Multi-Stage Stochastic Economic Dispatch under Renewable Energy Supply Uncertainty

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December 23, 2016
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Outline

- Motivation
- Stochastic dual dynamic programming
- Stochastic multi-period dispatch of pumped hydro resources
  - Renewable supply model
  - Stochastic multi-period economic dispatch
- A Case Study of Germany

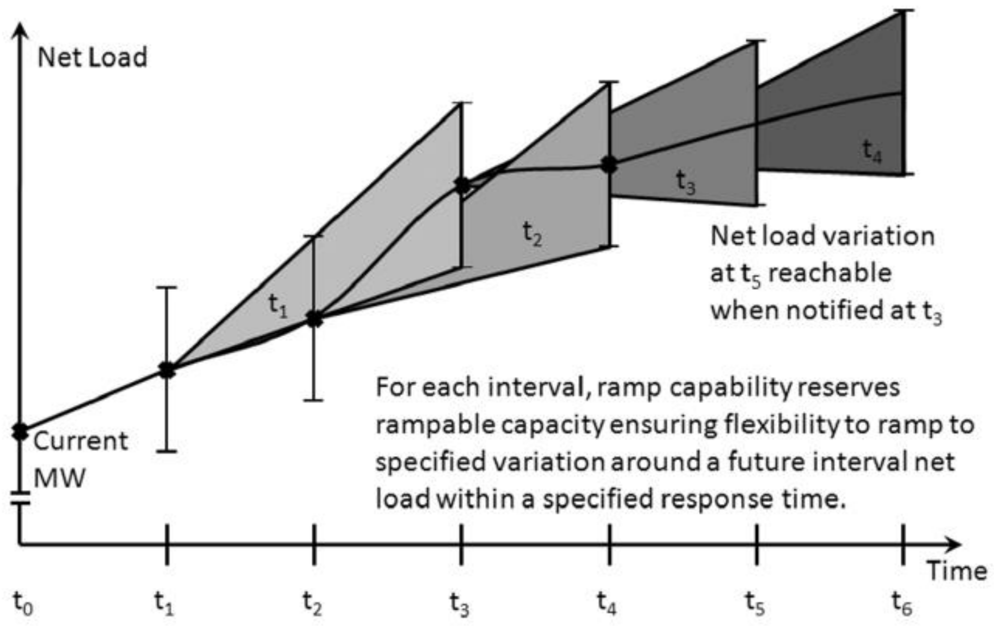
Motivation

Multi-Stage Stochastic Economic Dispatch

- Economic dispatch: function of
  - re-dispatching online units
  - mobilizing fast-start units

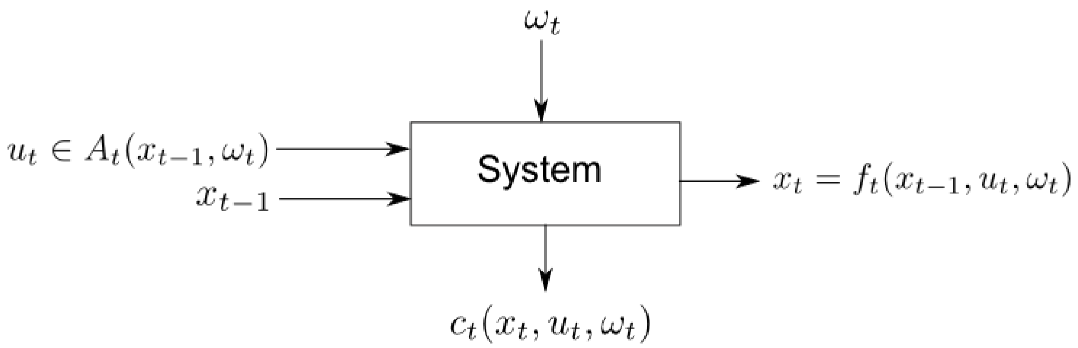
in intra-day and real time for purpose of load following

- Should be distinguished from day-ahead unit commitment
- Increasing sophistication of MSED:
  - Multi-period look-ahead
  - 'Rough' consideration of uncertainty by securing flexible ramp capacity (e.g. California ISO and Midwest ISO)
- Typical time scale: 5-minute time step, 15-minute look-ahead, solved 7.5 minutes in advance of operations



Multi-Period Decision Making Under Uncertainty

- At each stage:
  - Observe uncertainty (ω_t)
  - Make a decision (u_t) given realized uncertainty and state of the system (x_t)
  - Incur cost ($c_t(x_t, u_t, \omega_t)$)
  - Step forward
- Goal: minimize expected cost over optimization horizon
- Bellman's principle of optimality: at each stage, decide x_t such that present cost plus expected **cost-to-go** is minimized
- Dynamic programming algorithm: solve the problem by recursively computing **cost-to-go** -> avoids redundancy in computations



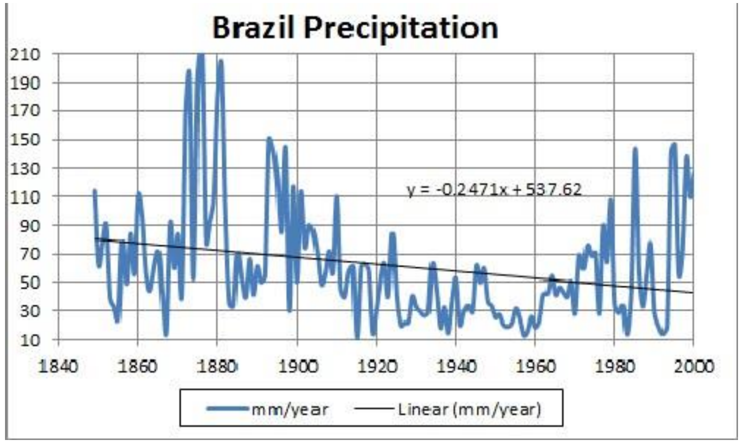
$$V_t(x_{t-1}) = \mathbb{E}_{\omega_t}[\min_{u_t \in A_t(x_{t-1})} (c_t(x_t, u_t, \omega_t) + V_{t+1}(x_t))|x_{t-1}, u_t]$$

$$x_t = f_t(x_{t-1}, u_t, \omega_t)$$

$$V_{T+1}(x_T) = 0.$$

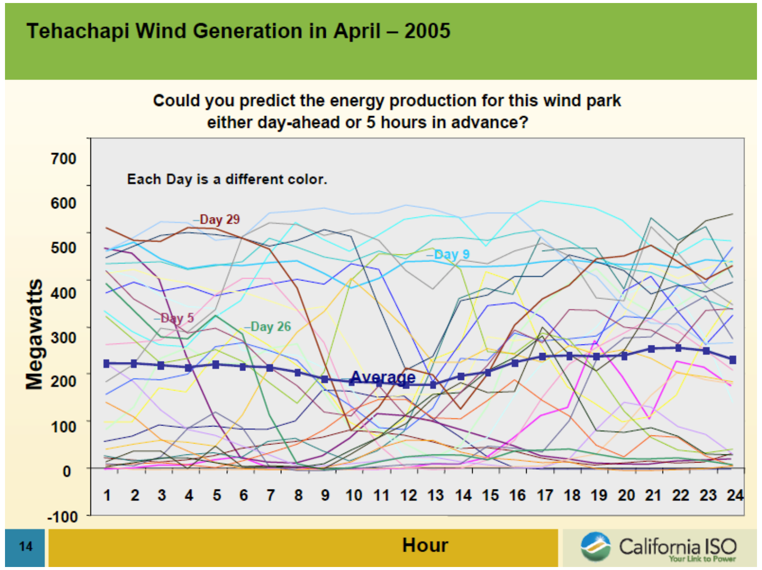
Applying An Effective Solution …

- Multi-stage stochastic linear programming
  - Specific class of problems for multi-period decision making under uncertainty
  - Natural formulation for various problems in power system planning / operations
- Stochastic Dual Dynamic Programming (SDDP)
  - Scalable: go-to solution for medium-term hydro-thermal planning
  - Extensive theoretical analysis (representation of uncertainty, convergence, binary decisions)



… To An Emerging Problem

- Multi-period stochastic economic dispatch
  - Limited analysis
  - Highly relevant (e.g. rooftop solar, distributed storage, pumped hydro)
  - Naturally cast as a multi-stage stochastic linear program
- Our **research agenda**:
  - Can dynamic programming solve MSED?
  - Is MSED an interesting problem?



Stochastic Dual Dynamic Programming

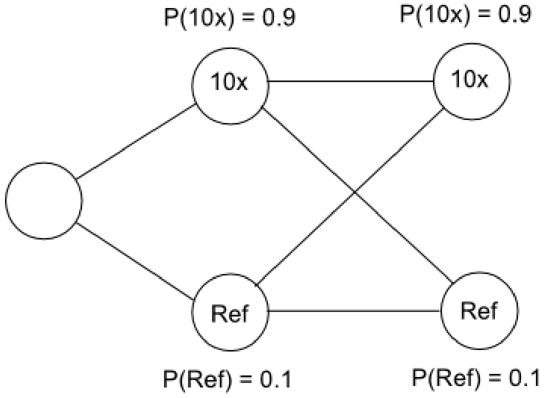
Multi-Stage Stochastic Linear Programming

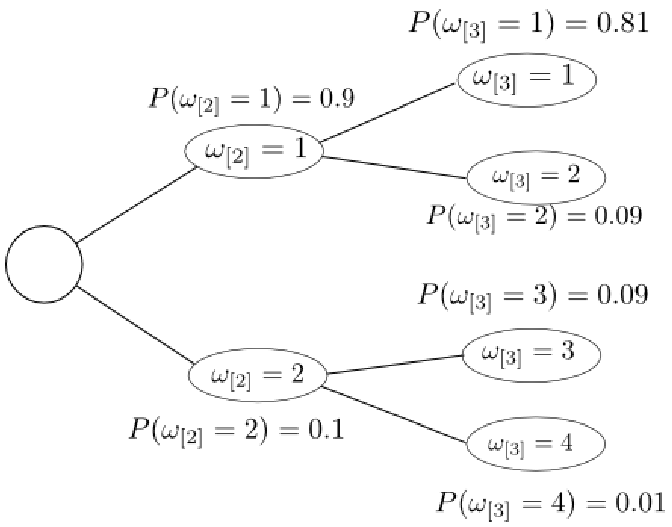
$$min_x \sum_{t=1}^{H} \sum_{\omega_{[t]} \in \Omega_{[t]}} p_{t,\omega_{[t]}} c_t^T x_{t\omega_{[t]}}$$

Set of possible history of events up to stage t: <u>Non-scalable</u>

$$T_{t,\omega_t} x_{t-1,\omega_{[t]},A(\omega_{[t]})} + W_t x_{t,\omega_{[t]}} = h_{t,\omega_t}, t \in T, \omega_{[t]} \in \Omega_{[t]}$$

$$x_{t,\omega_{[t]}} \geq 0, t \in T, \omega_{[t]} \in \Omega_{[t]}$$





Decomposing the Problem

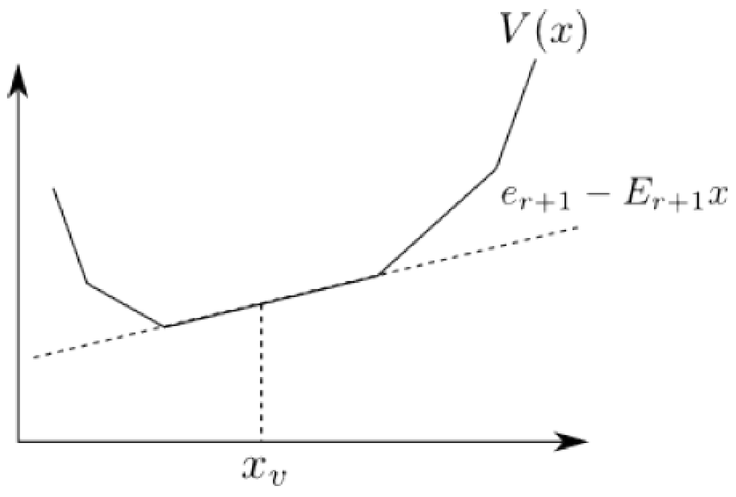
$NLDS_{t,k}(\hat{x}_{t-1})$: $min_x c_t^T x + \tilde{V}_t(x)$

Approximation of cost-to-go function

$W_t x = h_{t,k} - T_t \hat{x}_{t-1}$

Trial decision from previous period

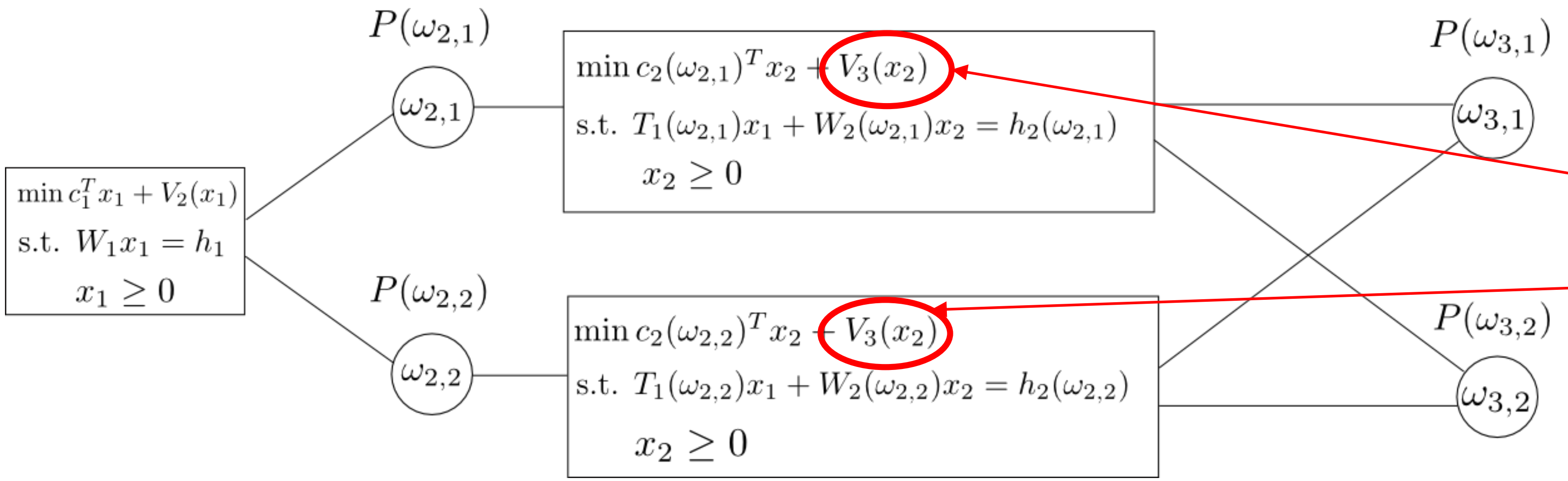
$x \geq 0$



- Solution approach: break the overall problem by time stage t, and uncertainty realization k -> **small** linear program $NLDS_{t,k}$ for each t, k
- The value function $\tilde{V}_t(x)$ is piecewise linear affine, question is how to 'discover' it

Describing Uncertainty in a Lattice

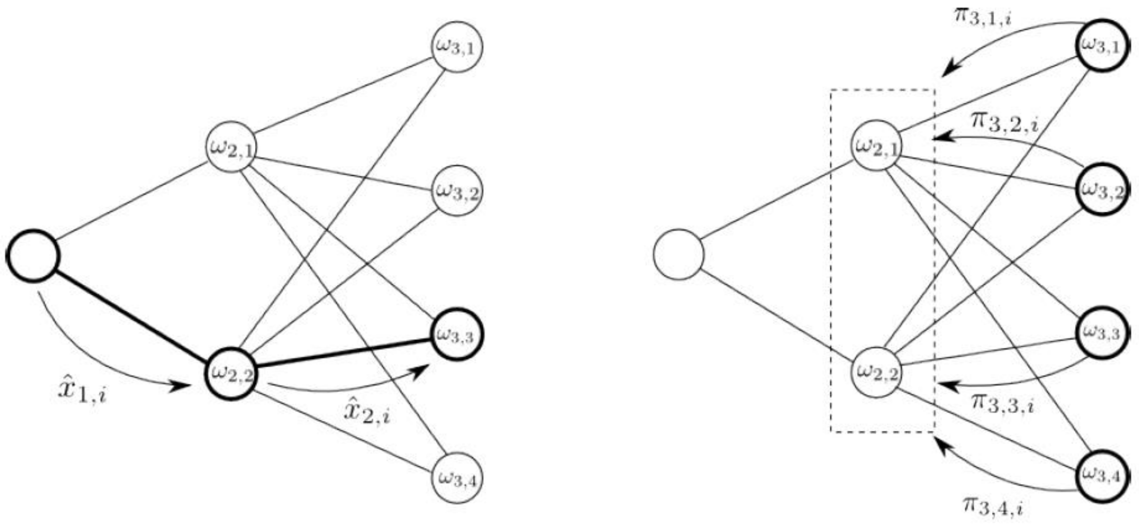
- A lattice is a graphical description of **Markovian** uncertainty:
  - Nodes: realization of uncertainty $h_t(\omega_t)$
  - Arcs: transition probability $\mathbb{P}[\omega_t|\omega_{t-1}]$
- **Serial independence**: specific class of lattices where $h_t(\omega_t)$ is distributed independently of history: $\mathbb{P}[\omega_t|\omega_{[t-1]}] = \mathbb{P}[\omega_t], \forall\omega_{[t-1]}, \forall t$

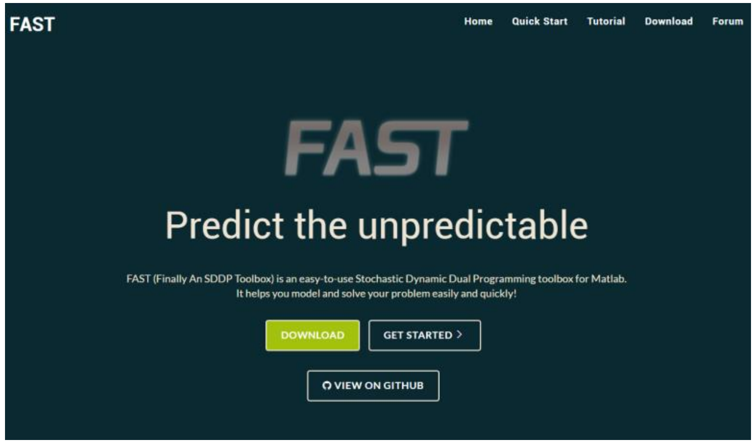


Serial independence =>
value functions are shared
across lattice nodes

Stochastic Dual Dynamic Programming Algorithm

- Forward pass
  - Generates trial decisions
  - Determines **probabilistic** upper bound
  - Determines lower bound
- Backward pass
  - Generates optimality cuts that approximate cost-to-go $\tilde{V}_t(x)$
- MATLAB open-source implementation: https://web.stanford.edu/~lcambier/fast/
  - User-defined decomposition subproblem
  - User-defined input lattice

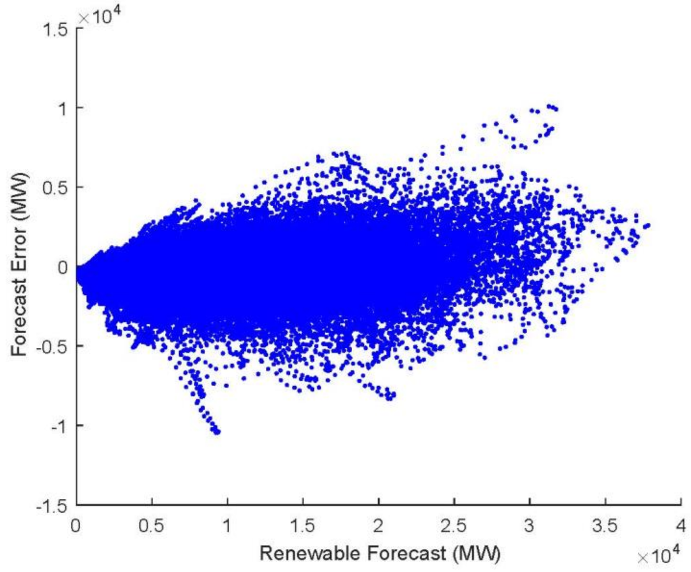




Stochastic Multi-Period Dispatch of Pumped-Hydro Resources

Renewable Supply Model

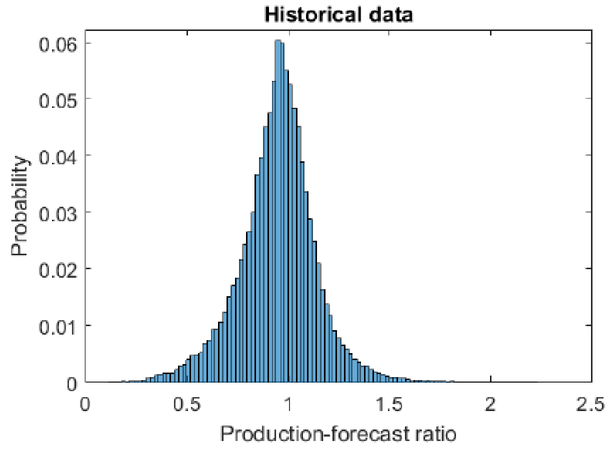
- Multiplicative model of forecast error/renewable production **ratio:**
  - Capture heteroscedasticity of data
  - Capture inter-temporal dependence of forecast error
  - Compatible with SDDP format (serial independence)

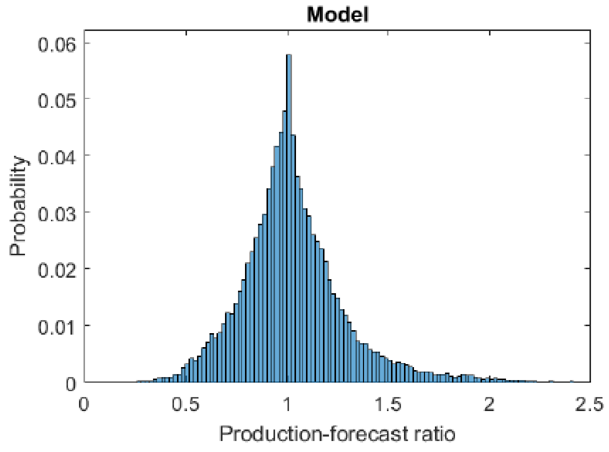


$$y_{t+1} = (c + \phi \cdot y_t) \cdot \eta_t$$

$$p_t = RF_t \cdot y_t$$

Serial independence => value functions are shared across lattice nodes





Stochastic Multi-Period Economic Dispatch

- Objective: minimize load shedding and fuel cost
- Coupling constraint: power balance
- ls_n: load shedding
- c_g: fuel cost
- D_l: load
- pd_g: pumping demand
- pp_g: pumping production
- p_g : power production
- RF_g : renewable forecast
- y_g : renewable forecast / realization ratio
- f_k : power flow over line

$$min \frac{1}{4} (\sum_{n \in N} (VOLL \cdot ls_n) + \sum_{g \in G} c_g)$$

$$\sum_{l \in L_n} D_l + \sum_{l \in L_n} pd_g + \sum_{k \in (n,\cdot)} f_k = \sum_{g \in G} p_g + \sum_{g \in PH_n} pp_g + \sum_{g \in GR_n} RF_g y_g + ls_n + \sum_{k \in (\cdot,n)} f_k \, , n \in N$$

Stochastic Multi-Period Economic Dispatch (II): Conventional Generators

- Piecewise affine fuel cost
- Technical minimum/maximum
- Ramp rate limits
- U_g : Unit commitment (on/off) decision
- $A_{g,m}, B_{g,m}$: cost function parameters
- RU_g, RD_g: ramp up/down limit
- c_g: fuel cost
- p_g : power production

$$c_g \geq F_g\left(A_{g,m} U_g + B_{g,m} p_g\right), g \in G, \mathrm{m} = 1, \ldots 3$$

$$PMin_g U_g \leq p_g \leq PMax_g U_g, g \in G$$

$$p_g - p_{g,t-1} \leq RU_g U_g + MTL_g\left(1 - U_{g,t-1}\right), g \in G$$

$$p_{g,t-1} - p_g \leq RD_g U_g + MTL_g\left(1 - U_{g,t-1}\right), g \in G$$

Unit commitment is **fixed** to the solution of a day-ahead unit commitment model

Stochastic Multi-Period Economic Dispatch (III): Pumped Hydro Units

- Storage dynamics
- Pumped hydro consumption limits
- Pumped hydro production limits
- s_g : stored energy
- $\eta_{g,m}$: pumped hydro unit efficiency
- $DMax_g$: power consumption limit
- $PMax_g$: power production limit

$$s_g = s_{g,t-1} + 0.25(\eta_g pd_g - pp_g), g \in PH$$

$$pd_g \leq DMax_g, g \in PH$$

$$pp_g \leq PMax_g, g \in PH$$

Stochastic Multi-Period Economic Dispatch (IV): Power Flow

- Fix reference bus angle
- Linearized DC power flow
- Line flow limits
- θ_m : bus angle
- B_k : line susceptance
- f_k: line power flow
- TC_k: line flow limit

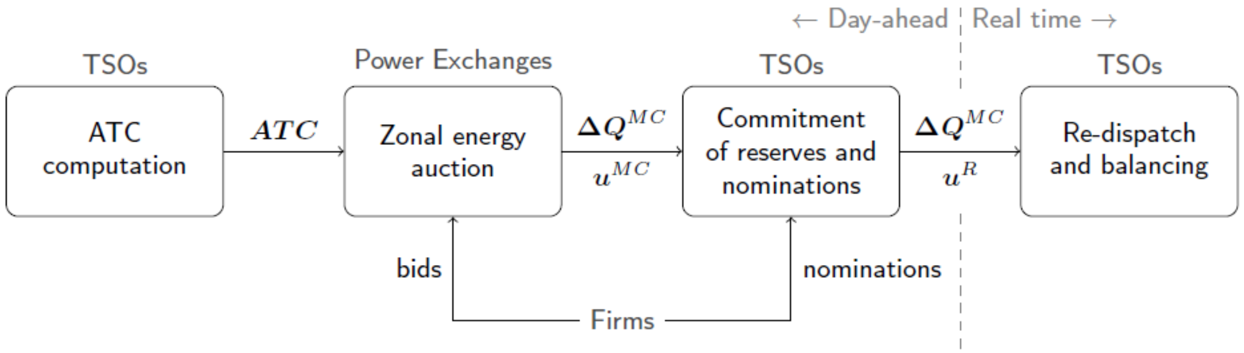
$$\theta_{hub} = 0$$

$$f_k = B_k(\theta_m - \theta_n), k = (m, n) \in \mathrm{K}$$

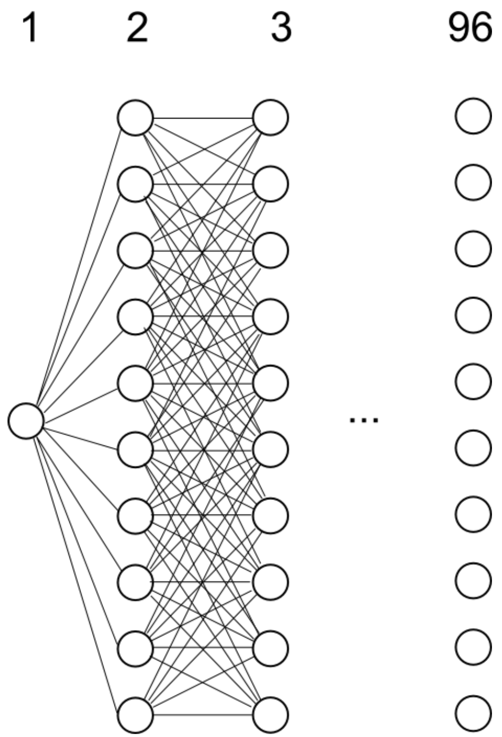
$$-TC_k \leq f_k \leq TC_k, k \in K$$

A Case Study of Germany

German System

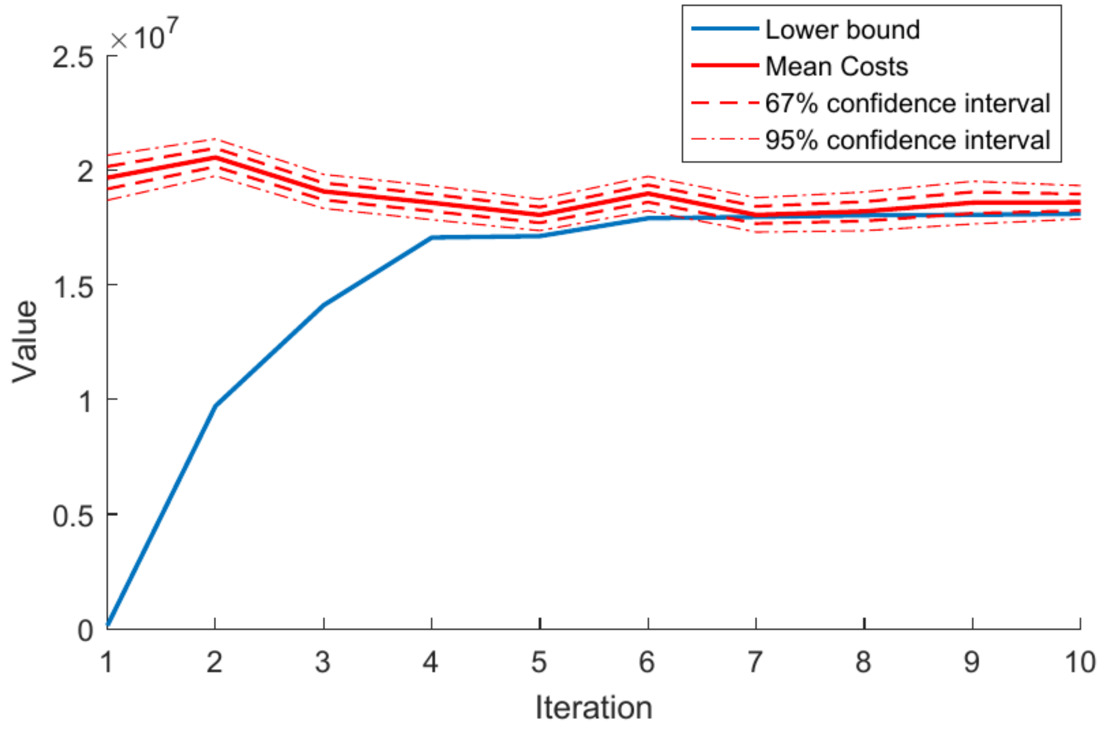


- Two-step simulation of German market:
  - Weekly clearing of reserve + energy exchange: unit commitment model with weekly horizon (September 22-28, 2014)
  - Real-time balancing: economic dispatch model for Thursday, with a horizon of 24 hours and a time step of 15 minutes
- Lattice: 96 stages, 10 nodes per stage
- 292 generators, 228 buses, 312 lines
- Assume fast-start resources at every node with marginal cost of 100 – 500 €/MWh



Convergence

- Run time for obtaining a **policy**: 4.3 hours
- Run time for obtaining a decision, given a history of uncertainty: sub-second

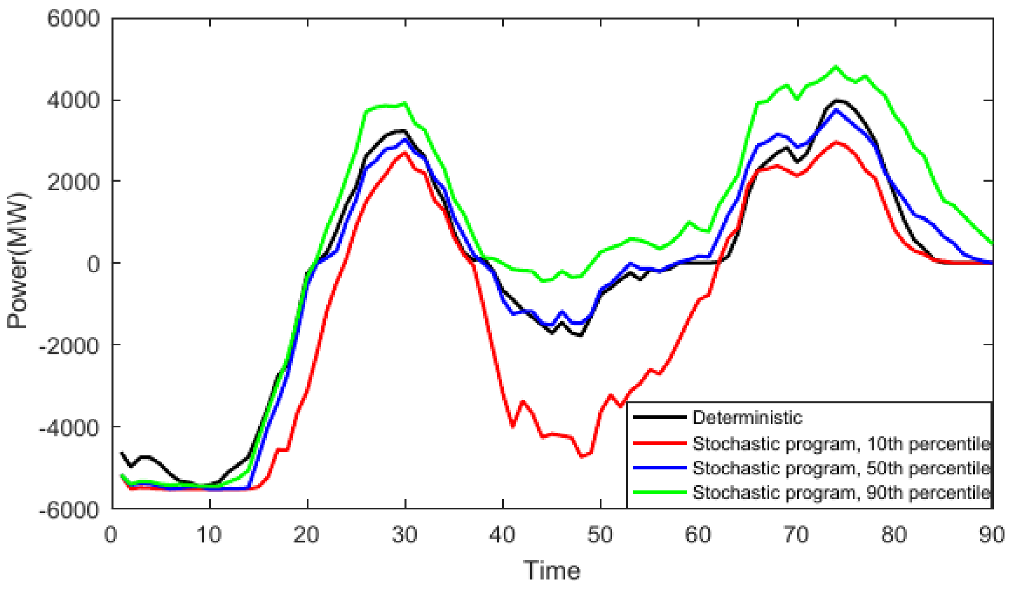


Policy Comparison

	Slow unit cost (10^3 €)	Fast-start cost (10^3 €)	Total cost (10^3 €)	σ total cost (10^3 €)	Fast-start energy (MWh)	Excess energy (MWh)
Perfect foresight	17380	850	18231	291	7204	1809
Stochastic programming	17423	955	18378	305	7511	1855
Deterministic	17373	1221	18594	350	8688	1879

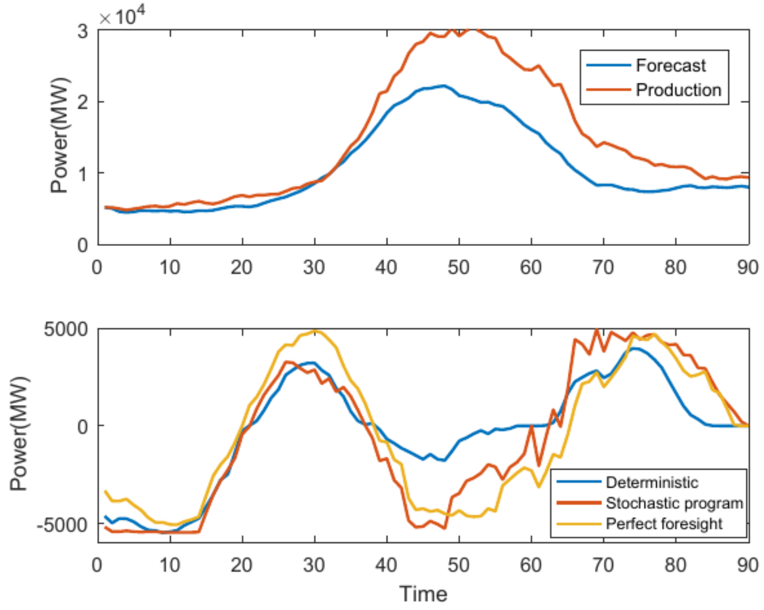
- Deterministic dispatch: fixed pumped hydro schedule to day-ahead solution
- Benefits of perfect foresight relative to stochastic programming: 0.8%
- Benefits of stochastic programming relative to deterministic dispatch: 1.2%

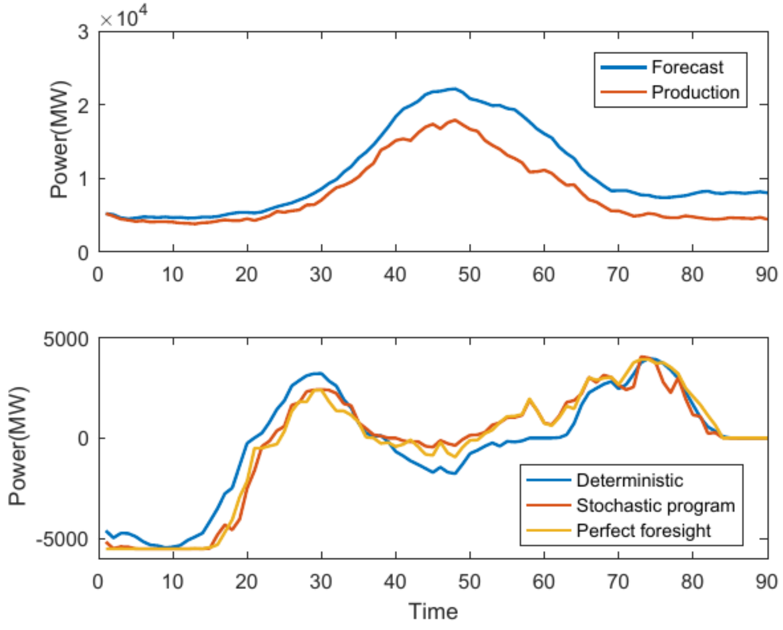
Adaptiveness of Stochastic Programming Dispatch



Under-forecast

Over-forecast





Effects of Transmission and Ramping

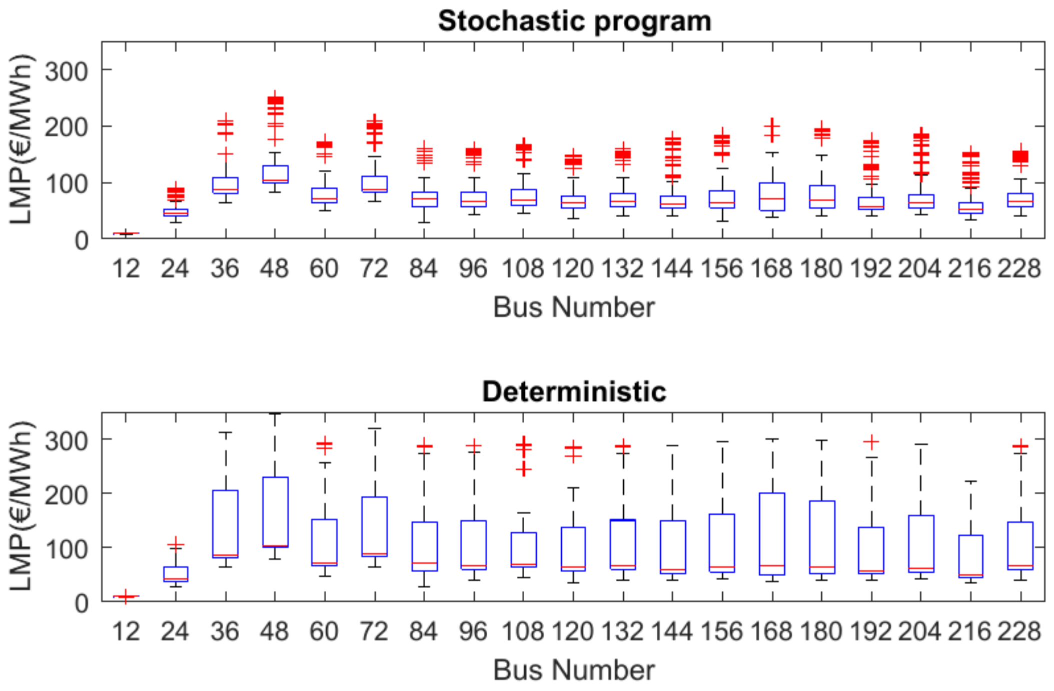
	Total cost (10^3 €)	σ total cost (10^3 €)
Perfect foresight (no transmission)	14797	97
Stochastic programming (no transmission)	14828	100
Deterministic (no transmission)	14867	105
Lookahead 1-step (no transmission)	14865	105
SP hydro-only (no transmission)	14830	101
Perfect foresight (no ramp / transmission)	14796	97
Stochastic programming (no ramp / transmission)	14828	100
Deterministic (no ramp / transmission)	14856	105

Some Observations

- Transmission constraints have major impact on results: in the absence of transmission constraints, all three policies attain very similar performance
- Incremental cost of ramp constraints is negligible => are flexible ramp products all that important?
- Incremental benefit of look-ahead is minimal => are short-term lookaheads in real-time markets as important as controlling pumped hydro optimally?
- Performance of ‘SP hydro-only’ very close to stochastic programming optimal => are short-term lookaheads in real-time markets as important as controlling pumped hydro optimally?

Price Behavior

- Tendency of pumped hydro storage to level out prices over time periods and realizations



Thank you

For more information

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