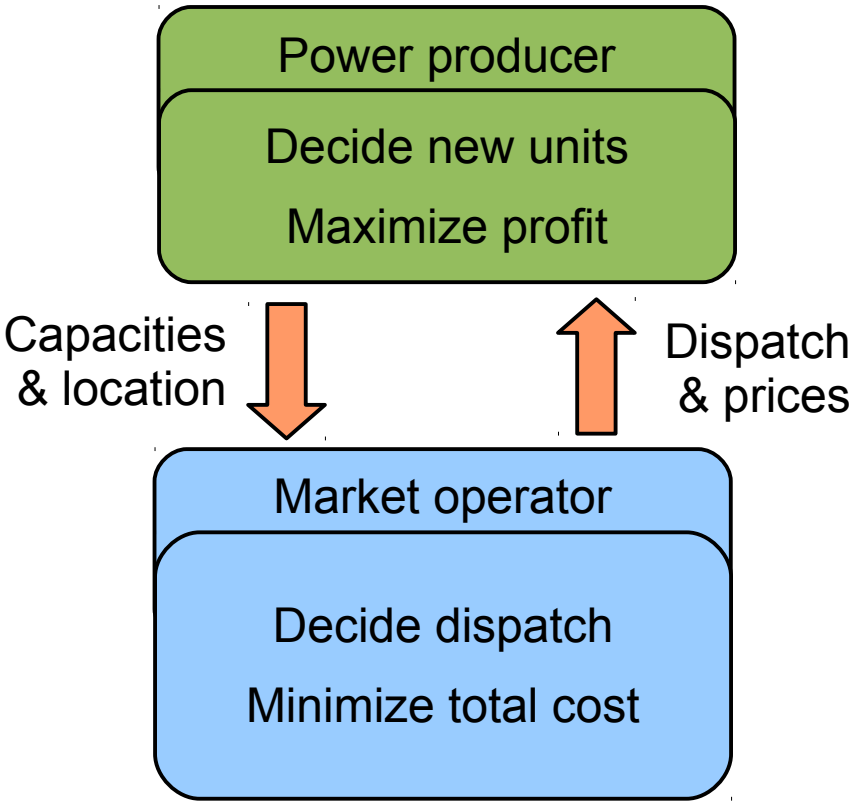
- DA dispatch: out of merit-order
- Balancing operation included
- Minimizes total cost
- Reduces imbalance cost
- Flexible units may incur losses

Outline

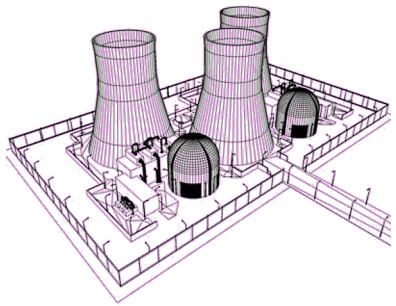
- Electricity markets: basic concepts
- Electricity markets & uncertainty
- Electricity markets & investment

Expansion of stochastic units





Expansion of stochastic units



Power producer

$$\underset{p_G^{max}}{\text{Maximize}} \quad \Pi^{\mathrm{D}}\left(p_G, \lambda^{\mathrm{D}}\right) - \mathcal{C}^{\mathrm{I}}\left(p_G^{max}\right)$$
$$\text{s.t.} \quad i\left(p_G^{max}\right) \leq 0$$

p_G^{max}

$p_G, \lambda^{\mathrm{D}}$

Market operator

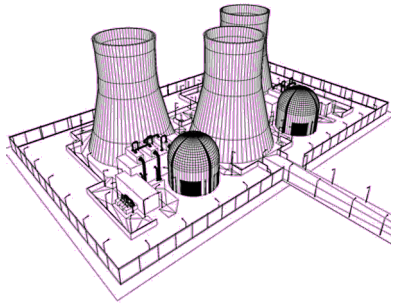
$$\underset{p_G, \delta^0}{\text{Min}} \quad \mathcal{C}^{\mathrm{D}}\left(p_G\right)$$
$$\text{s.t.} \quad h^{\mathrm{D}}\left(p_G, \delta^0\right) - l = 0 : \lambda^{\mathrm{D}}$$
$$g^{\mathrm{D}}\left(p_G, \delta^0, p_G^{max}\right) \leq 0$$

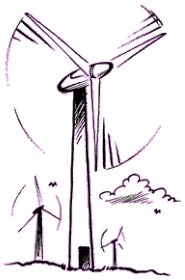
Bilevel programming

$$\underset{p_G^{max}}{\text{Maximize}} \quad \Pi^{\mathrm{D}}\left(p_G, \lambda^{\mathrm{D}}\right) - \mathcal{C}^{\mathrm{I}}\left(p_G^{max}\right)$$
$$\text{s.t.} \quad i\left(p_G^{max}\right) \leq 0$$
$$\left(p_G, \lambda^{\mathrm{D}}\right) \in \arg \left\{ \begin{array}{ll} \underset{p_G, \delta^0}{\text{Min}} & \mathcal{C}^{\mathrm{D}}\left(p_G\right) \\ \text{s.t.} & h^{\mathrm{D}}\left(p_G, \delta^0\right) - l = 0 : \lambda^{\mathrm{D}} \\ & g^{\mathrm{D}}\left(p_G, \delta^0, p_G^{max}\right) \leq 0 \end{array} \right\}$$

Solve replacing lower-level problem by its KKT conditions

Expansion of stochastic units





?

Power producer

Decide new units

Maximize profit

Capacities & location

Dispatch & prices

Market operator

Decide dispatch

Minimize total cost

Power producer

Decide new units

Maximize profit

Capacities & location

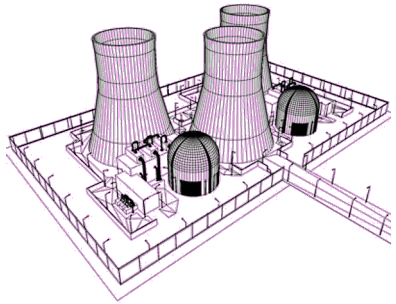
Dispatch & prices

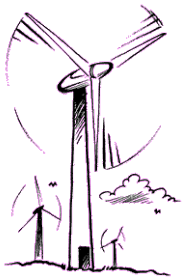
Market operator

Decide dispatch

Minimize total cost

Expansion of stochastic units





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Power producer

Decide new units

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Capacities & location

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Power producer

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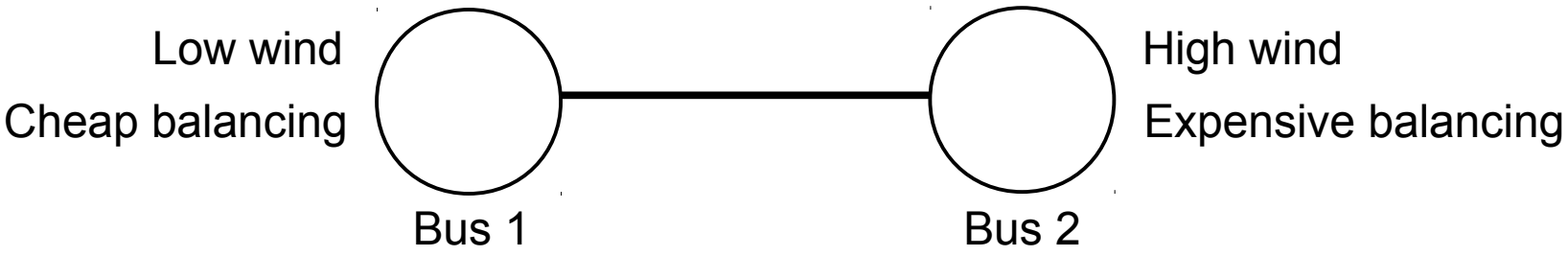
Capacities & location

Dispatch & prices

Day-ahead market

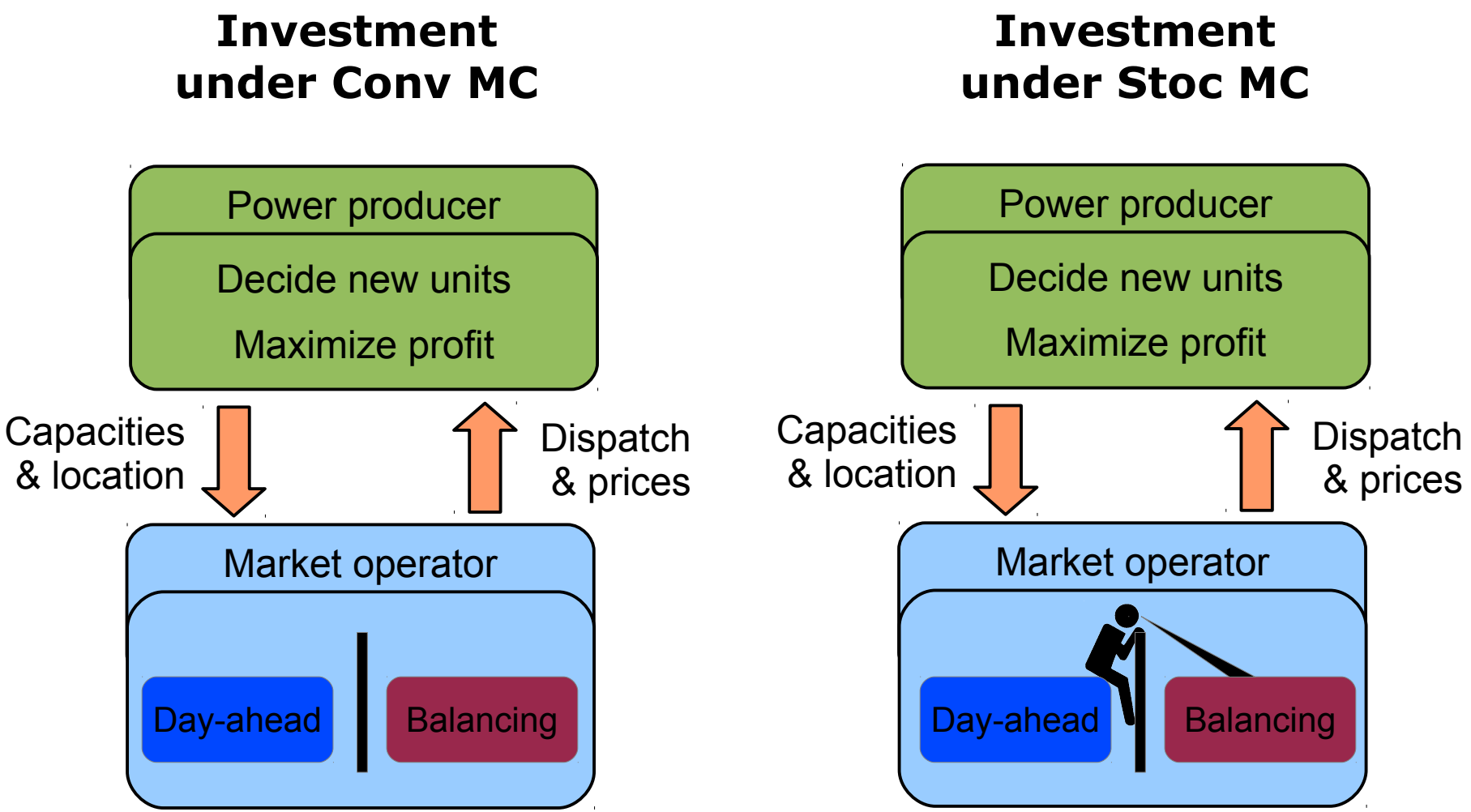
Balancing market

Expansion of stochastic units



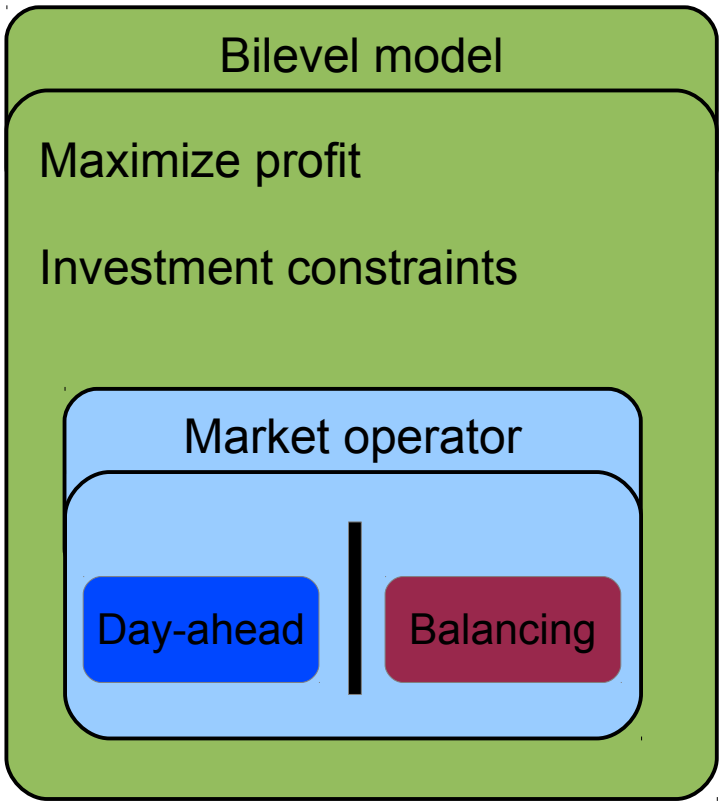
- Where would you locate new wind generating units?
- What about wind forecast errors?
- We need to model both day-ahead and balancing markets
- Will the coordination between DA-B affect investment?

Expansion of stochastic units

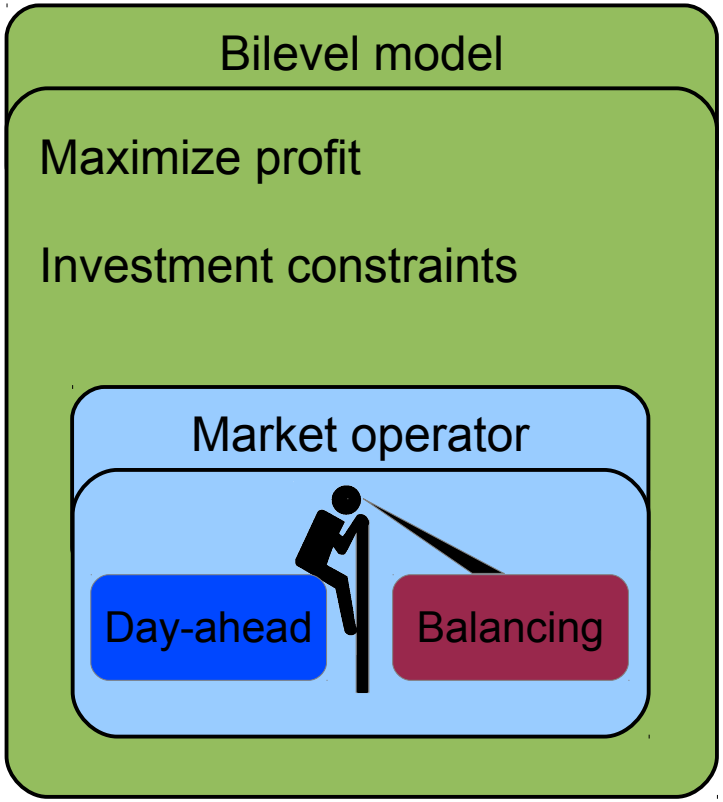


Expansion of stochastic units

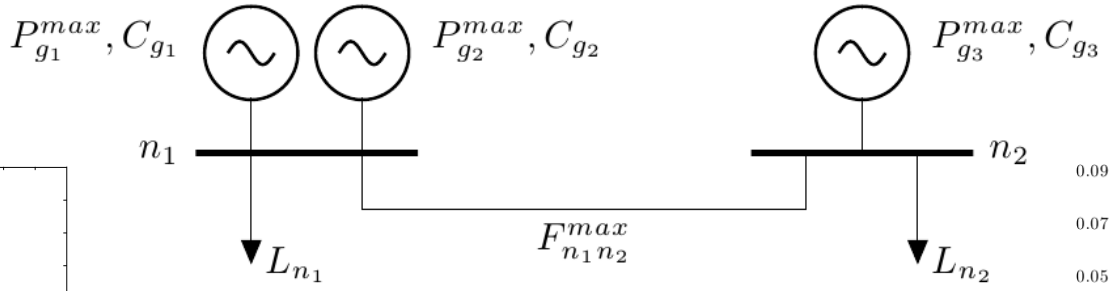
Investment under Conv MC



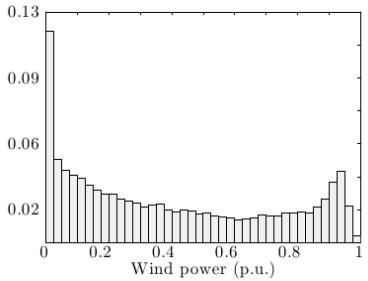
Investment under Stoc MC



Expansion of stochastic units



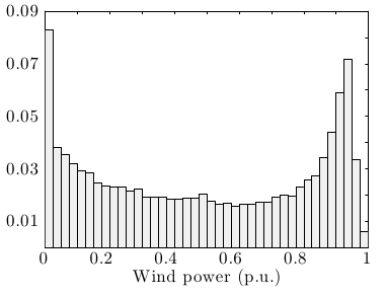
Bus1



Capacity factor = 0.39

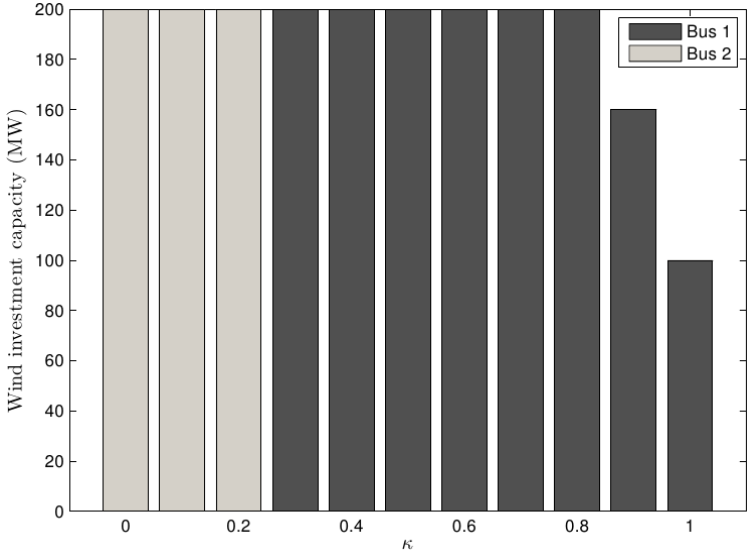
g	P_g^{max}	C_g	$P_g^{max,u}$	C_g^u	$P_g^{max,d}$	C_g^d
g_1	400	20	-	-	-	-
g_2	400	30	50	35	50	29
g_3	600	22	-	-	-	-

Bus2

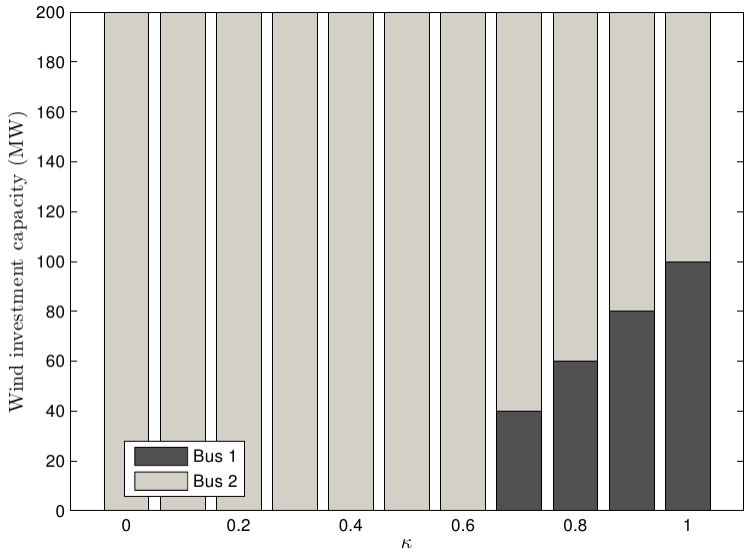


Capacity factor = 0.49

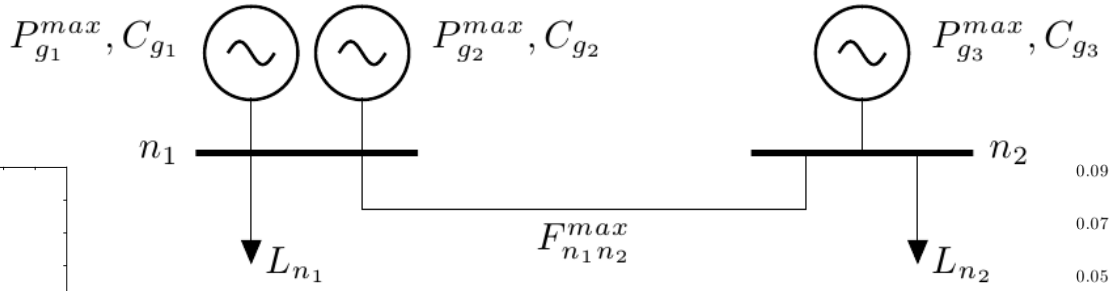
Conv MC



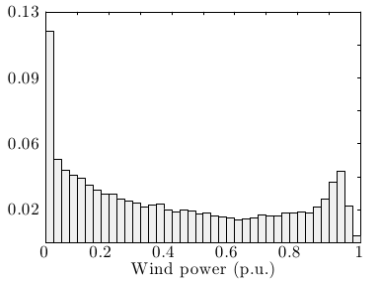
Stoc MC



Expansion of stochastic units

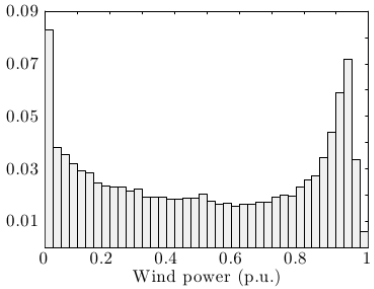


Bus1

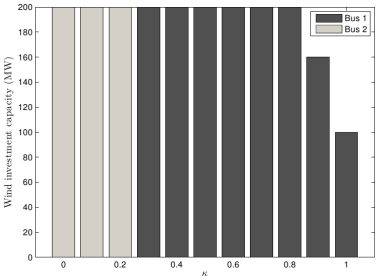


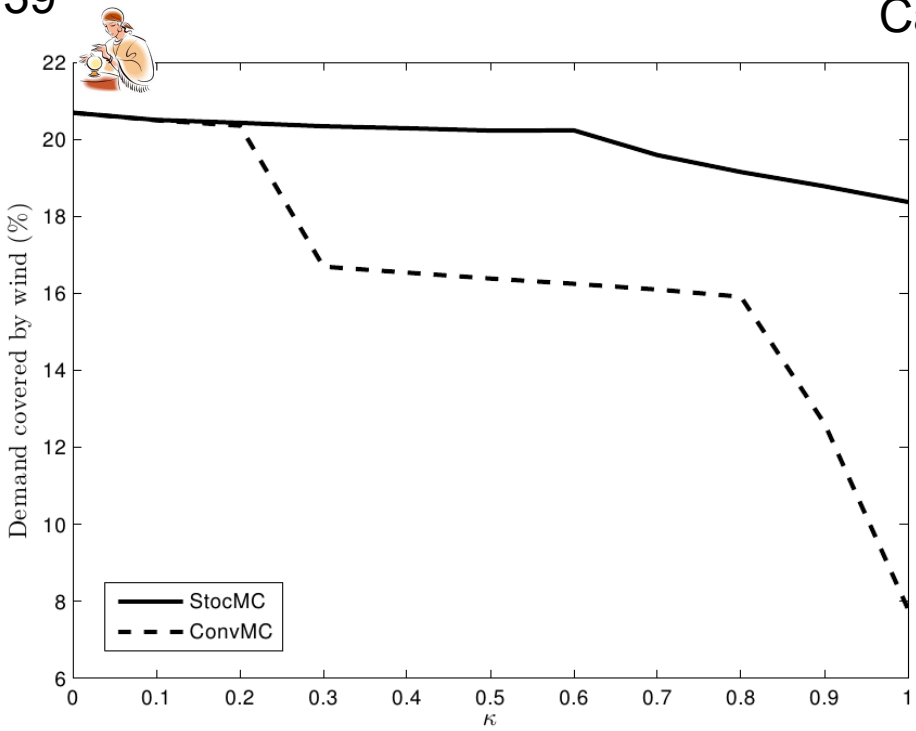
Capacity factor = 0.39

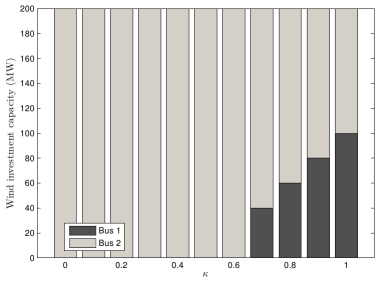
Bus2



Capacity factor = 0.49





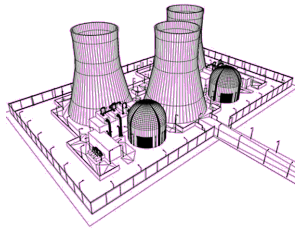


Expansion of stochastic units

Investment model

Maximize profit

Day-ahead



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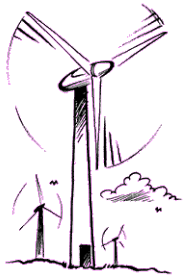


Investment model

Maximize profit

Day-ahead

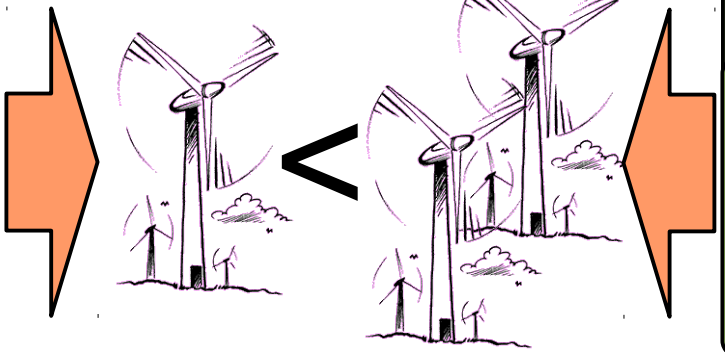
Balancing

Investment (Conv MC)

Maximize profit

Day-ahead

Balancing



Investment (Stoc MC)

Maximize profit

Day-ahead

Balancing

Thanks for your attention!

Questions?