Facultad de Ciencias Económicas y Empresariales
UNIVERSIDAD AUTÓNOMA DE MADRID

DTU

Electricity market clearing under uncertainty and its impact on investments

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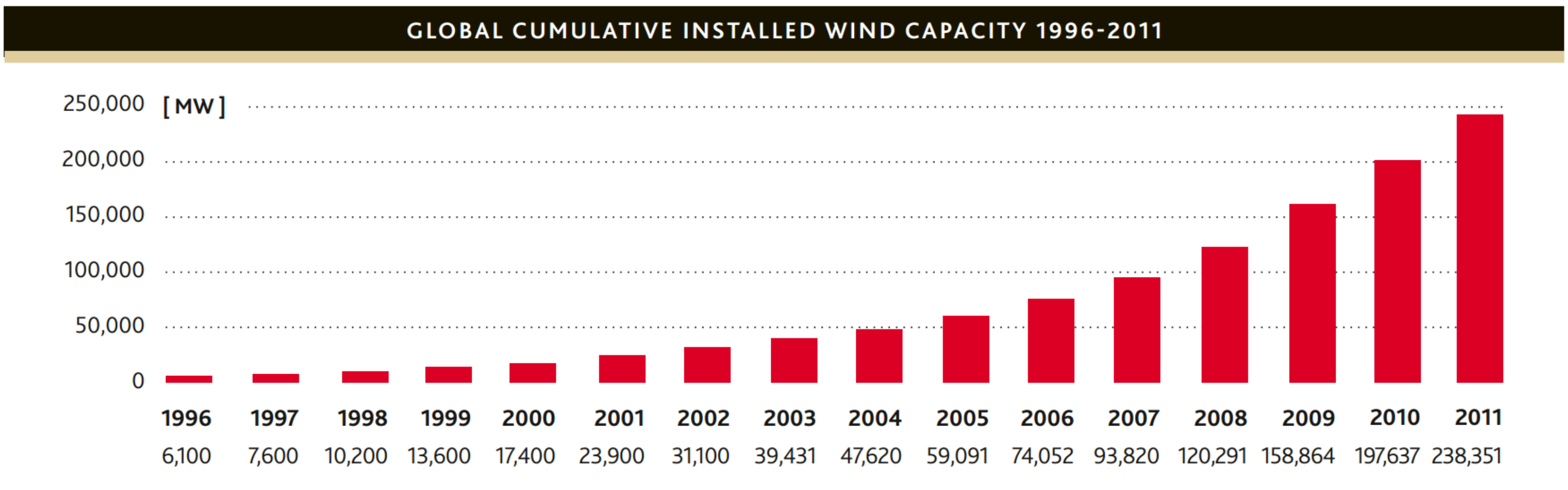
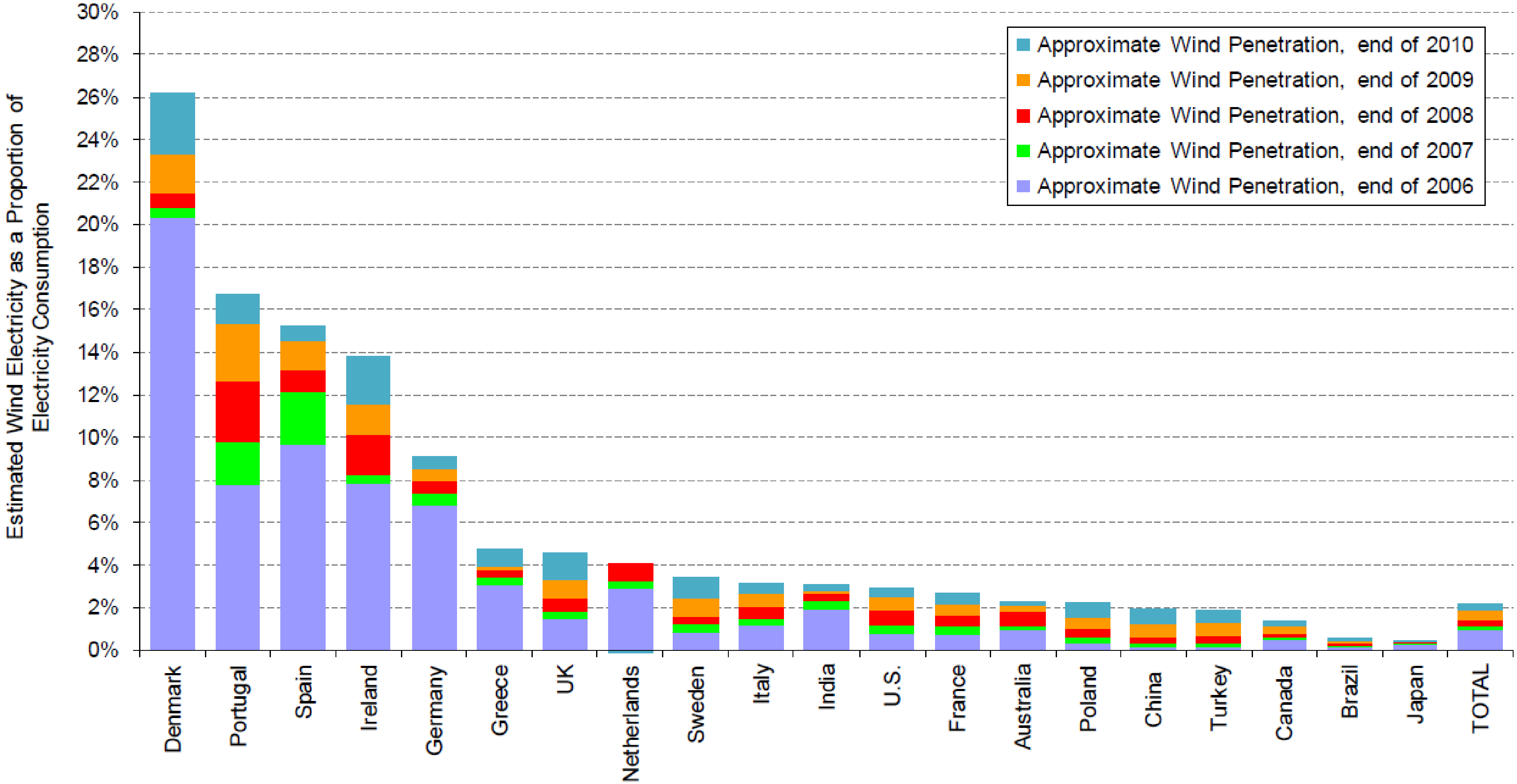
Universidad Autónoma de Madrid
March 8, 2013

The Facts

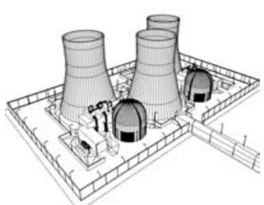

GLOBAL CUMULATIVE INSTALLED WIND CAPACITY 1996-2011
[MW]
250,000
200,000
150,000
100,000
50,000
0
1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011
6,100 7,600 10,200 13,600 17,400 23,900 31,100 39,431 47,620 59,091 74,052 93,820 120,291 158,864 197,637 238,351

The Facts


30%
28%
26%
24%
22%
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
Estimated Wind Electricity as a Proportion of Electricity Consumption
Approximate Wind Penetration, end of 2010
Approximate Wind Penetration, end of 2009
Approximate Wind Penetration, end of 2008
Approximate Wind Penetration, end of 2007
Approximate Wind Penetration, end of 2006
Denmark
Portugal
Spain
Ireland
Germany
Greece
UK
Netherlands
Sweden
Italy
India
U.S.
France
Australia
Poland
China
Turkey
Canada
Brazil
Japan
TOTAL

Problem description
(Motivation)

Day-ahead market → **Balancing market**

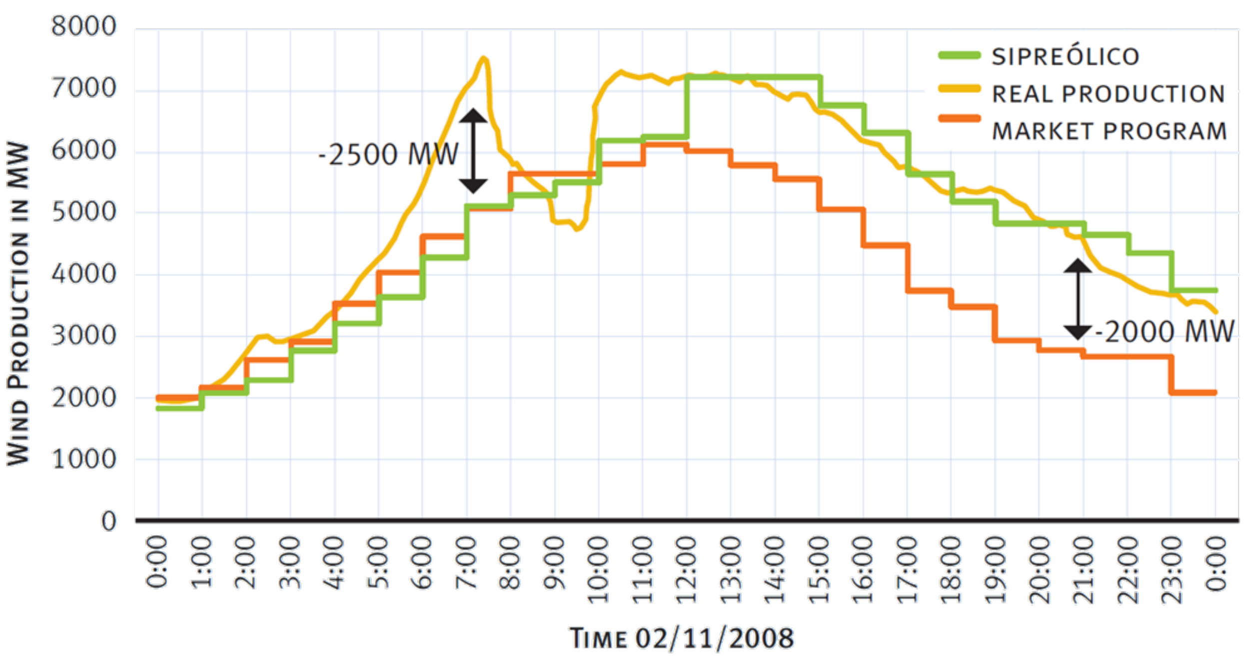


Time

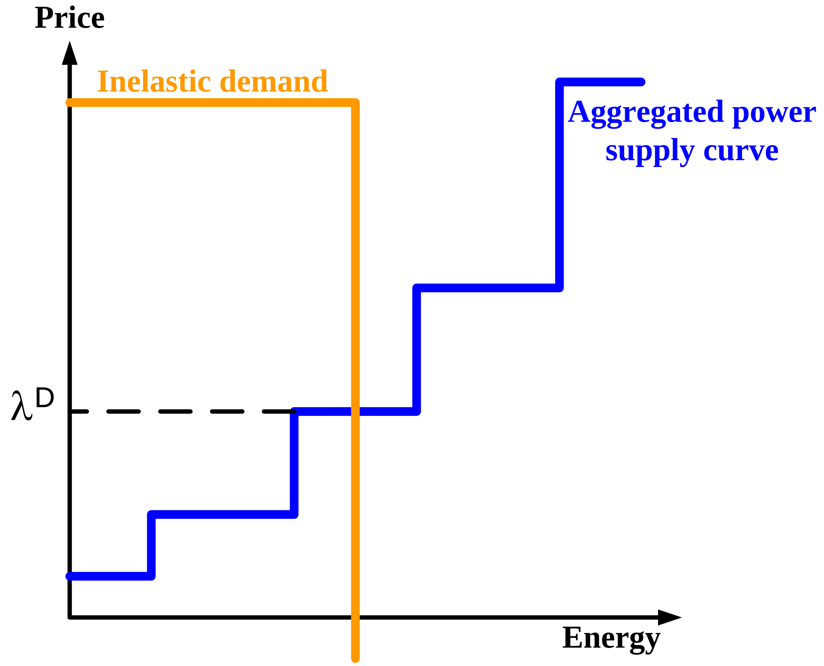
Day d-1 | Day d

Problem description
(Motivation)

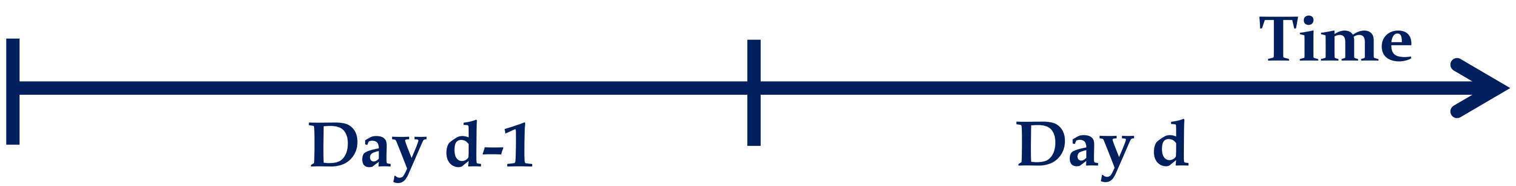
FIGURE 16: WIND FORECAST ERROR IN SPAIN



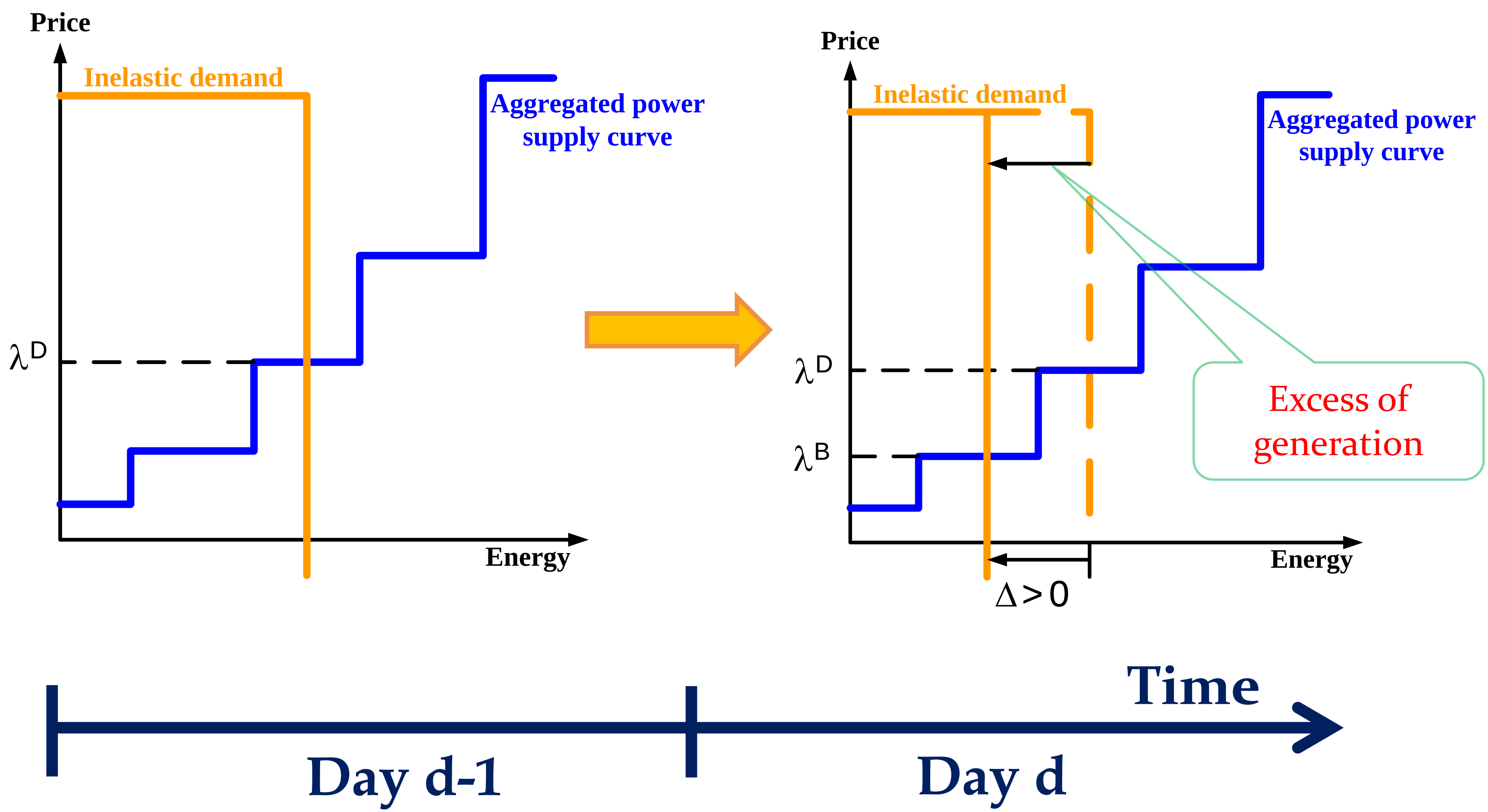
Problem description
(Motivation)



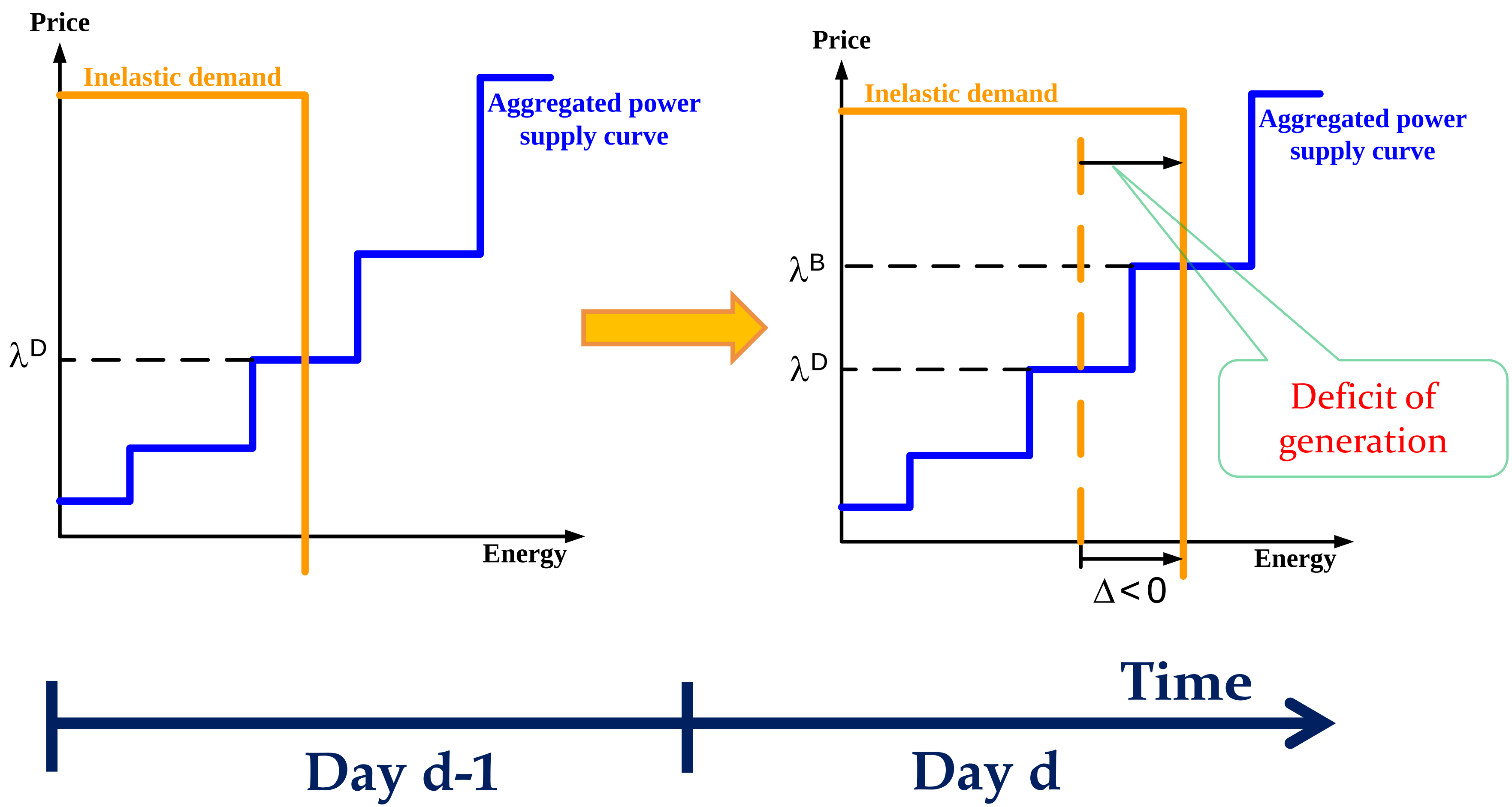
Merit-order principle



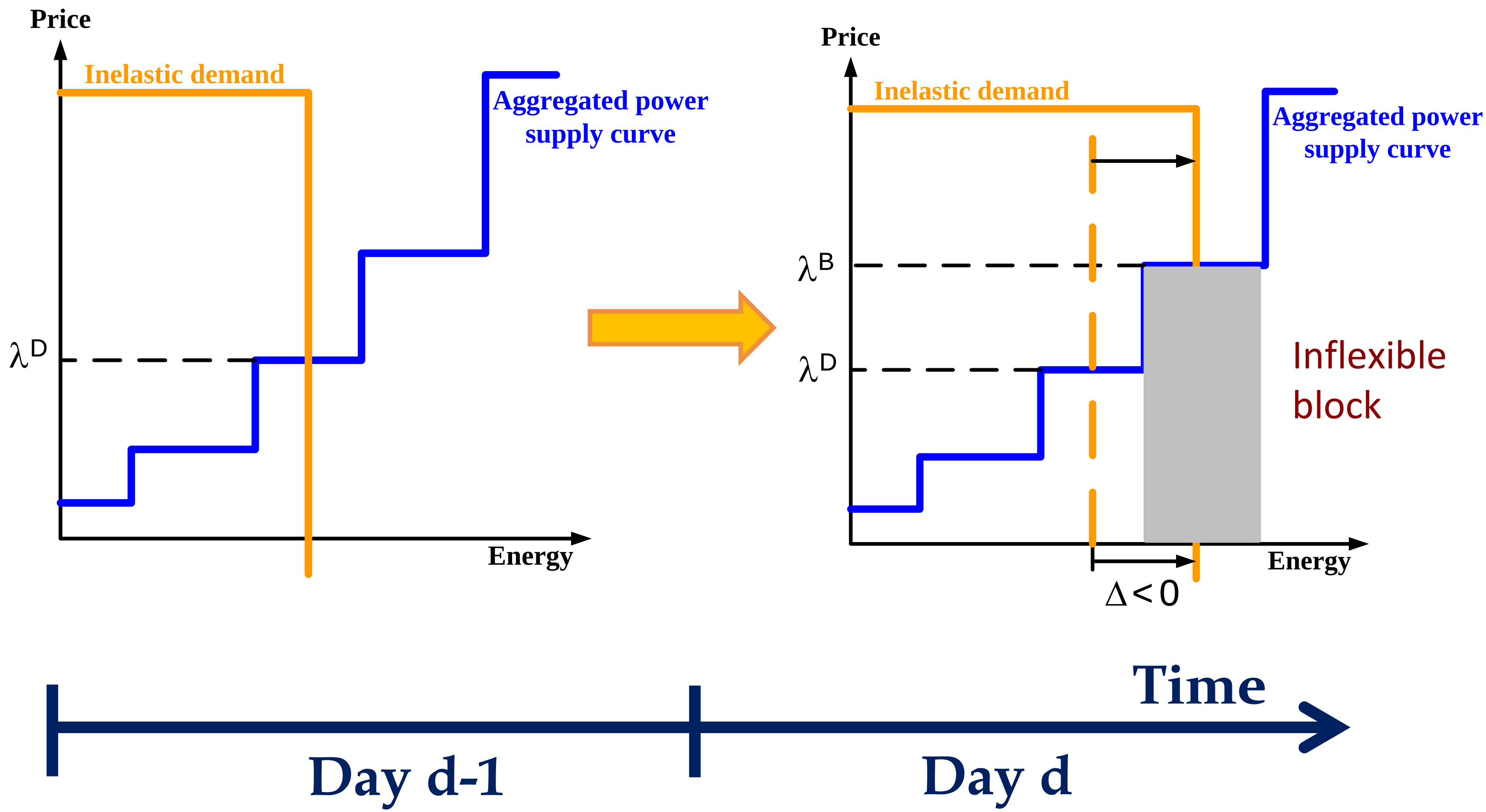
Problem description (Motivation)



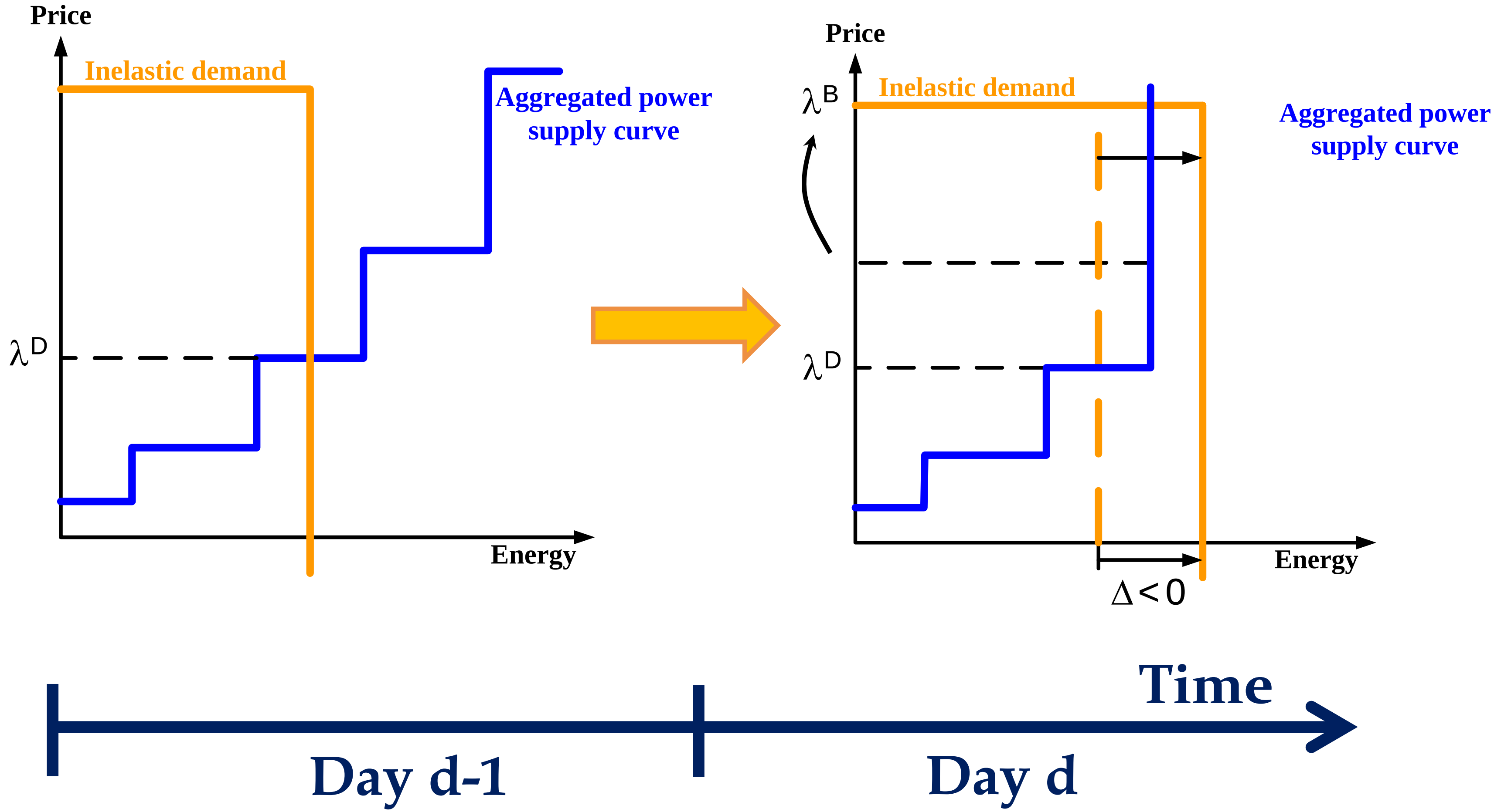
Problem description (Motivation)



Problem description (Motivation)

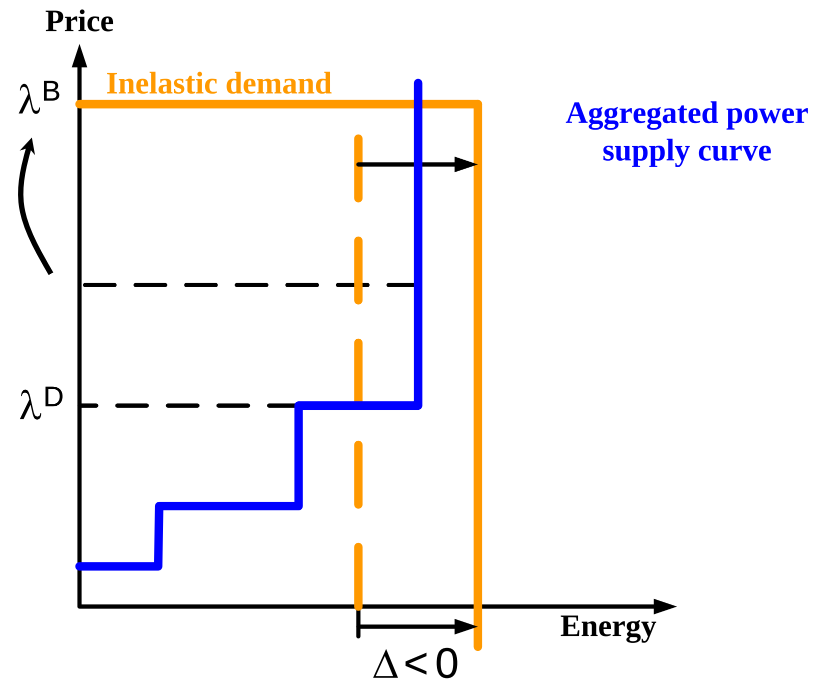


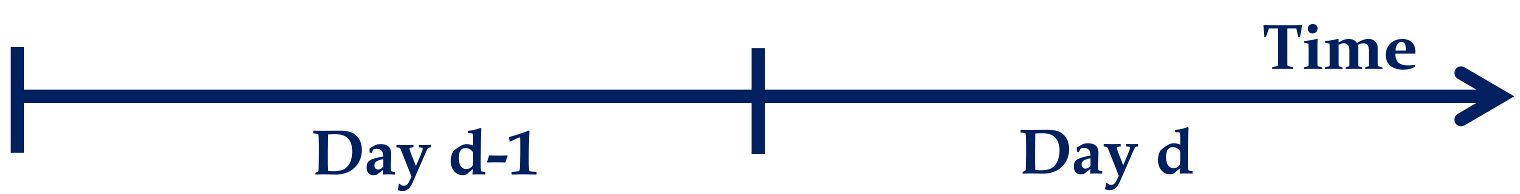
Problem description (Motivation)



Problem description (Motivation)

- Uncertainty ↑ (stochastic production ↑) and flexibility ↓ ⇒ Balancing costs ↑
- The forward dispatch has an impact on balancing costs

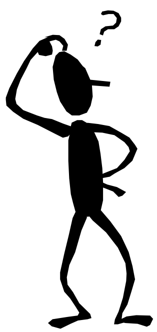


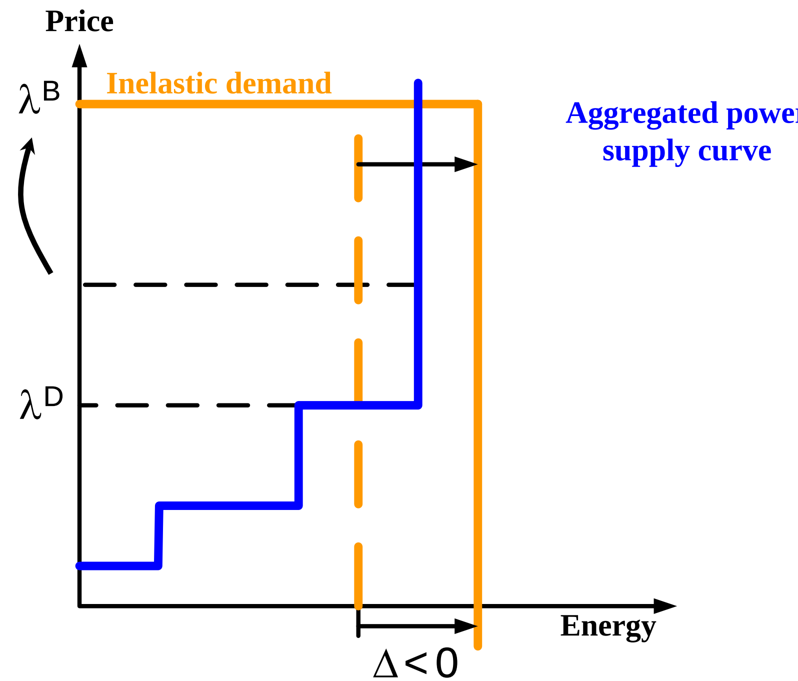


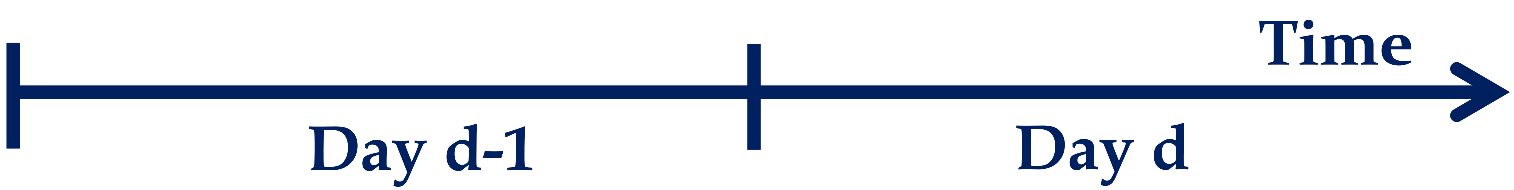
Problem description (Motivation)

- Uncertainty $\uparrow$ (stochastic production $\uparrow$) and flexibility $\downarrow \Rightarrow$ Balancing costs $\uparrow$

- The forward dispatch has an impact on balancing costs

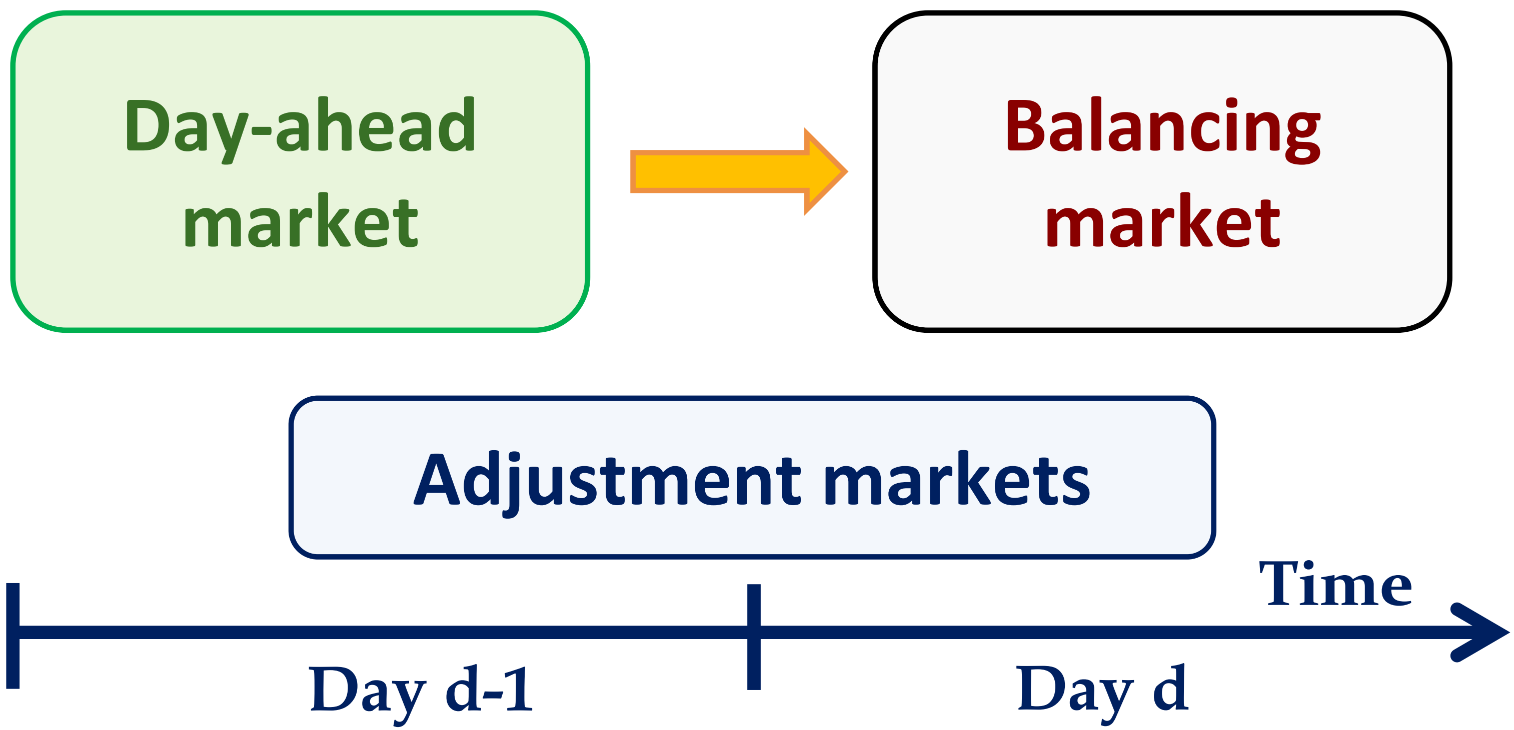






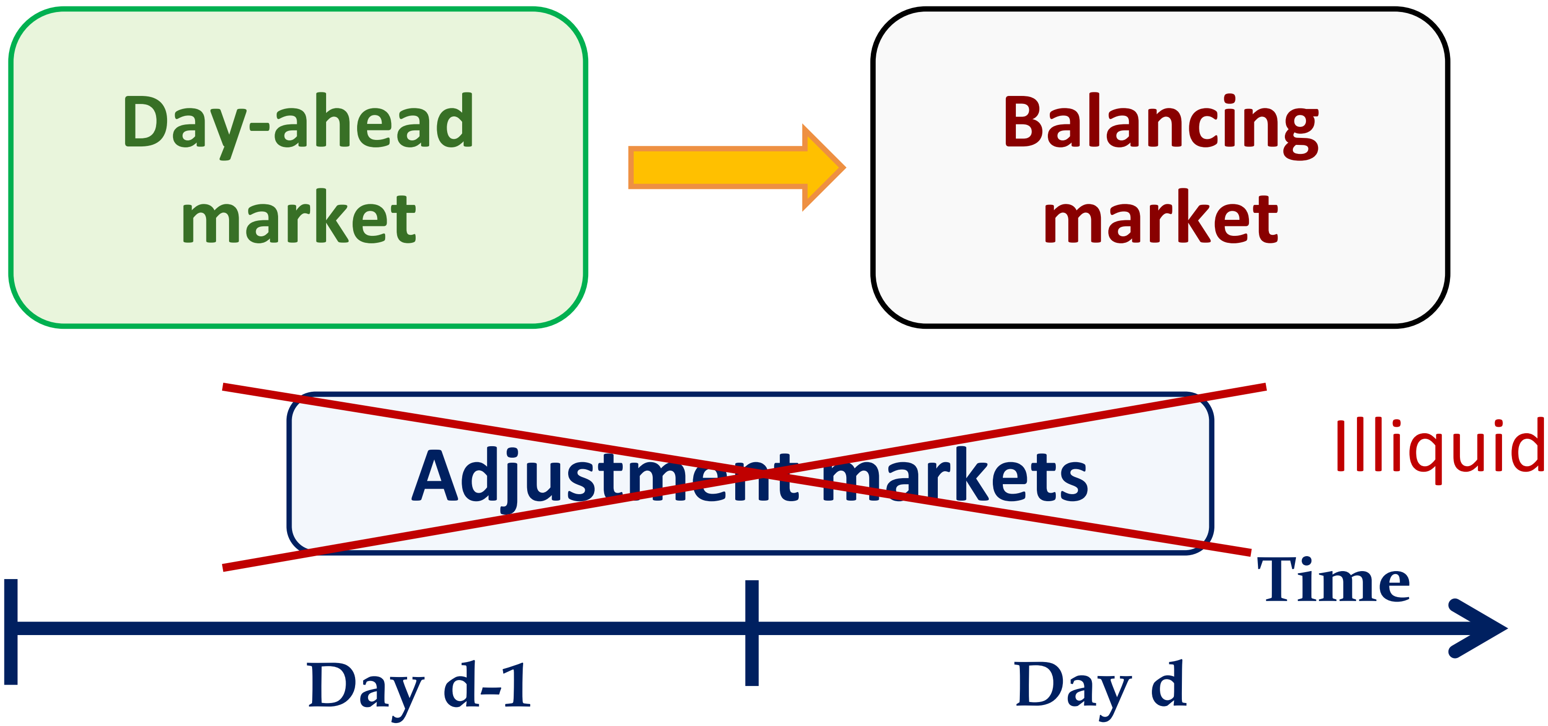
Problem description
(Adjustment markets)

- Adjustment markets allow redefining forward positions and trading with a lesser degree of uncertainty



Problem description
(Adjustment markets)

- Adjustment markets allow redefining forward positions and trading with a lesser degree of uncertainty



Problem description
(Capacity markets)

- Guarantee balancing resources

- Promote flexible generation via capacity payments (missing money in price-capped energy markets)

?

Day-ahead market

Reserve capacity markets

Balancing market

Day d

Day d-1

Time

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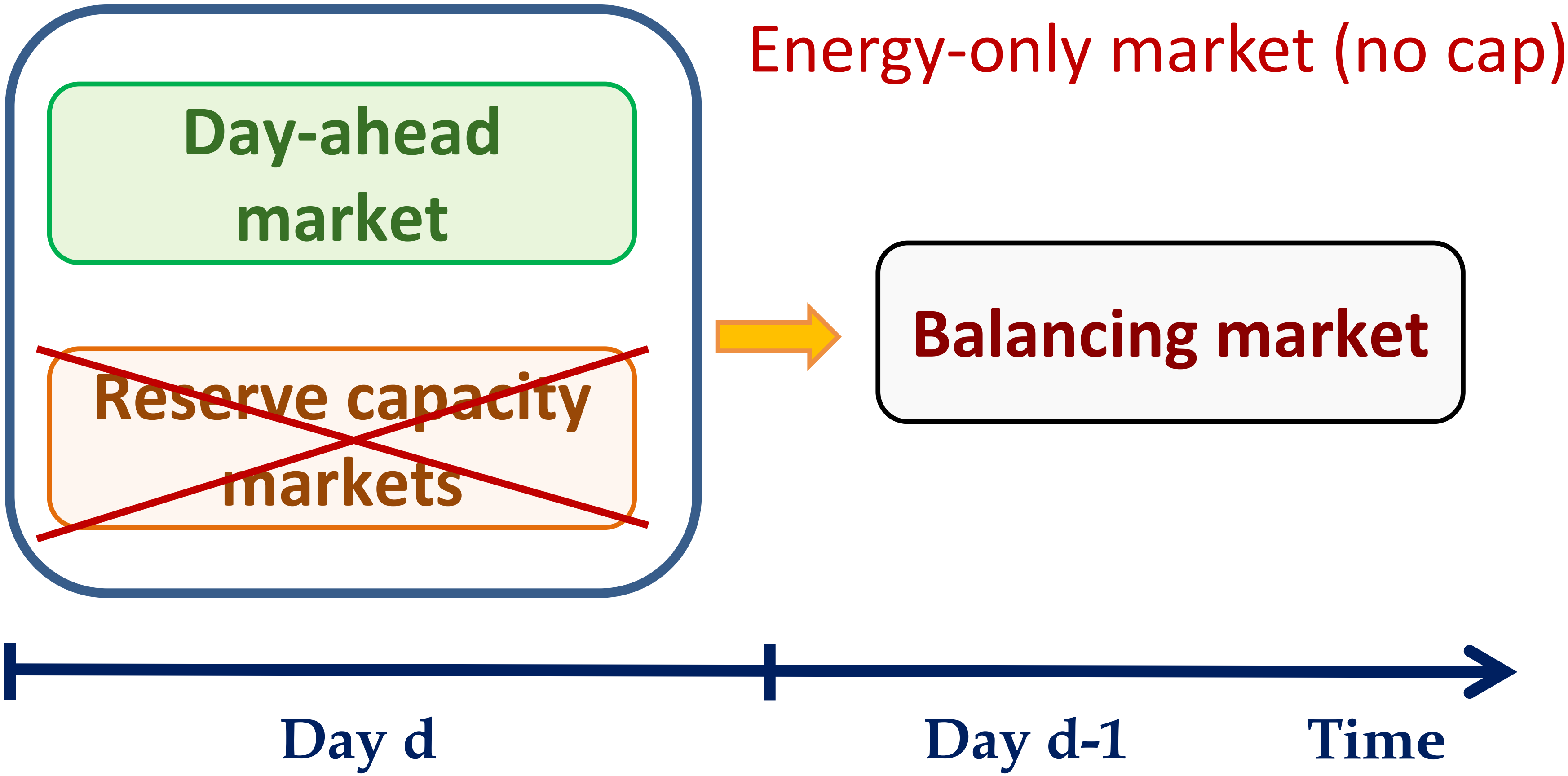
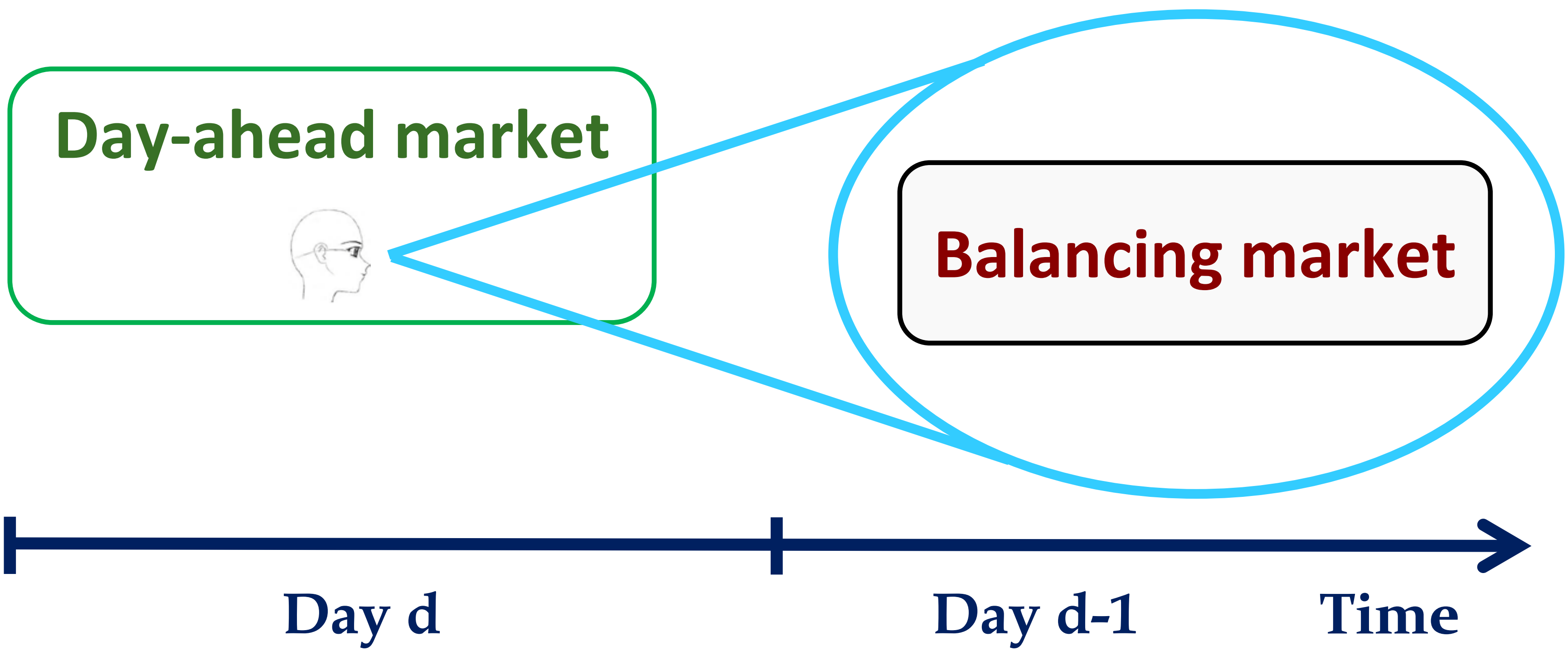
Problem description
(Energy-only market)

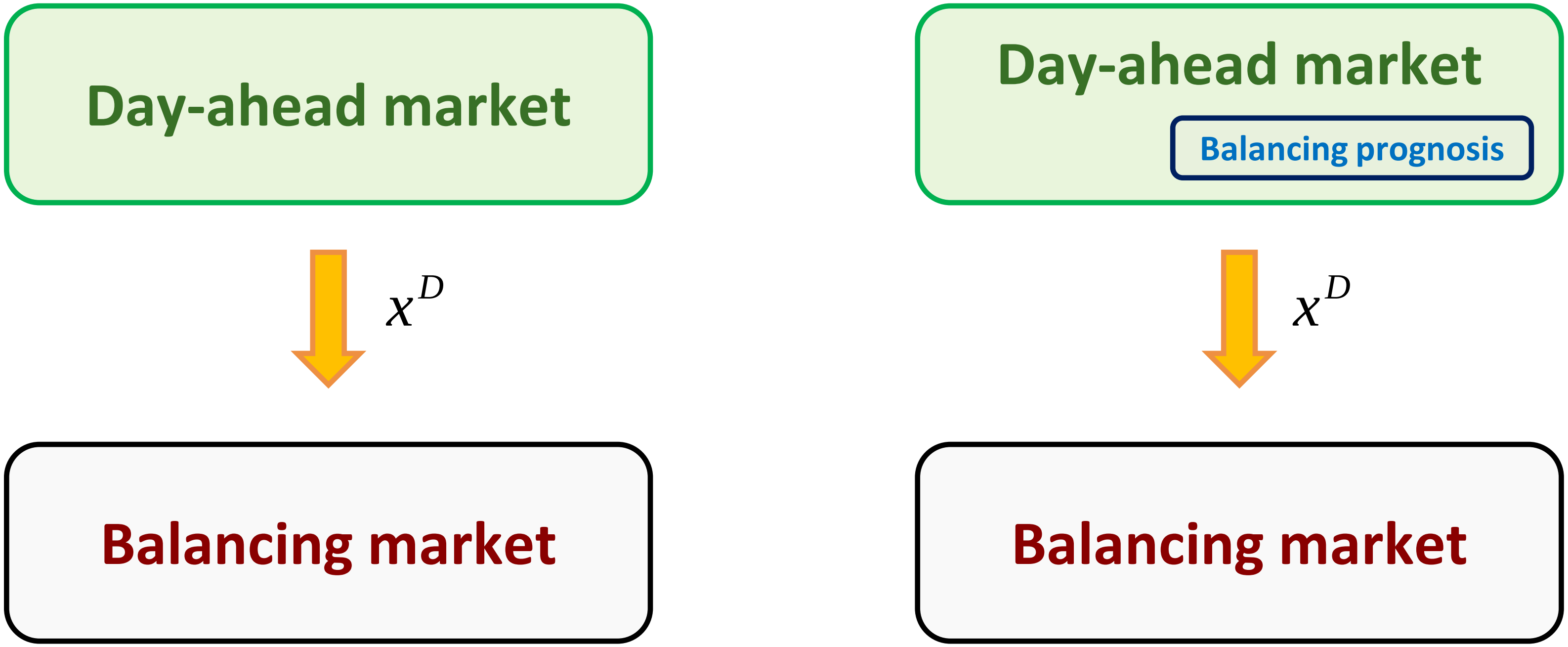


Problem description
(Clearing mechanism)

- The day-ahead market is cleared by accounting for the projected impact on subsequent balancing operation



Clearing mechanism
(Decoupled vs. Coupled)



Decoupled
(DAM and BM are cleared independently)

Coupled
(Day-ahead energy dispatch decisions account for balancing operation)

Clearing mechanism
(Decoupled vs. Coupled)

$$\underset{x^D}{Minimize} \quad C^D(x^D)$$
$$s.t. \quad h^D(x^D)=0$$
$$x^D \in X^D$$

$$\Big\downarrow \, x^{D*}$$

$$\underset{x^B_{\omega'}}{Minimize} \quad C^B(x^B_{\omega'},\omega')$$
$$s.t. \quad h^B(x^B_{\omega'},x^{D*},\omega')=0$$
$$x^B_{\omega'} \in X^B(x^{D*},\omega')$$

Decoupled

Clearing mechanism (Decoupled vs. Coupled)

$$\begin{aligned} \underset{x^D}{\text{Minimize}} \quad & \boxed{C^D(x^D)} \\ \text{s.t.} \quad & h^D(x^D) = 0 \\ & x^D \in X^D \end{aligned}$$

Day-ahead dispatch costs

$$\sum_{i=1}^{N_G} C_i P_i$$

$$\Big\downarrow x^{D*}$$

$$\begin{aligned} \underset{x^B_{\omega'}}{\text{Minimize}} \quad & \boxed{C^B(x^B_{\omega'}, \omega')} \\ \text{s.t.} \quad & h^B(x^B_{\omega'}, x^{D*}, \omega') = 0 \\ & x^B_{\omega'} \in X^B(x^{D*}, \omega') \end{aligned}$$

Balancing dispatch costs

$$\sum_{i=1}^{N_G} \left(C_i^{U} r_{i\omega'}^{U} - C_i^{D} r_{i\omega'}^{D}\right) + \sum_{j=1}^{N_L} V_j^{LOL} L_{j\omega'}^{shed}$$

Decoupled

Clearing mechanism (Decoupled vs. Coupled)

$$\underset{x^D}{\text{Minimize}} \quad \boxed{C^D(x^D)}$$

$$\text{s.t.} \quad h^D(x^D) = 0$$

$$x^D \in X^D$$

Day-ahead dispatch costs

$$\sum_{i=1}^{\mathrm{N_G}} C_i P_i$$

$$x^{D*}$$

Actual production from “stochastic” energy sources

$$\underset{x^B_{\omega'}}{\text{Minimize}} \quad \boxed{C^B(x^B_{\omega'}, \omega')}$$

$$\text{s.t.} \quad h^B(x^B_{\omega'}, x^{D*}, \omega') = 0$$

$$x^B_{\omega'} \in X^B(x^{D*}, \omega')$$

Balancing dispatch costs

$$\sum_{i=1}^{\mathrm{N_G}} \left(C_i^{\mathrm{U}} r_{i\omega'}^{\mathrm{U}} - C_i^{\mathrm{D}} r_{i\omega'}^{\mathrm{D}} \right) + \sum_{j=1}^{\mathrm{N_L}} V_j^{\mathrm{LOL}} L_{j\omega'}^{\mathrm{shed}}$$

Decoupled

Clearing mechanism (Decoupled vs. Coupled)

$$\underset{x^D}{\text{Minimize}} \quad C^D(x^D)$$
$$\text{s.t.} \quad \boxed{h^D(x^D)=0}$$
$$x^D \in X^D$$

$$\downarrow x^{D*}$$

$$\underset{x^B_{\omega'}}{\text{Minimize}} \quad C^B(x^B_{\omega'},\omega')$$
$$\text{s.t.} \quad \boxed{h^B(x^B_{\omega'},x^{D*},\omega')=0}$$
$$x^B_{\omega'} \in X^B(x^{D*},\omega')$$

Decoupled

Power balance at the day-ahead stage

$$\sum_{i\in\Phi_n^{\mathrm{G}}} P_i + \sum_{q\in\Phi_n^{\mathrm{Q}}} W_q^{\mathrm{S}} - \sum_{j\in\Phi_n^{\mathrm{L}}} L_j - \sum_{\ell|o(\ell)=n} b_\ell\left(\delta^0_{o(\ell)} - \delta^0_{e(\ell)}\right)$$
$$+ \sum_{\ell|e(\ell)=n} b_\ell\left(\delta^0_{o(\ell)} - \delta^0_{e(\ell)}\right) = 0 \quad \forall n$$

Power balance at the balancing stage

$$\sum_{i\in\Phi_n^{\mathrm{G}}} (r^{\mathrm{U}}_{i\omega'} - r^{\mathrm{D}}_{i\omega'}) + \sum_{j\in\Phi_n^{\mathrm{L}}} L^{\mathrm{shed}}_{j\omega'} + \sum_{q\in\Phi_n^{\mathrm{Q}}} (W_{q\omega'} - W_q^{\mathrm{S}} - W^{\mathrm{spill}}_{q\omega'})$$
$$+ \sum_{\ell|o(\ell)=n} b_\ell\left(\delta^0_{o(\ell)} - \delta_{o(\ell)\omega'} - \delta^0_{e(\ell)} + \delta_{e(\ell)\omega'}\right)$$
$$-\sum_{\ell|e(\ell)=n} b_\ell\left(\delta^0_{o(\ell)} - \delta_{o(\ell)\omega'} - \delta^0_{e(\ell)} + \delta_{e(\ell)\omega'}\right) = 0 \quad \forall n$$

Clearing mechanism (Decoupled vs. Coupled)

$$\underset{x^D}{Minimize} \quad C^D(x^D)$$
$$s.t. \quad h^D(x^D) = 0$$
$$\boxed{x^D \in X^D}$$

$$\Big\downarrow \; x^{D*}$$

$$\underset{x^B_{\omega'}}{Minimize} \quad C^B(x^B_{\omega'}, \omega')$$
$$s.t. \quad h^B(x^B_{\omega'}, x^{D*}, \omega') = 0$$
$$\boxed{x^B_{\omega'} \in X^B(x^{D*}, \omega')}$$

Decoupled

Offer limits

$$P_i^{\max} \leq \overline{P}_i, \forall i$$
$$W_q^{\max} \leq \overline{W}_q, \forall q$$

Offer limits

$$r^{\mathrm{U}}_{i\omega'} \leq R_i^{\mathrm{U,max}}, \forall i$$
$$r^{\mathrm{D}}_{i\omega'} \leq R_i^{\mathrm{D,max}}, \forall i$$
$$P_i^* - r^{\mathrm{D}}_{i\omega'} \geq 0, \forall i$$
$$P_i^* + r^{\mathrm{U}}_{i\omega'} \leq \overline{P}_i, \forall i$$

Clearing mechanism
(Decoupled vs. Coupled)

$$\underset{x^D}{\text{Minimize}} \quad C^D(x^D)$$
$$s.t. \quad h^D(x^D) = 0$$
$$\boxed{x^D \in X^D}$$

$$\Big\downarrow \; x^{D*}$$

$$\underset{x^B_{\omega'}}{\text{Minimize}} \quad C^B(x^B_{\omega'}, \omega')$$
$$s.t. \quad h^B(x^B_{\omega'}, x^{D*}, \omega') = 0$$
$$\boxed{x^B_{\omega'} \in X^B(x^{D*}, \omega')}$$

Decoupled

- Transmission capacity limits, variable bounds, reference node …
- Non convexities are disregarded!

Clearing mechanism (Decoupled vs. Coupled)

$$\begin{aligned} \underset{x^D}{Minimize} \quad & C^D(x^D) \\ s.t. \quad & h^D(x^D) = 0 \\ & x^D \in X^D \end{aligned}$$

$$\Big\downarrow x^{D*}$$

$$\begin{aligned} \underset{x^B_{\omega'}}{Minimize} \quad & C^B(x^B_{\omega'}, \omega') \\ s.t. \quad & h^B(x^B_{\omega'}, x^{D*}, \omega') = 0 \\ & x^B_{\omega'} \in X^B(x^{D*}, \omega') \end{aligned}$$

Decoupled

$$\begin{aligned} \underset{x^D, x^B_\omega}{Minimize} \quad & C^D(x^D) + \mathrm{E}_\omega \{ C^B(x^B_\omega, \omega) \} \\ s.t. \quad & h^D(x^D) = 0 \\ & x^D \in X^D \\ & h^B(x^B_\omega, x^D, \omega) = 0, \ \forall \omega \\ & x^B_\omega \in X^B(x^D, \omega), \ \forall \omega \end{aligned}$$

$$\Big\downarrow x^{D*}$$

$$\begin{aligned} \underset{x^B_{\omega'}}{Minimize} \quad & C^B(x^B_{\omega'}, \omega') \\ s.t. \quad & h^B(x^B_{\omega'}, x^{D*}, \omega') = 0 \\ & x^B_{\omega'} \in X^B(x^{D*}, \omega') \end{aligned}$$

Coupled

Clearing mechanism (Decoupled vs. Coupled)

$$\underset{x^D}{Minimize} \quad C^D(x^D)$$
$$s.t. \quad h^D(x^D) = 0$$
$$x^D \in X^D$$

$$\downarrow x^{D*}$$

$$\underset{x^B_{\omega'}}{Minimize} \quad C^B(x^B_{\omega'}, \omega')$$
$$s.t. \quad h^B(x^B_{\omega'}, x^{D*}, \omega') = 0$$
$$x^B_{\omega'} \in X^B(x^{D*}, \omega')$$

Decoupled

$$\underset{x^D, x^B_\omega}{Minimize} \quad C^D(x^D) + \boxed{\mathrm{E}_\omega\left\{C^B(x^B_\omega, \omega)\right\}}$$
$$s.t. \quad h^D(x^D) = 0$$
$$x^D \in X^D$$
$$\boxed{\begin{array}{l} h^B(x^B_\omega, x^D, \omega) = 0, \forall \omega \\ x^B_\omega \in X^B(x^D, \omega), \forall \omega \end{array}}$$

Balancing prognosis

$$\downarrow x^{D*}$$

$$\underset{x^B_{\omega'}}{Minimize} \quad C^B(x^B_{\omega'}, \omega')$$
$$s.t. \quad h^B(x^B_{\omega'}, x^{D*}, \omega') = 0$$
$$x^B_{\omega'} \in X^B(x^{D*}, \omega')$$

Coupled

Clearing mechanism (Decoupled vs. Coupled)

- Expectation of the balancing costs: It requires a centralized forecasting tool
- Scenario-based modeling of uncertainty

$$\sum_{i=1}^{\mathrm{N_G}} C_i P_i + \boxed{\sum_{\omega=1}^{\mathrm{N_\Omega}} \pi_\omega \left[\sum_{i=1}^{\mathrm{N_G}} (C_i^{\mathrm{U}} r_{i\omega}^{\mathrm{U}} - C_i^{\mathrm{D}} r_{i\omega}^{\mathrm{D}}) + \sum_{j=1}^{\mathrm{N_L}} V_j^{\mathrm{LOL}} L_{j\omega}^{\mathrm{shed}} \right]}$$

$$\underset{x^D, x_\omega^B}{\text{Minimize}} \quad C^D(x^D) + \boxed{\mathrm{E}_\omega \{ C^B(x_\omega^B, \omega) \}}$$

$$\text{s.t.} \quad h^D(x^D) = 0$$

$$x^D \in X^D$$

$$\boxed{\begin{array}{l} h^B(x_\omega^B, x^D, \omega) = 0, \forall \omega \\ x_\omega^B \in X^B(x^D, \omega), \forall \omega \end{array}}$$

$$\big\downarrow x^{D*}$$

$$\underset{x_{\omega'}^B}{\text{Minimize}} \quad C^B(x_{\omega'}^B, \omega')$$

$$\text{s.t.} \quad h^B(x_{\omega'}^B, x^{D*}, \omega') = 0$$

$$x_{\omega'}^B \in X^B(x^{D*}, \omega')$$

Coupled

Clearing mechanism (Decoupled vs. Coupled)

- Expectation of the balancing costs: It requires a centralized forecasting tool
- Scenario-based modeling of uncertainty
- Two-stage stochastic programming problem

$$
\begin{aligned}
\underset{x^D, x^B_\omega}{Minimize} \quad & C^D(x^D) + \mathrm{E}_\omega \left\{ C^B(x^B_\omega, \omega) \right\} \\
s.t. \quad & h^D(x^D) = 0 \\
& x^D \in X^D \\
& h^B(x^B_\omega, x^D, \omega) = 0, \forall \omega \\
& x^B_\omega \in X^B(x^D, \omega), \forall \omega
\end{aligned}
$$

$$\Big\downarrow x^{D*}$$

$$
\begin{aligned}
\underset{x^B_{\omega'}}{Minimize} \quad & C^B(x^B_{\omega'}, \omega') \\
s.t. \quad & h^B(x^B_{\omega'}, x^{D*}, \omega') = 0 \\
& x^B_{\omega'} \in X^B(x^{D*}, \omega')
\end{aligned}
$$

Coupled

Clearing mechanism (Decoupled vs. Coupled)

- Expectation of the balancing costs: It requires a centralized forecasting tool
- Scenario-based modeling of uncertainty
- Two-stage stochastic programming problem
- Two-settlement energy market: The balancing market is still there!

$$\begin{aligned}
\underset{x^D, x^B_\omega}{\text{Minimize}} \quad & C^D(x^D) + \mathrm{E}_\omega \left\{ C^B(x^B_\omega, \omega) \right\} \\
s.t. \quad & h^D(x^D) = 0 \\
& x^D \in X^D \\
& h^B(x^B_\omega, x^D, \omega) = 0, \forall \omega \\
& x^B_\omega \in X^B(x^D, \omega), \forall \omega
\end{aligned}$$

$$\Big\downarrow x^{D*}$$

$$\begin{aligned}
\underset{x^B_{\omega'}}{\text{Minimize}} \quad & C^B(x^B_{\omega'}, \omega') \\
s.t. \quad & h^B(x^B_{\omega'}, x^{D*}, \omega') = 0 \\
& x^B_{\omega'} \in X^B(x^{D*}, \omega')
\end{aligned}$$

Coupled

Clearing mechanism (Decoupled vs. Coupled)

- Expectation of the balancing costs: It requires a centralized forecasting tool
- Scenario-based modeling of uncertainty
- Two-stage stochastic programming problem
- Two-settlement energy market: The balancing market is still there!
- A more detailed formulation of the problem can be found in:

J. M. Morales, A. J. Conejo, K. Liu, J. Zhong (2012). *Pricing Electricity in Pools with Wind Producers*, IEEE Transactions on Power Systems 27(3): 1366 – 1376.

$$
\begin{aligned}
\underset{x^D,\, x^B_\omega}{\text{Minimize}} \quad & C^D(x^D) + \mathrm{E}_\omega \left\{ C^B(x^B_\omega, \omega) \right\} \\
\text{s.t.} \quad & h^D(x^D) = 0 \\
& x^D \in X^D \\
& h^B(x^B_\omega, x^D, \omega) = 0, \ \forall \omega \\
& x^B_\omega \in X^B(x^D, \omega), \ \forall \omega
\end{aligned}
$$

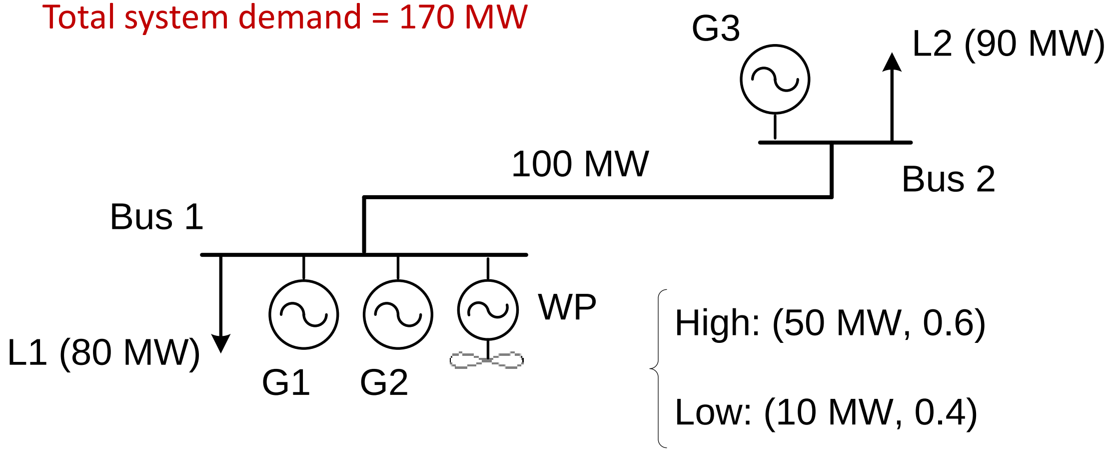
$$\Big\downarrow \, x^{D*}$$

$$
\begin{aligned}
\underset{x^B_{\omega'}}{\text{Minimize}} \quad & C^B(x^B_{\omega'}, \omega') \\
\text{s.t.} \quad & h^B(x^B_{\omega'}, x^{D*}, \omega') = 0 \\
& x^B_{\omega'} \in X^B(x^{D*}, \omega')
\end{aligned}
$$

Coupled

Clearing mechanism (Example)

Total system demand = 170 MW



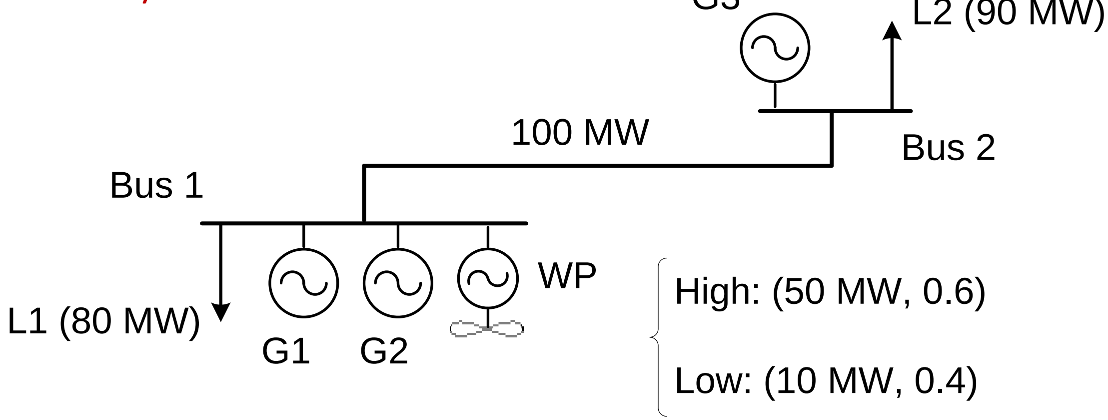
- Unit capacity and offer cost in DAM

Unit	$P^{\max}$	C	C^U	C^D	$R_U^{\max}$	$R_D^{\max}$
G1	100	35	40	34	20	40
G2	110	30	–	–	0	0
G3	50	10	–	–	0	0

Powers in MW; costs in $/MWh

Clearing mechanism (Example)

Total system demand = 170 MW



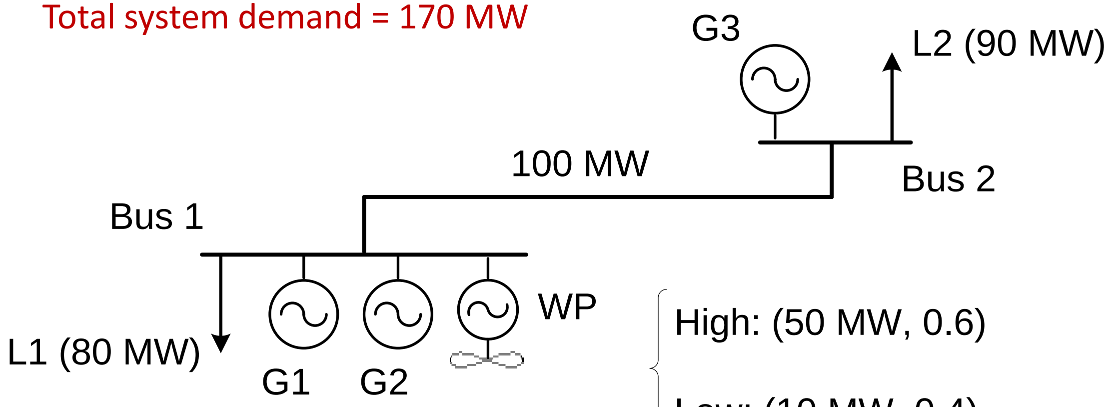
- Unit capacity and offer cost in DAM
- Offer limit and cost for the energy sold in BM

Unit	$P^{\max}$	C	C^U	C^D	$R_U^{\max}$	$R_D^{\max}$
G1	100	35	40	34	20	40
G2	110	30	–	–	0	0
G3	50	10	–	–	0	0

Powers in MW; costs in \$/MWh

Clearing mechanism (Example)

Total system demand = 170 MW



High: (50 MW, 0.6)

Low: (10 MW, 0.4)

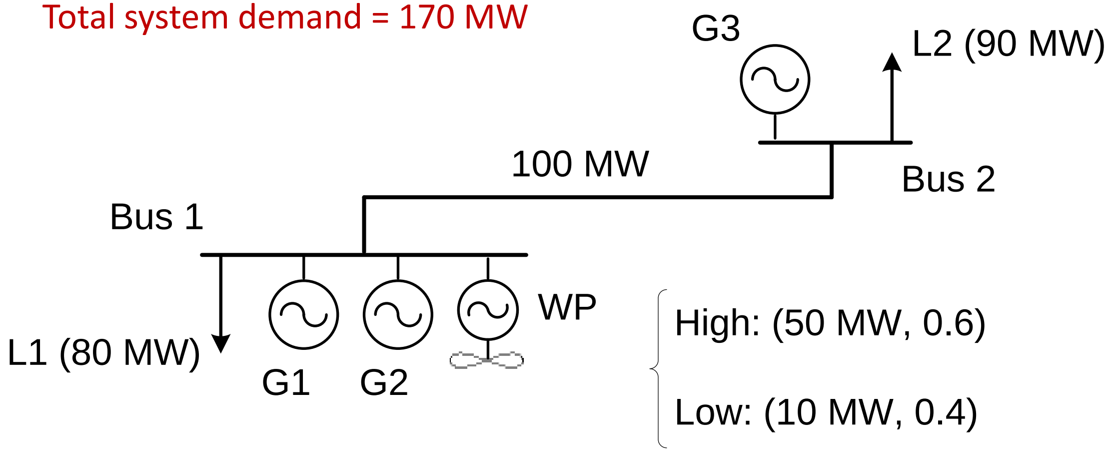
- Unit capacity and offer cost in DAM
- Offer limit and cost for the energy sold in BM
- Offer limit and cost for the energy repurchased in BM

Unit	$P^{\max}$	C	C^U	C^D	$R_U^{\max}$	$R_D^{\max}$
G1	100	35	40	34	20	40
G2	110	30	–	–	0	0
G3	50	10	–	–	0	0

Powers in MW; costs in $/MWh

Clearing mechanism (Example)

Total system demand = 170 MW



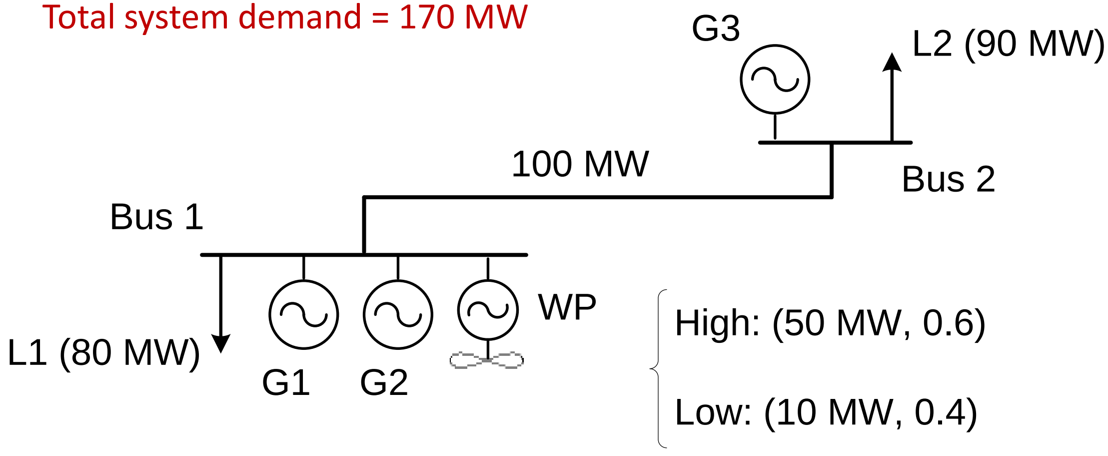
Expensive, but flexible

Unit	$P^{\max}$	C	C^U	C^D	$R_U^{\max}$	$R_D^{\max}$
G1	100	35	40	34	20	40
G2	110	30	–	–	0	0
G3	50	10	–	–	0	0

Powers in MW; costs in $/MWh

Clearing mechanism (Example)

Total system demand = 170 MW



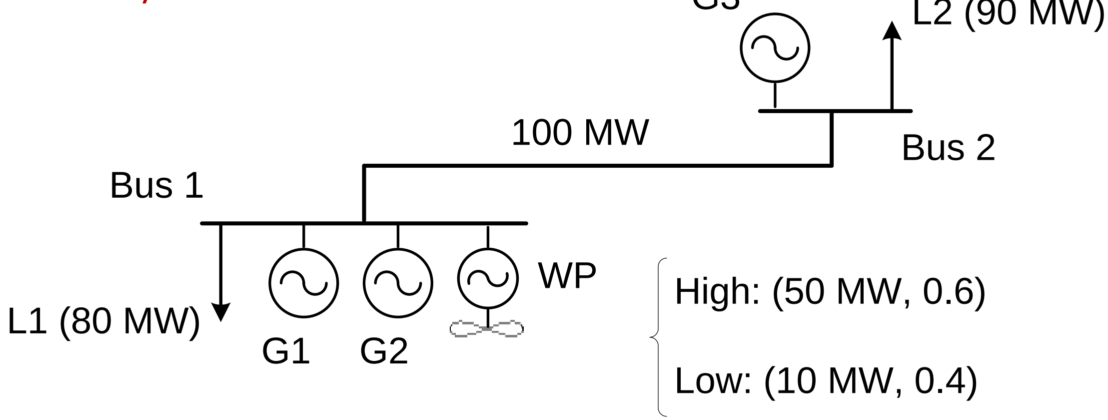
Unit	$P^{\max}$	C	C^U	C^D	$R_U^{\max}$	$R_D^{\max}$
G1	100	35	40	34	20	40
G2	110	30	–	–	0	0
G3	50	10	–	–	0	0

Less expensive, but inflexible

Powers in MW; costs in $/MWh

Clearing mechanism (Example)

Total system demand = 170 MW



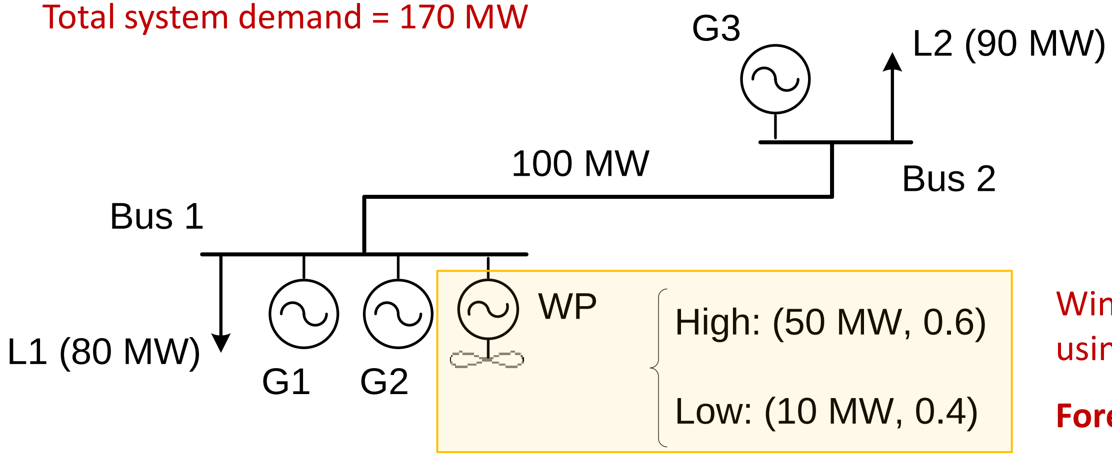
Unit	$P^{\max}$	C	C^U	C^D	$R_U^{\max}$	$R_D^{\max}$
G1	100	35	40	34	20	40
G2	110	30	–	–	0	0
G3	50	10	–	–	0	0

Cheap, but inflexible

Powers in MW; costs in $/MWh

Clearing mechanism (Example)

Total system demand = 170 MW



Wind power production modeled using two scenarios

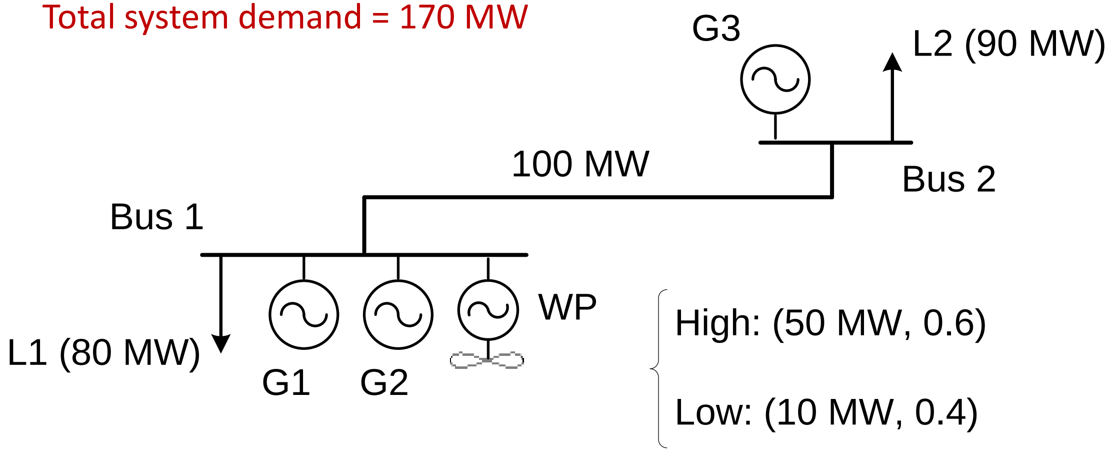
Forecast = 34 MW

Unit	$P^{\max}$	C	C^U	C^D	$R_U^{\max}$	$R_D^{\max}$
G1	100	35	40	34	20	40
G2	110	30	–	–	0	0
G3	50	10	–	–	0	0

Powers in MW; costs in $/MWh

Clearing mechanism (Example)

Total system demand = 170 MW



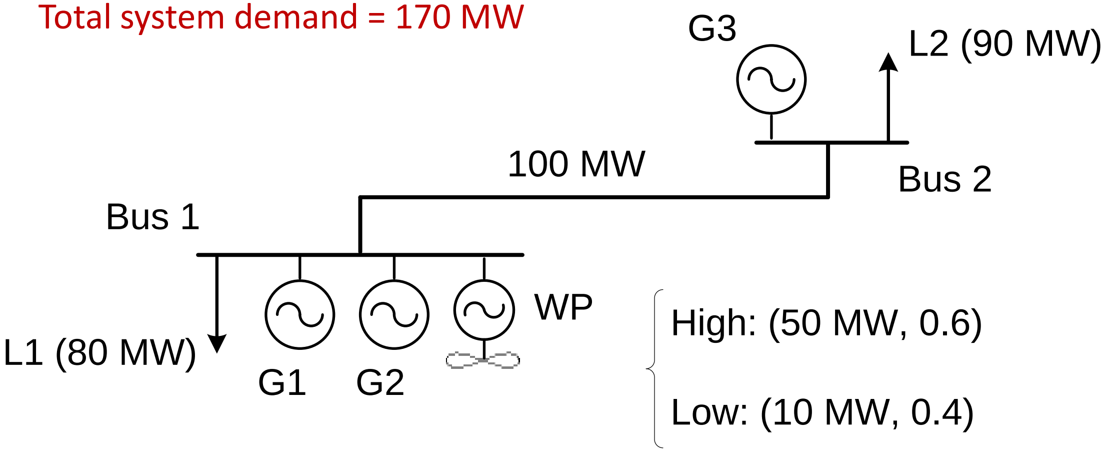
Decoupled

Unit	$P^{\max}$	C	P^{sch}
G1	100	35	0
G2	110	30	86
G3	50	10	50
WP	34	0	34

Powers in MW; costs in $/MWh

Clearing mechanism (Example)

Total system demand = 170 MW



Decoupled

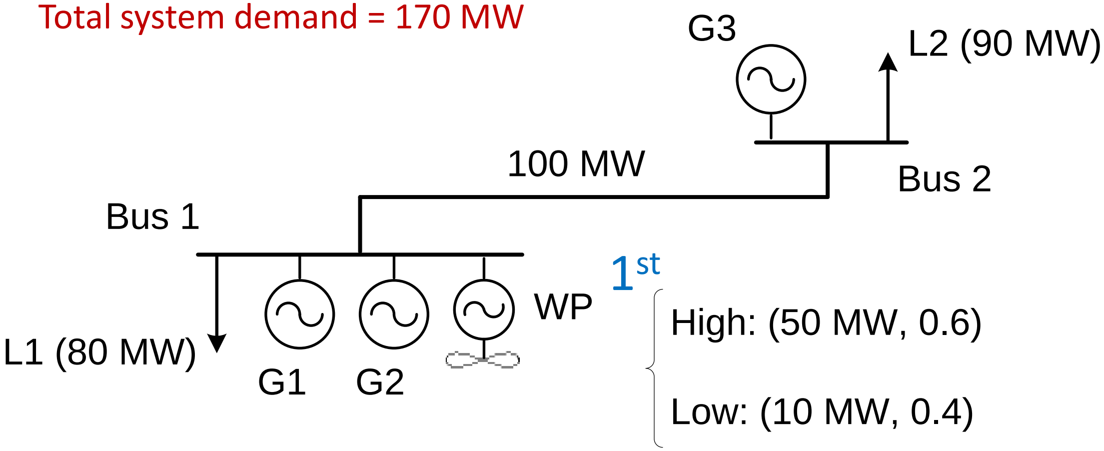
Unit	$P^{\max}$	C	P^{sch}
G1	100	35	0
G2	110	30	86
G3	50	10	50
WP	34	0	34

Powers in MW; costs in $/MWh

Forecast bid

Clearing mechanism (Example)

Total system demand = 170 MW



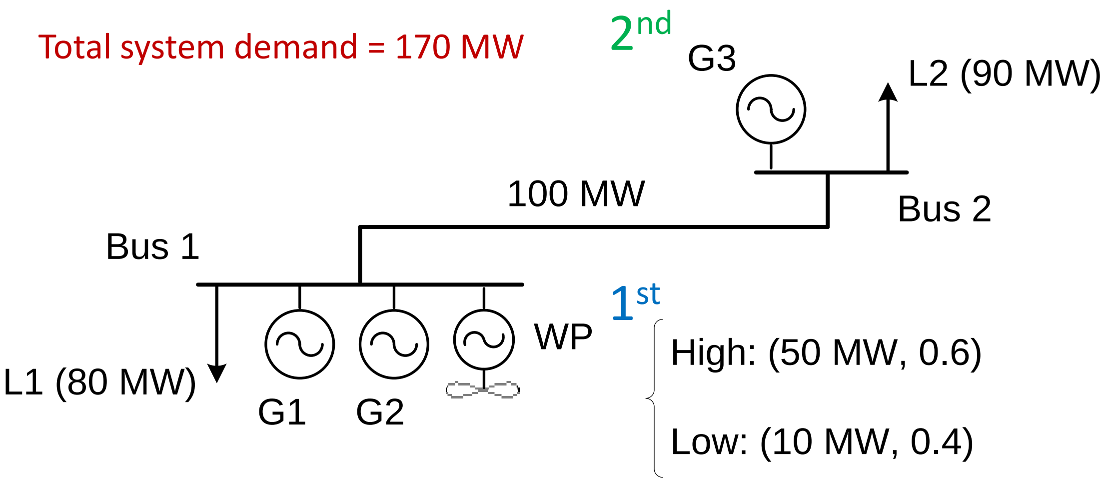
Decoupled

Unit	$P^{\max}$	C	P^{sch}
G1	100	35	0
G2	110	30	86
G3	50	10	50
WP	34	0	34

Powers in MW; costs in $/MWh

Clearing mechanism (Example)

Total system demand = 170 MW



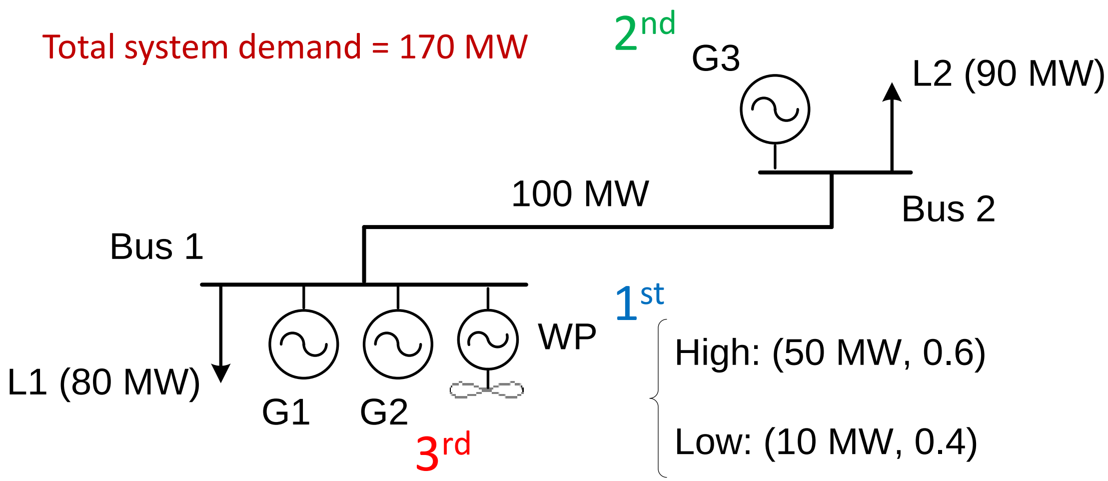
Decoupled

Unit	$P^{\max}$	C	P^{sch}
G1	100	35	0
G2	110	30	86
G3	50	10	50
WP	34	0	34

Powers in MW; costs in $/MWh

Clearing mechanism (Example)

Total system demand = 170 MW



Decoupled

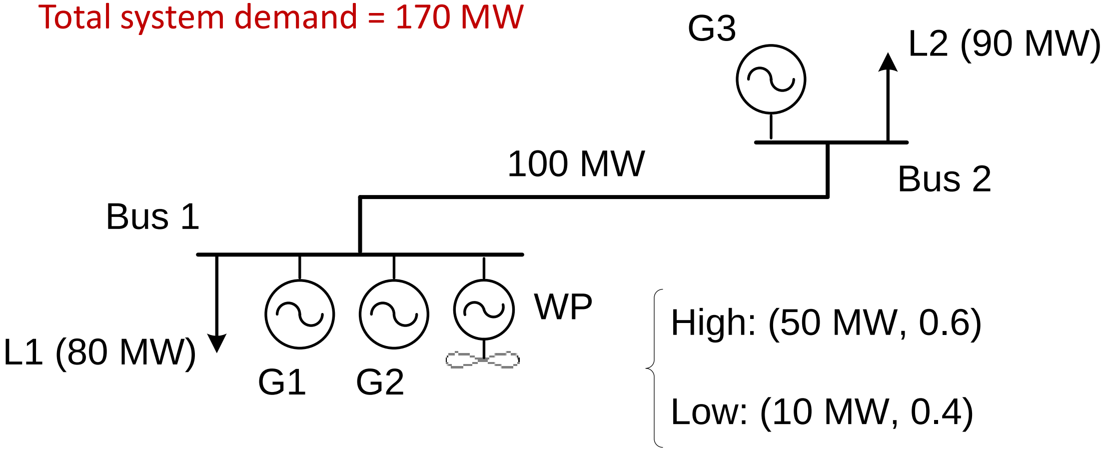
Unit	$P^{\max}$	C	P^{sch}
G1	100	35	0
G2	110	30	86
G3	50	10	50
WP	34	0	34

Powers in MW; costs in $/MWh

Units are dispatched following a **merit-order principle**

Clearing mechanism (Example)

Total system demand = 170 MW



Decoupled

Unit	$P^{\max}$	C	P^{sch}
G1	100	35	0
G2	110	30	86
G3	50	10	50
WP	34	0	34

Powers in MW; costs in $/MWh

- The wind producer is dispatched only to 10 MW
- G1 is dispatched to 40, even though it is more expensive than G2
- The “traditional” merit-order principle does not hold in “Coupled”
- G1 is dispatched to exploit its ability to reduce production in real time

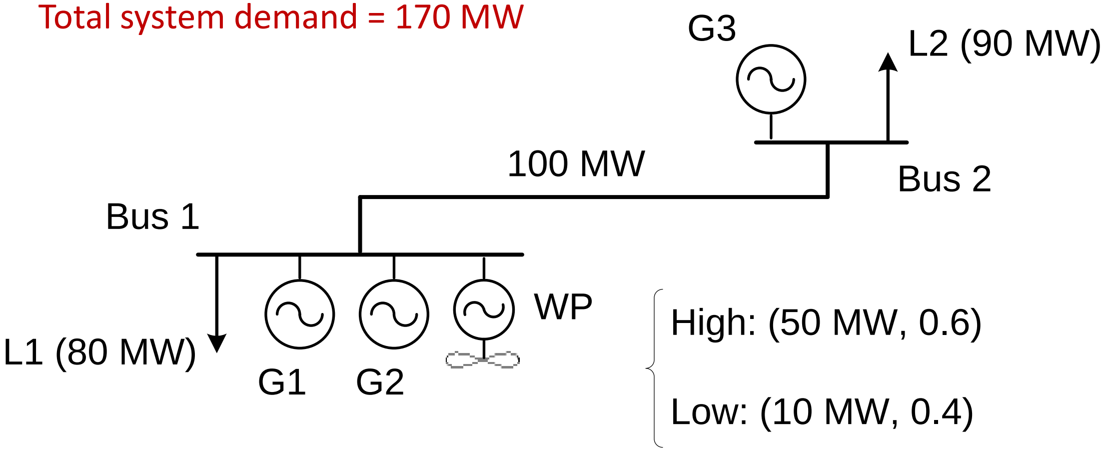
Coupled

Unit	$P^{\max}$	C	P^{sch}
G1	100	35	40
G2	110	30	70
G3	50	10	50
WP	34	0	10

Powers in MW; costs in $/MWh

Clearing mechanism (Example)

Total system demand = 170 MW



	Total	Day ahead	Balancing
Decoupled	3720	3080	740
Coupled	3184	4000	-826

"Coupled" results in a more expensive day-ahead dispatch that leads, however, to a much more efficient balancing operation

Decoupled

Unit	$P^{\max}$	C	P^{sch}
G1	100	35	0
G2	110	30	86
G3	50	10	50
WP	34	0	34

Powers in MW; costs in $/MWh

Coupled

Unit	$P^{\max}$	C	P^{sch}
G1	100	35	40
G2	110	30	70
G3	50	10	50
WP	34	0	10

Powers in MW; costs in $/MWh

Clearing mechanism (Prices & Revenues)

$$\begin{aligned}
&\underset{x^D}{\text{Minimize}} \quad C^D(x^D) \\
&\text{s.t.} \quad h^D(x^D) = 0 : \boxed{\lambda_n^D} \\
&\qquad\; x^D \in X^D
\end{aligned}$$

$$\Big\downarrow x^{D*}$$

$$\begin{aligned}
&\underset{x^B_{\omega'}}{\text{Minimize}} \quad C^B(x^B_{\omega'}, \omega') \\
&\text{s.t.} \quad h^B(x^B_{\omega'}, x^{D*}, \omega') = 0 : \boxed{\lambda^B_{n\omega'}} \\
&\qquad\; x^B_{\omega'} \in X^B(x^{D*}, \omega')
\end{aligned}$$

Decoupled

$$\begin{aligned}
&\underset{x^D, x^B_\omega}{\text{Minimize}} \quad C^D(x^D) + \mathrm{E}_\omega\left\{C^B(x^B_\omega, \omega)\right\} \\
&\text{s.t.} \quad h^D(x^D) = 0 : \boxed{\hat{\lambda}_n^D} \\
&\qquad\; x^D \in X^D \\
&\qquad\; h^B(x^B_\omega, x^D, \omega) = 0, \forall \omega \\
&\qquad\; x^B_\omega \in X^B(x^D, \omega), \forall \omega
\end{aligned}$$

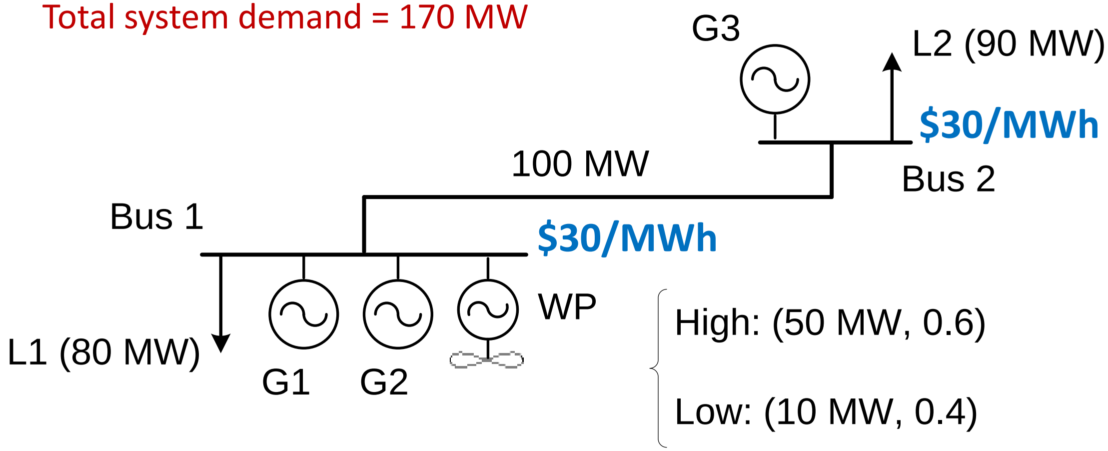
$$\Big\downarrow x^{D*}$$

$$\begin{aligned}
&\underset{x^B_{\omega'}}{\text{Minimize}} \quad C^B(x^B_{\omega'}, \omega') \\
&\text{s.t.} \quad h^B(x^B_{\omega'}, x^{D*}, \omega') = 0 : \boxed{\lambda^B_{n\omega'}} \\
&\qquad\; x^B_{\omega'} \in X^B(x^{D*}, \omega')
\end{aligned}$$

Coupled

Clearing mechanism
(Example: Day-ahead market prices)

Total system demand = 170 MW



Decoupled

Unit	P^{max}	C	P^{sch}
G1	100	35	0
G2	110	30	86
G3	50	10	50
WP	34	0	34

Powers in MW; costs in $/MWh

Coupled

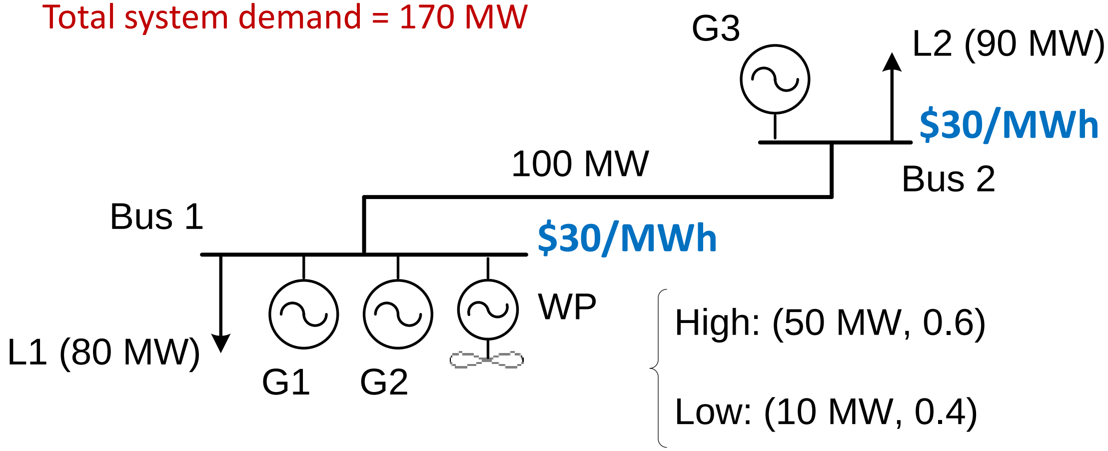
Unit	P^{max}	C	P^{sch}
G1	100	35	40
G2	110	30	70
G3	50	10	50
WP	34	0	10

Powers in MW; costs in $/MWh

In “Coupled” unit G1 is dispatched day ahead in a **loss-making position**

Clearing mechanism
(Example: Day-ahead market prices)

Total system demand = 170 MW



Profit G1	Expected	Per scenario	
		High	Low
Decoupled	1320	0	3300
Coupled	24	173.33	-200

In "Coupled" unit G1 incur losses if scenario "low" happens

Decoupled

Unit	P^{max}	C	P^{sch}
G1	100	35	0
G2	110	30	86
G3	50	10	50
WP	34	0	34

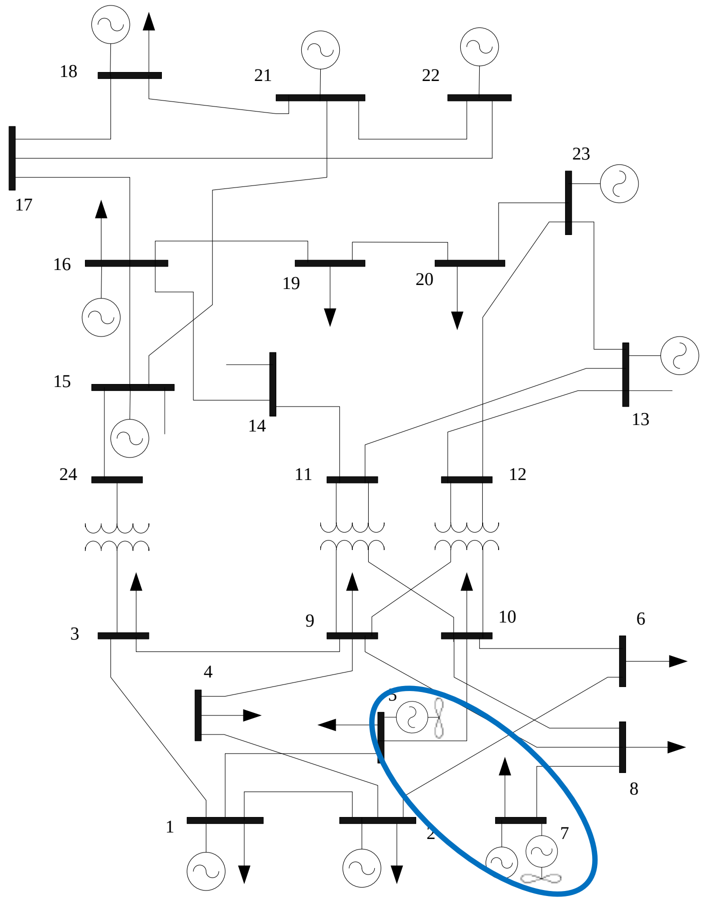
Powers in MW; costs in $/MWh

Coupled

Unit	P^{max}	C	P^{sch}
G1	100	35	40
G2	110	30	70
G3	50	10	50
WP	34	0	10

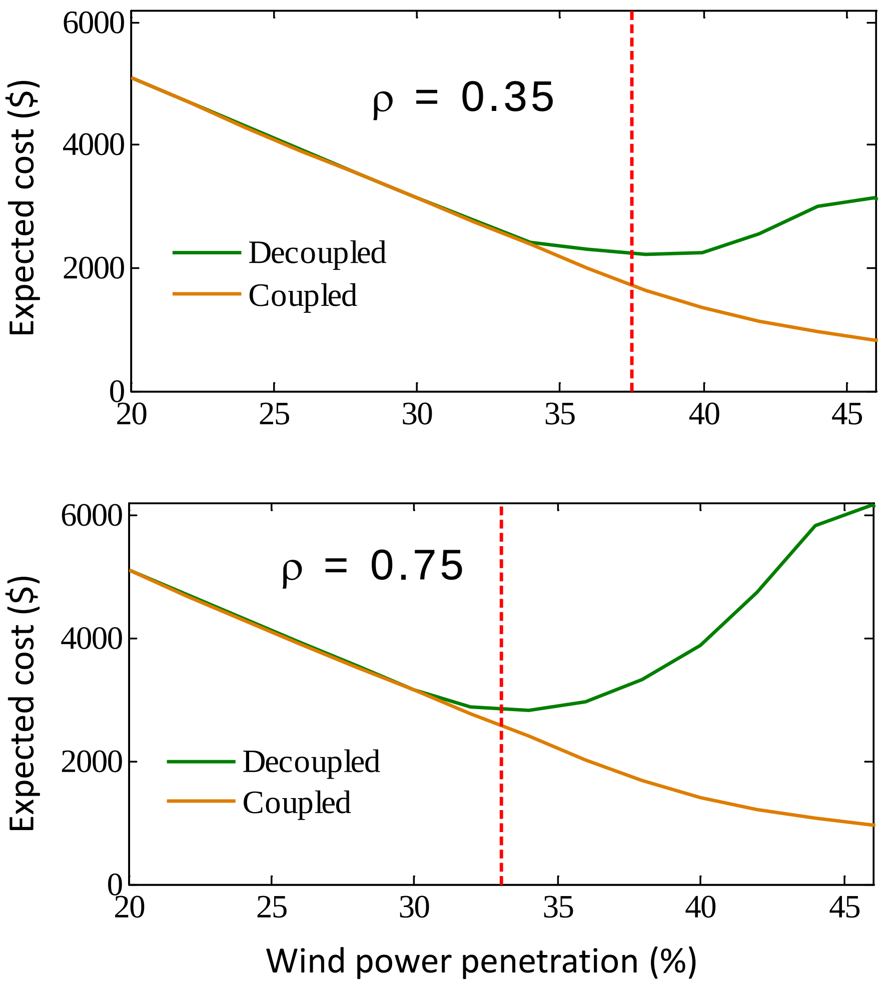
Powers in MW; costs in $/MWh

Clearing mechanism (24-bus Case Study)



- Based on the IEEE Reliability test System
- Total system demand = 2000 MW
- Per-unit wind power productions are modeled using Beta distributions with a correlation coefficient ρ

Clearing mechanism (24-bus Case Study)



- Under “coupled”, stochastic production “never” leads to an increase in the expected cost
- “Coupled” is barely affected by the spatial correlation of stochastic energy sources

Clearing mechanism (24-bus Case Study)

Wind penetration 38% $\rho = 0.35$		Unit			
		1	6	11	12
Coupled	Expected profit ($)	47.9	49.4	102.2	67.4
	Avearge losses ($)	–14.9	–10.7	–16.5	–9.7
	Probability profit < 0	0.81	0.71	0.71	0.75

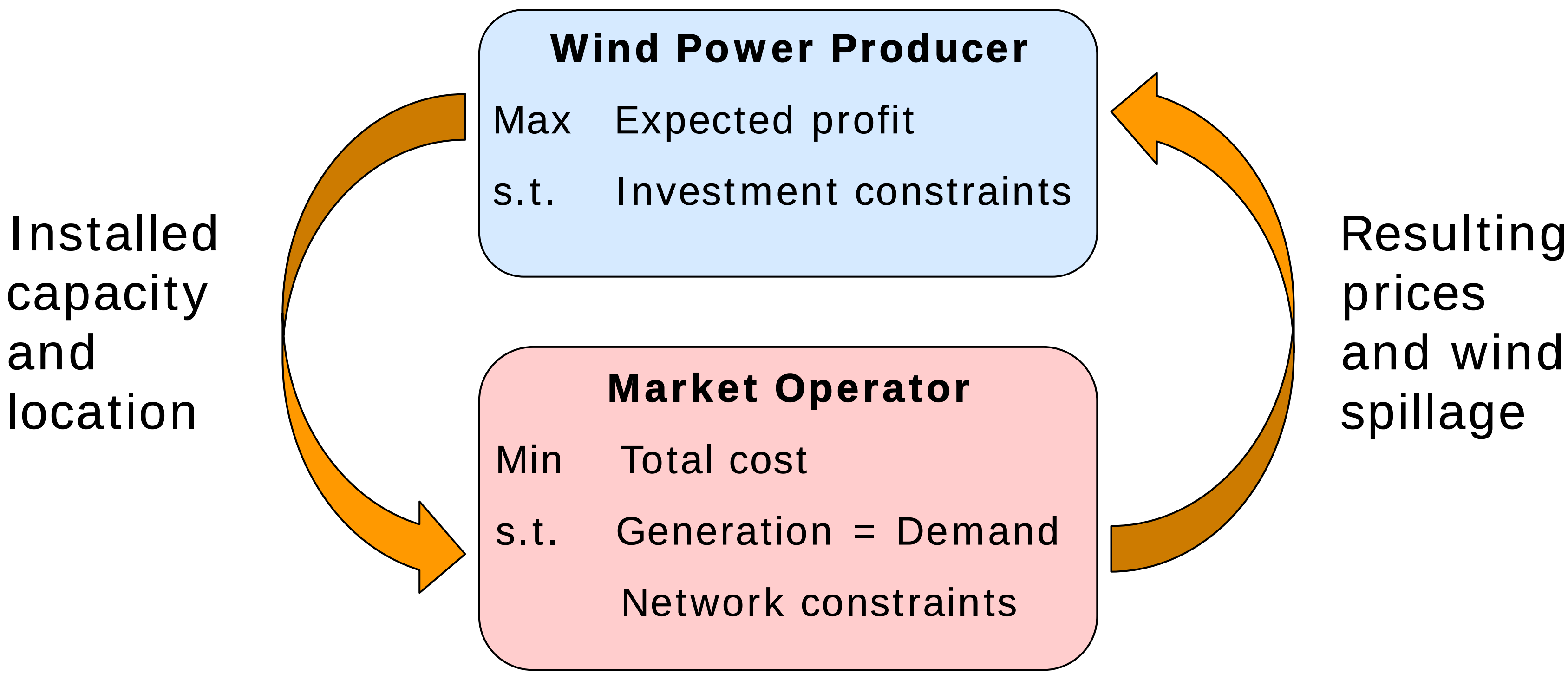
"Coupled" guarantees revenue reconciliation in expectation for both the system and market participants, but not per scenario

Clearing mechanism
(Conclusions)

- Clearing mechanism for the day-ahead market that accounts for the expected balancing costs using stochastic programming
- It uses information on units' flexibility and relies on a probabilistic model for stochastic generation (centralized forecasting tool)
- It manages to decrease system total costs and reduce price volatility by breaking the "traditional" merit-order principle
- It guarantees revenue adequacy in expectation, but not per scenario, which poses the following questions:
    - Are flexible producers willing to take the risk?
    - What if the probabilistic model for stochastic generation is not well calibrated?

Impact on investments

Wind power investment model



Impact on investments

Bi-level optimization problem (MPEC)

Wind Power Producer

Max Expected profit

s.t. Investment constraints

Market Operator

Min Total cost

s.t. Generation = Demand

Network constraints

Impact on investments

Impact of imbalance costs ⇒ day-ahead + balancing markets

Wind Power Producer

Max Expected profit (day-ahead + balancing)

s.t. Investment constraints

Day-ahead market

Min Day-ahead cost

s.t. Gen + Exp.Wind = Dem

Network constraints

Balancing market

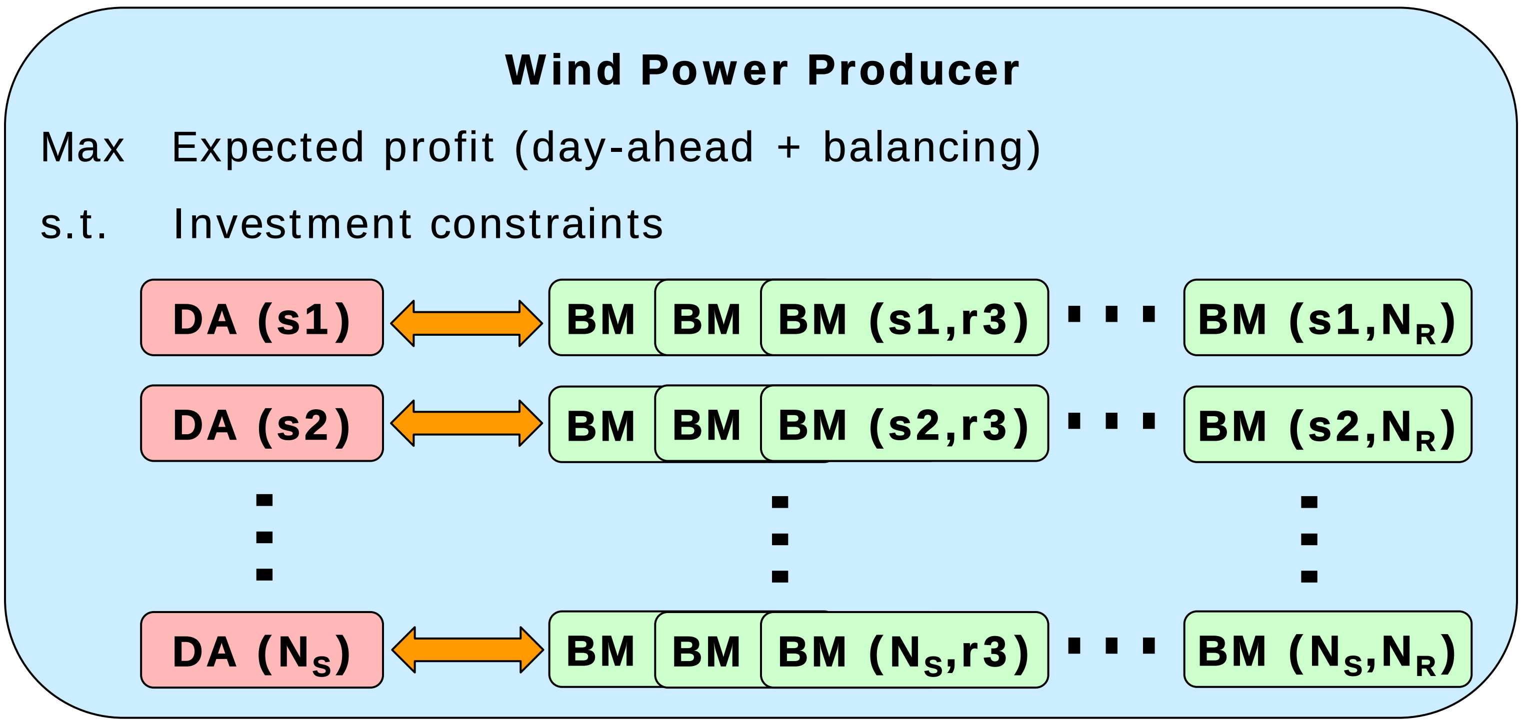
Min Balancing cost

s.t. ΔGen + ΔWind = ΔDem

Network constraints

Impact on investments

Impact of imbalance costs $\Rightarrow$ day-ahead + balancing markets



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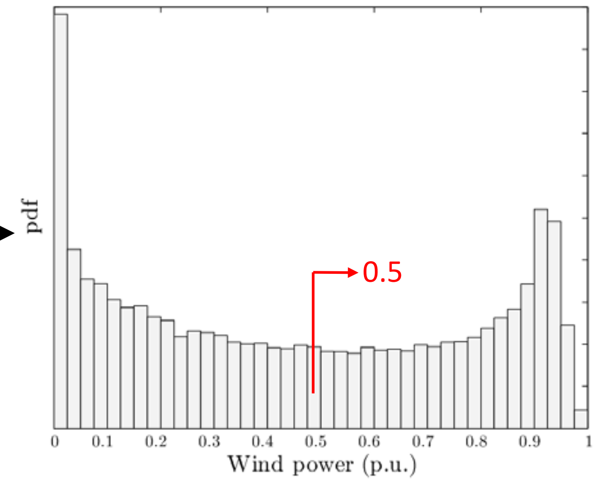
Impact on investments

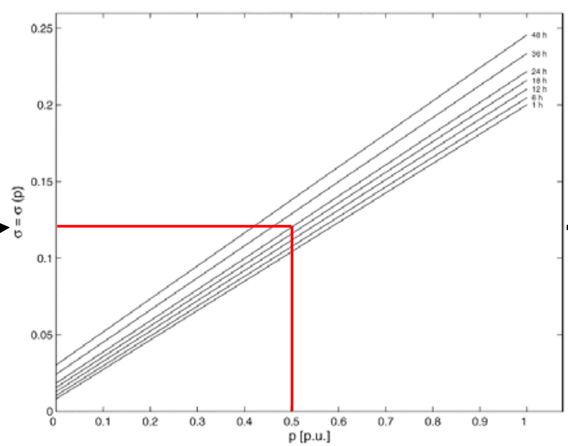
Modeling of wind forecast errors

Historical data



[Fabbri et al. (2005)]

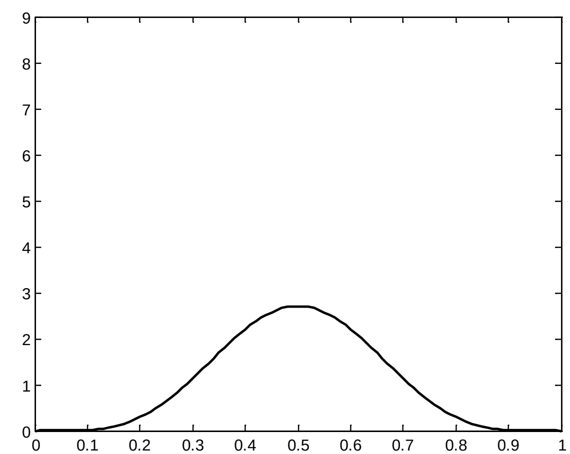
p=0.5



p=0.5
σ=0.12

Beta distribution

[Fabbri et al. (2005)]



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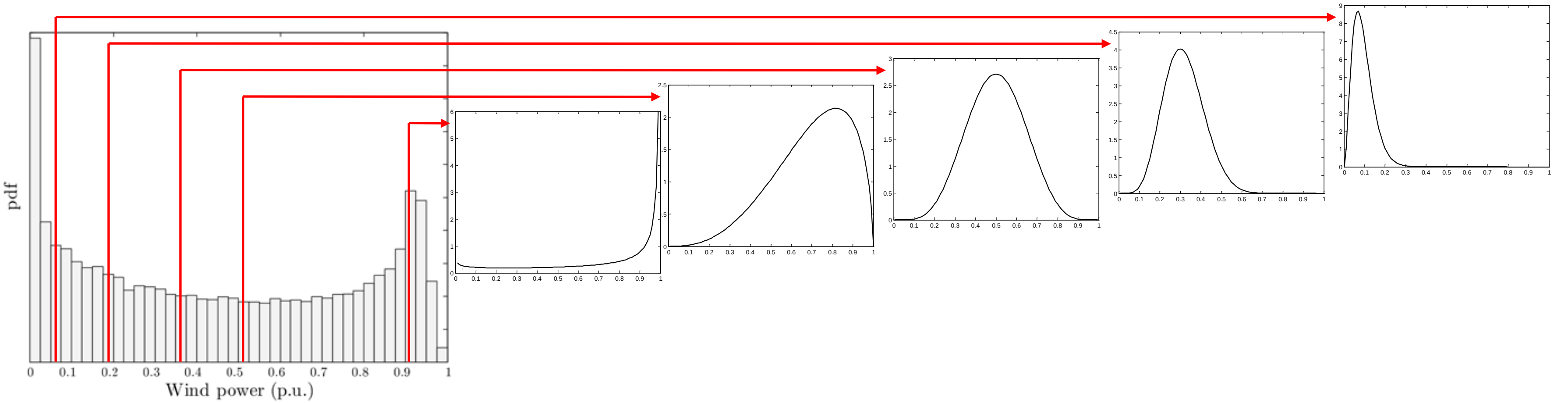
Impact on investments

Modeling of wind forecast errors

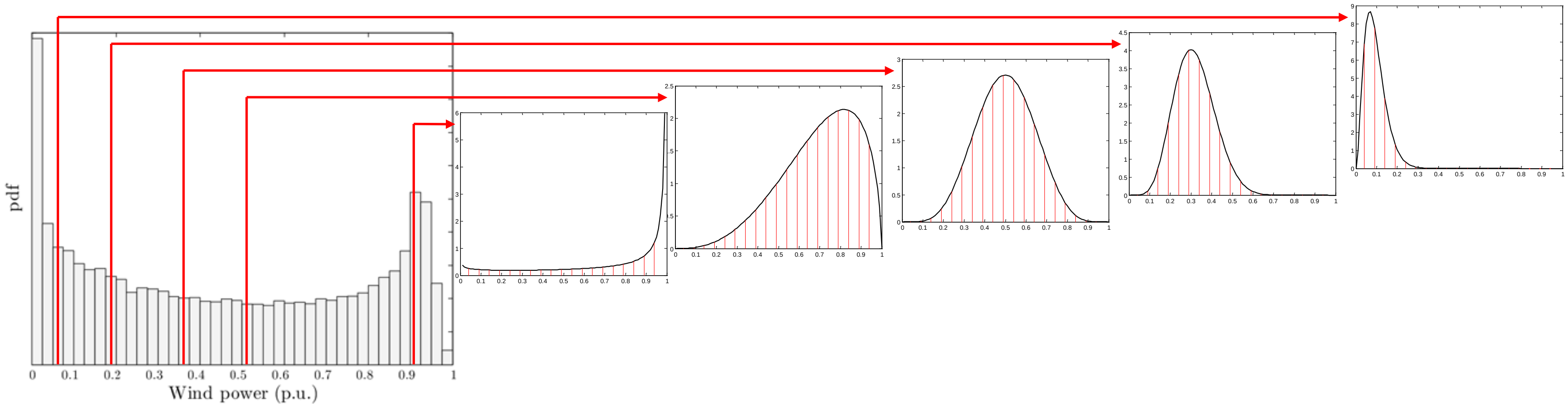
MC



Impact on investments

Modeling of wind forecast errors

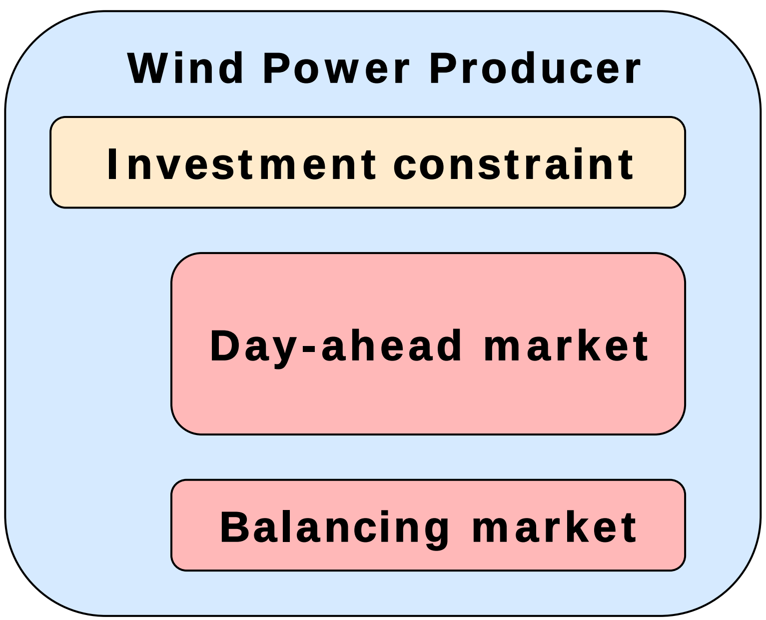
MC



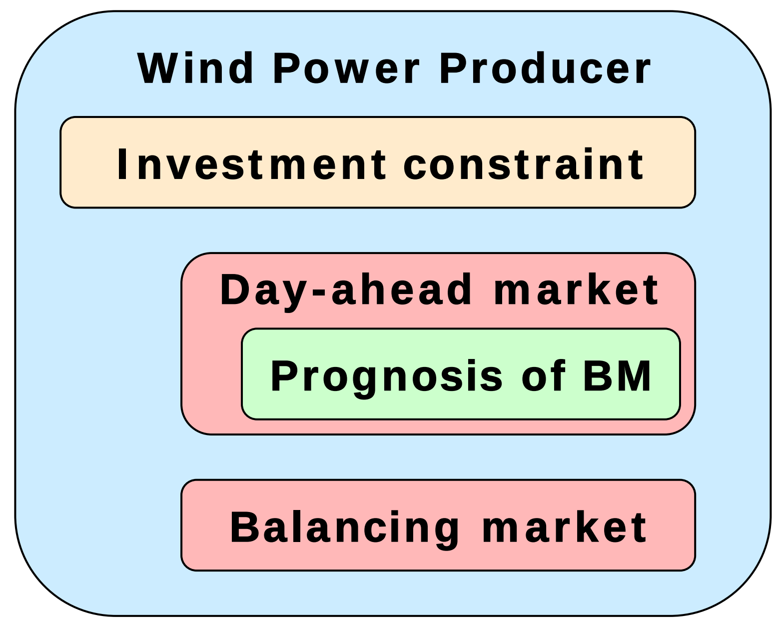
Impact on investments

Impact of market design

Decoupled

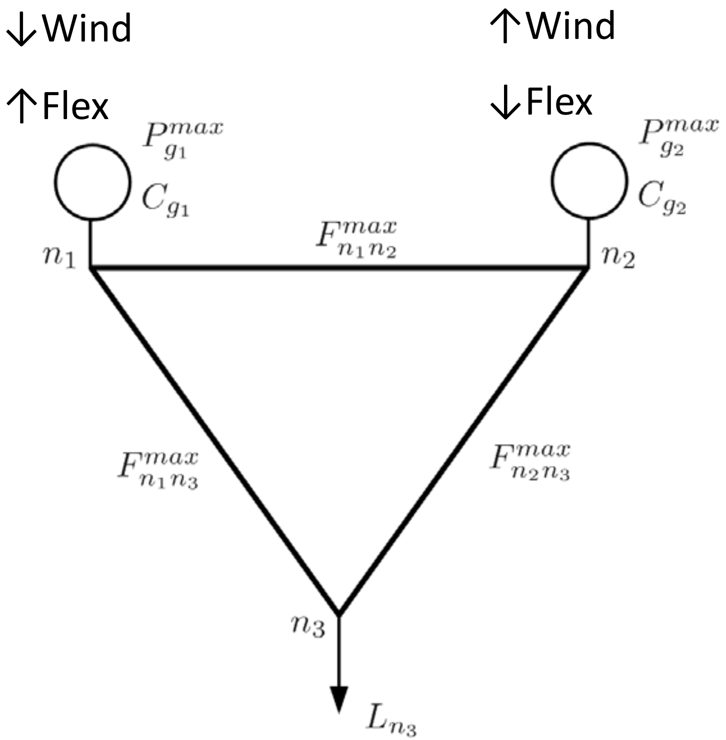


Coupled



Impact on investments (Example)

Data



Units						
g	P_g^{max}	C_g	$P_g^{max,u}$	C_g^u	$P_g^{max,d}$	C_g^d
g_1	150	20	50	21	50	19
g_2	500	20.1	50	50	50	5

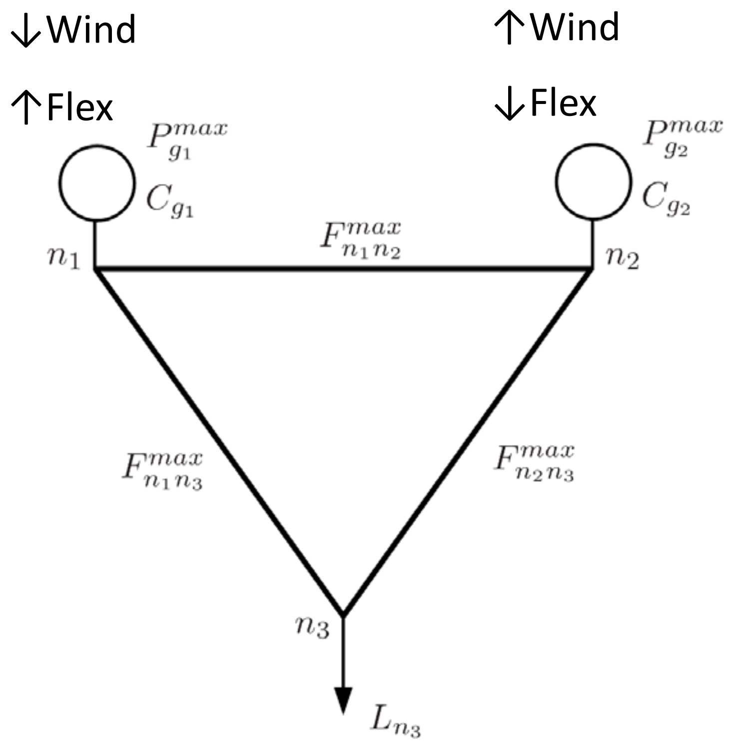
Lines			Wind					Prob	
nm	F_{nm}^{max}	B_{nm}	n	$\widehat{W}_{ns_1}$	$\widetilde{W}_{ns_1r_1}$	$\widetilde{W}_{ns_1r_2}$	$\widetilde{W}_{ns_1r_3}$	r	π_{s_1r}
n_1n_2	10	7.69	n_1	0.6	-Δ	0	+Δ	r_1	0.4
n_1n_3	250	7.69	n_2	0.7	-Δ	0	+Δ	r_2	0.2
n_2n_3	250	7.69	n_3	-	-	-	-	r_3	0.4

$$L_{n_3} = 225\text{MW}$$

$$P_{w_1'}^{max} = 50\text{MW}$$

Impact on investments (Example)

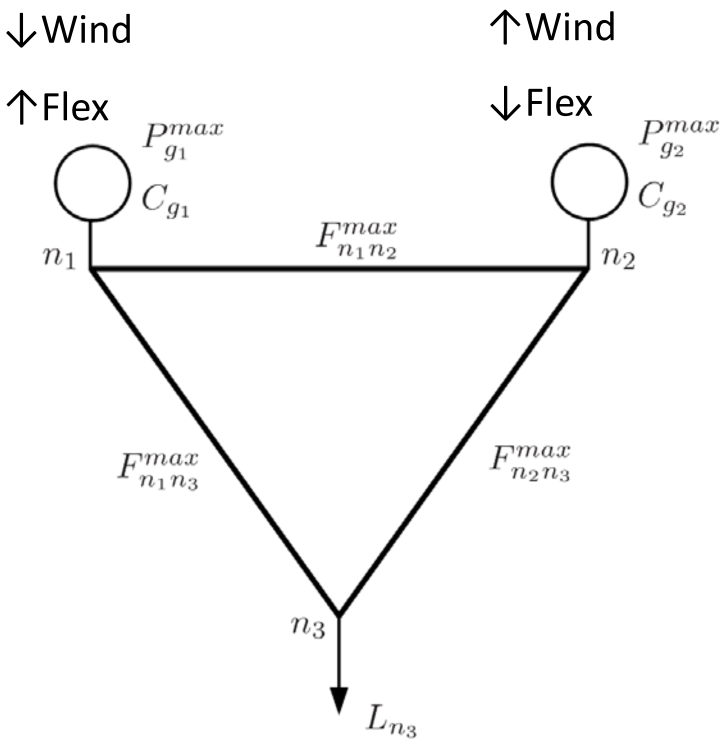
Results: Impact of forecast errors



Dec	Bus1	Bus2
Δ=0.1	DA profit = \$600 B profit = -\$4 Total profit = \$596	DA profit = \$704 B profit = -\$62 Total profit = \$642

Impact on investments (Example)

Results: Impact of forecast errors

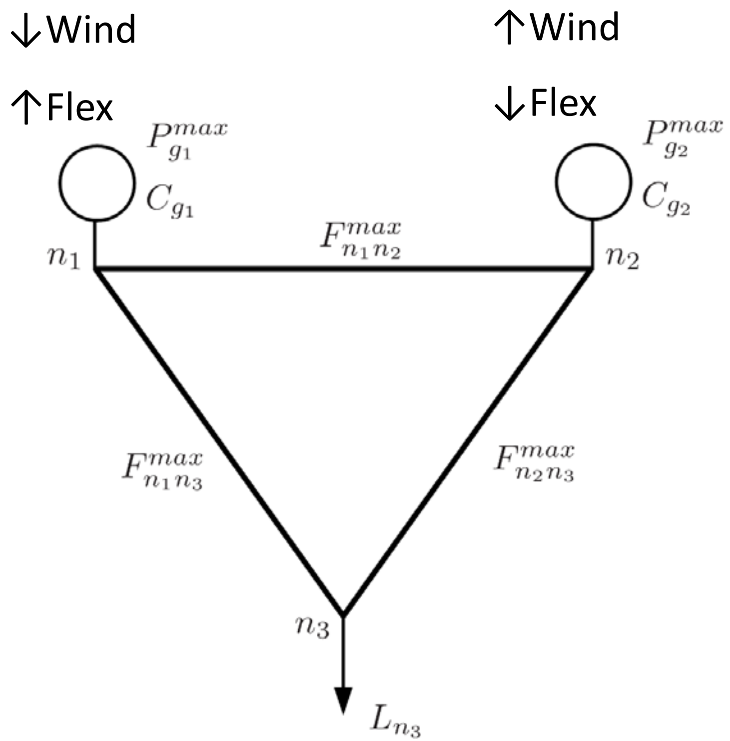


Dec	Bus1	Bus2
Δ=0.1	DA profit = \$600 B profit = -\$4 Total profit = \$596	DA profit = \$704 B profit = -\$62 Total profit = \$642
Δ=0.3	DA profit = \$600 B profit = -\$12 Total profit = \$588	DA profit = \$704 B profit = -\$186 Total profit = \$518

Forecast errors may have a significant impact on wind investment decisions

Impact on investments (Example)

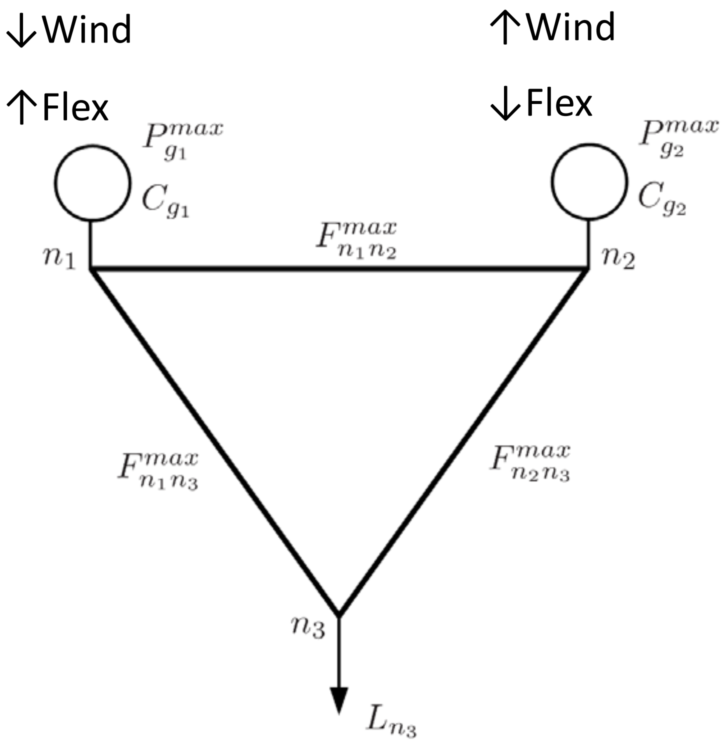
Results: Impact of market design



Δ=0.3	Bus1	Bus2
Dec	DA profit = \$600 B profit = -\$12 Total profit = \$588	DA profit = \$704 B profit = -\$186 Total profit = \$518

Impact on investments (Example)

Results: Impact of market design



Δ=0.3	Bus1	Bus2
Dec	DA profit = \$600 B profit = -\$12 Total profit = \$588	DA profit = \$704 B profit = -\$186 Total profit = \$518
Coup	DA profit = \$600 B profit = -\$12 Total profit = \$588	DA profit = \$704 B profit = -\$14 Total profit = \$690

The wind producer achieves a higher profit with the Coup market clearing

Impact on investments (Conclusions)

- Imbalance cost is an important factor to be accounted for in wind power generation expansion

- The coupled market clearing reduces the imbalance costs of stochastic generation and facilitates the investment in new wind farms

Thanks for your attention!

Questions?

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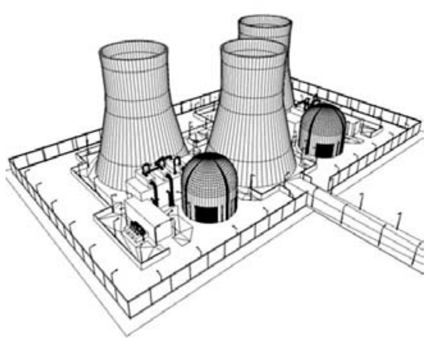
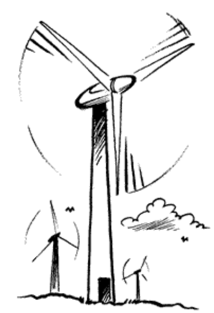
Problem description
(Motivation)

Day-ahead market



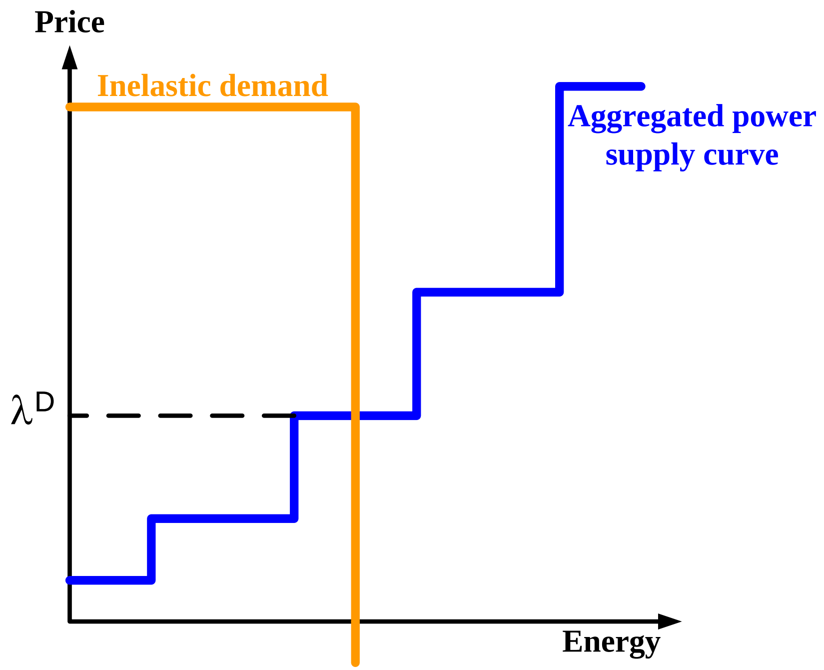
Balancing market



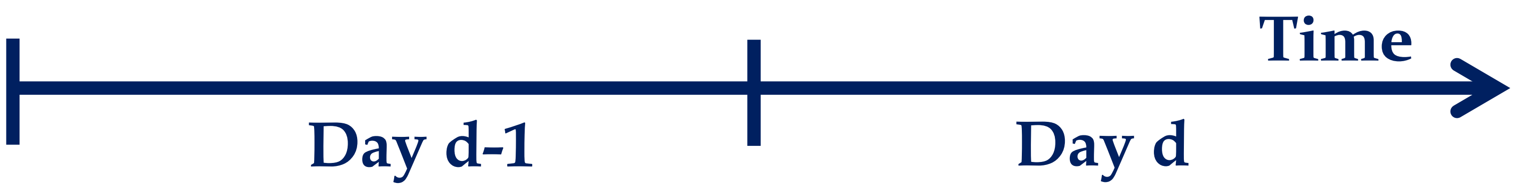
Inflexible units
(need advance planning)

Wind producers/consumers
(need balancing energy)

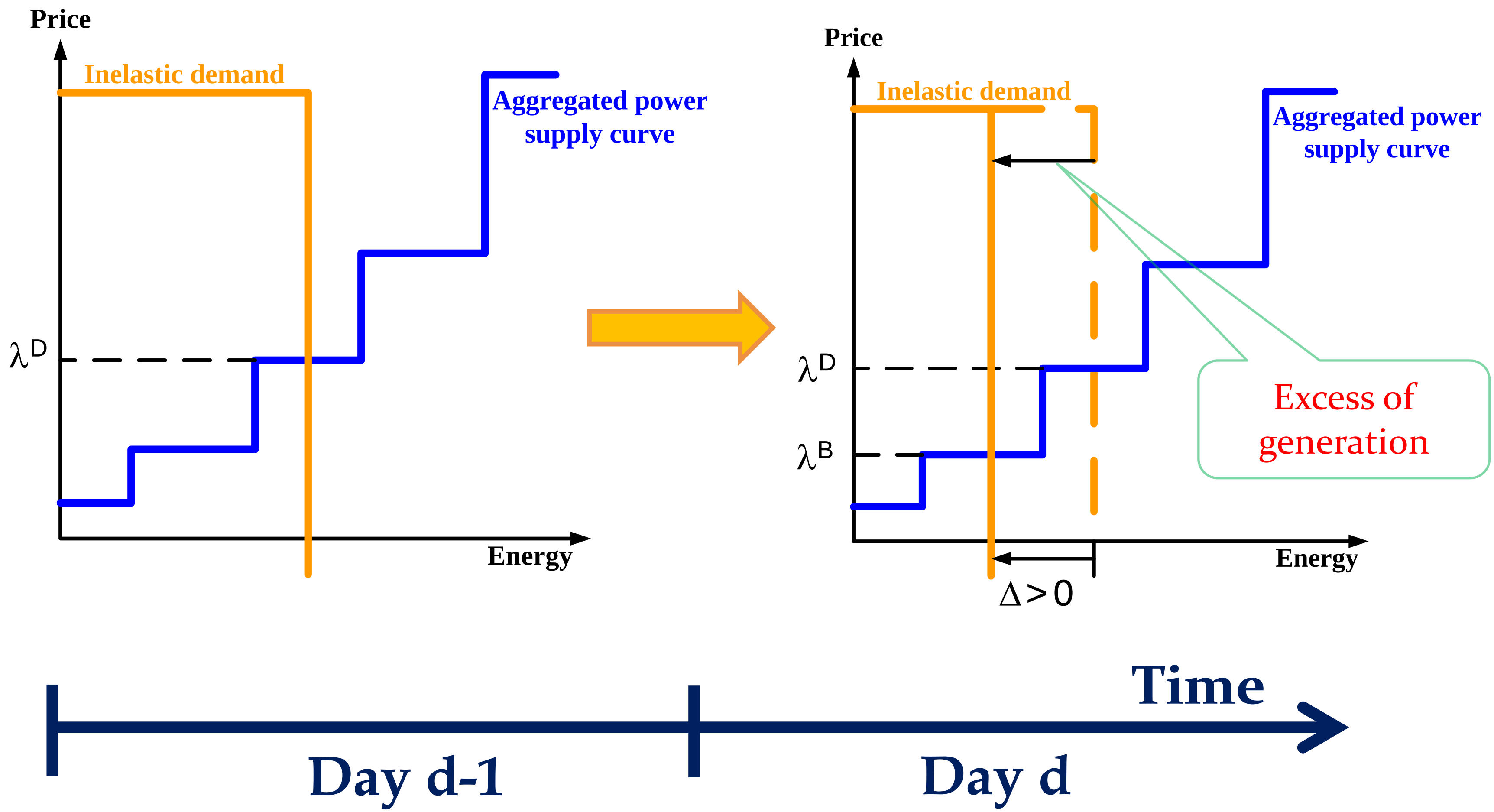
Problem description
(Motivation)



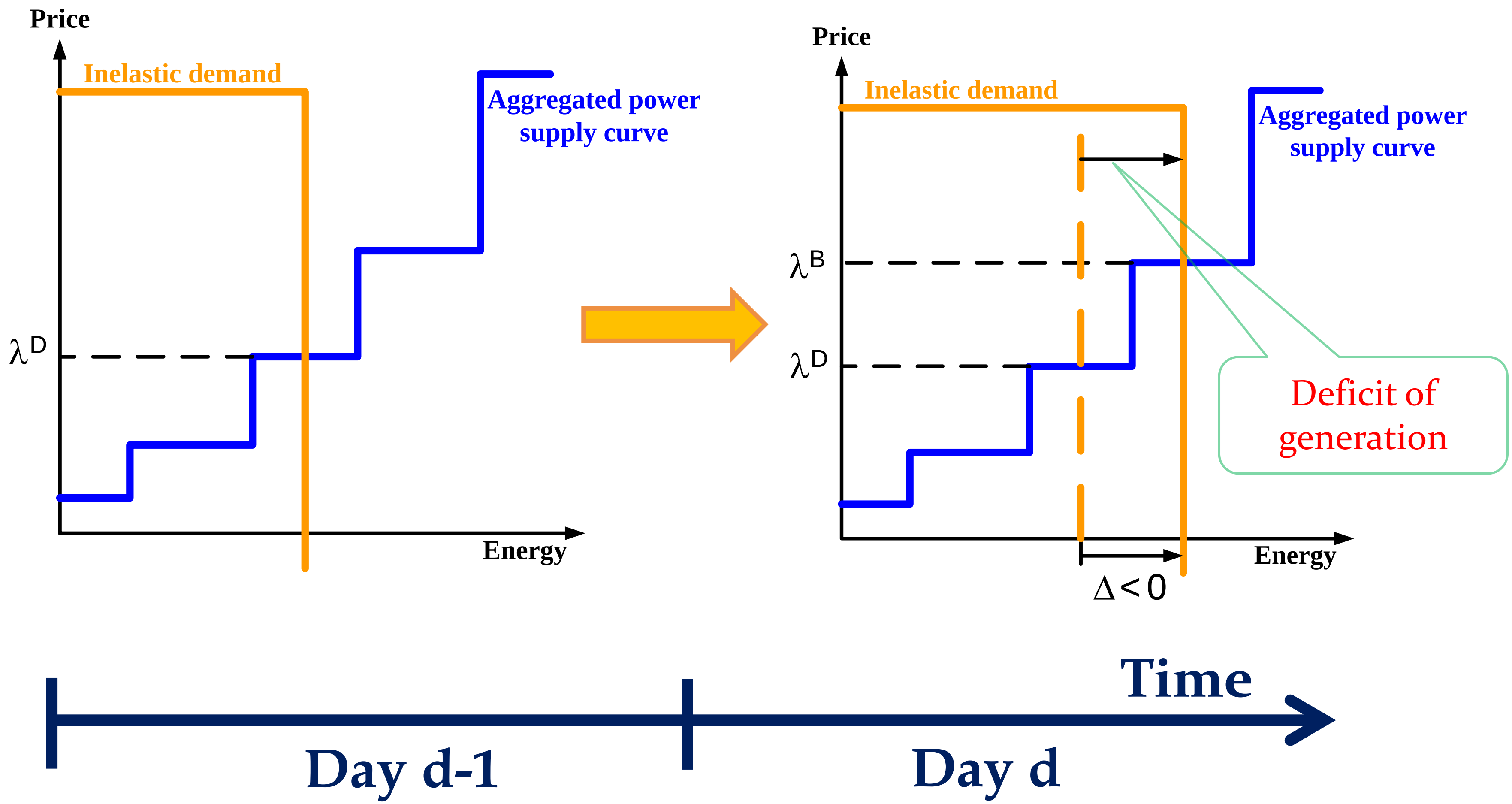
Merit-order principle



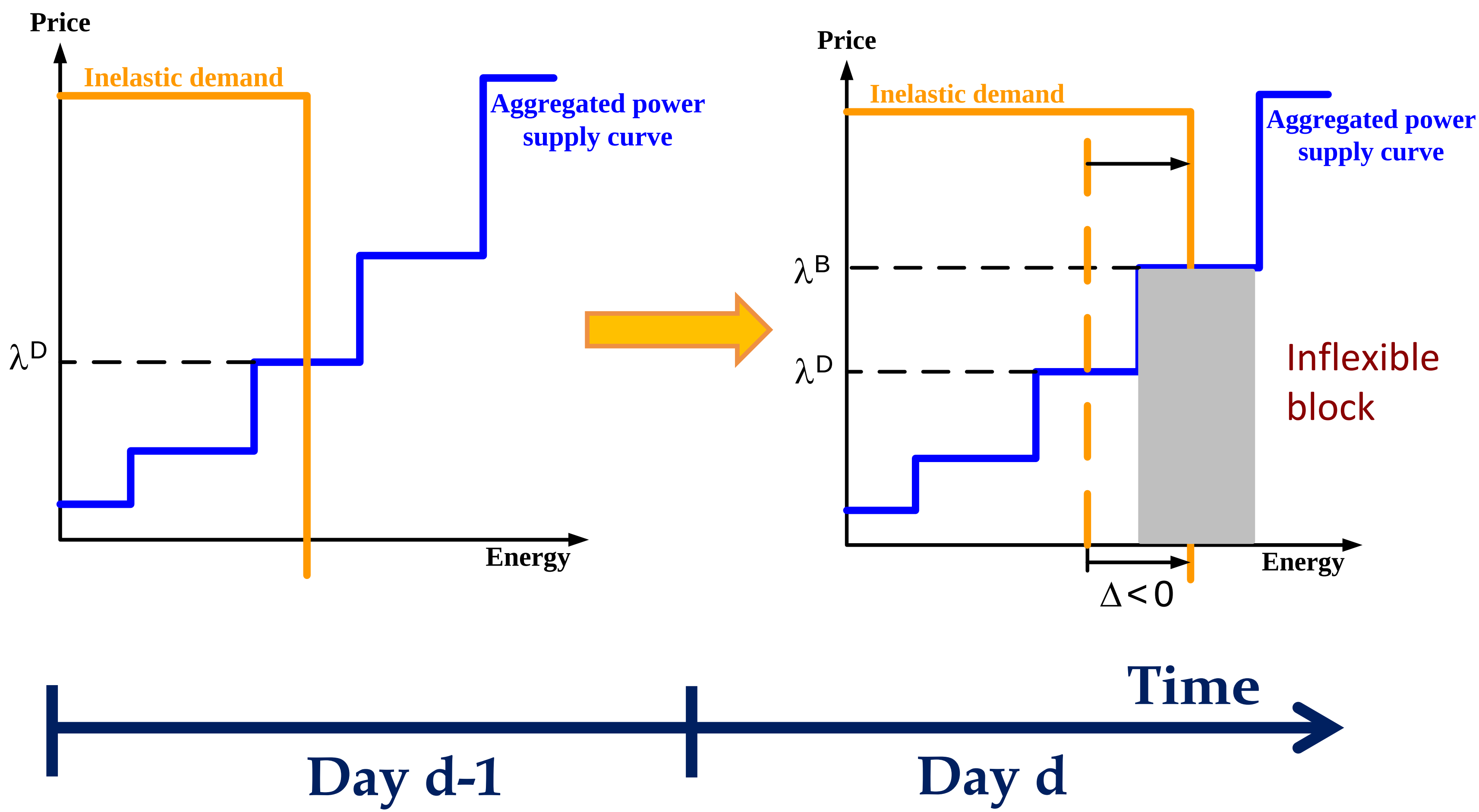
Problem description
(Motivation)



Problem description (Motivation)



Problem description (Motivation)



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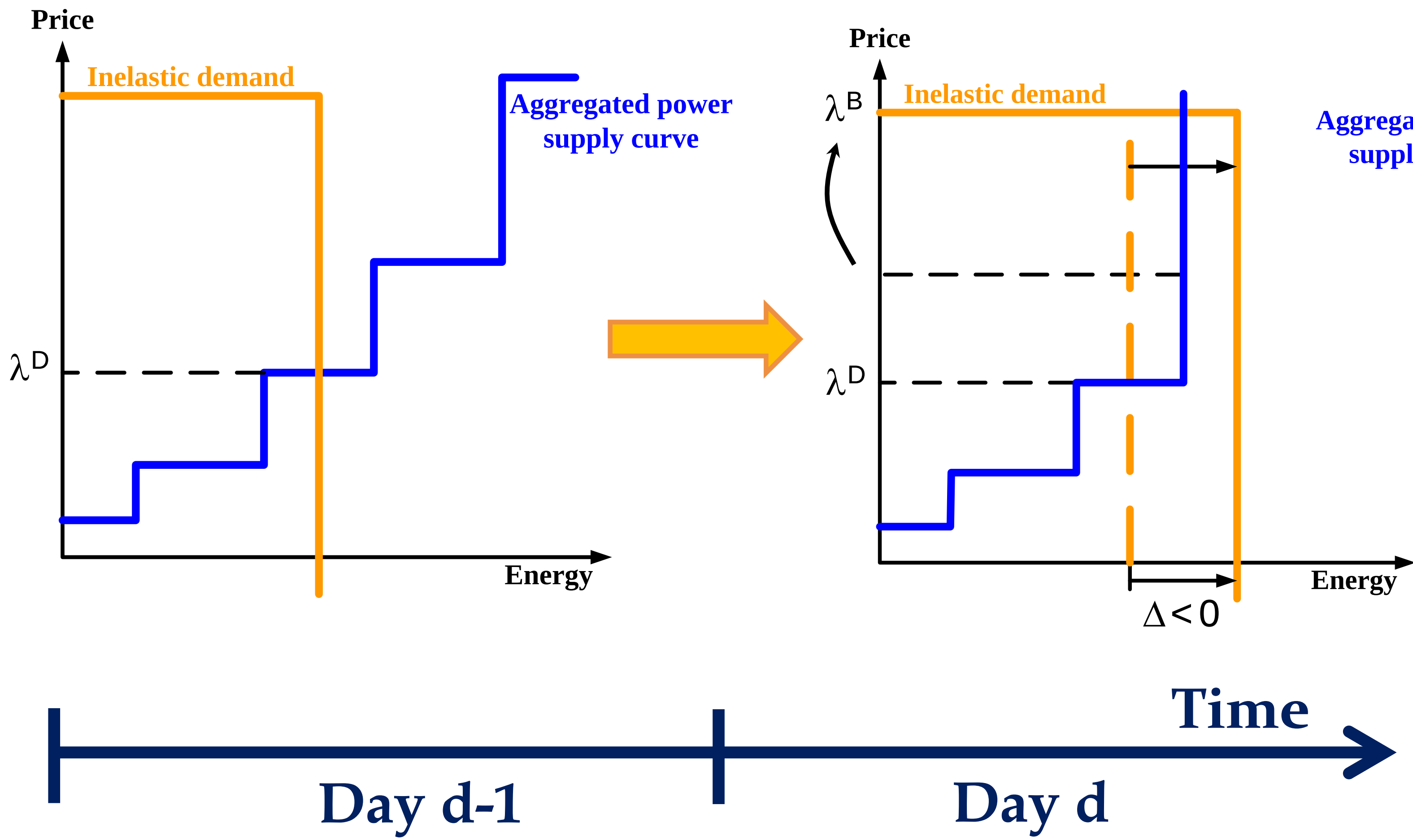
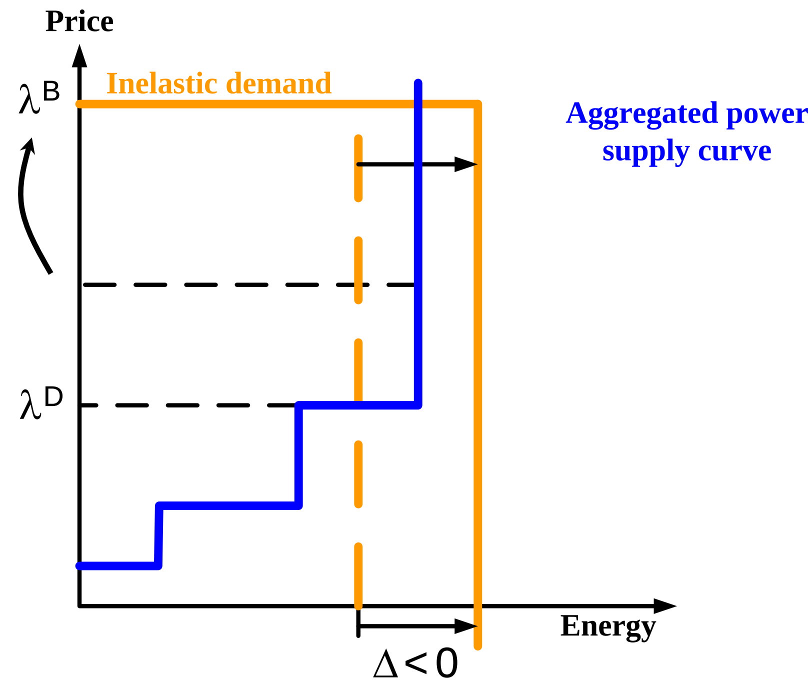
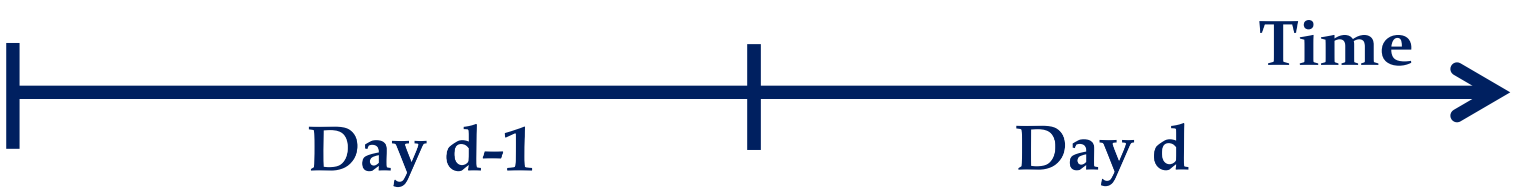
Problem description
(Motivation)



Problem description (Motivation)

- Uncertainty $\uparrow$ (stochastic production $\uparrow$) and flexibility $\downarrow$ $\Rightarrow$ Balancing costs $\uparrow$
- The forward dispatch has an impact on balancing costs

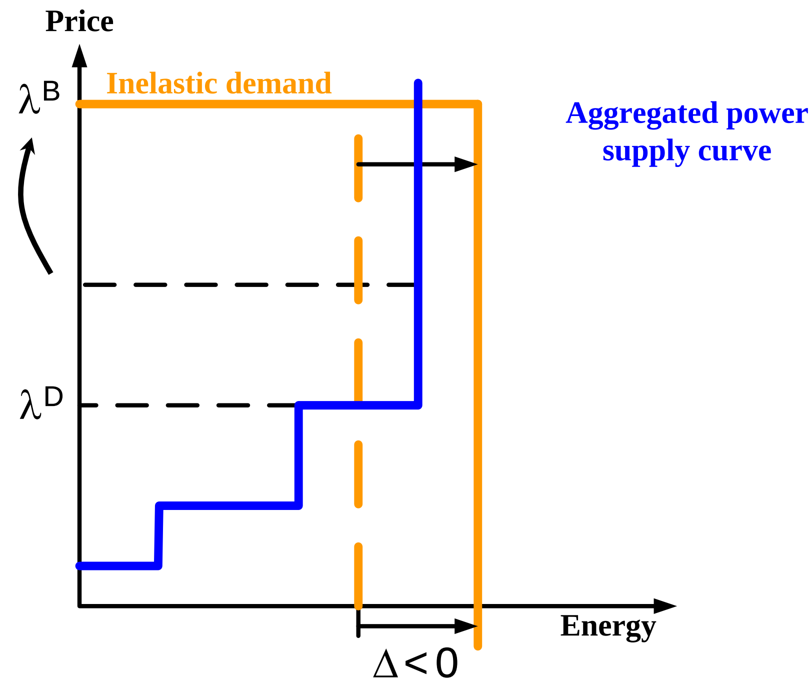


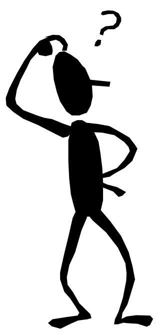


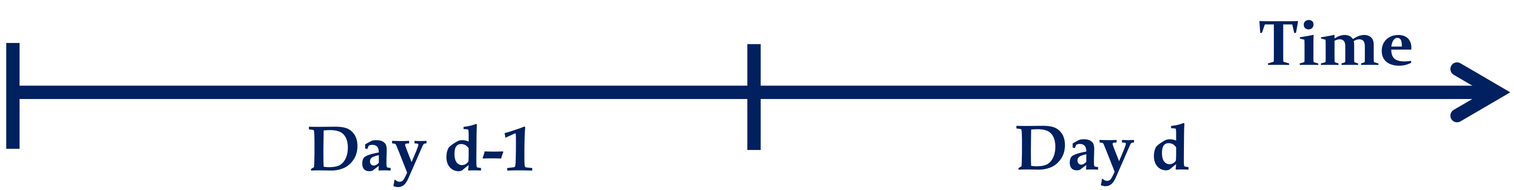
Problem description (Motivation)

- Uncertainty ↑ (stochastic production ↑) and flexibility ↓ ⇒ Balancing costs ↑

- The forward dispatch has an impact on balancing costs







Clearing mechanism (Prices & Revenues)

- $\dfrac{\gamma_{n\omega}}{\pi_\omega}$ is dual optimal for the balancing problem (Wong and Fuller 2007)

- $\dfrac{\gamma_{n\omega}}{\pi_\omega}$ is a prediction of the balancing market price in ω

- The set of prices $\left\{\hat{\lambda}_n^D, \dfrac{\gamma_{n\omega}}{\pi_\omega}\right\}$ are expected profit maximizing

π_ω : probability of occurrence of scenario ω

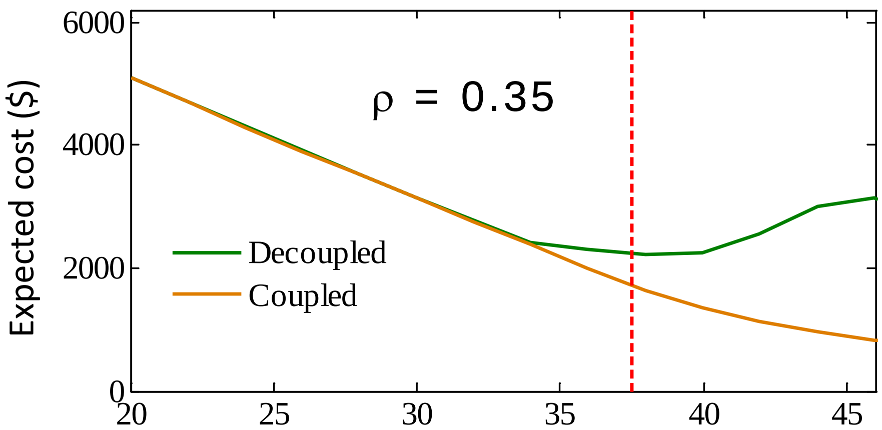
$$
\begin{aligned}
\underset{x^D, x^B_\omega}{Minimize} \quad & C^D(x^D) + \mathrm{E}_\omega \left\{ C^B(x^B_\omega, \omega) \right\} \\
s.t. \quad & h^D(x^D) = 0 : \boxed{\hat{\lambda}_n^D} \\
& x^D \in X^D \\
& h^B(x^B_\omega, x^D, \omega) = 0, \ \forall \omega : \boxed{\gamma_{n\omega}} \\
& x^B_\omega \in X^B(x^D, \omega), \ \forall \omega
\end{aligned}
$$

$$\Big\downarrow \, x^{D*}$$

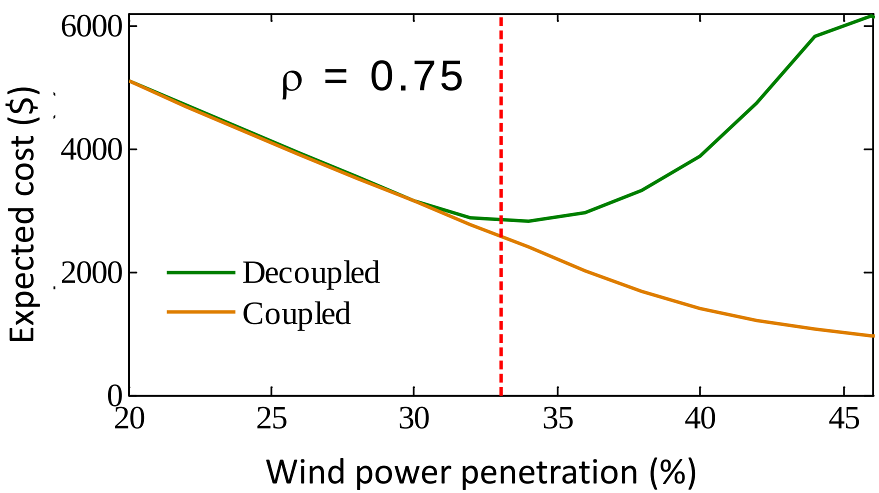
$$
\begin{aligned}
\underset{x^B_{\omega'}}{Minimize} \quad & C^B(x^B_{\omega'}, \omega') \\
s.t. \quad & h^B(x^B_{\omega'}, x^{D*}, \omega') = 0 : \boxed{\lambda^B_{n\omega'}} \\
& x^B_{\omega'} \in X^B(x^{D*}, \omega')
\end{aligned}
$$

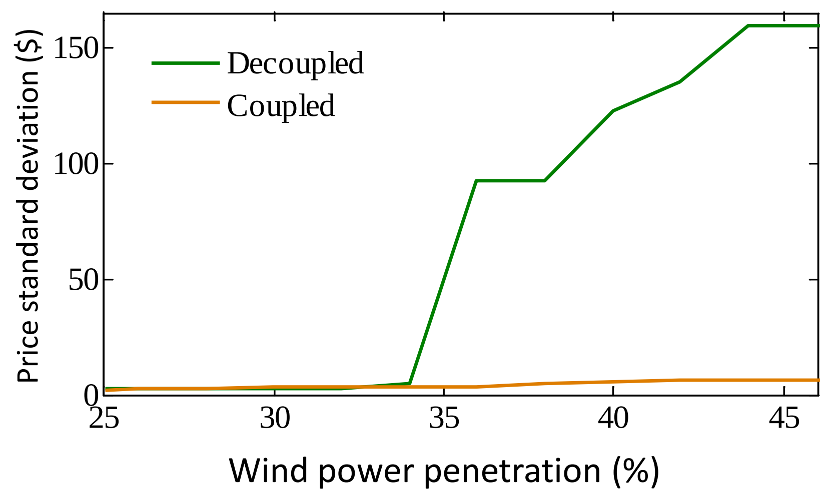
Coupled

Clearing mechanism (24-bus Case Study)



- Under "coupled", stochastic production "never" leads to an increase in the expected cost
- "Coupled" is barely affected by the spatial correlation of stochastic energy sources
- "Coupled" produces more stable real-time market prices





Clearing mechanism (Future work)

- The balancing prognosis may be focused on the worst-case scenario (robust optimization)
- Analysis of the impact of modeling errors on revenue adequacy, expected costs, prices, etc.
- An extended framework to control the degree of coupling between day-ahead and balancing dispatch decisions
- The balancing prognosis might only affect a group of agents (e.g. the stochastic producers)
- J. M. Morales, M. Zugno, P. Pinson, S. Pineda. Electricity Market Clearing Under Uncertainty: A Bilevel Programming Framework, under review