Optimal Location of Wind Power Capacity: A Point-estimate Solution Approach

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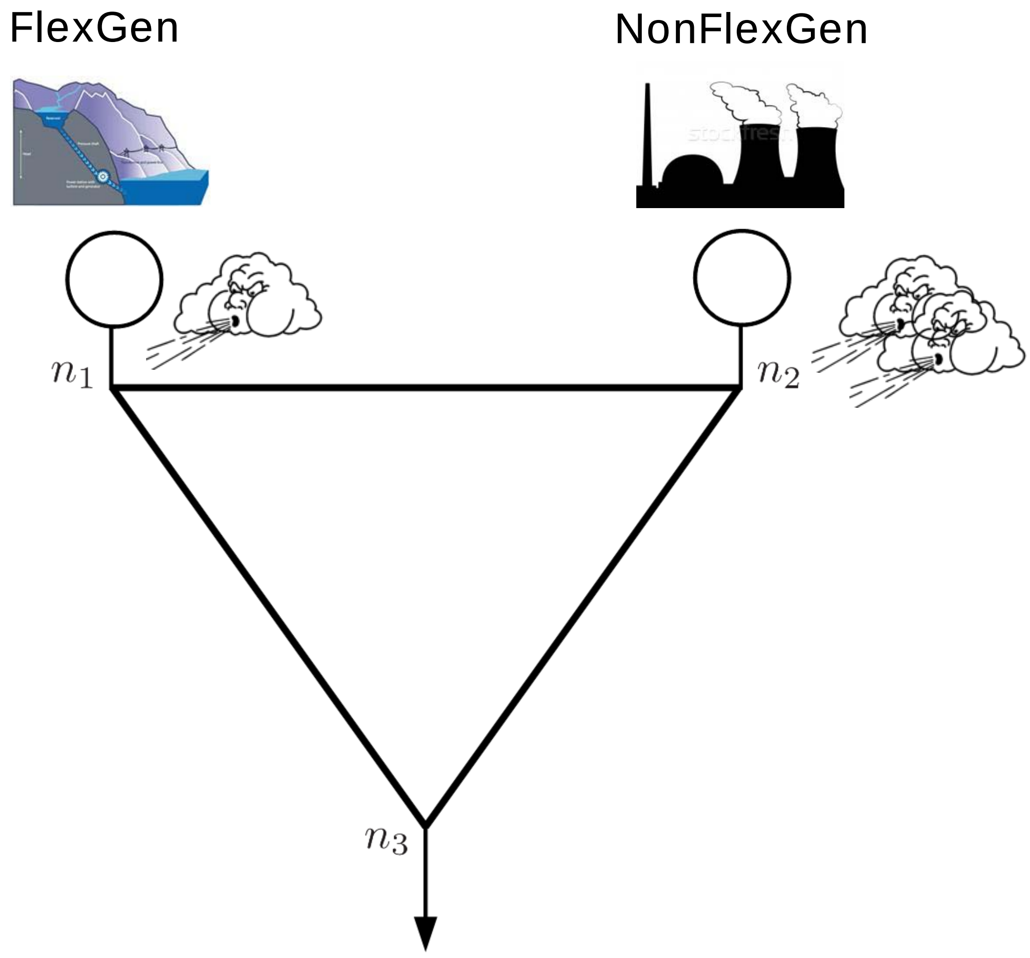
Motivation



The model

- How can a wind power investment model be formulated?
- How can imbalance costs be included in the investment decisions of a wind power producer?
- How can we evaluate the impact of the market design on wind investment decisions?
- How do we model wind forecast errors?
- How can the computational burden of large-scale investment models be reduced?

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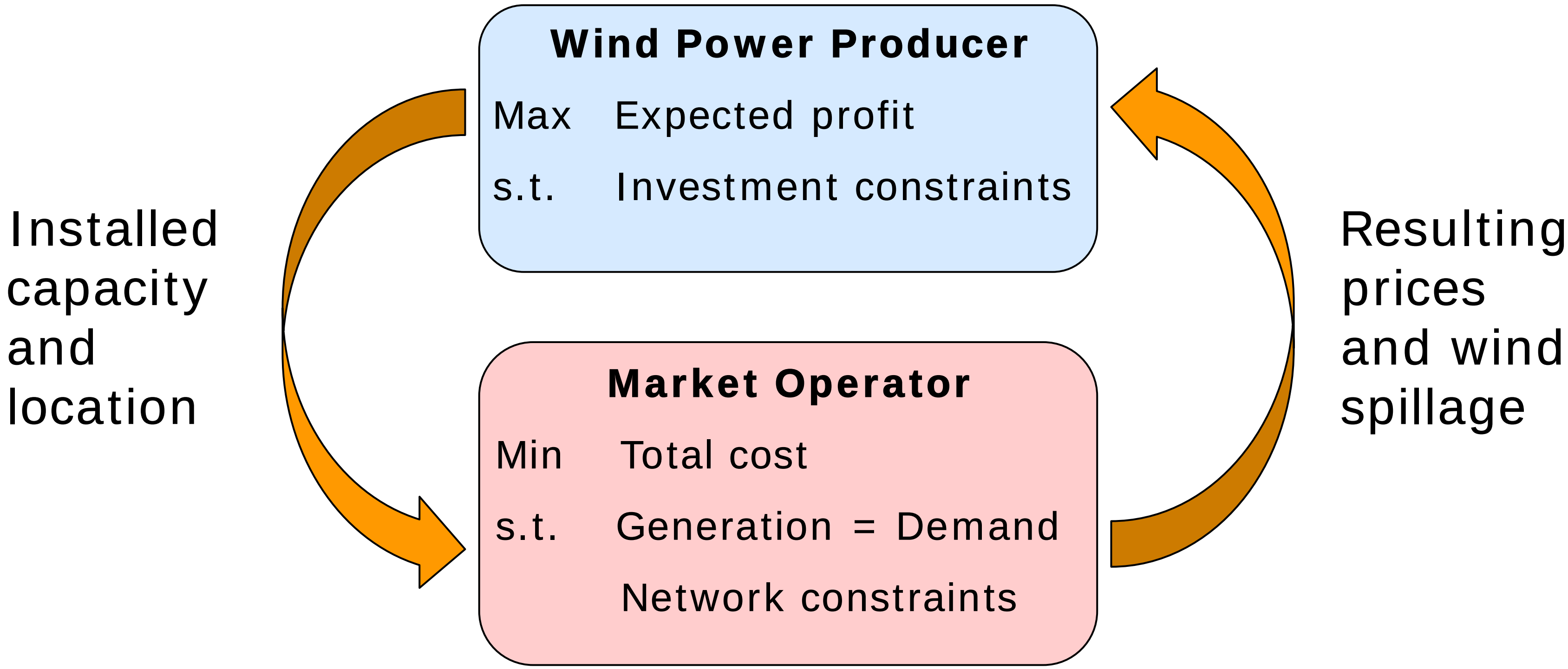
- How can a wind power investment model be formulated?



The model

- How can a wind power investment model be formulated?
  - ✓Bilevel optimization problem

Wind Power Producer

Max Expected profit

s.t. Investment constraints

Market Operator

Min Total cost

s.t. Generation = Demand

Network constraints

The model

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The model

- How can imbalance costs be included in the investment decisions of a wind power producer?
  - ✓Including both day-ahead and 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

The model

- How can imbalance costs be included in the investment decisions of a wind power producer?
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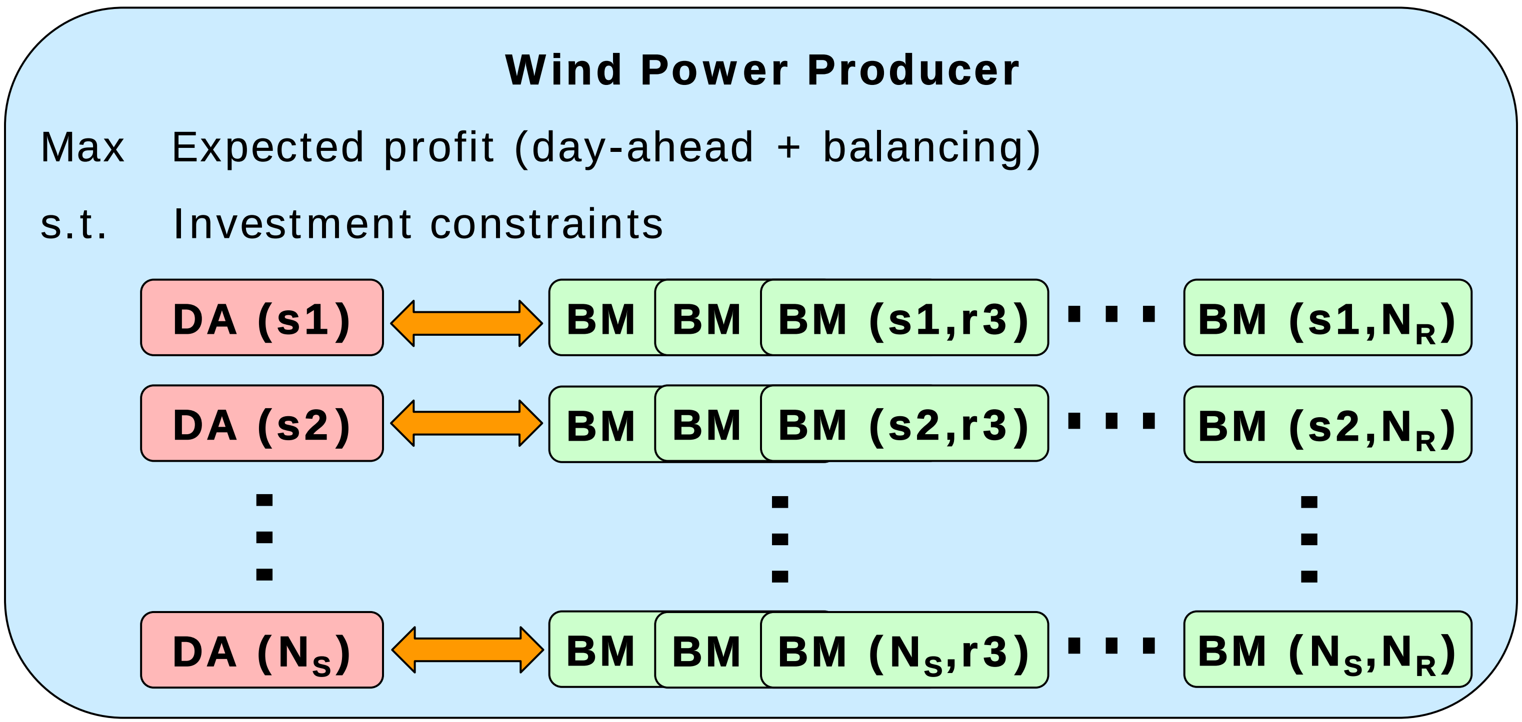

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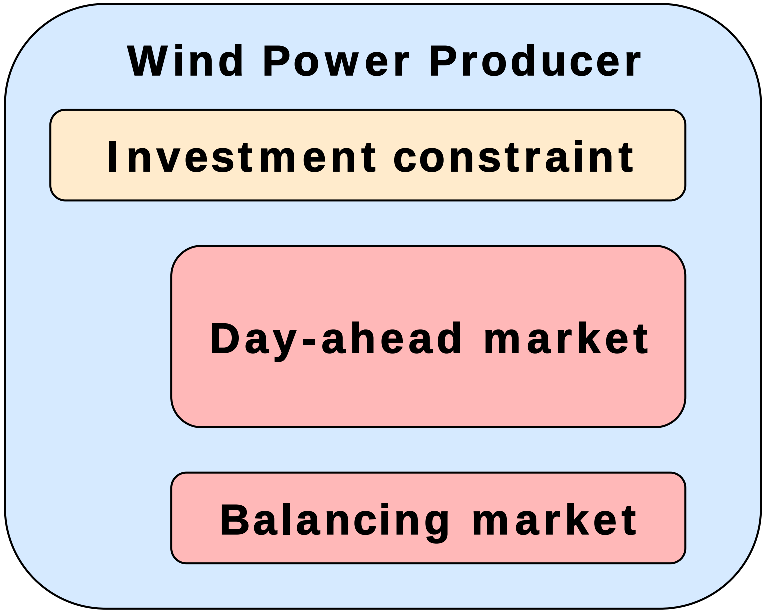
The model

- How can we evaluate the impact of the market design on wind investment decisions?

✓Comparing two market designs: coupled and decoupled

Decoupled market design

- Day-ahead dispatch is determined without considering the balancing needs
- It follows the merit-order principle in the day-ahead market



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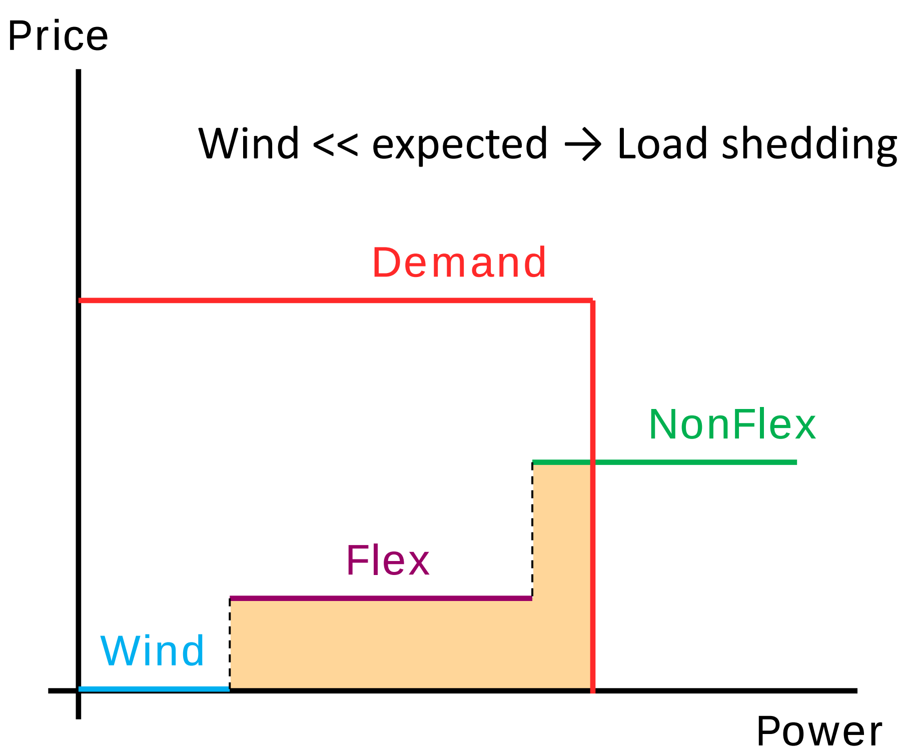
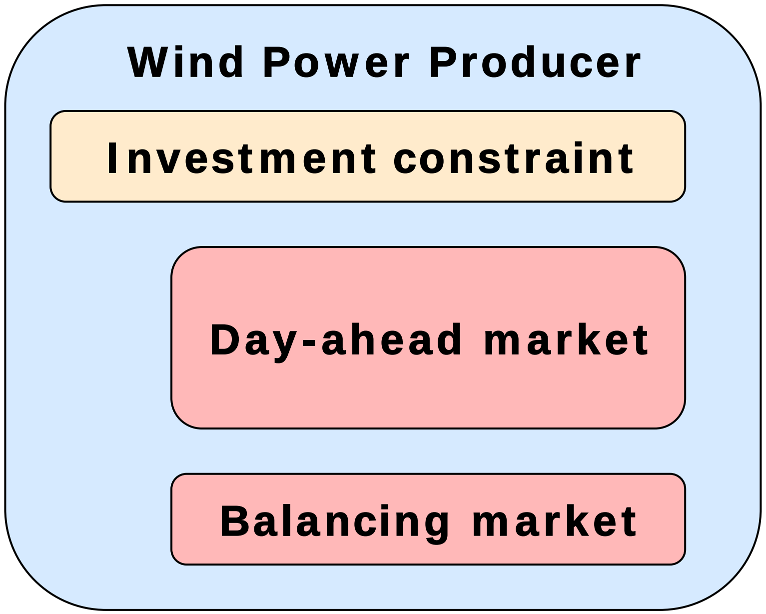


Decoupled market design



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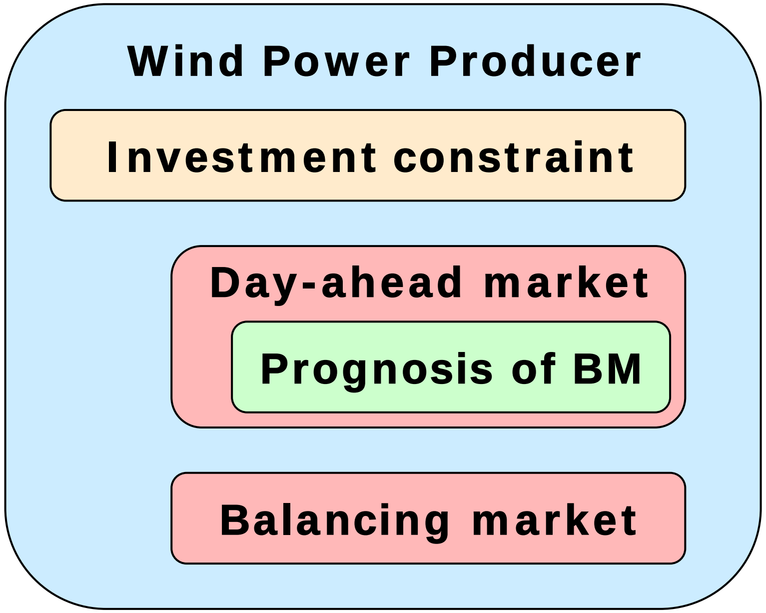
Coupled market design



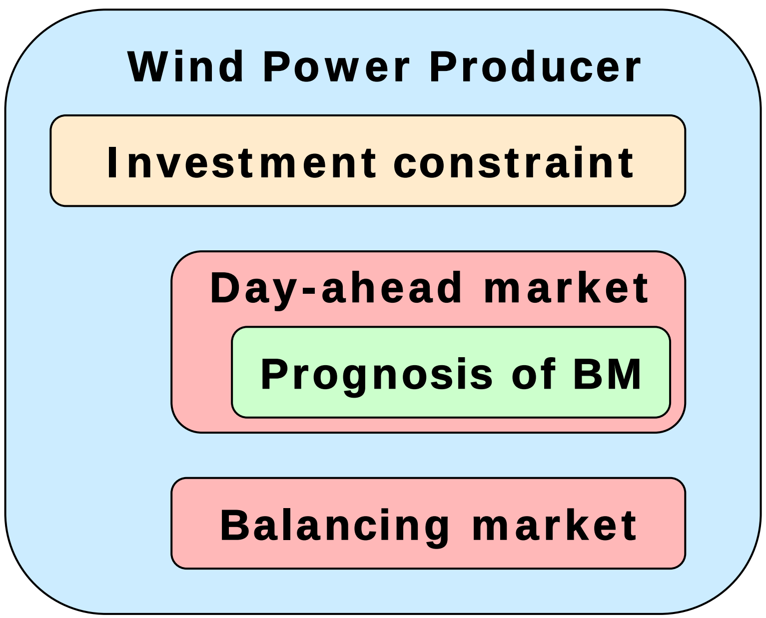
- Day-ahead dispatch is determined accounting for the balancing needs
- Day-ahead and balancing cost are jointly minimized

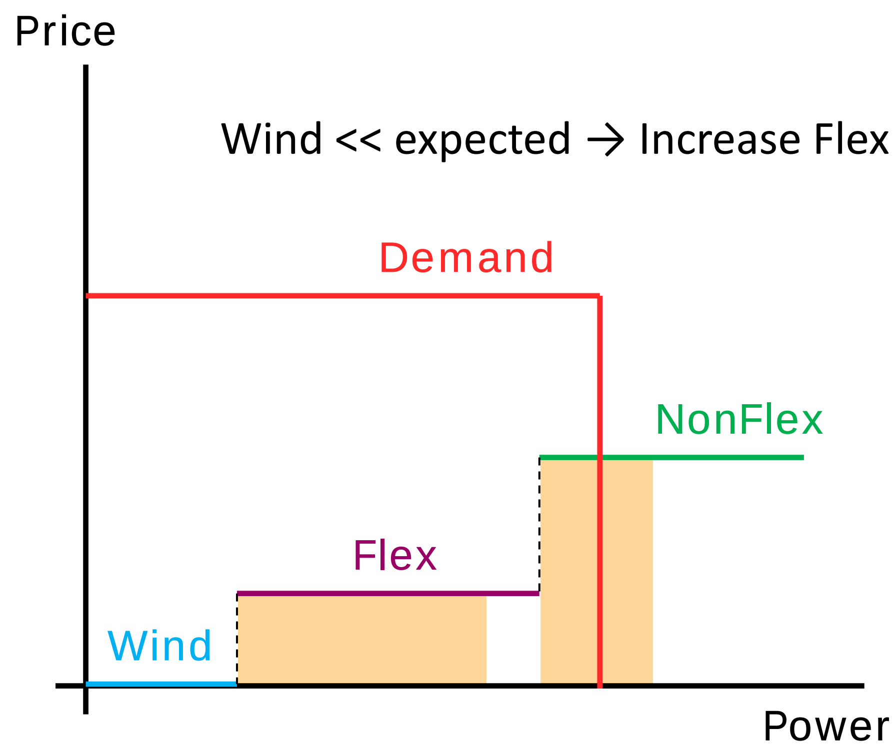
The model

- How can we evaluate the impact of the market design on wind investment decisions?

  ✓Comparing two market designs: coupled and decoupled

Coupled market design





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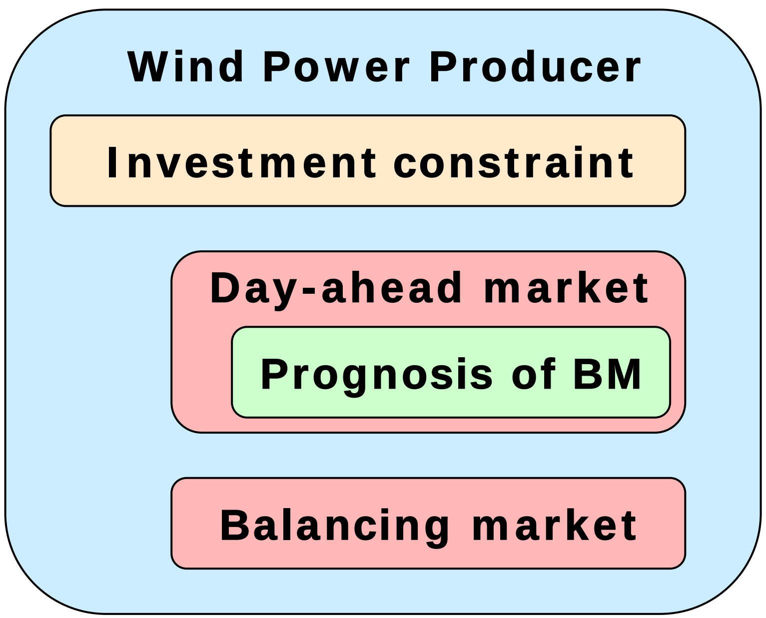
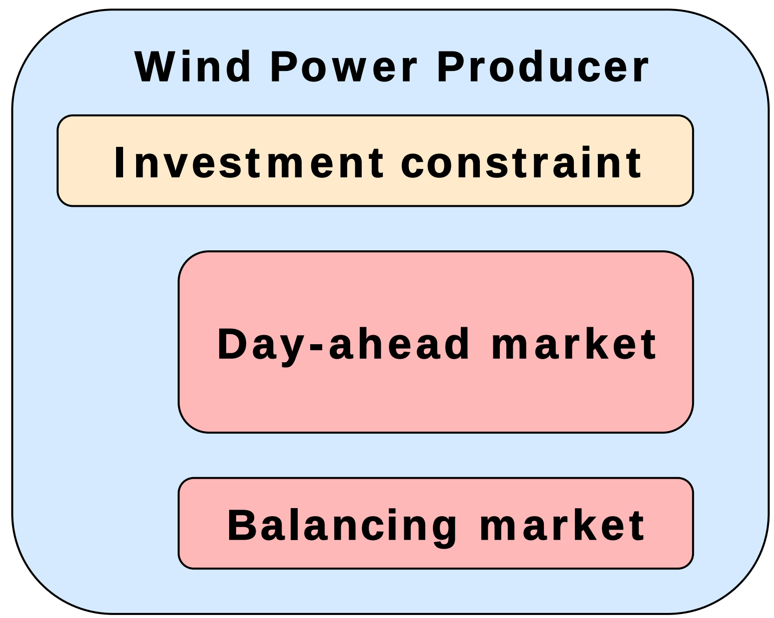


Decoupled market design



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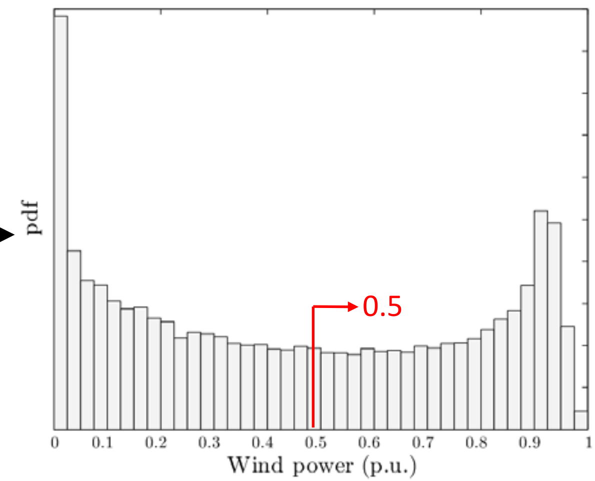
The model

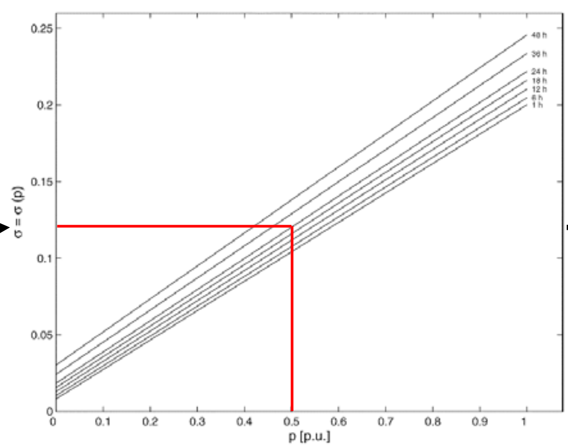
- How do we model wind forecast errors?

Historical data



[Fabbri et al. (2005)]

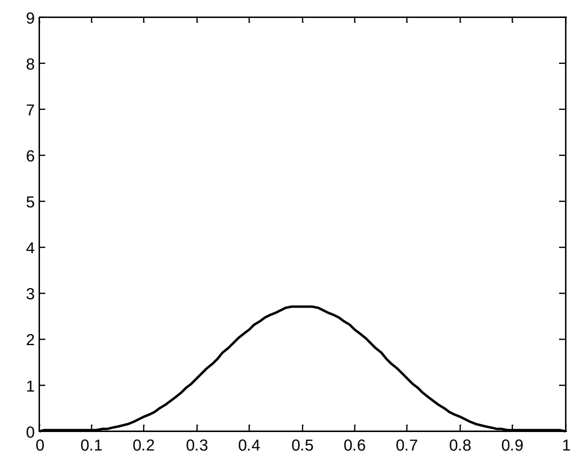
p=0.5



p=0.5
σ=0.12

Beta distribution

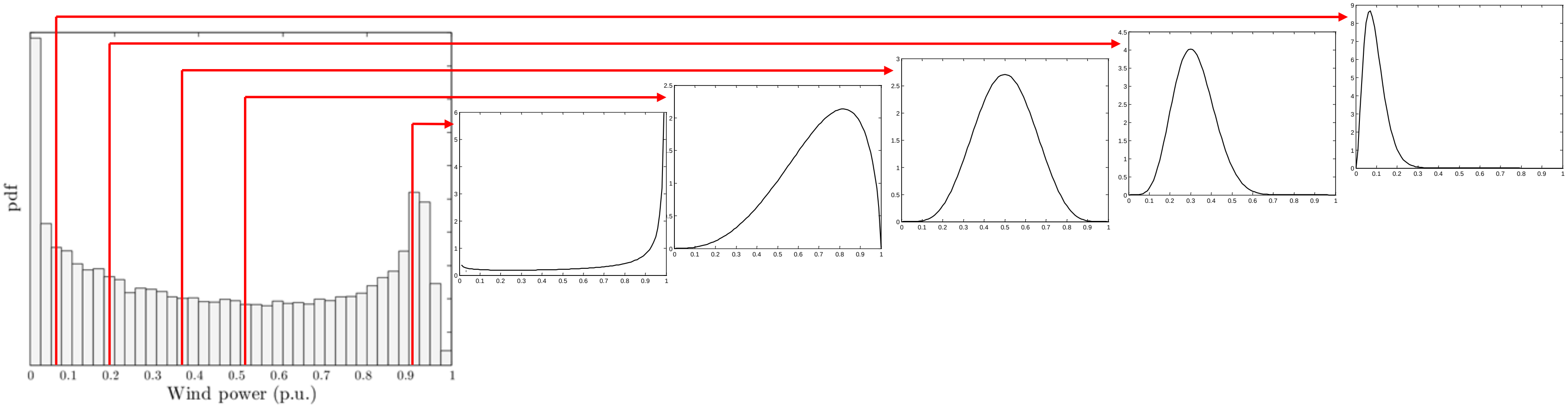
[Fabbri et al. (2005)]



The model

- How can the computational burden of large-scale investment models be reduced?

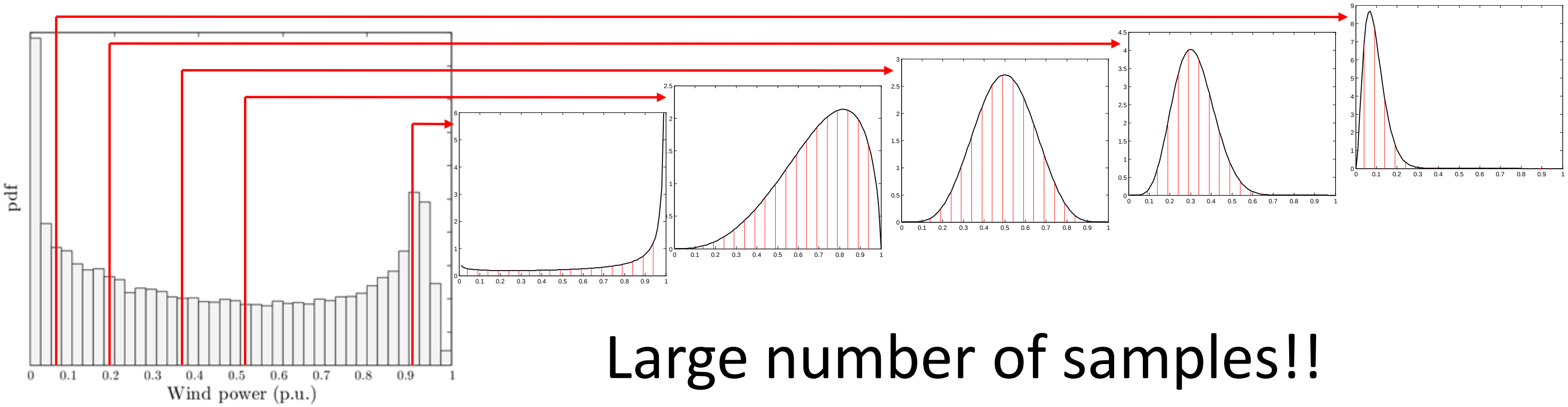
MC



The model

- How can the computational burden of large-scale investment models be reduced?

MC



Large number of samples!!

The model

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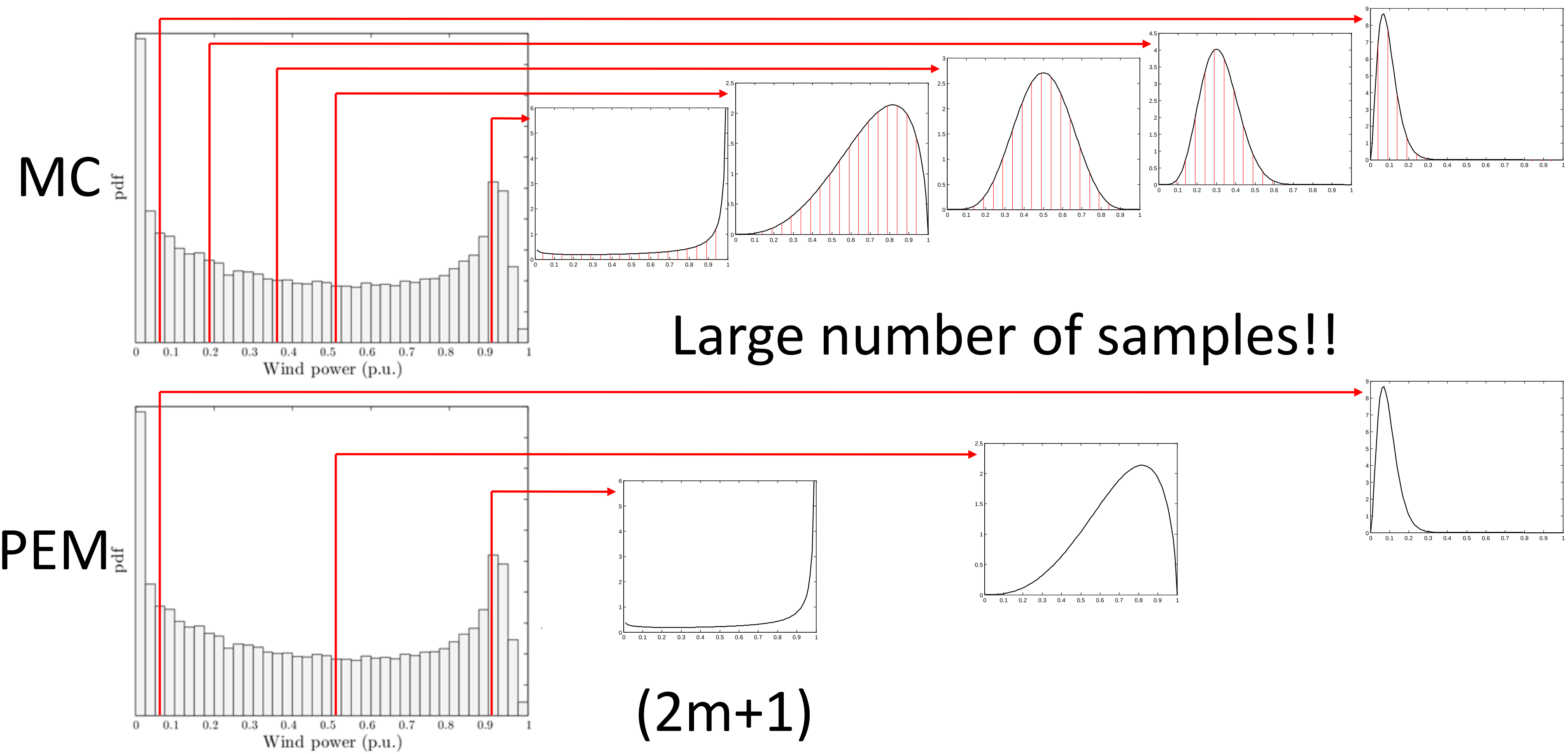
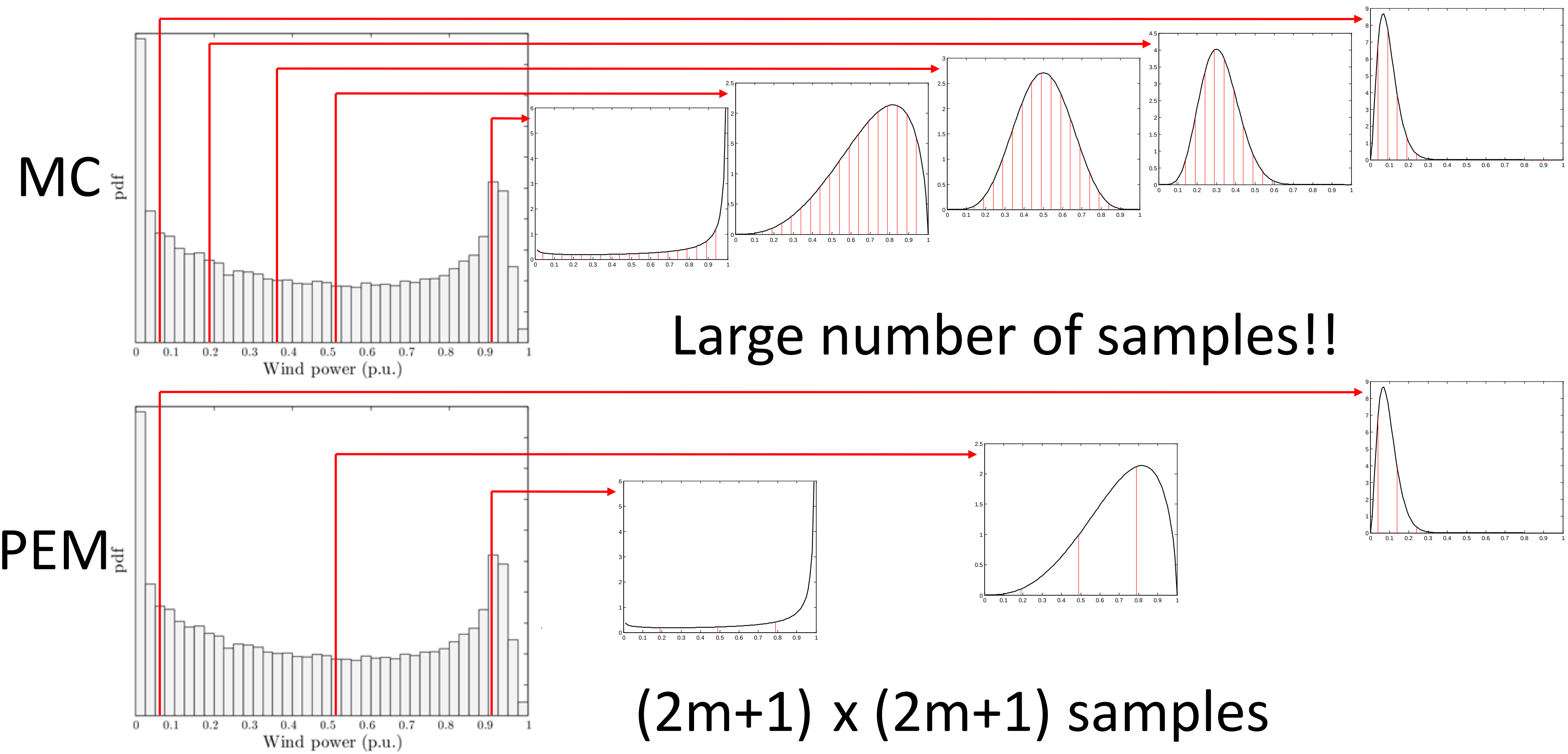


The model

- How can the computational burden of large-scale investment models be reduced?



Large number of samples!!

(2m+1) x (2m+1) samples

Summary

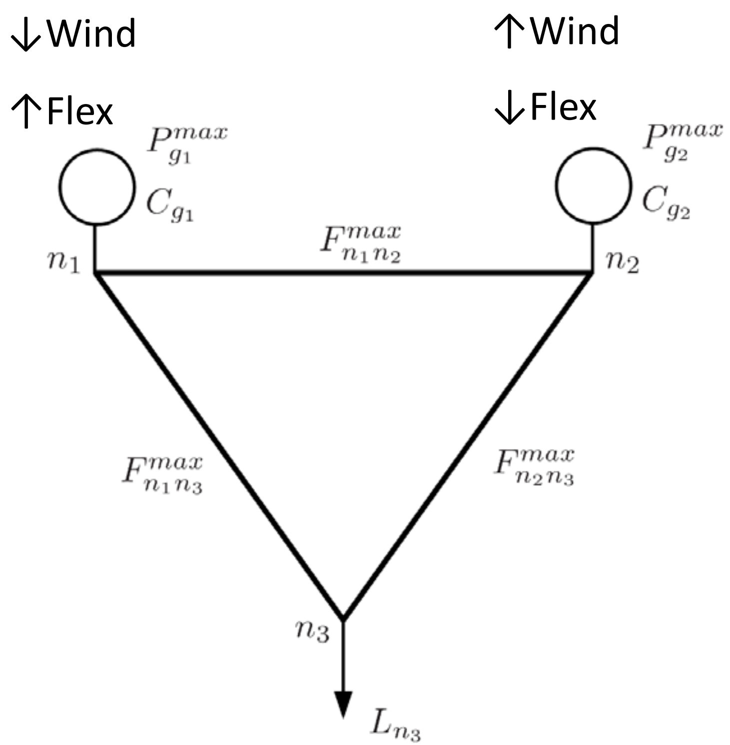
- How can a wind power investment model be formulated?
  - ✓Bilevel optimization problem
- How can imbalance costs be included in the investment decisions of a wind power producer?
  - ✓Including both day-ahead and balancing markets
- How can we evaluate the impact of the market design on wind investment decisions?
  - ✓Comparing two market designs: coupled and decoupled
- How do we model wind forecast errors?
  - ✓Using beta distributions depending on forecast level
- How can the computational burden of large-scale investment models be reduced?
  - ✓Using Point-Estimate methods instead of MonteCarlo

Additional model assumptions

- Static expansion model (single future target year)
- Economies of scale (discrete and large investments)
- Energy-only markets (no payments from ancillary or capacity)
- Uncertainty in demand and wind speed (set of samples)
- DC power flow (locational marginal prices)
- Inelastic demand (load shedding)

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

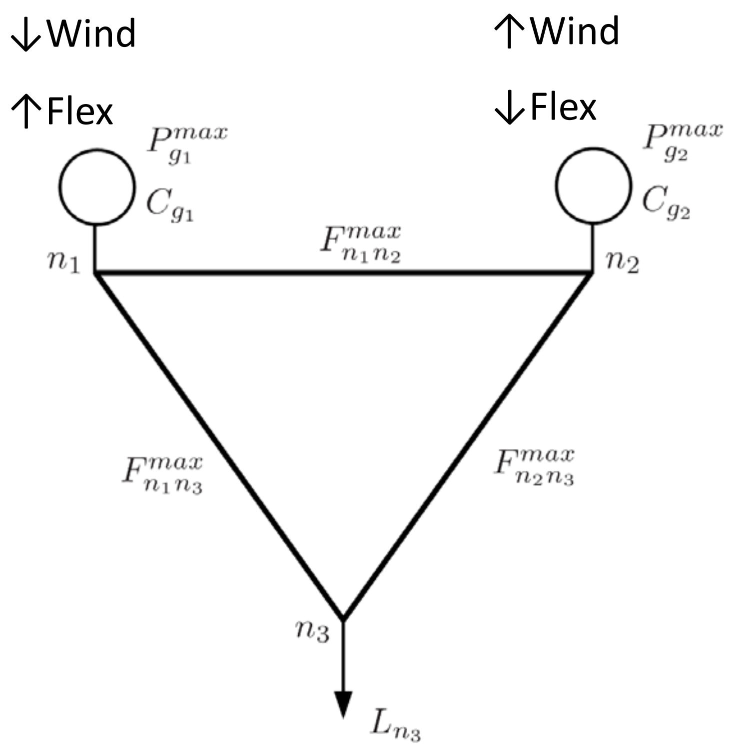
Lines			Wind					Prob	
nm	F_{nm}^{max}	B_{nm}	n	$\widetilde{W}_{ns_1}$	$\widetilde{W}_{ns_1r_1}$	$\widetilde{W}_{ns_1r_2}$	$\widetilde{W}_{ns_1r_3}$	r	π_{s_1r}
n_1n_2	10	7.69	n_1	0.6	-Δ	0	+Δ	r_1	0.4
n_1n_3	250	7.69	n_2	0.7	-Δ	0	+Δ	r_2	0.2
n_2n_3	250	7.69	n_3	-	-	-	-	r_3	0.4

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

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

Example

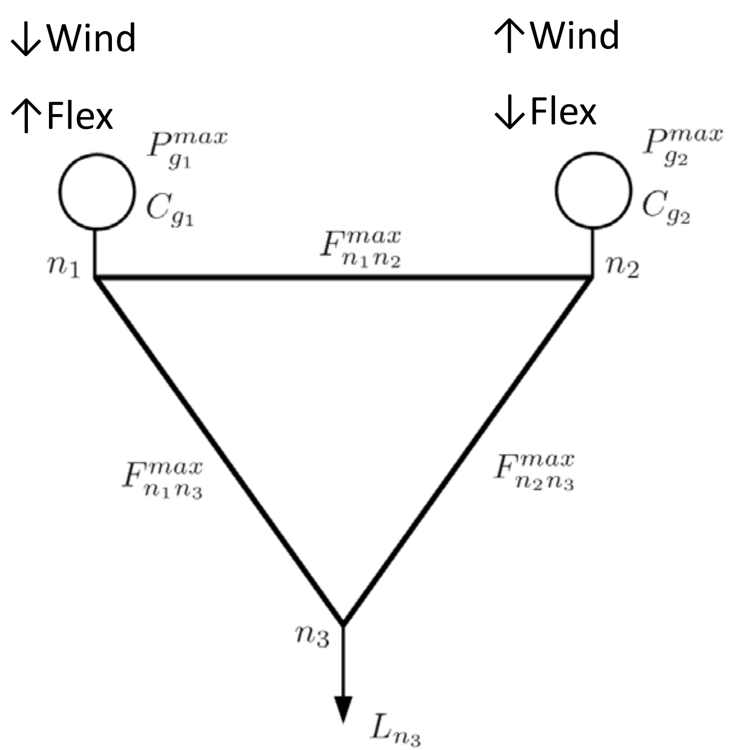
- Results: impact of forecast error



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

Example

- Results: impact of forecast error

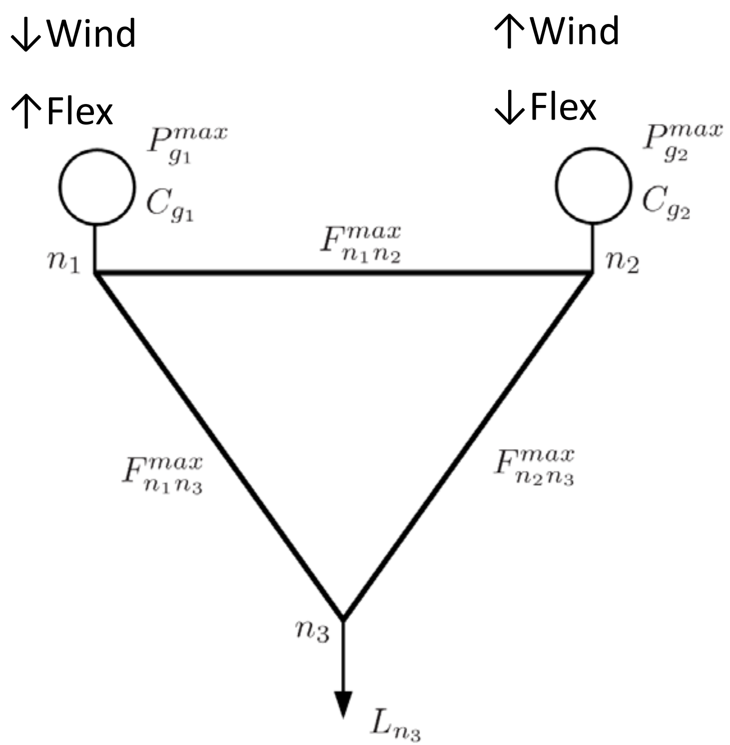


Dec	Bus1	Bus2
Δ=0.1	DA profit = \$600 B profit = -\$4 Total profit = \$596	DA profit = \$704 B profit = -\$62 Total profit = \$642
Δ=0.3	DA profit = \$600 B profit = -\$12 Total profit = \$588	DA profit = \$704 B profit = -\$186 Total profit = \$518

Imbalance cost may have a significant impact on wind investment decisions

Example

- Results: impact of market design



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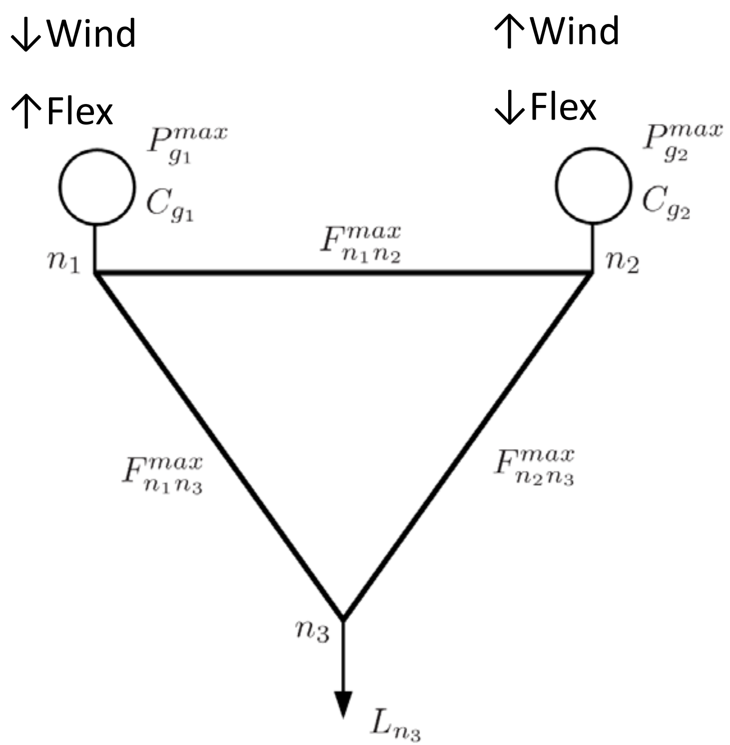
- Results: impact of market design

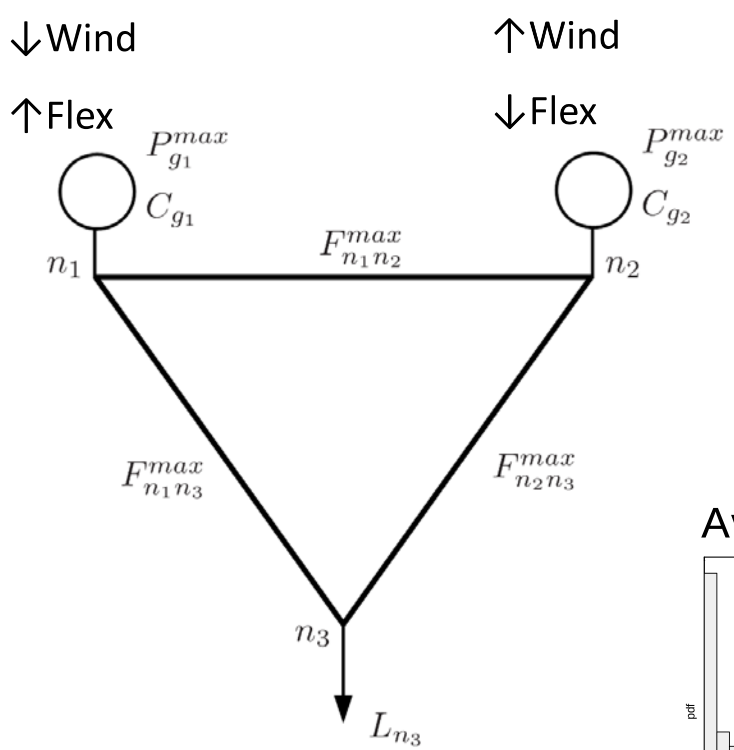


Δ=0.3	Bus1	Bus2
Dec	DA profit = \$600 B profit = -\$12 Total profit = \$588	DA profit = \$704 B profit = -\$186 Total profit = \$518
Coup	DA profit = \$600 B profit = -\$12 Total profit = \$588	DA profit = \$704 B profit = -\$14 Total profit = \$690

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

Example

- Results: use of PEM



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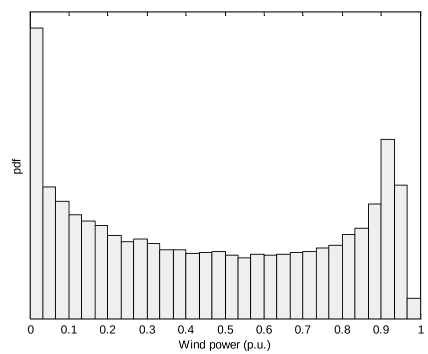
g_2	500	20.1	50	50	50	5

Lines		
nm	F_{nm}^{max}	B_{nm}
$n_1 n_2$	10	7.69
$n_1 n_3$	250	7.69
$n_2 n_3$	250	7.69

$$L_{n_3} = 225\text{MW}, \ \sigma = 5\text{MW}$$

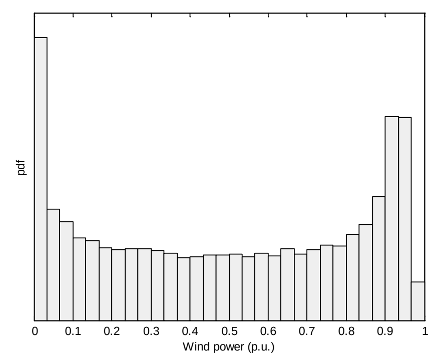
$$P_{w_1'}^{max} = 50\text{MW}$$

Av. wind = 0.4563



Bus 1

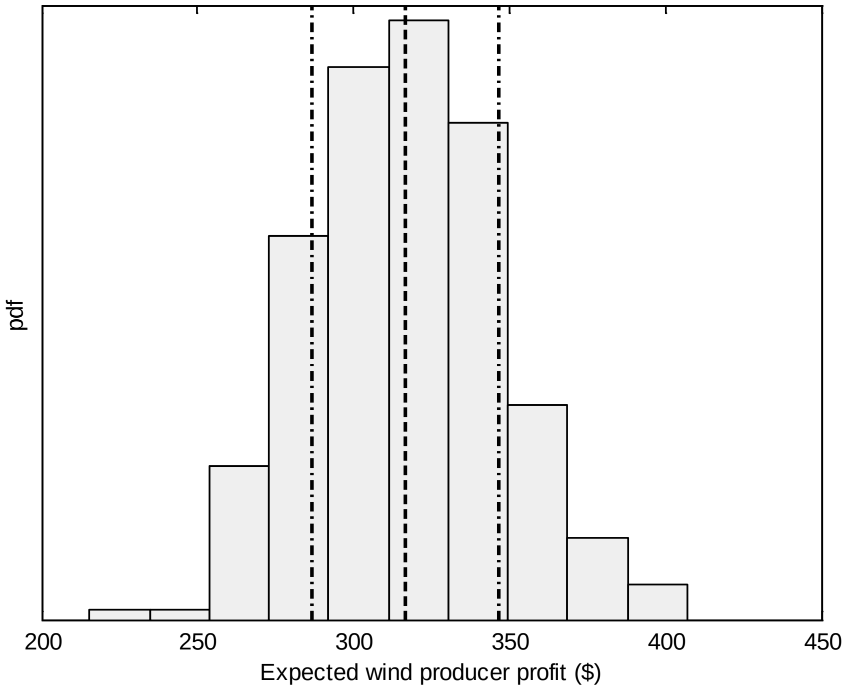
Av. wind = 0.4927



Bus 2

Example

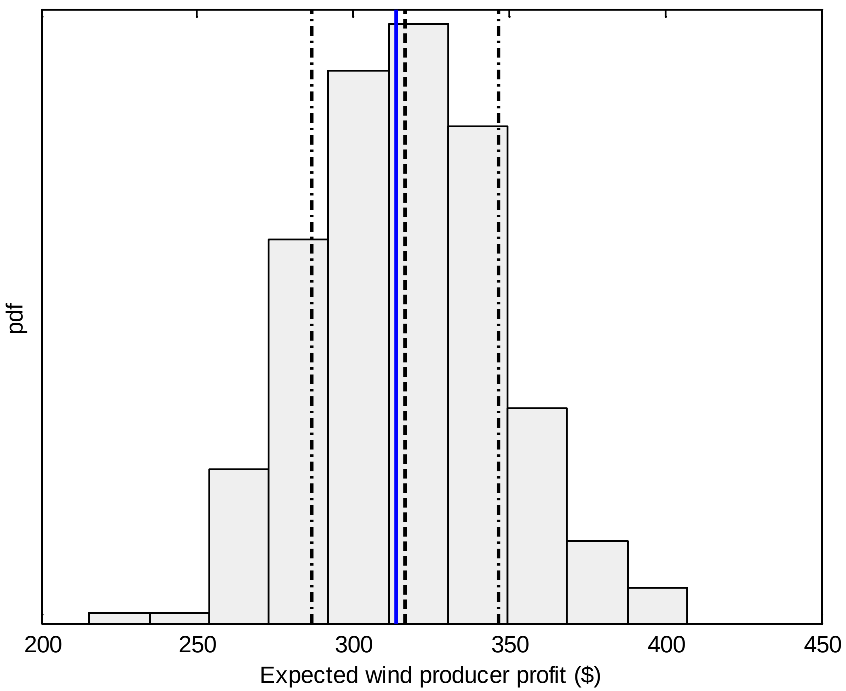
- Results: use of PEM



- Fix location to Bus 1
- Decoupled market clearing
- Run 500 cases with
  - 100 samples (DA)
  - 100 samples (B)
  - 10,000 total samples
- Determine mean and std

Example

- Results: use of PEM



- Fix location to Bus 1
- Decoupled market clearing
- Run 500 cases with
  - 100 samples (DA)
  - 100 samples (B)
  - 10,000 total samples
- Determine mean and std
- Solve problem with PEM
- Error = 0.9%

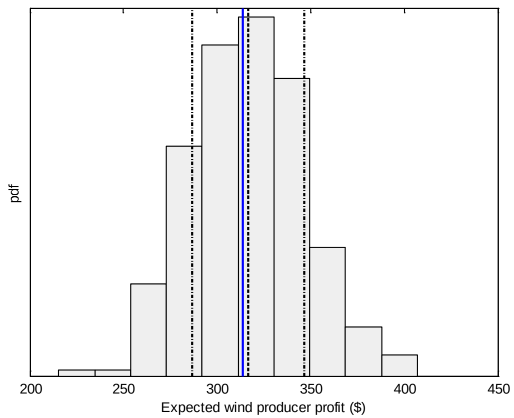
Example

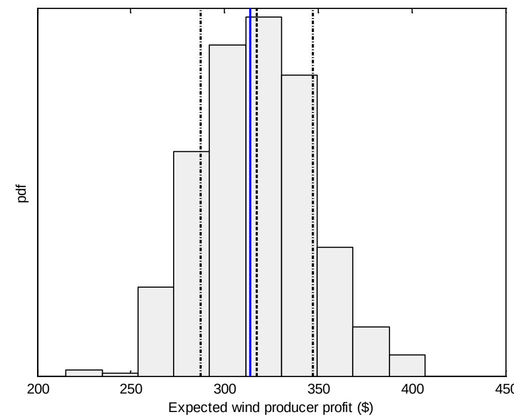
- Results: use of PEM

Coupled MC | Decoupled MC

BUS 1

Error = 0.9%



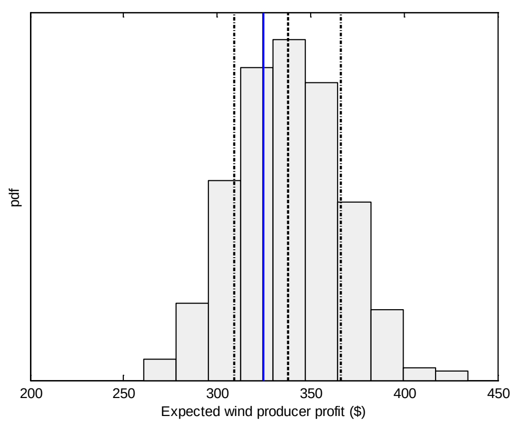


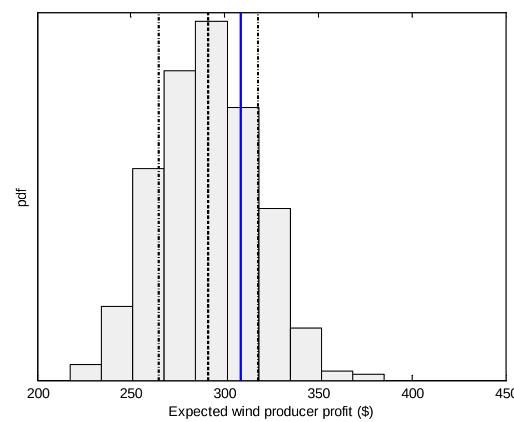
BUS 1

Error = 1.0%

BUS 2

Error = 3.8%





BUS 2

Error = 6.1%

Example

- Results: use of PEM

Coupled MC

	Samples	BUS 2	Time
PEM	7x7	100%	< 2s

Decoupled MC

	Samples	BUS 1	Time
PEM	7x7	100%	< 2s

Example

- Results: use of PEM

Coupled MC

	Samples	BUS 2	Time
PEM	7x7	100%	< 2s
MC (500)	10x10	60%	3s
	30x30	62%	14s
	50x50	66%	67s
	100x50	68%	210s

Decoupled MC

	Samples	BUS 1	Time
PEM	7x7	100%	< 2s
MC (500)	10x10	58%	5s
	30x30	62%	18s
	50x50	65%	74s
	100x50	73%	215s

Conclusions

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

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

- Using a point estimate method to represent the uncertainty involved in the investment model reduces its computational burden

Thanks for your attention!

Questions?

The model

Coupled market design

Wind Power Producer

Investment constraint

Day-ahead market

Prognosis of BM

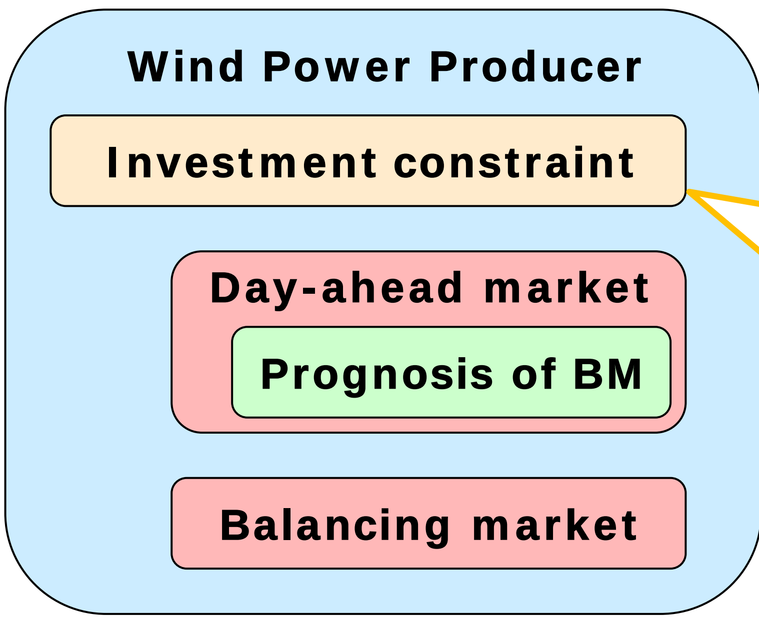
Balancing market

$$\underset{\boxed{u_{w'n}}}{\text{Maximize}} \quad \sum_{sr} \underbrace{\boxed{\pi_s \pi_{sr} \Pi_{sr}}}_{\text{Profit}} - \sum_{w'n} \underbrace{\boxed{u_{w'n} Q_{w'n}}}_{\text{Cost}}$$

Binary variable

The model

Coupled market design



$$\sum_{n} u_{w'n} \leq 1, \quad \forall w'$$

$$\Pi_{sr} = \overbrace{\sum_{w'n} u_{w'n} \lambda_{ns} P^{max}_{w'} \widehat{W}_{ns}}^{\text{Profit DA}} + \underbrace{\sum_{w'nr} u_{w'n} \lambda^{R}_{nsr} \left(P^{max}_{w'} \widetilde{W}_{nsr} - W^{S}_{w'nsr} \right)}_{\text{Profit BM}}$$

The model

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Balancing market

$$\text{Min} \overbrace{\boxed{\sum_g C_g P_{gs}}}^{\text{DA Cost}} + \overbrace{\boxed{\sum_{gr} \pi_{sr}\left(C_g^u P_{gsr}^u - C_g^d P_{gsr}^d\right)}}^{\text{Expected Balancing Cost}} + \overbrace{\boxed{\sum_{nr} \pi_{sr} V^L L_{nsr}^S}}^{\text{Load Shed}}$$

Subject to

$$\sum_{g\in\Psi_n} P_{gs} + \sum_{w\in\Theta_n} P_w^{max}\widehat{W}_{ns} + \sum_{w'} u_{w'n} P_{w'}^{max}\widehat{W}_{ns} =$$

$$= \widehat{L}_{ns} + \sum_{m\in\Omega_n} B_{nm}(\delta_{ns} - \delta_{ms}) : \underbrace{\boxed{\lambda_{ns}}}_{\text{DA price}} \quad \forall n$$

$$\sum_{g\in\Psi_n} \left(P_{gsr}^u - P_{gsr}^d\right) + \sum_{w\in\Theta_n} \left(P_w^{max}\widetilde{W}_{nsr} - W_{wsr}^S\right) +$$

$$+ \sum_{w'} \left(u_{w'n} P_{w'}^{max}\widetilde{W}_{nsr} - W_{w'nsr}^S\right) =$$

$$= \widetilde{L}_{nsr} - L_{nsr}^S + \sum_{m\in\Omega_n} B_{nm}(\delta_{nsr}^R - \delta_{msr}^R) : \underbrace{\boxed{\lambda_{nsr}^R}}_{\text{B price}}$$

Unit and network technical limits

Linear programming model !!

The model

Coupled market design

Wind Power Producer

Investment constraint

Primal constraints

Dual constraints

Strong duality theorem

$$\text{Min} \overbrace{\boxed{\sum_g C_g P_{gs}}}^{\text{DA Cost}} + \overbrace{\boxed{\sum_{gr} \pi_{sr}\left(C_g^u P_{gsr}^u - C_g^d P_{gsr}^d\right)}}^{\text{Expected Balancing Cost}} + \overbrace{\boxed{\sum_{nr} \pi_{sr} V^L L_{nsr}^S}}^{\text{Load Shed}}$$

Subject to

$$\sum_{g\in\Psi_n} P_{gs} + \sum_{w\in\Theta_n} P_w^{max}\widehat{W}_{ns} + \sum_{w'} u_{w'n} P_{w'}^{max}\widehat{W}_{ns} =$$
$$= \widehat{L}_{ns} + \sum_{m\in\Omega_n} B_{nm}(\delta_{ns} - \delta_{ms}) : \underset{\text{DA price}}{\boxed{\lambda_{ns}}} \quad \forall n$$

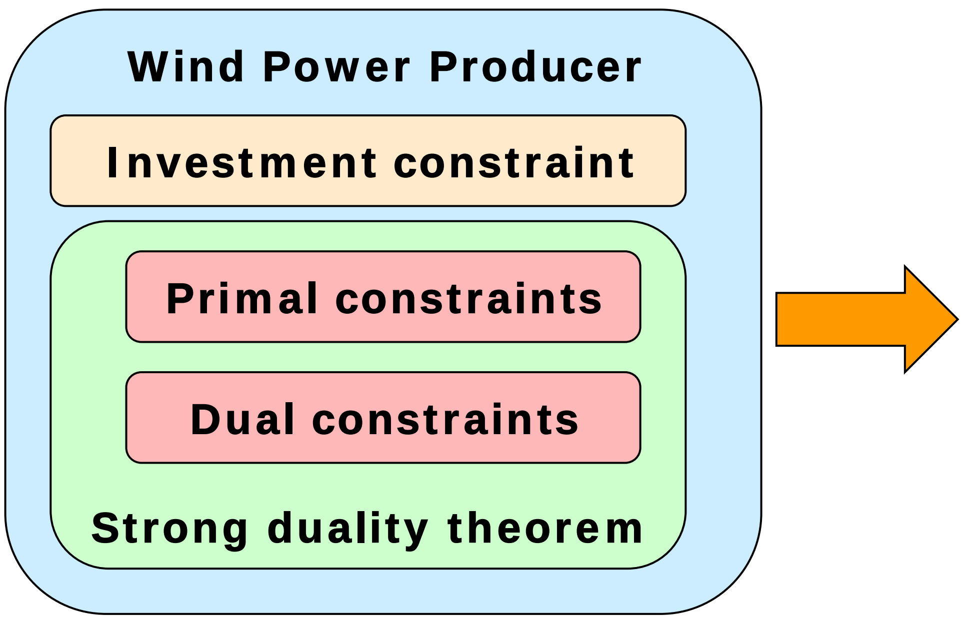
$$\sum_{g\in\Psi_n} \left(P_{gsr}^u - P_{gsr}^d\right) + \sum_{w\in\Theta_n} \left(P_w^{max}\widetilde{W}_{nsr} - W_{wsr}^S\right) +$$
$$+ \sum_{w'} \left(u_{w'n} P_{w'}^{max}\widetilde{W}_{nsr} - W_{w'nsr}^S\right) =$$
$$= \widetilde{L}_{nsr} - L_{nsr}^S + \sum_{m\in\Omega_n} B_{nm}(\delta_{nsr}^R - \delta_{msr}^R) : \underset{\text{B price}}{\boxed{\lambda_{nsr}^R}}$$

Unit and network technical limits

Linear programming model !!

The model

Coupled market design



Mixed-integer linear model

The model

$$\underset{\boxed{u_{w'n}}\ \text{Binary variable}}{\text{Maximize}} \sum_{sr} \underbrace{\boxed{\pi_s \pi_{sr} \Pi_{sr}}}_{\text{Profit}} - \sum_{w'n} \underbrace{\boxed{u_{w'n} Q_{w'n}}}_{\text{Cost}}$$

$$\sum_{n} u_{w'n} \leq 1, \quad \forall w'$$

$$\Pi_{sr} = \overbrace{\boxed{\sum_{w'n} u_{w'n} \lambda_{ns} P^{max}_{w'} \widehat{W}_{ns}}}^{\text{Profit DA}} + \underbrace{\boxed{\sum_{w'nr} u_{w'n} \lambda^{R}_{nsr} (P^{max}_{w'} \widetilde{W}_{nsr} - W^{S}_{w'nsr})}}_{\text{Profit BM}}$$

Decoupled market design

Wind Power Producer

Investment constraint

Day-ahead market

Balancing market

The model

$$\text{Min}\underbrace{\boxed{\sum_{gr}\pi_{sr}\left(C_g^u P_{gsr}^u - C_g^d P_{gsr}^d\right)}}_{}^{\text{Expected Balancing Cost}} + \overbrace{\boxed{\sum_{nr}\pi_{sr}V^L L_{nsr}^S}}^{\text{Load Shed}}$$

Subject to

$$\sum_{g\in\Psi_n}\left(P_{gsr}^u - P_{gsr}^d\right) + \sum_{w\in\Theta_n}\left(P_w^{max}\widetilde{W}_{nsr} - W_{wsr}^S\right) +$$
$$+\sum_{w'}\left(u_{w'n}P_{w'}^{max}\widetilde{W}_{nsr} - W_{w'nsr}^S\right) =$$
$$= \widetilde{L}_{nsr} - L_{nsr}^S + \sum_{m\in\Omega_n} B_{nm}(\delta_{nsr}^R - \delta_{msr}^R) : \underbrace{\boxed{\lambda_{nsr}^R}}_{\text{B price}}$$

$$0 \le \underbrace{\boxed{P_{gs}}}_{\text{DA}} + \underbrace{\boxed{P_{gsr}^u - P_{gsr}^d}}_{\text{BM}} \le P_g^{max}$$

Unit and network technical limits

$$(P_{gs}, \delta_{ns}) \in \arg\left\{\text{Min}\sum_g C_g P_{gs}\right.$$

Unit and network technical limits

LP!!

Decoupled market design

Wind Power Producer

Investment constraint

Day-ahead market

Balancing market

The model

Linear programming model !!

$$\text{Min} \underbrace{\sum_{gr} \pi_{sr}\left(C^u_g P^u_{gsr} - C^d_g P^d_{gsr}\right)}_{\text{Expected Balancing Cost}} + \underbrace{\sum_{nr} \pi_{sr} V^L L^S_{nsr}}_{\text{Load Shed}}$$

Subject to

$$\sum_{g\in\Psi_n}\left(P^u_{gsr} - P^d_{gsr}\right) + \sum_{w\in\Theta_n}\left(P^{max}_w \widetilde{W}_{nsr} - W^S_{wsr}\right) +$$
$$+\sum_{w'}\left(u_{w'n} P^{max}_{w'} \widetilde{W}_{nsr} - W^S_{w'nsr}\right) =$$
$$= \widetilde{L}_{nsr} - L^S_{nsr} + \sum_{m\in\Omega_n} B_{nm}(\delta^R_{nsr} - \delta^R_{msr}) : \underbrace{\boxed{\lambda^R_{nsr}}}_{\text{B price}}$$

$$0 \le \underbrace{\boxed{P_{gs}}}_{\text{DA}} + \underbrace{\boxed{P^u_{gsr} - P^d_{gsr}}}_{\text{BM}} \le P^{max}_g$$

Unit and network technical limits

- Primal constraints
- Dual constraints
- Strong duality theorem

Linear constraints ensuring that DA variables minimize DA cost

Decoupled market design

Wind Power Producer

- **Investment constraint**
- **Day-ahead market**
- **Balancing market**

informs DTU

The model

Linear programming model !!

$$\text{Min} \overbrace{\boxed{\sum_{gr} \pi_{sr}\left(C^u_g P^u_{gsr} - C^d_g P^d_{gsr}\right)}}^{\text{Expected Balancing Cost}} + \overbrace{\boxed{\sum_{nr} \pi_{sr} V^L L^S_{nsr}}}^{\text{Load Shed}}$$

Subject to

$$\sum_{g\in\Psi_n}\left(P^u_{gsr} - P^d_{gsr}\right) + \sum_{w\in\Theta_n}\left(P^{max}_w \widetilde{W}_{nsr} - W^S_{wsr}\right) +$$
$$+ \sum_{w'}\left(u_{w'n} P^{max}_{w'} \widetilde{W}_{nsr} - W^S_{w'nsr}\right) =$$
$$= \widetilde{L}_{nsr} - L^S_{nsr} + \sum_{m\in\Omega_n} B_{nm}(\delta^R_{nsr} - \delta^R_{msr}) : \underbrace{\boxed{\lambda^R_{nsr}}}_{\text{B price}}$$

$$0 \le \underbrace{\boxed{P_{gs}}}_{\text{DA}} + \underbrace{\boxed{P^u_{gsr} - P^d_{gsr}}}_{\text{BM}} \le P^{max}_g$$

Unit and network technical limits

Primal constraints

Dual constraints

Strong duality theorem

Linear constraints ensuring that DA variables minimize DA cost

Decoupled market design

Wind Power Producer

Investment constraint

Primal constraints

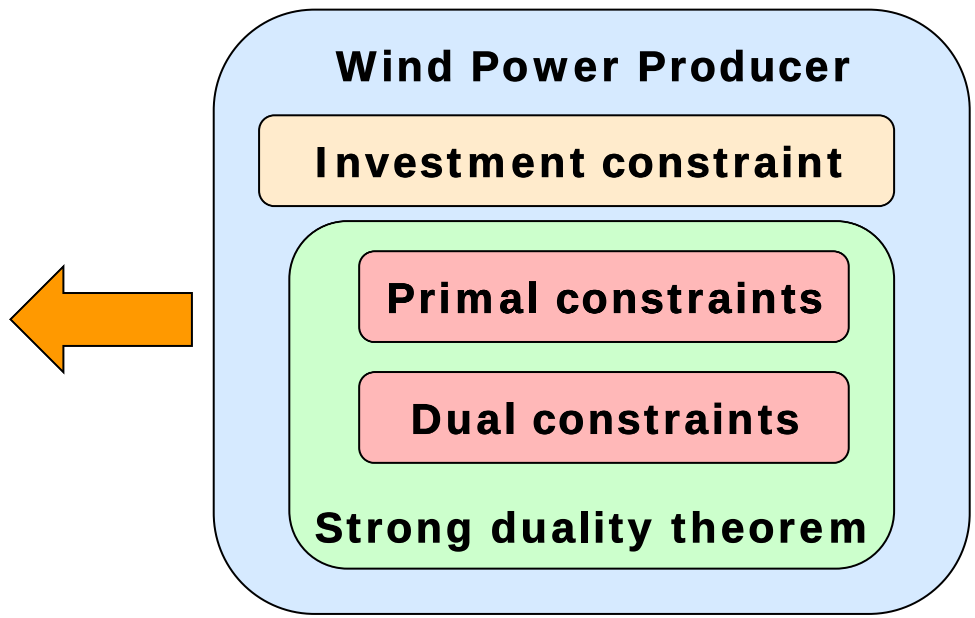
Dual constraints

Strong duality theorem

The model

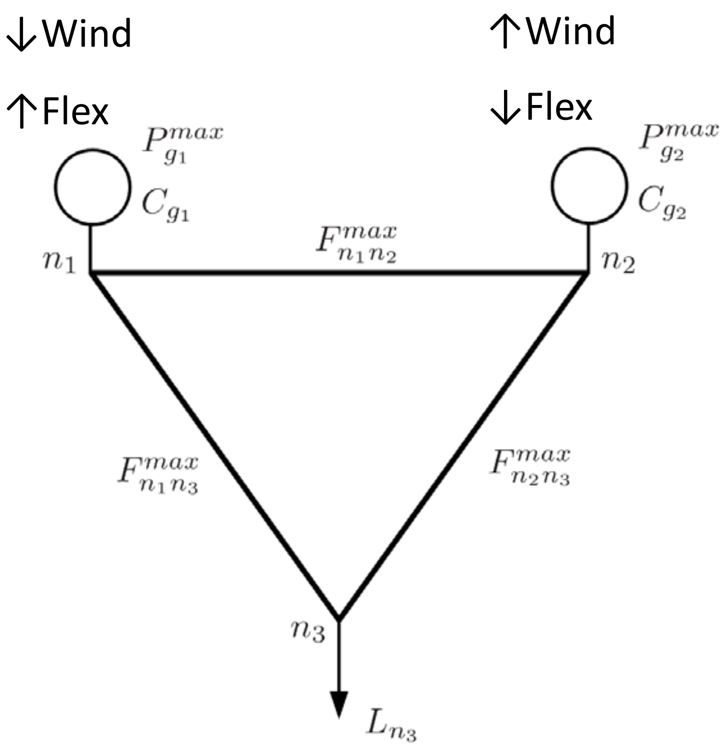
Decoupled market design

Mixed-integer linear model



Example

- Results: impact of forecast error

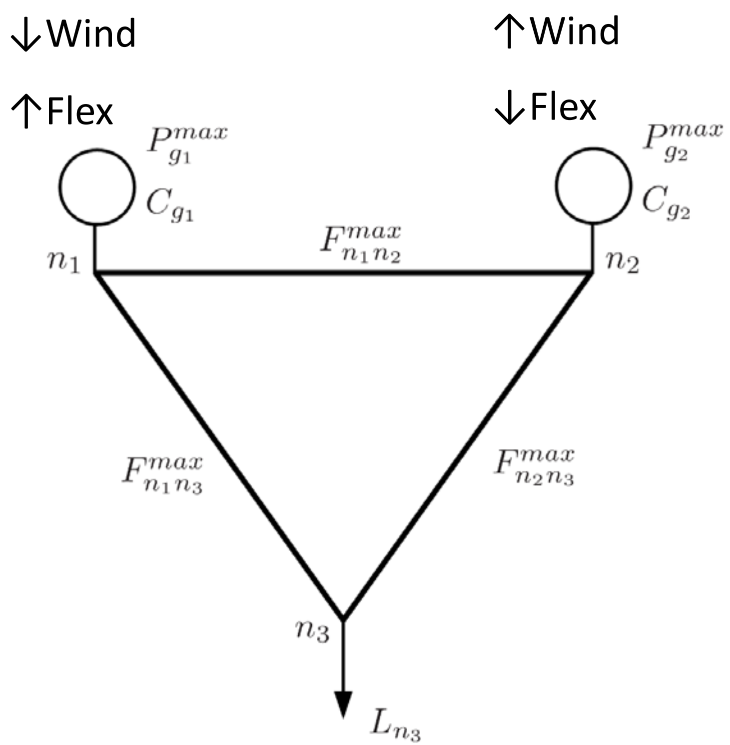


Dec	Bus1	Bus2
Δ=0.1	DA profit = \$600 B profit = -\$4 Total profit = \$596 Cost = \$3914	DA profit = \$704 B profit = -\$62 Total profit = \$642 Cost = \$3868
Δ=0.3	DA profit = \$600 B profit = -\$12 Total profit = \$588 Cost = \$3922(+0.2%)	DA profit = \$704 B profit = -\$186 Total profit = \$518 Cost = \$3992(+3.2%)

The forecast error also affects the total cost of operating the system

Example

- Results: impact of market design



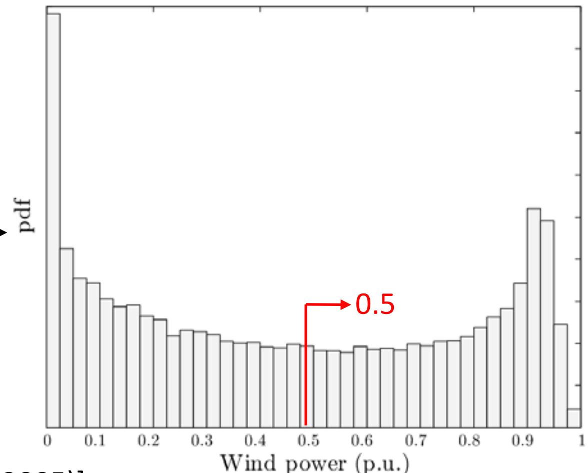
Δ=0.3	Bus1	Bus2
Dec	DA profit = \$600 B profit = -\$12 Total profit = \$588 Cost = \$3922	DA profit = \$704 B profit = -\$186 Total profit = \$518 Cost = \$3992
Coup	DA profit = \$600 B profit = -\$12 Total profit = \$588 Cost = \$3922	DA profit = \$704 B profit = -\$14 Total profit = \$69 Cost = \$3820

The lower total cost is also obtained for the Coup market clearing

The model

- How do we model wind forecast errors?

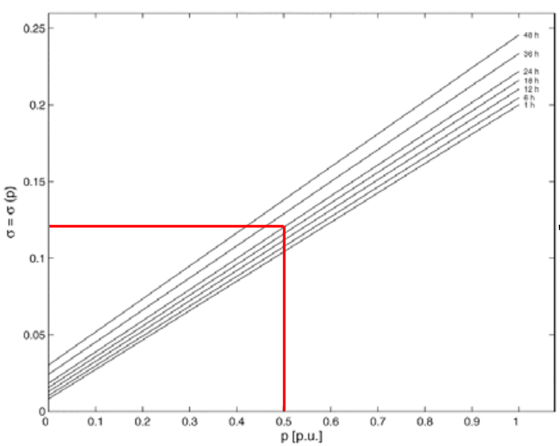
Historical data



Forecast

s	**w**	π
s1	0.5	$1/N_S$

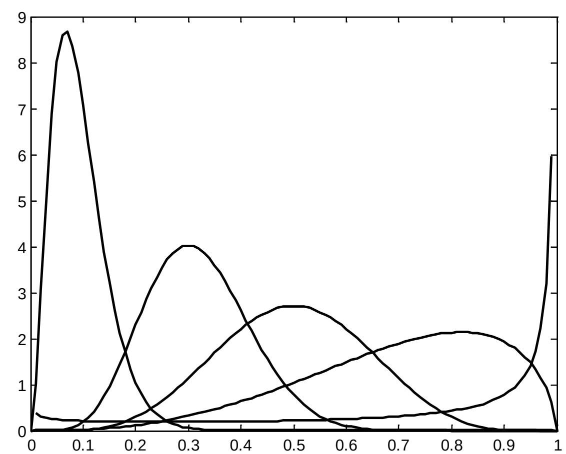
[Fabbri et al. (2005)]



p=0.5
σ=0.12

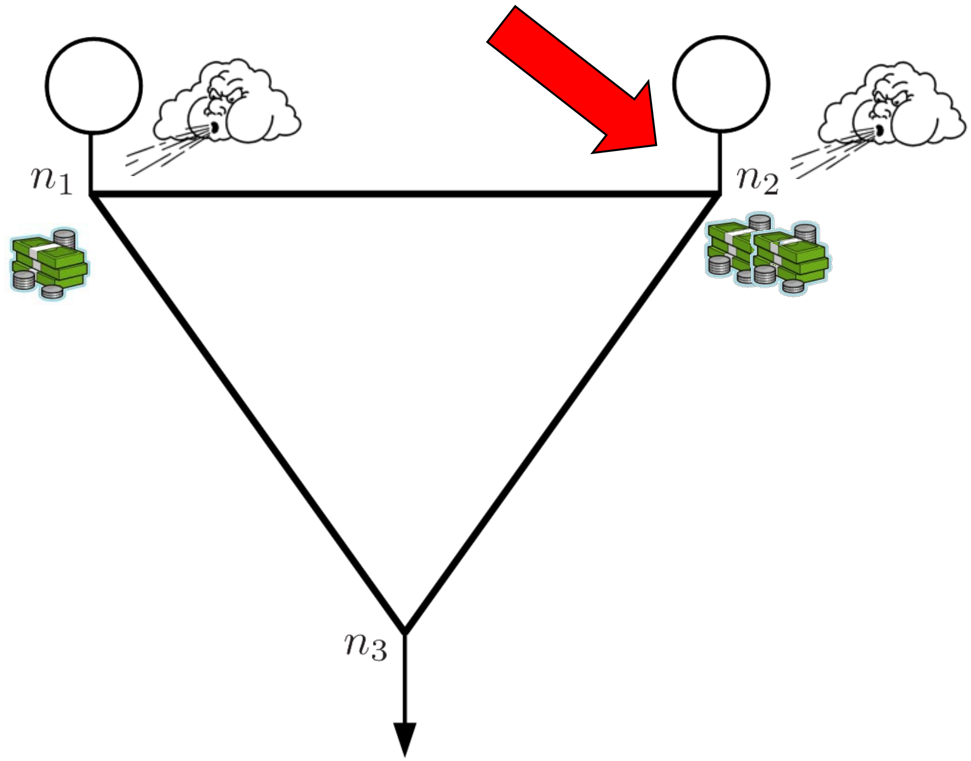
Beta distribution

[Fabbri et al. (2005)]



The model

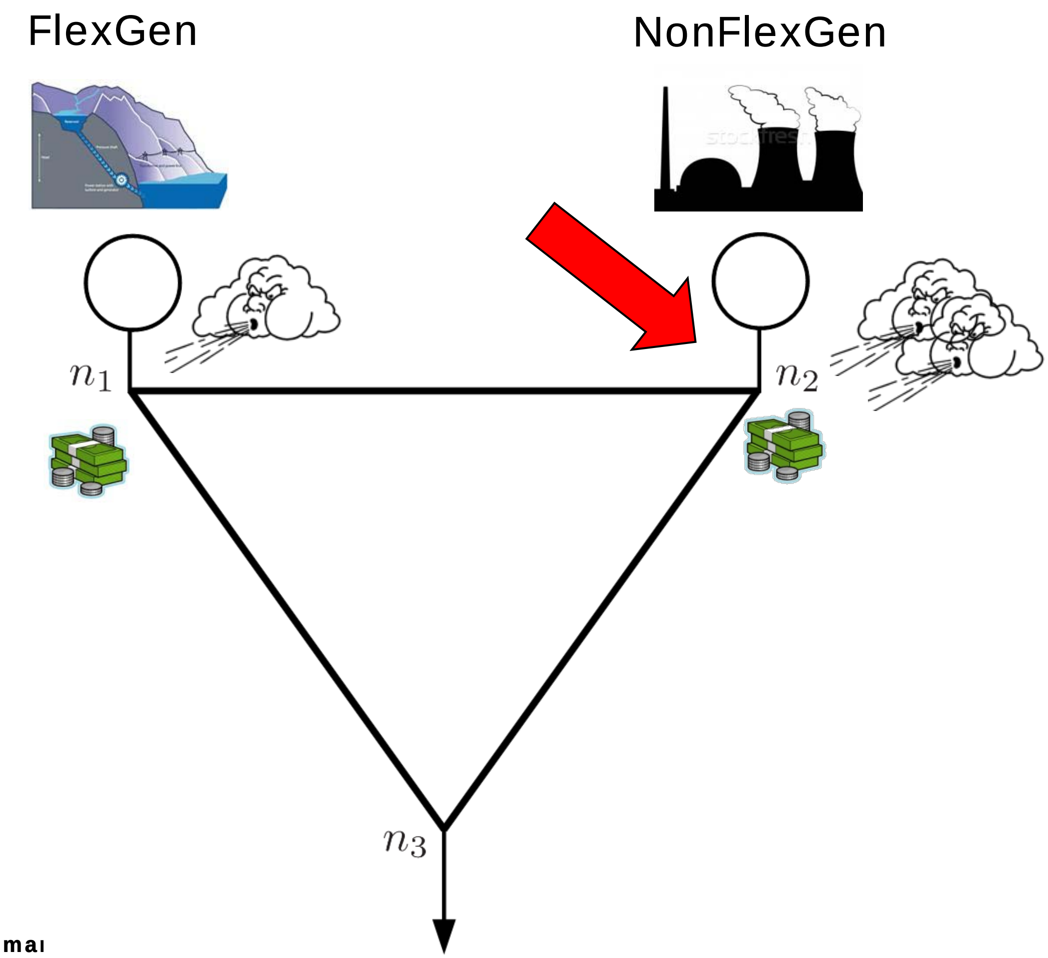
- How can a wind power investment model be formulated?
  - 3 bus system
  - Wind n1 = Wind n2
  - Prices n2 >> Prices n1
  - Optimal location n2?
  - It depends on the impact of such a wind farm on the market outcomes



The model

- How can imbalance costs be included in the investment decisions of a wind power producer?

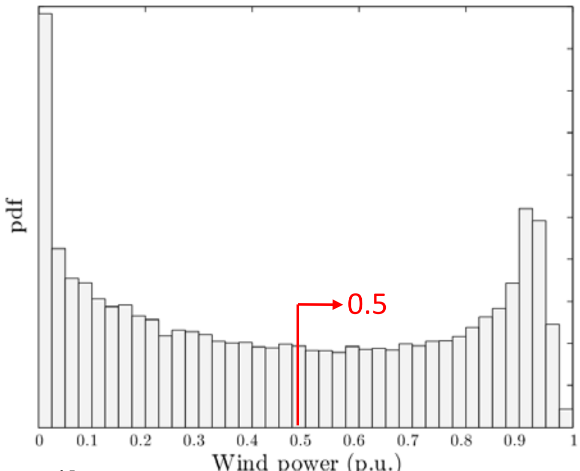
  - 3 bus system
  - Prices n1 = Prices n2
  - Wind n2 >> Wind n1
  - Optimal location n2?
  - It depends on the imbalance costs at each bus



The model

- How do we model wind forecast errors?

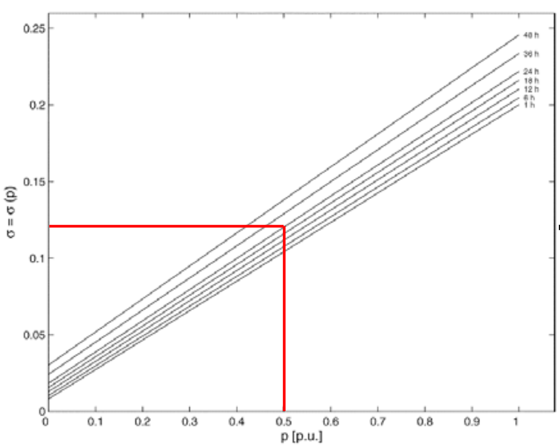
Historical data



Forecast

s	**w**	π
s1	0.5	$1/N_S$

[Fabbri et al. (2005)]

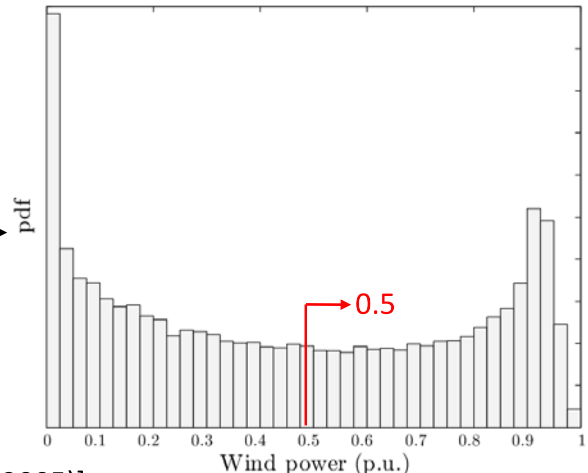


p=0.5
σ=0.12

The model

- How do we model wind forecast errors?

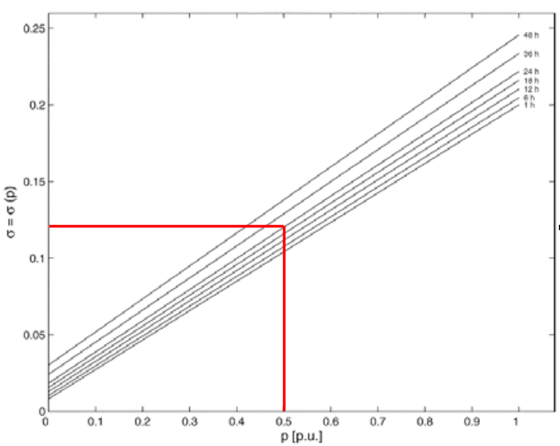
Historical data



Forecast

s	**w**	π
s1	0.5	$1/N_S$

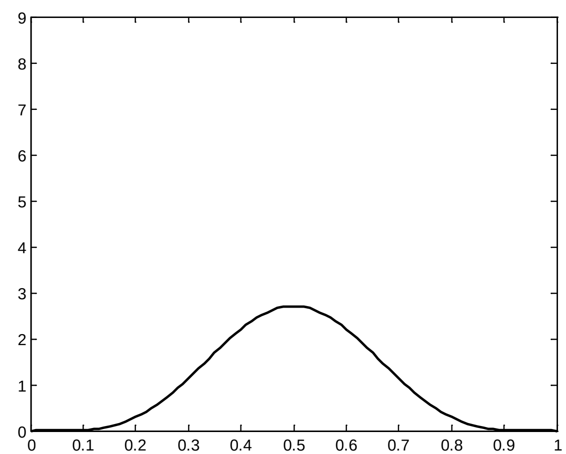
[Fabbri et al. (2005)]



p=0.5
σ=0.12

Beta distribution

[Fabbri et al. (2005)]



The model

- How do we model wind forecast errors?

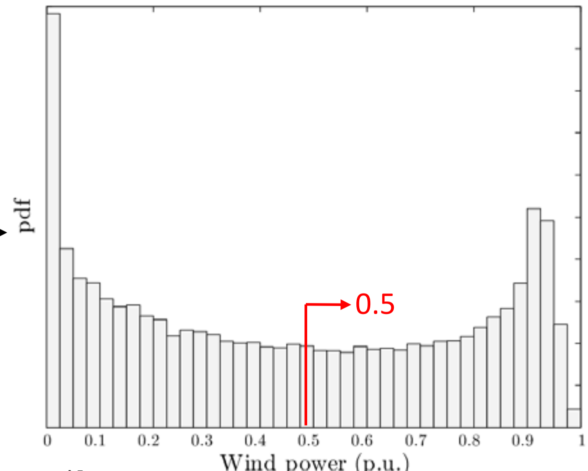
Forecast

s	W	π
s1	0.5	$1/N_S$

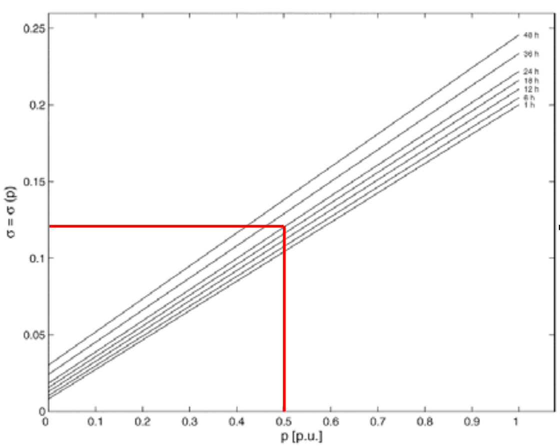
Error

ΔW	r1	r2	r3	• • •	N_R
s1	0.1	-0.1	0	• • •	

Historical data



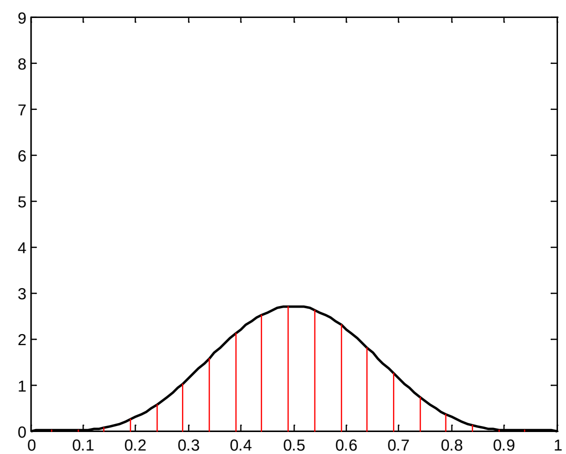
[Fabbri et al. (2005)]



p=0.5
σ=0.12

Beta distribution

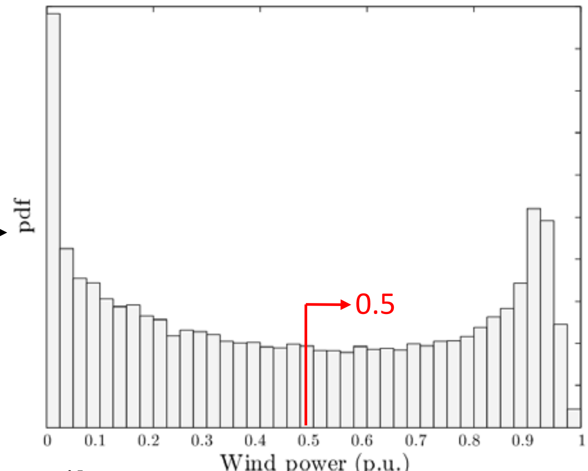
[Fabbri et al. (2005)]



The model

- How do we model wind forecast errors?

Historical data



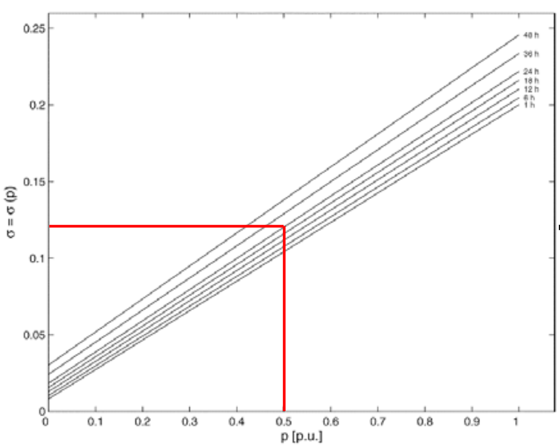
Forecast

s	**W**	π
s1	0.5	$1/N_S$
s2		
s3		
⋮	⋮	⋮
N_S		

Error

ΔW	r1	r2	r3	• • •	N_R
s1	0.1	-0.1	0	• • •	
s2				• • •	
s3				• • •	
⋮	⋮	⋮	⋮	⋱	
N_S					

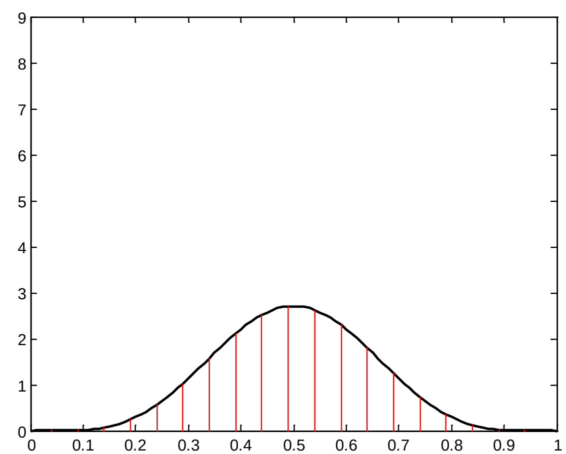
[Fabbri et al. (2005)]



p=0.5
σ=0.12

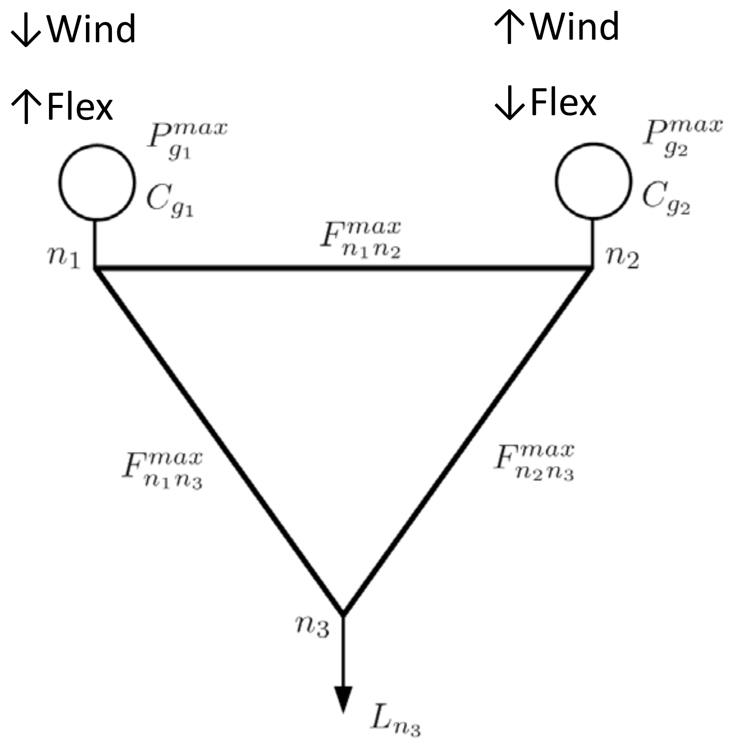
Beta distribution

[Fabbri et al. (2005)]



Example

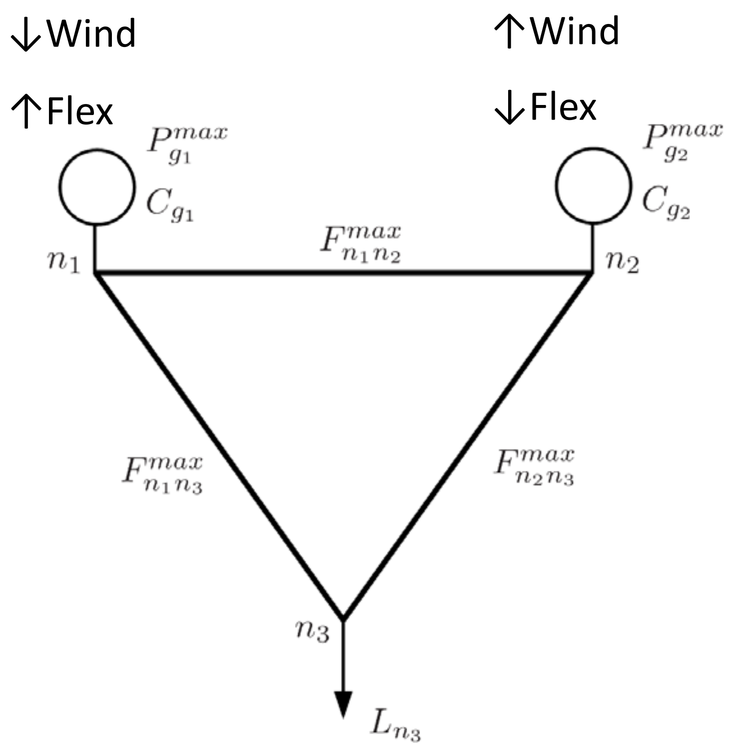
- Results: impact of forecast error



Dec	Bus1
Δ=0.1	

Example

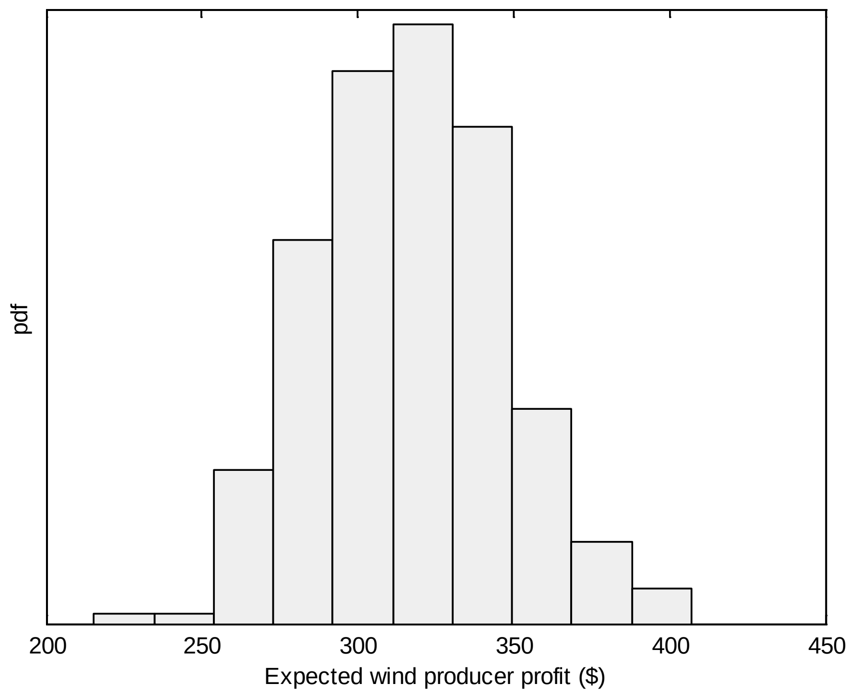
- Results: impact of forecast error



Dec	Bus1
Δ=0.1	DA profit = \$600 B profit = -\$4 Total profit = \$596

Example

- Results: use of PEM



- Fix location to Bus 1
- Decoupled market clearing
- Run 500 cases with
  - 100 samples (DA)
  - 100 samples (B)
  - 10,000 total samples