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The Effect of Variable Renewable Energy Sources on Wholesale Electricity Prices – Implementation of a Stochastic Wind Feed-in

Thomas Möbius

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Agenda

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1. Motivation
2. Methodology
3. Basic Model
4. Results – Perfect Foresight
5. Results – Uncertain Wind Feed-in
6. Conclusion

Motivation

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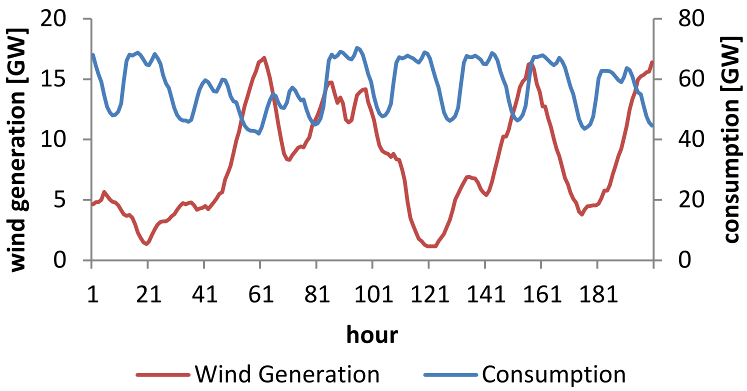
- Structural changes to many electricity systems as intermittent RES as wind and PV enter the market

  – Highly fluctuating availability

  – Low correlation between intermittent RES generation and demand



  → The system adjusts

  → Over capacities will leave the market

  → Prices will reflect the structural changes in the system

Motivation

- … implications for wholesale electricity prices, power plant revenues, flexibility requirements and market design are among the most fundamental issues currently discussed in electricity markets

  – How will prices behave in a market with high shares of intermittent RES in the long run?

  – Increasing price variances due to intermittent RES generation?

  – How is the price variance driven considering a long term equilibrium?

Methodology

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- Analyzing the price variance on a fundamental basis by applying a linear electricity market model

- Long term (partial) market equilibria
  - System optimal decision about capacity investments
  - System optimal generation dispatch depending on the available capacities

- Full cost approach
  - Variable costs and investment costs are represented in the resulting market price
  - Scarcities and scarcity prices will occur as investments have to be covered

- Green field approach
  - No existing power plants – avoiding sunk investment costs

Methodology

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- Stylized system with two thermal technologies and one intermittent RES technology
  - Base-Load Technology: High fix and low variable costs
  - Peak-Load Technology : Low fix and high variable costs

Technology	Annual fixed costs [€/MW*a] ic_i	Variable production costs [€/MWh] vc_i	Start-up costs [€/ΔMW] sc_i	Minimal load [%] g_i^{min}	Efficiency loss at minimum load [%-pt]
Base Load	132,000	34	105	40	6
Peak Load	56,000	70	40	20	22
Wind	-	0	0	0	0

- Variable wind generation as the only intermittent RES
  - Wind capacities exogenously implemented

Basic Model

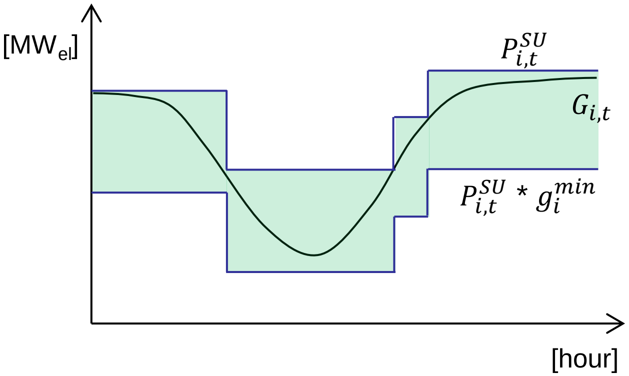
- Objective Function

$$\min TC = \sum_{i,t} vc_i * G_{i,t}$$ Variable generation costs

$$+ \sum_{i} ic_i * D_i$$ Annualized investment costs

$$+ \sum_{i,t} sc_i * SU_{i,t}$$ Start-up Costs

$$+ \sum_{i,t} \left(P_{i,t}^{SU} - G_{i,t}\right) * z_i$$ Costs at partial load



- Upper bound constraint

$$0 \leq G_{i,t} \leq P_{i,t}^{SU} \quad \forall\, i,t$$

- Lower bound constraint

$$P_{i,t}^{SU} * g_i^{min} \leq G_{i,t} \quad \forall\, i,t$$

Basic Model

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- Activating start-up costs $P_{i,t}^{SU} - P_{i,t-1}^{SU} \leq SU_{i,t} \quad \forall\, i, t$

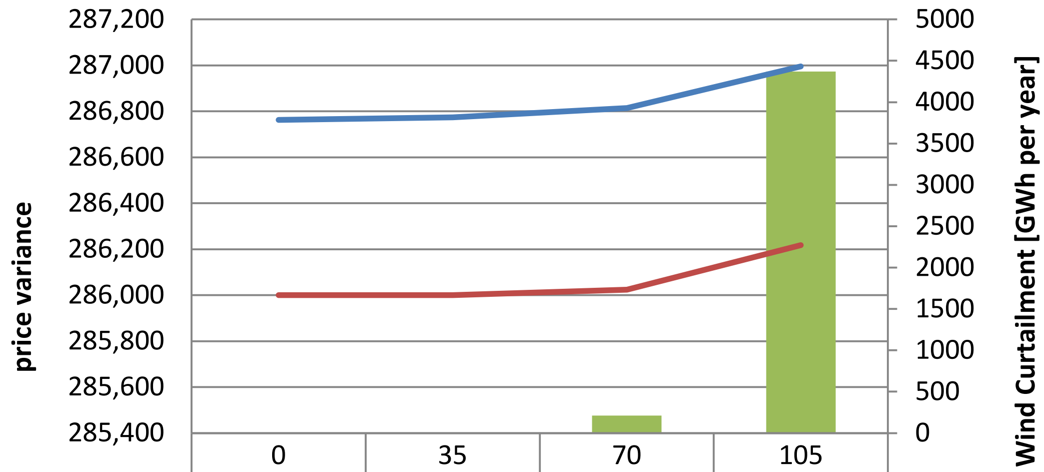
- Upper limit for started capacity $P_{i,t}^{SU} \leq D_i * af_i \quad \forall\, i, t$

- Wind feed-in $0 \leq G_{"Wind",t} \leq pf_t * \text{cap}_{"Wind"} \quad \forall\, t$

- Energy Balance - Clearing the market in every time period

$$\sum_i G_{i,t} = dem_t \quad \forall\, t$$

- Price volatility with perfect foresight



	0 GW	35 GW	70 GW	105 GW
Wind Curtailment	0	0	213	4371
with start-up restrictions	286,762	286,774	286,814	286,996
without start-up restrictions	286,000	286,000	286,024	286,217

Installed wind capacity

> **Increasing start-up activities do not have a significant impact on the price variance as wind curtailment activities**

Results – Analytical Explanation

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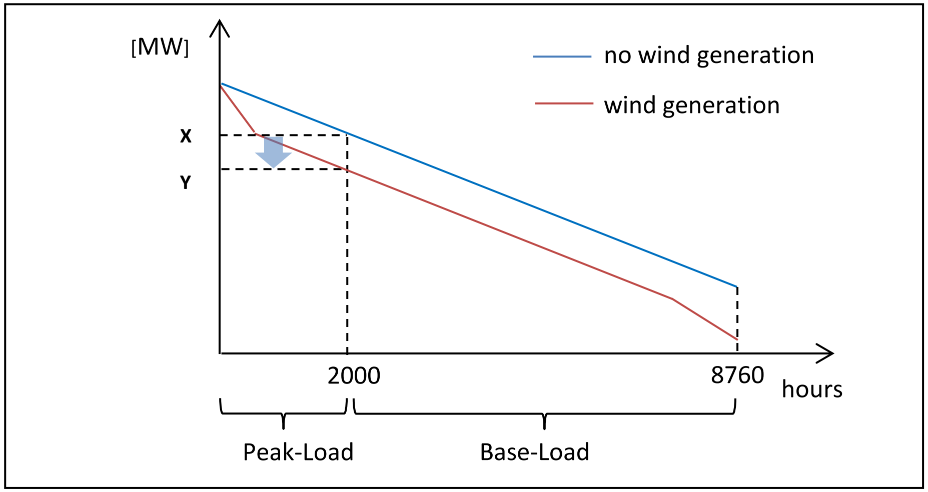
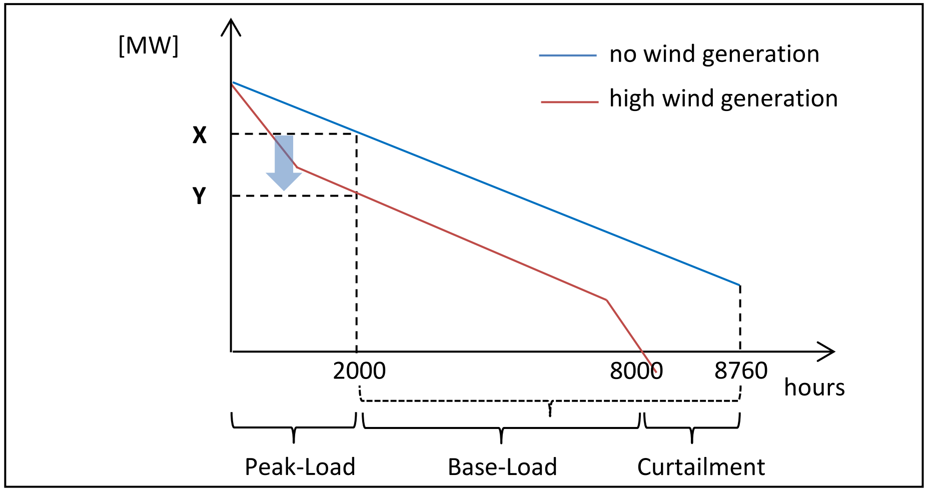
- "Textbook" example
  - No start-up restrictions
  - Price only influenced by fuel and investment costs
  - Only three possible prices to occur within the considered year
    - Base-Load Price
    - Peak-Load Price
    - Scarcity Price



$$Var = \frac{1}{n} * \left(\sum_{1}^{B} (p^{Base} - \bar{p})^2 + \sum_{1}^{P} (p^{Peak} - \bar{p})^2 + (p^{Scarce} - \bar{p})^2 \right)$$

Results – Analytical Explanation

- "Textbook" example - part II
  - With an increasing shares of RES wind curtailment becomes an option
  - During times of wind **curtailment prices** at 0 €/MWh appear



$$Var = \frac{1}{n} * \left(\sum_{1}^{B} (p^{Base} - \bar{p})^2 + \sum_{1}^{C} (p^{Curt} - \bar{p})^2 + \sum_{1}^{P} (p^{Peak} - \bar{p})^2 + (p^{Scarce} - \bar{p})^2 \right)$$

Results – Volatility under Uncertainty

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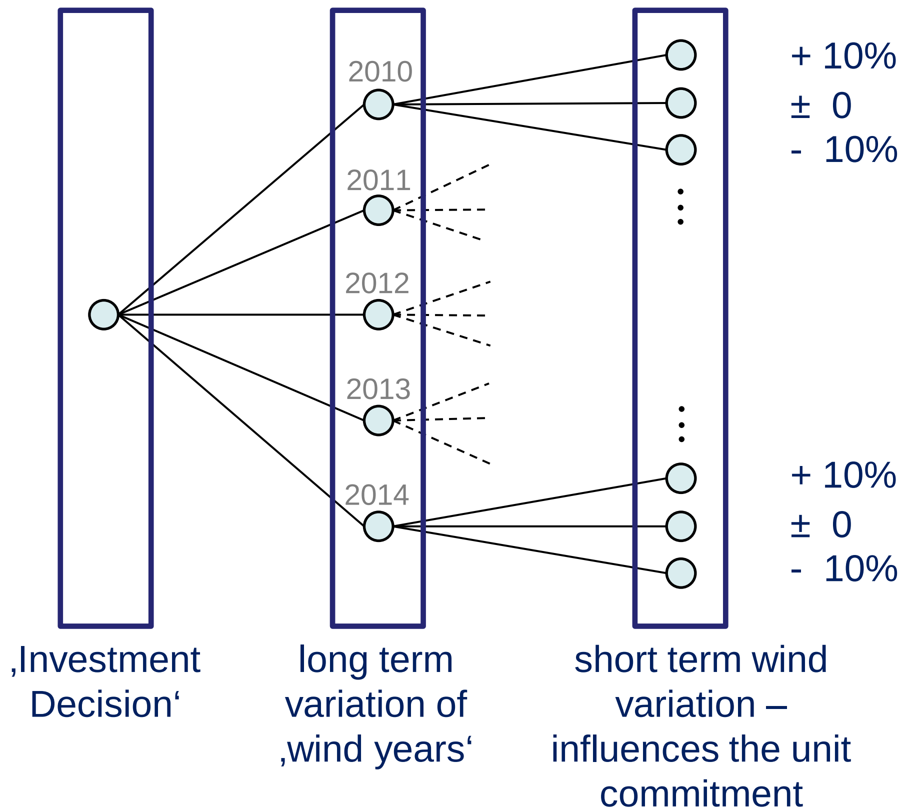
- Implementing uncertain wind realization



- global investment decision considering an uncertain wind realization
- Long term uncertainty due to a set of different ‘wind years’
- Short term uncertainty with a strong impact at the start-up decision
  - Started capacity is fixed at the second stage of the scenario tree, but has to hold for all variations at the third stage

➢ ‘one stage’ electricity market model

Results – Volatility under Uncertainty

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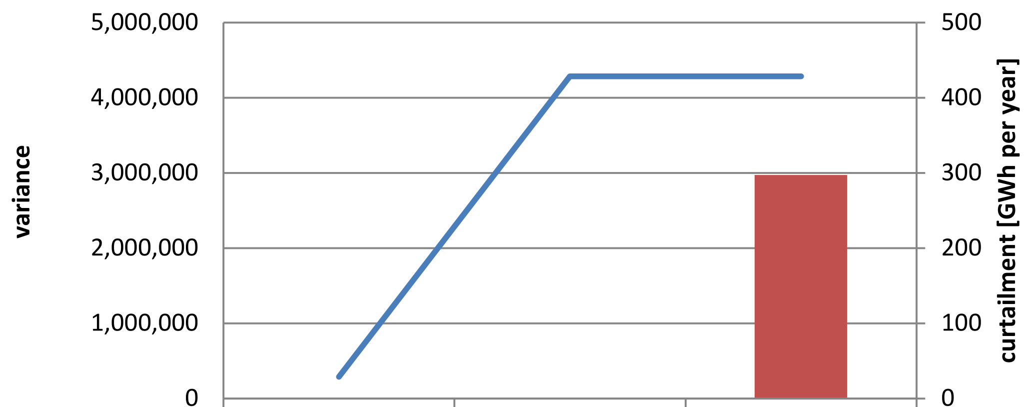
- Generally higher values due to lower likelihood for the occurrence of the scarcity hour and thus, a significant higher value for the scarcity price
- Increasing price volatility with the implementation of wind capacities



	0 GW	35 GW	70 GW
wind curtailment [GWh per year]	0	0	297
price variance	286,000	4,282,914	4,282,976

Installed wind capacity

Conclusion

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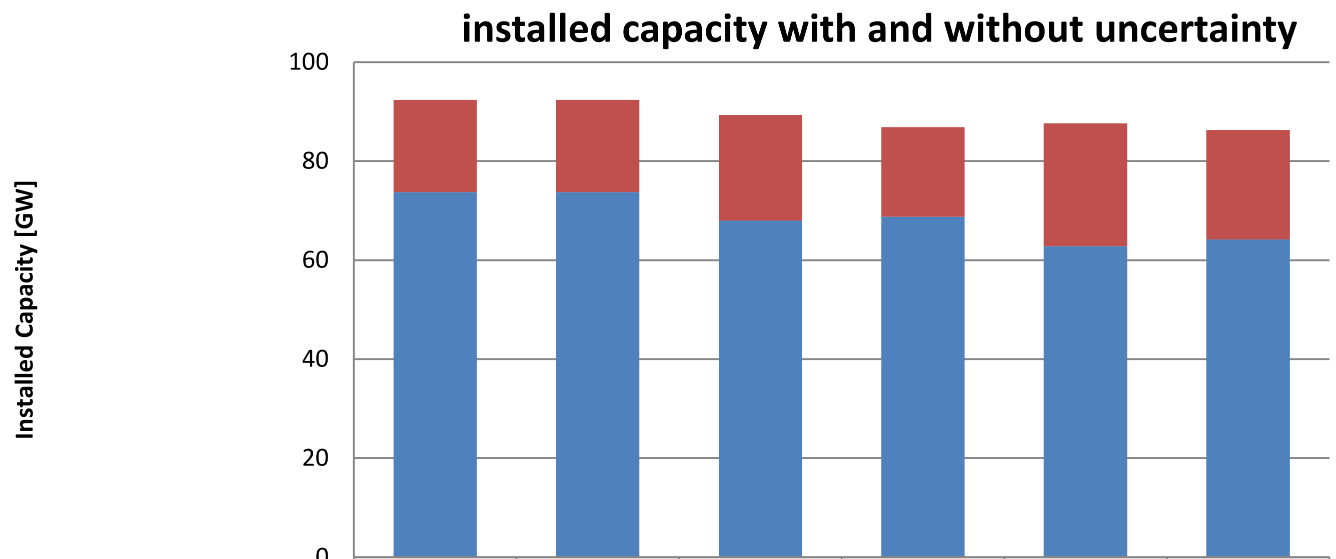
- The volatility of electricity wholesale prices is an important indicator to future electricity markets
  - Regarding the need of flexibility options
- Price volatility in the first place is mainly driven by upcoming wind curtailment activities
- We find a (partial) market equilibrium with regard of an uncertain wind realization
  - The problem is solved within one stage
- The increase of the volatility is mainly driven by the ‘uncertain’ appearance of the scarcity hour and thus, the scarcity price is significantly higher

Thank you very much!

Questions?

Backup I

- Comparison of resulting investment decision with and without considering uncertainty
  - Uncertain wind realization encourages a higher share of peak load plants



	0 GW - w	0 GW - w/o	35 GW - w	35 GW - w/o	70 GW - w	70 GW - w/o
Peak Load Technology	18.6	18.6	21.3	18.1	24.8	22.1
Base Load Technology	73.8	73.8	68.0	68.8	62.8	64.1

Backup II – Basic Model

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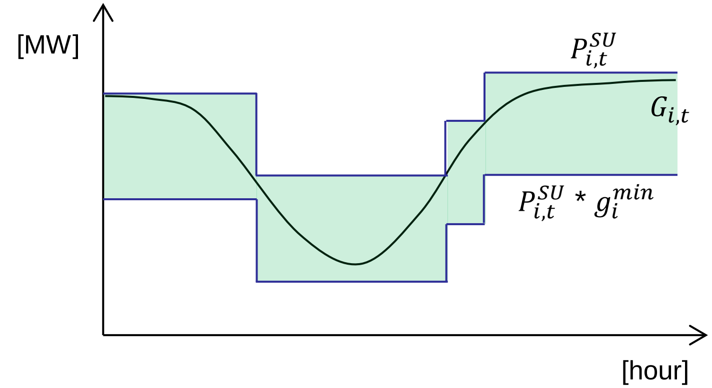
- Objective Function

$$\min TC = \sum_{i,t}(vc_i * G_{i,t} + sc_i * SU_{i,t}) + \sum_{i,t}(P^{SU}_{i,t} - G_{i,t}) * z_i + \sum_i (ic_i * D_i)$$

$$z_i = \Delta vc_i * g_i^{min} / (1 - g_i^{min})$$

$$P^{SU}_{i,t} - P^{SU}_{i,t-1} \leq SU_{i,t} \quad \forall\, i,t$$



– Operating at partial load is causing lower efficiency rates and thus, higher variable costs