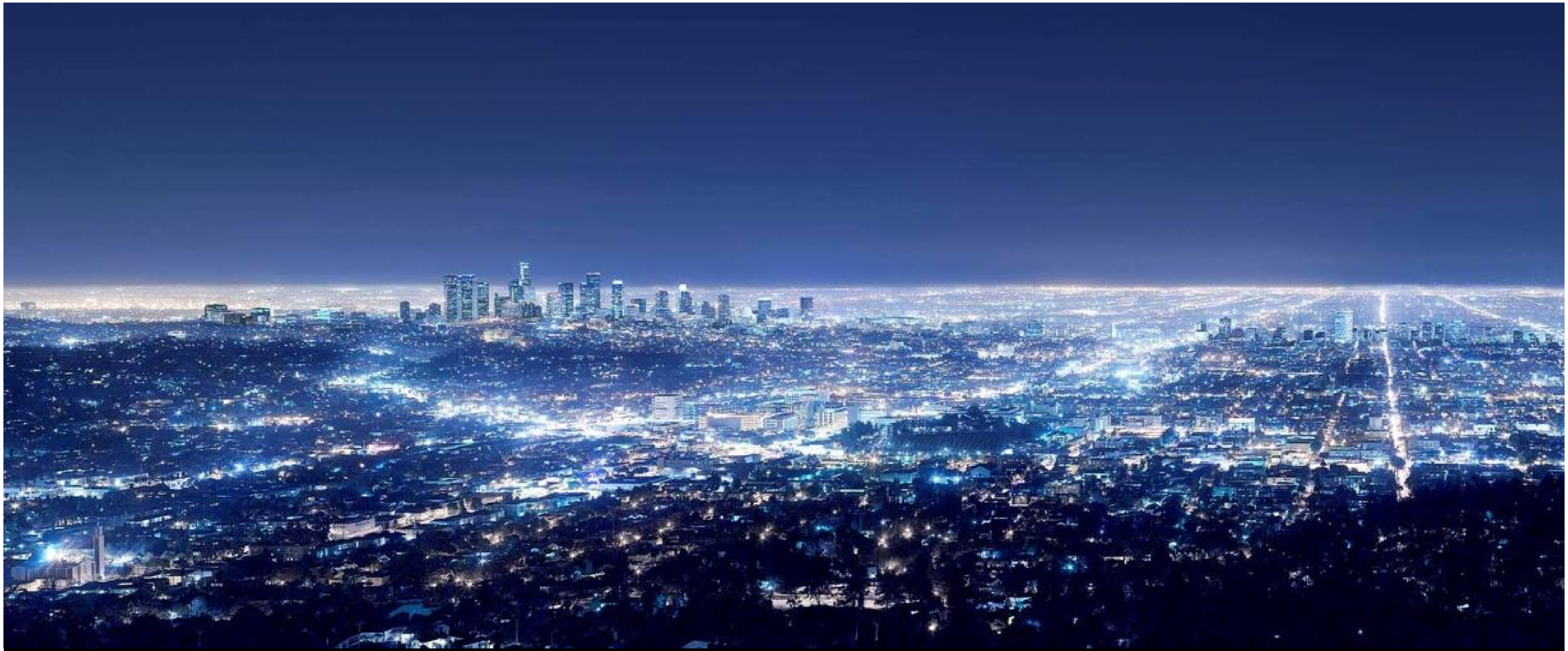


Xiaoming Feng, ABB, Feb 2-3, 2015

Managing Renewable Uncertainty in Grid Operation

FESC Workshop “Integration of Renewable Energy into the Grid”, Orlando, FL

Power and productivity
for a better world™

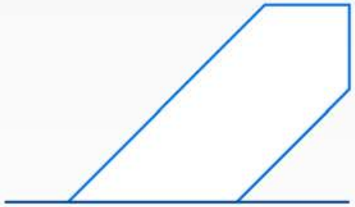
Outline

- Renewable power & limitations
- Options for managing renewable volatility
- ES and technical challenges
- Review of two stage and multi stage stochastic optimization
- Choices of stochastic SCUC definition and implications

A global leader in power and automation technologies
Leading market positions in main businesses

- ~145,000

employees



$42 billion

In revenue (2013)

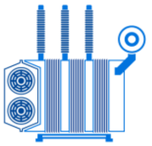
Present in +100

countries

Formed in 1988

merger of Swiss (BBC, 1891) and Swedish (ASEA, 1883) engineering companies

Power and productivity for a better world
ABB’s vision



Power Products

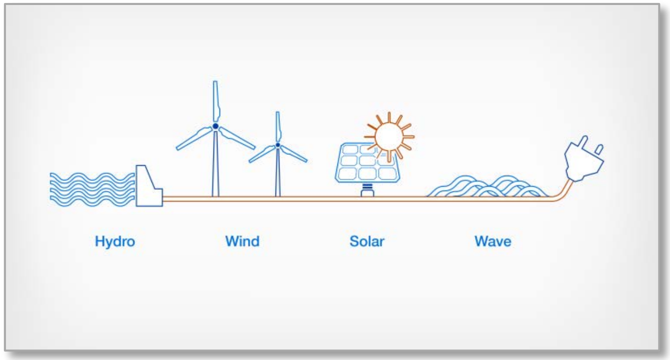
Power Systems

Discrete Automation and Motion

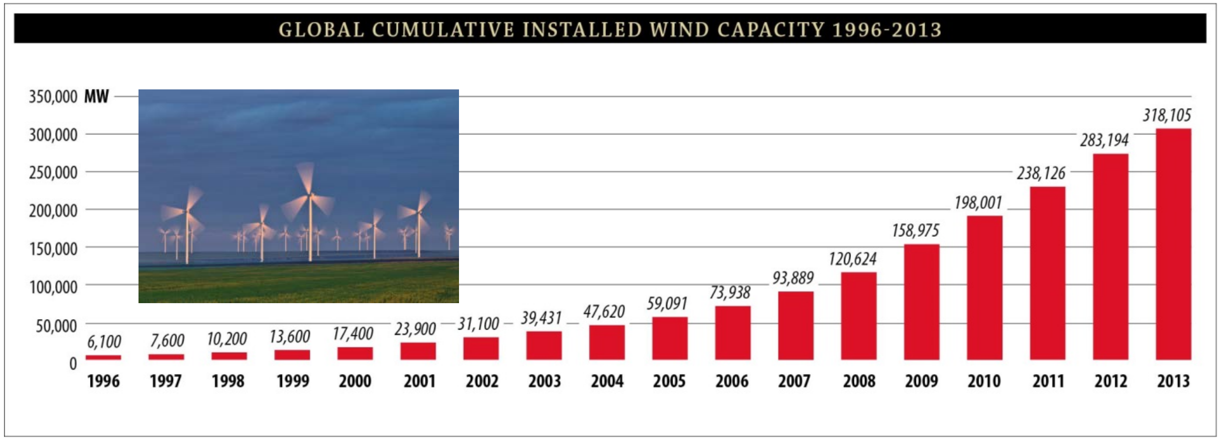
Low Voltage Products

Process Automation

As one of the world’s leading engineering companies, we help our customers to use electrical power efficiently, to increase industrial productivity and to lower environmental impact in a sustainable way.



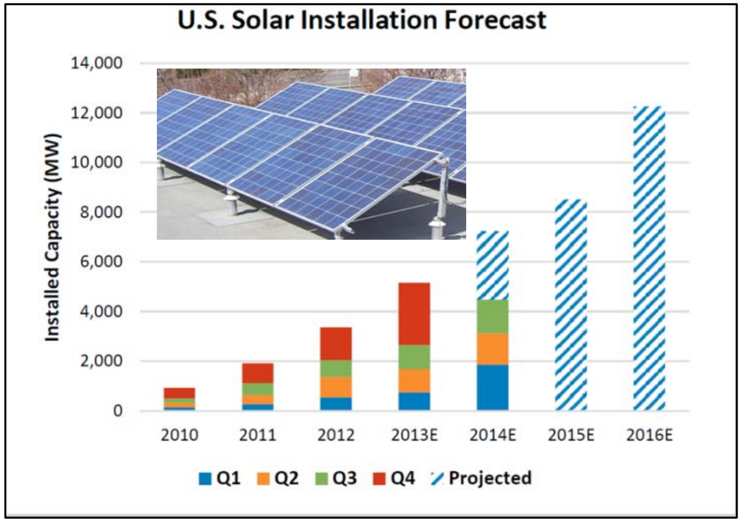
Growth of Renewable Power



GLOBAL CUMULATIVE INSTALLED WIND CAPACITY 1996-2013

- Source: GWEC

Almost ten fold growth in last decade



U.S. Solar Installation Forecast

- Source: GTM Research, SEIA

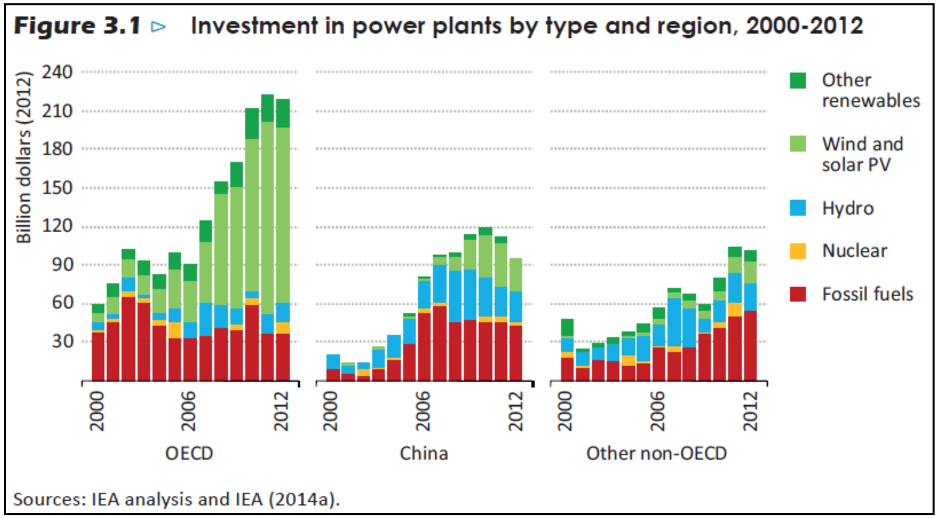


Figure 3.1 ▷ Investment in power plants by type and region, 2000-2012

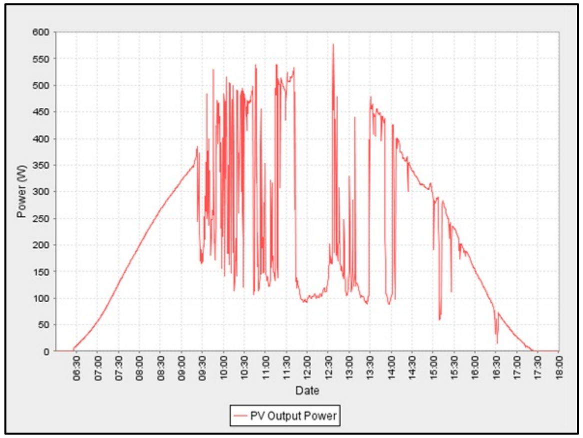
Sources: IEA analysis and IEA (2014a).

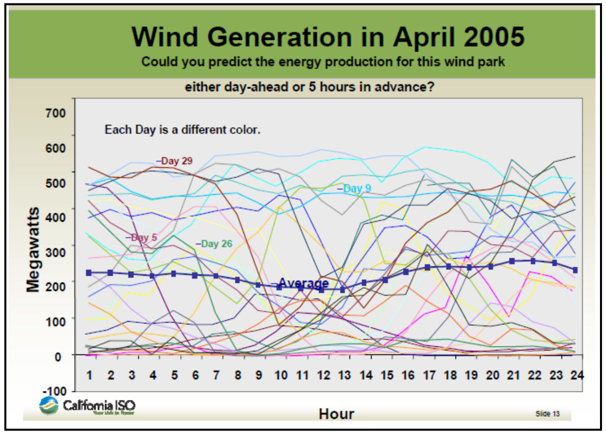
Renewable no longer a marginal player

- On November 4th 2013, Denmark's wind turbines reached 122% of the countries demand for electricity
- October 3rd, 2013, Germany's renewable energy peaked at 59.1% with a combination of solar and wind, with solar contributing 11% at 20.5 gigawatts at its peak
- A drop in demand for conventional power plants led the electricity price index at 2:00pm to 2.75 cents per kilowatt hour.

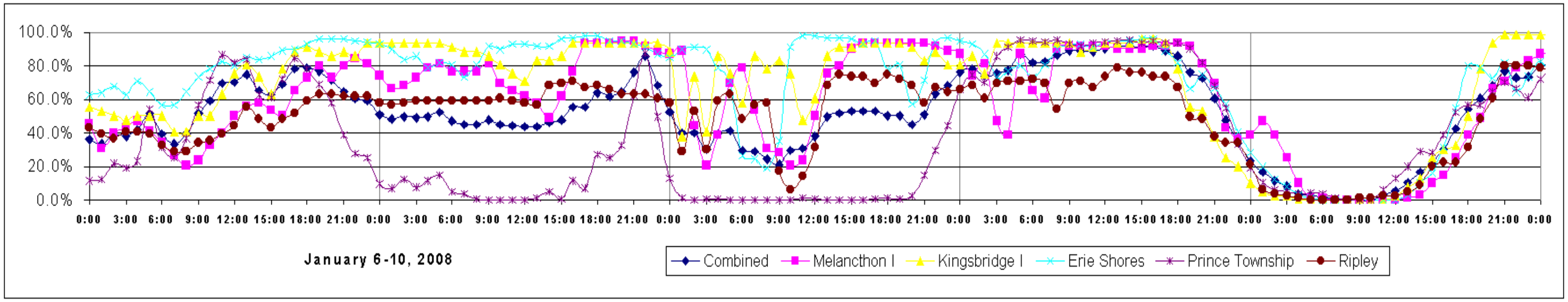
Operation characteristics of renewables

- Not on demand resource
- Intermittence (variability)
- Uncertainty (high prediction error)





Source: CAISO, *Tehachapi Wind Generation in April 2005*



Aggregation Effect on Variability

- Aggregation reduces variability, if correlation is low
- Aggregation not possible if network constraints are to be considered (location matters)
- Shorter lead time in forecast lower forecast error

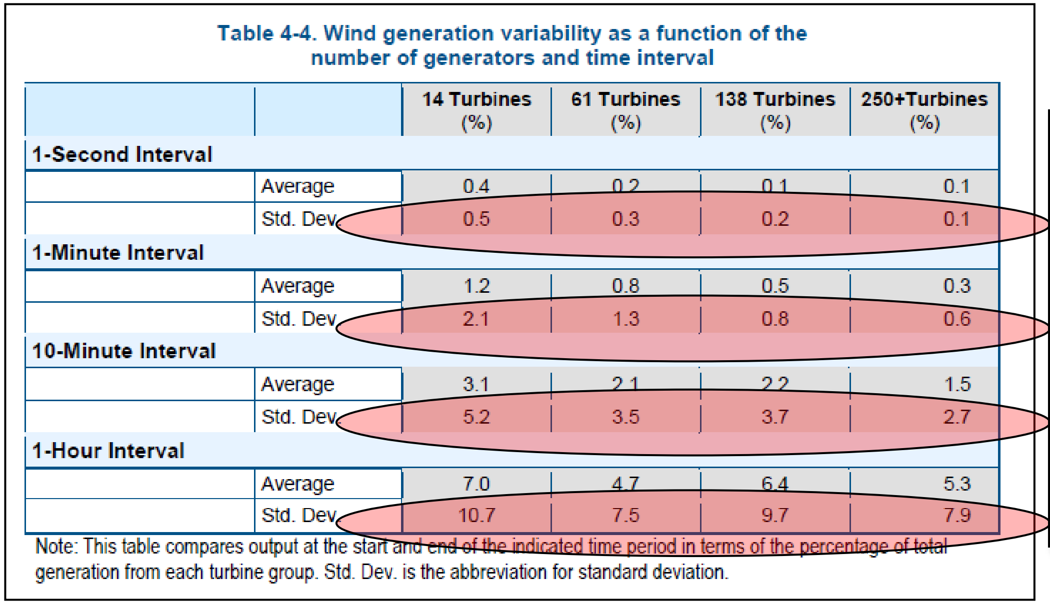
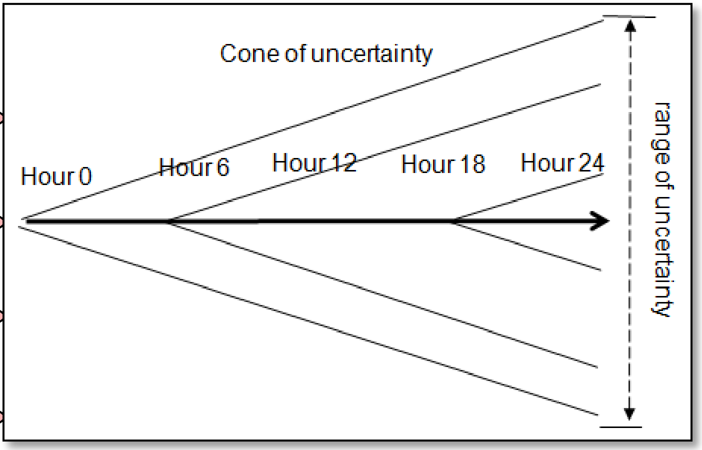


Table 4-4. Wind generation variability as a function of the number of generators and time interval

		14 Turbines (%)	61 Turbines (%)	138 Turbines (%)	250+Turbines (%)
1-Second Interval					
	Average	0.4	0.2	0.1	0.1
	Std. Dev.	0.5	0.3	0.2	0.1
1-Minute Interval					
	Average	1.2	0.8	0.5	0.3
	Std. Dev.	2.1	1.3	0.8	0.6
10-Minute Interval					
	Average	3.1	2.1	2.2	1.5
	Std. Dev.	5.2	3.5	3.7	2.7
1-Hour Interval					
	Average	7.0	4.7	6.4	5.3
	Std. Dev.	10.7	7.5	9.7	7.9

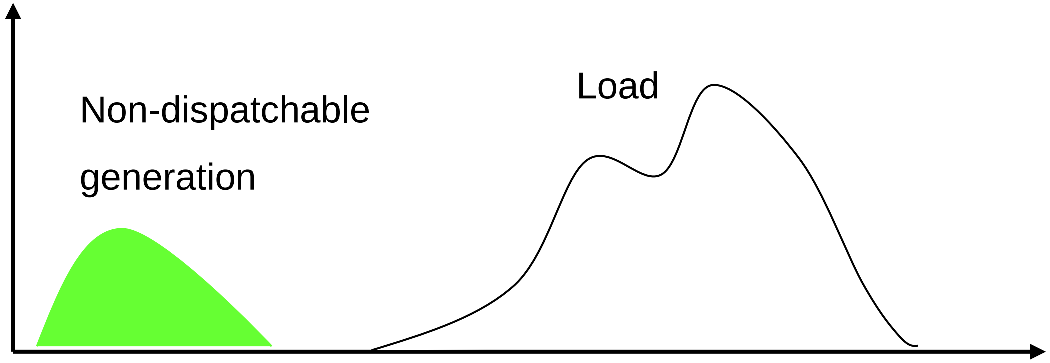
Note: This table compares output at the start and end of the indicated time period in terms of the percentage of total generation from each turbine group. Std. Dev. is the abbreviation for standard deviation.



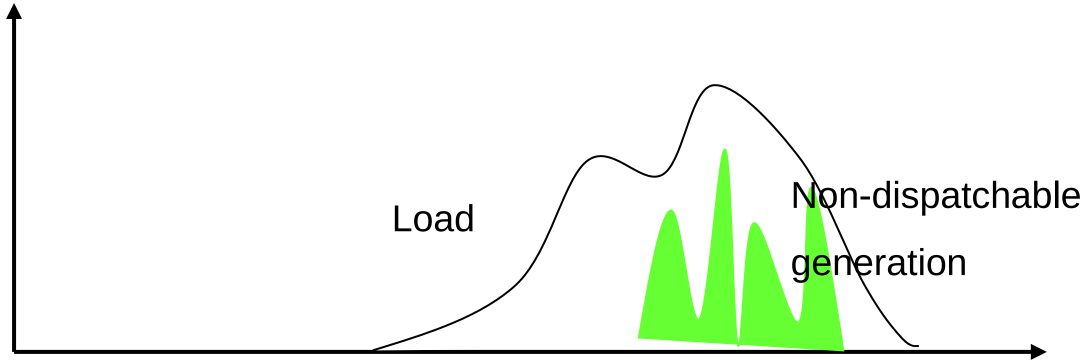
Source: 2008 DOE 20% Wind Energy by 2030

Weakness of renewable power

- Power must be supplied when customers need it
- Power must be closely balanced for frequency and stability
- Power provided when not needed, if not stored, is of less value



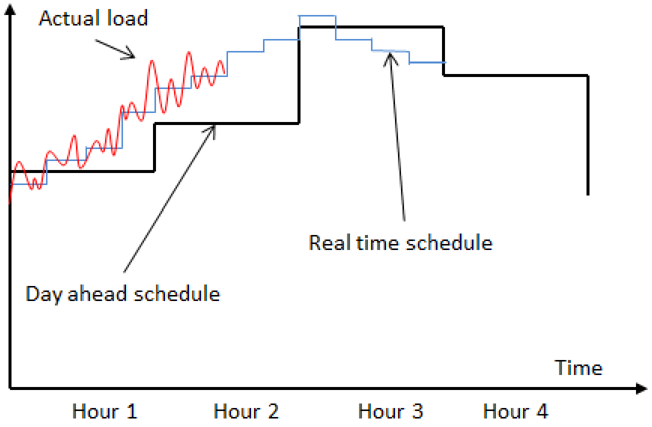
Temporal mismatch



Intermittence
and uncertainty

Flexibility needed for renewable volatility

- Energy storage
- Stochastic control and optimization
- Demand response
- Super grids (diversity)
- Controllable grids (FACTS, DC transmission)



$$G_{base}(t) + G_{cycle}(t) + G_{peak}(t) = L(t)$$

- Without renewable

$$G_{base}(t) + G_{cycle}(t) + G_{peak}(t) = L(t) - RE(t)$$

- With renewable

$$G_{base}(t) + G_{cycle}(t) + G_{peak}(t) + DR(t) + ES(t) = L(t) - RE(t)$$

- With renewable, demand response, energy storage

Energy Storage effect on renewable variability

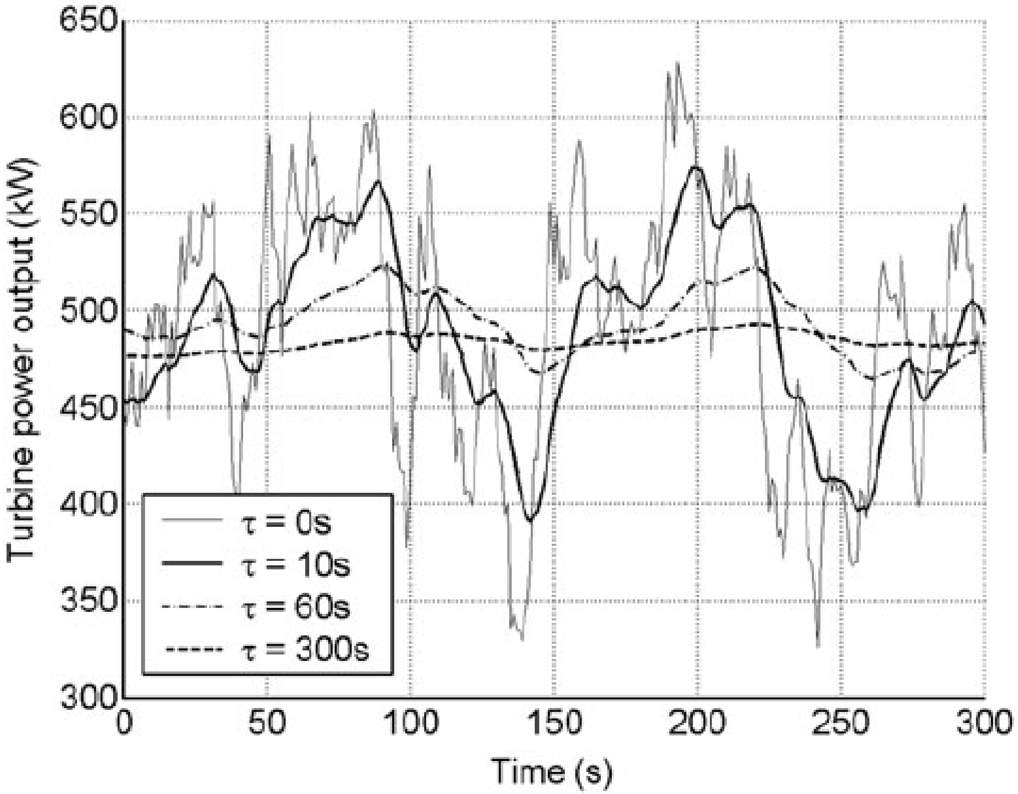


Figure 2. Demonstration of the effects of increasing τ (energy storage capacity) on the amplitude of the wind power fluctuation for a real wind power case

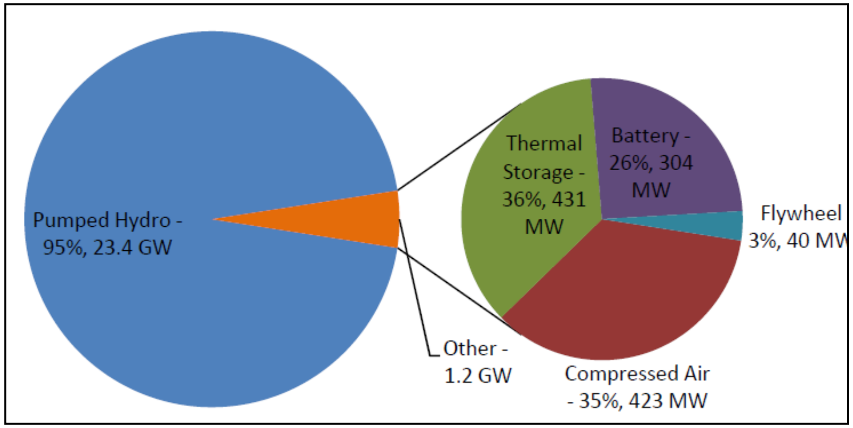
Source: Jukka V. Paatero, *Effect of Energy Storage on Variations in Wind Power, 2005*

Energy storage mandate and incentives

- California (2013) - 1.3GW of grid storage by 2020
- New York – target 100 MW load reduction
    - $2100 per kilowatt for battery storage
    - $2600 for thermal storage.
- Puerto Rico’s (2013) - all new renewable energy projects must have 30% 10-minute frequency regulation & 45% one-minute ramping control
- Germany (2013) - $35 million in energy storage subsidies, up to 30% of the cost of the storage
- Japan offers US$100 million in subsidies to homeowners and businesses for energy storage

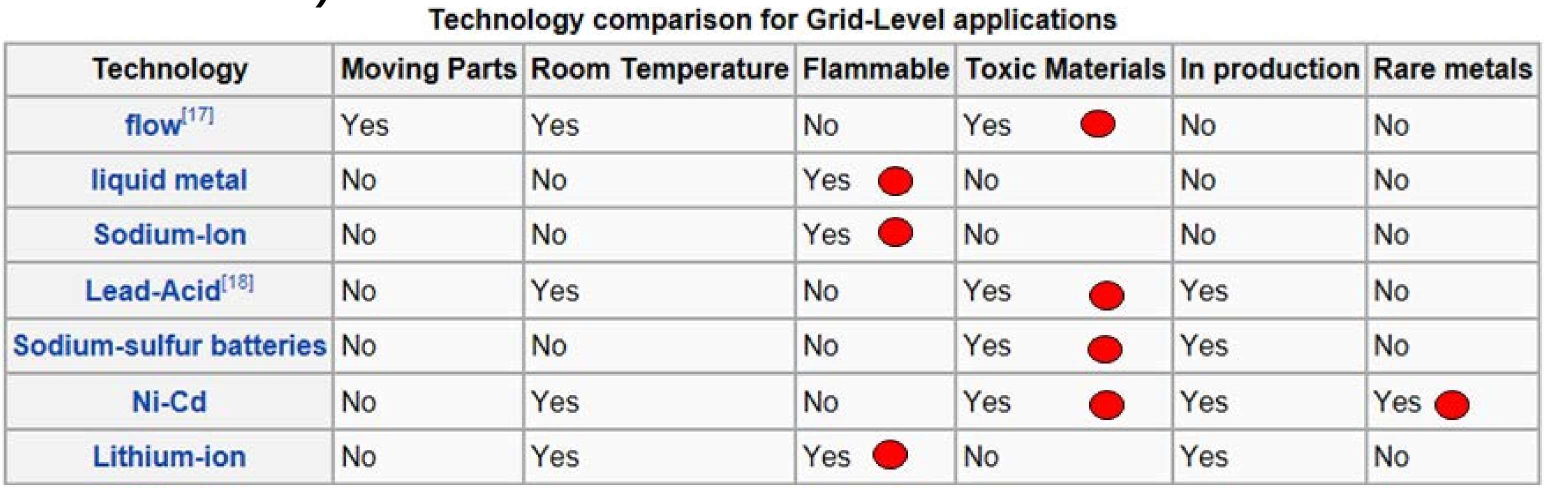
Energy Storage Technology Challenges

- Cost
- Safety and reliability
- Regulation
- Industry acceptance



Source: DOE Grid Energy Storage Report

- US has 1.26 GW storage capacity, 0.12% of total production capacity (pumped hydro not included)



Technology comparison for Grid-Level applications

Technology	Moving Parts	Room Temperature	Flammable	Toxic Materials	In production	Rare metals
flow[17]	Yes	Yes	No	Yes ●	No	No
liquid metal	No	No	Yes ●	No	No	No
Sodium-Ion	No	No	Yes ●	No	No	No
Lead-Acid[18]	No	Yes	No	Yes ●	Yes	No
Sodium-sulfur batteries	No	No	No	Yes ●	Yes	No
Ni-Cd	No	Yes	No	Yes ●	Yes	Yes ●
Lithium-ion	No	Yes	Yes ●	No	Yes	No

Table source: http://en.wikipedia.org/wiki/Grid_energy_storage#Load_leveling

Two stage stochastic optimization linear model

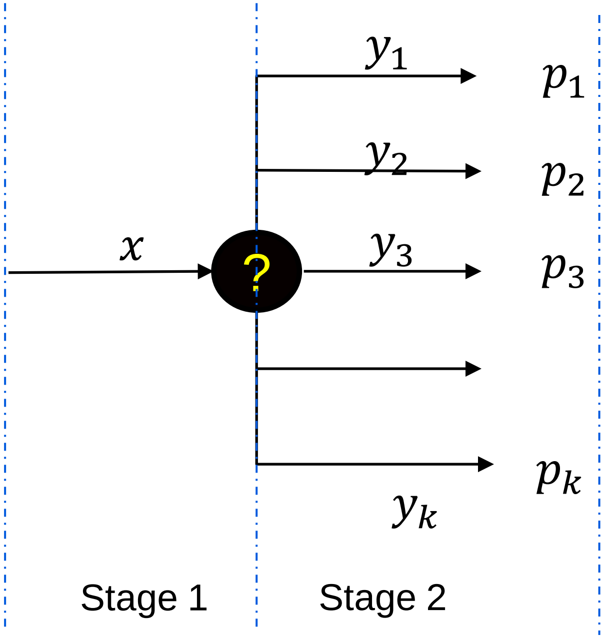
$$\underset{x}{\text{Min}} \quad c^T x + \mathbb{E}\big[Q\big(x, \xi(\omega)\big)\big]$$

$$s.t. \qquad Ax = b$$

$$Q\big(x, \xi(\omega)\big) =$$

$$\underset{y}{\text{Min}} \qquad q^T y$$

$$s.t. \qquad Tx + Wy = h$$



- ω - random variable
- $\xi(\omega)$ - probability distribution
- $\xi = (q, h, T, W)$ - the random vector
- x – first stage decision, made before random vector outcome is known
- $y_k, k = 1, \ldots K$ – second stage decision, made after random vector is known

- 2nd stage decisions are also called recourses
- Each stage can have multiple time intervals
- The stages are demarcated by the revelation of random variables' outcomes

Two stage stochastic optimization linear modeling

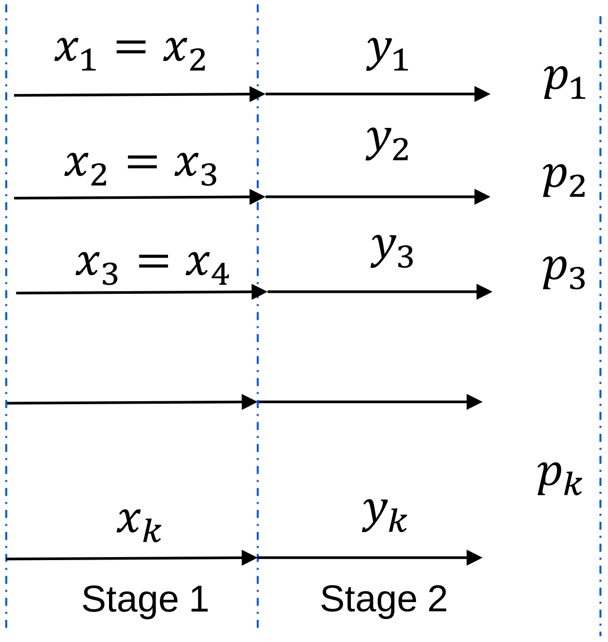
- Tree form

$$\begin{aligned} \underset{x,y_1,\dots,y_K}{\text{Min}} \quad & c^T x + \sum_{k=1}^{K} p_k q_k^T y_k \\ s.t. \quad & Ax = b \\ & T_k x + W_k y_k = h_k, k = 1, \dots, K \end{aligned}$$

- Scenario form

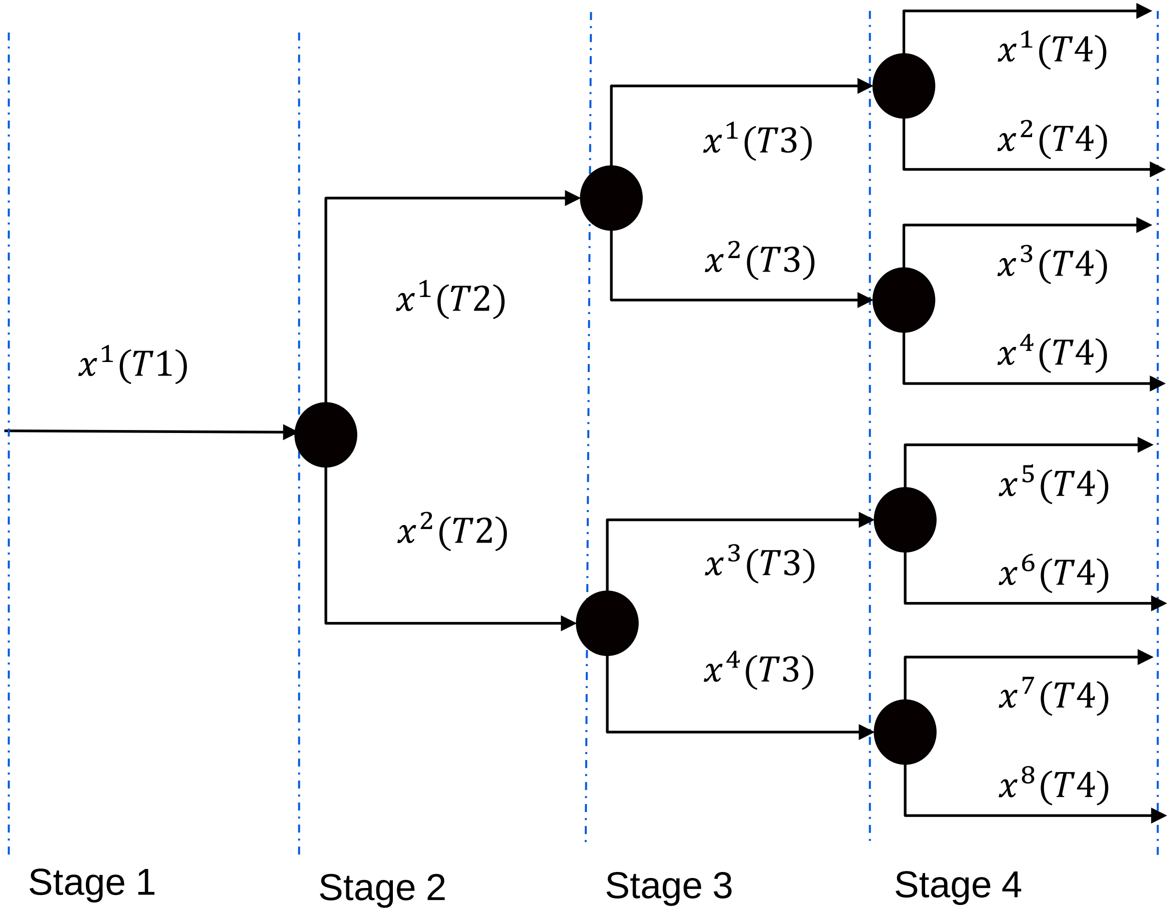
$$\begin{aligned} \underset{x_1,\dots,x_K,y_1,\dots,y_K}{\text{Min}} \quad & \sum_{k=1}^{K} p_k (c^T x_k + q_k^T y_k) \\ s.t. \quad & Ax_k = b, k = 1, \dots, K \\ & T_k x_k + W_k y_k = h_k, k = 1, \dots, K \\ & x_i = x_{i+1}, i = 1, \dots, K-1 \end{aligned}$$

  - Non-anticipativity constraints in scenario form are needed for implement ability



Extending to multi-stages

- $$Q_1 = \underset{x_1}{\mathrm{Min}}\left[c_1^T x_1 + E\left(\underset{x_2}{\mathrm{Min}}\left[c_2^T x_2 + E\left(\underset{x_3}{\mathrm{Min}}\left[c_3^T x_3 + E\left(\underset{x_4}{\mathrm{Min}}[c_4^T x_4]\right)\right]\right)\right]\right)\right]$$



Choice in objectives

- Risk neutral – optimize the expected value of outcomes, need p.d.f.

$$\underset{x}{\mathrm{Min}}\{\underset{\omega}{\mathbb{E}}\big(F(x,\omega)\big)\}$$

- Risk aversion - including variance term to expected value, need p.d.f. – even harder

$$\underset{x}{\mathrm{Min}}\{\underset{\omega}{\mathbb{E}}\big(F(x,\omega)\big) + k\psi(\underset{\omega}{Var}\big(F(x,\omega)\big))\}$$

- Extreme risk aversion - optimize outcome in the worst case, p.d.f. not needed (often called robust optimization)

$$\underset{x}{\mathrm{Min}}\{\underset{\omega}{\mathrm{Max}}\big(F(x,\omega)\big)\}$$

- Other possible formulations
- Rational choice depends on risk attitude and risk tolerance capacity

Constraints enforcement choices

- Deterministic constraints - All constraints must be met under all scenarios – may be impossible to achieve with large uncertainty range (feasibility for scenario once in 10 years or 100 years)

$$g(x,\omega) \geq 0$$

- Expected constraints - Constraints are satisfied on average (try this with your bank)

$$\mathbb{E}_{\omega}\big(g(x,\omega)\big) \geq 0$$

- Different choices in objective and constraints definition lead to potentially very different decisions
- The ’correct’ formulation depends on the risk attitude and risk tolerance capacity

Solution Strategies

- Direct solution
  - Solve the deterministic equivalent directly by LP solvers
  - Suitable only when the number stages and number of outcome per stage are small
- Decomposition (to reduce problem size and use parallel computing)
  - Bender's decomposition (L-shaped method Slyke and Wets 1969) (OA of the cost to go function)
  - Modified Lagrangian Relaxation (Progressive hedging, Rockafellar and Wets, 1991)
  - Sampling Average Approximation

Pros and cons of scenario decomposition

- Non-anticipativity and implement ability
- Challenge in handling integer
- Post processing required for admissibility and implement ability
- pros - parallelization

Security constrained unit commitment

- Minimize operation cost

$$\min_{\{x,u,p\}} J = \sum_{t=1}^{T}\sum_{i}^{N}\{C_i(g_i(t),t) + u_i(t)c_i^{ST} + x_i(t)c_i^{NL}\}$$

- Nodal power balance constraints

$$\sum_{i}^{N}\{g_i(t) - d_i(t)\} = 0, \forall t$$

- Network constraints under normal and contingences

$$f_i^{min} \leq \sum_{j}^{N} A_{i,j}\{g_i(t) - d_i(t)\} \leq f_i^{max}, \forall i, \forall t$$

- (Other constraints not shown)

- Effect of renewable on transmission constraints depends on location

Wind power uncertainty modeling for SCUC

- Joint p.d.f characterize the stochastic processes of renewables, reflecting both auto and cross correlations – very hard to get from historical data
- The number of scenarios grows exponentially fast
  - W – the number of wind farms = 10
  - T - number of stages = 24
  - N - number of possible state = 2 (very crude)
  - Number of Scenarios $(N)^{T*W}$(independence assumed) =$(2)^{(24*10)} \cong 10^{3*24}$
- Sampling necessary to keep tractability – congestion scenarios may be different with financial consequences

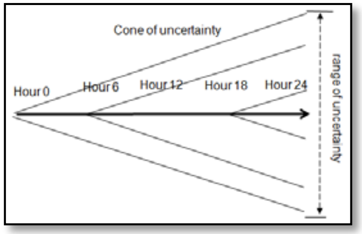
Two Stage or Multi Stage Model for SCUC?

- 2- stage
- (x- commitment,y - dispatch)
- Decision($x_1, x_2, \ldots, x_T$)
- Observation ($\xi_1, \xi_2, \ldots, \xi_{T-1}, \xi_T$)
- Decision($y_1, y_2, \ldots, y_{T-1}, y_T$)

- All uncertainties go away at the beginning of second stage, leaving a completely deterministic scenario for the entire operation horizon

- Can more commitment decisions be deferred?

- Multi stage
- (x- commitment,y - dispatch)
- Decision(x_1)
- Observation(ξ_1), Decision(y_1, x_2)
- Observation(ξ_2), Decision(y_2, x_3)
- Observation(ξ_3), Decision(y_3, x_4)
- …
- Observation(ξ_{T-1}), Decision(y_{T-1}, x_T)
- Observation(ξ_T), Decision(y_T)



Compatibility with market process

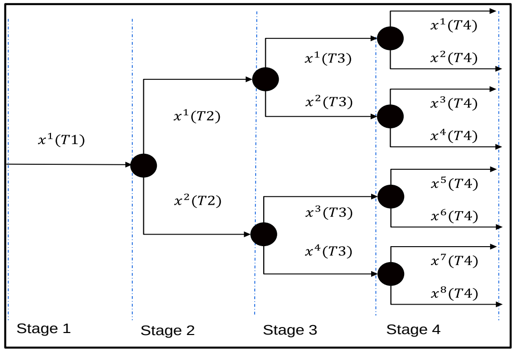
- DA market is financially binding and provides deterministic LMP for market settlement, hours before the first hour of the operating day

Deterministic Parameters → Deterministic SCUC → Deterministic Schedule, LMP

- Stochastic unit comment does not produce one deterministic solution, but many solutions contingent upon uncertain outcomes

Stochastic Parameters → Stochastic SCUC → Contingent Schedule, LMP

- For hour two, four conditionally optimal commitment/disp exists before hour 1 starts, and two before hour 2 starts
- Problem exists for 2-stage also



LMP calculation issues with stochastic SCUC

- Before entering the second stage, multiple conditional optimal solutions exist, → multiple LMP values
- How to settle the market? What needs to be done to ensure physical feasibility and revenue adequacy?

Scenario	L	M	H	Expected Value
Prob	0.333	0.333	0.333	
LMP ($/MWh)	$40	$30	$5	$25.00
Single Cap Block at $27/MWh	100	100	0	66.67

Scenario	L	M	H	Total
Prob	0.333	0.333	0.333	
Revenue	$1,333	$1,000	$0	$2,333
Expected generation MWh	33.33	33.33	0	67
Double weighted LMP				$35.00

Summary

- Multiple strategies to deal with integration of high level of renewables
- Choice in stochastic unit commitment definition have important market consequences
- Transmission constraint consideration limits aggregation of renewable power in market scheduling
- Scenarios explosion is big challenge, even in two stage model, sampling approach may create repeatability and fairness issues
- Non technical challenges exist in addition to computational ones

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