Selling Wind Randomly

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Outline

- Some CA energy numbers
- Variability of wind (and solar)
- Integrating wind into current operations is very costly
- Sell wind randomly
- What does this get us?

California energy numbers

- Daily peak power 60GW
- Bulk energy cost $52/MWh; retail price $130-$400/MWh
- Wind power
  - CA wind purchased at ~$200/MWh
  - MA retail av $90/MWh; wind purchased at $200/MWh+3.5%/yr
  - RI retail av $130/MWh; wind purchased at $244/MWh+3.5%/yr
- Ancillary services (reserves) costs in CA:
  - $15-$18 per MW capacity per hour for regulation
  - $6-$9 ($2-$3) per MW capacity per hour for spinning (non-spinning) reserve
  - $80-$120 MWh for real time energy
- Wind integration cost EWITS estimates: $6-$8 per MWh (seems low)
- Carbon tax can make fossil fuel power more expensive

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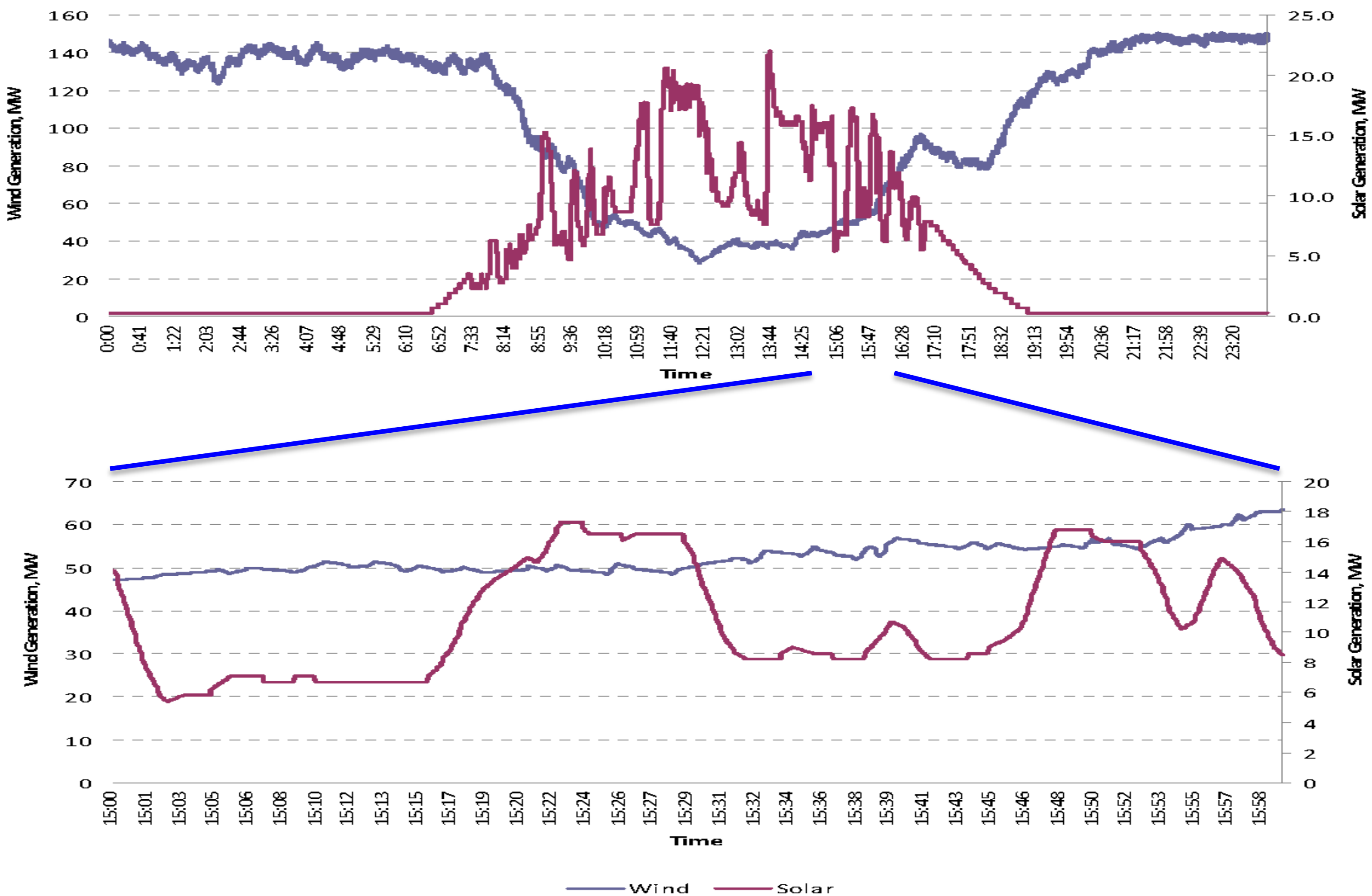
Normal variability in wind, solar power



- Variability in single wind farm and solar PV plant

Hourly wind power variation in CA

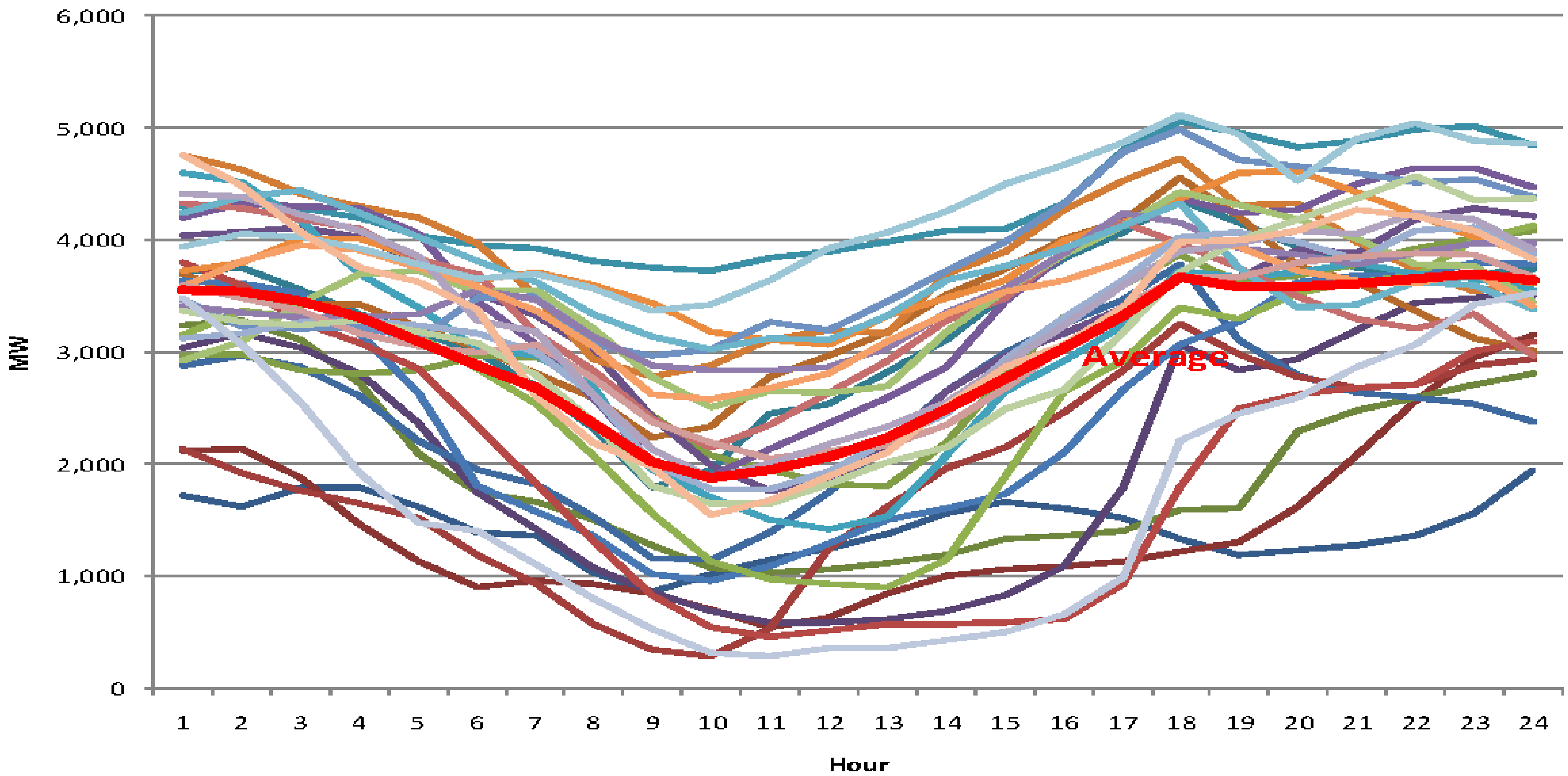
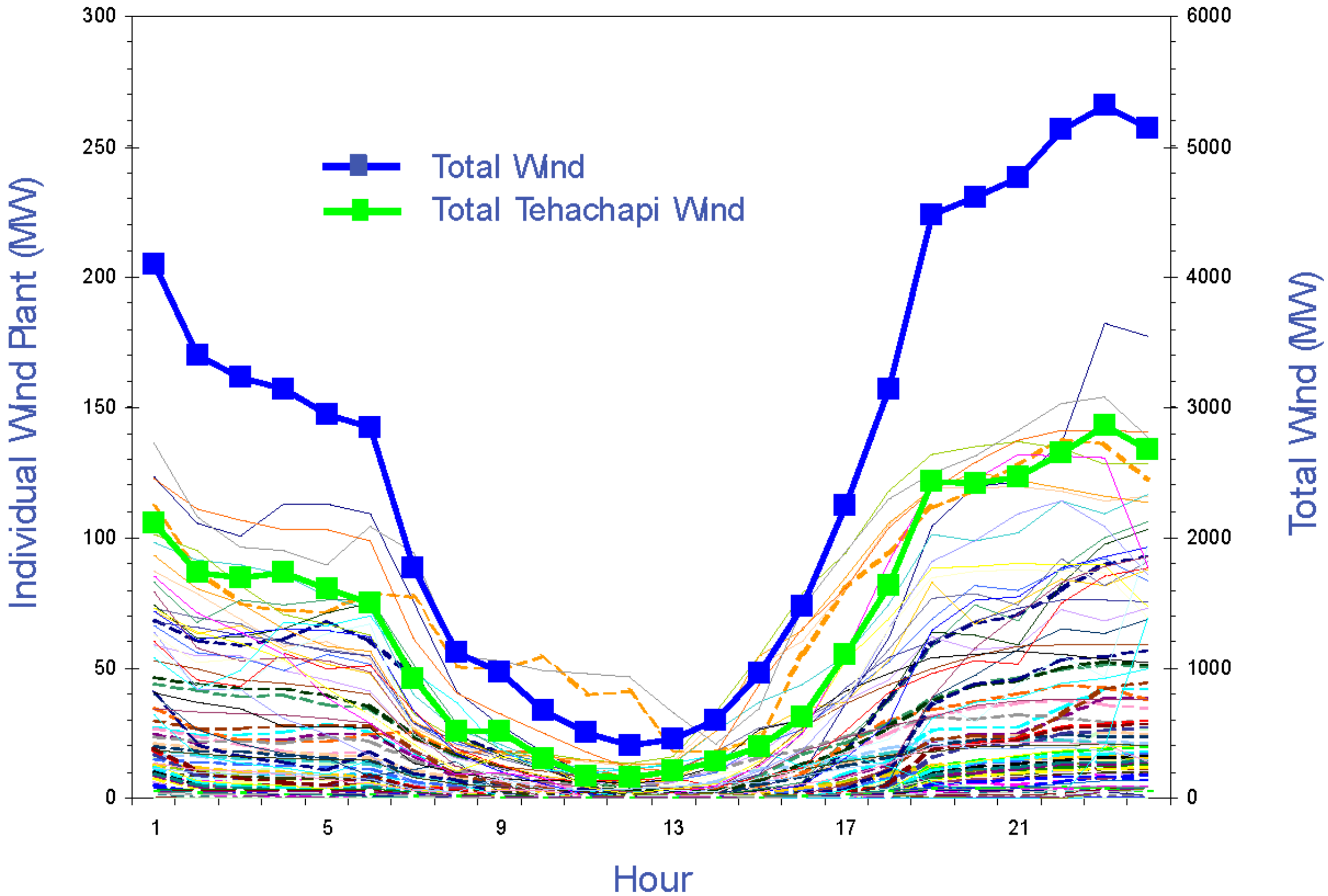


Figure 1-8: Wind Production in May 2012 based on 2005 production patterns

- CA total hourly wind power varies from maximum to zero

Not much spatial diversity



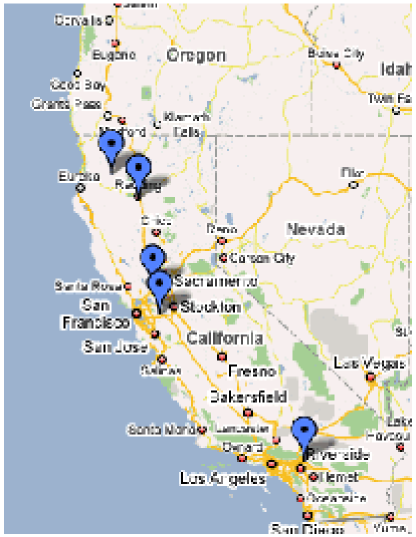
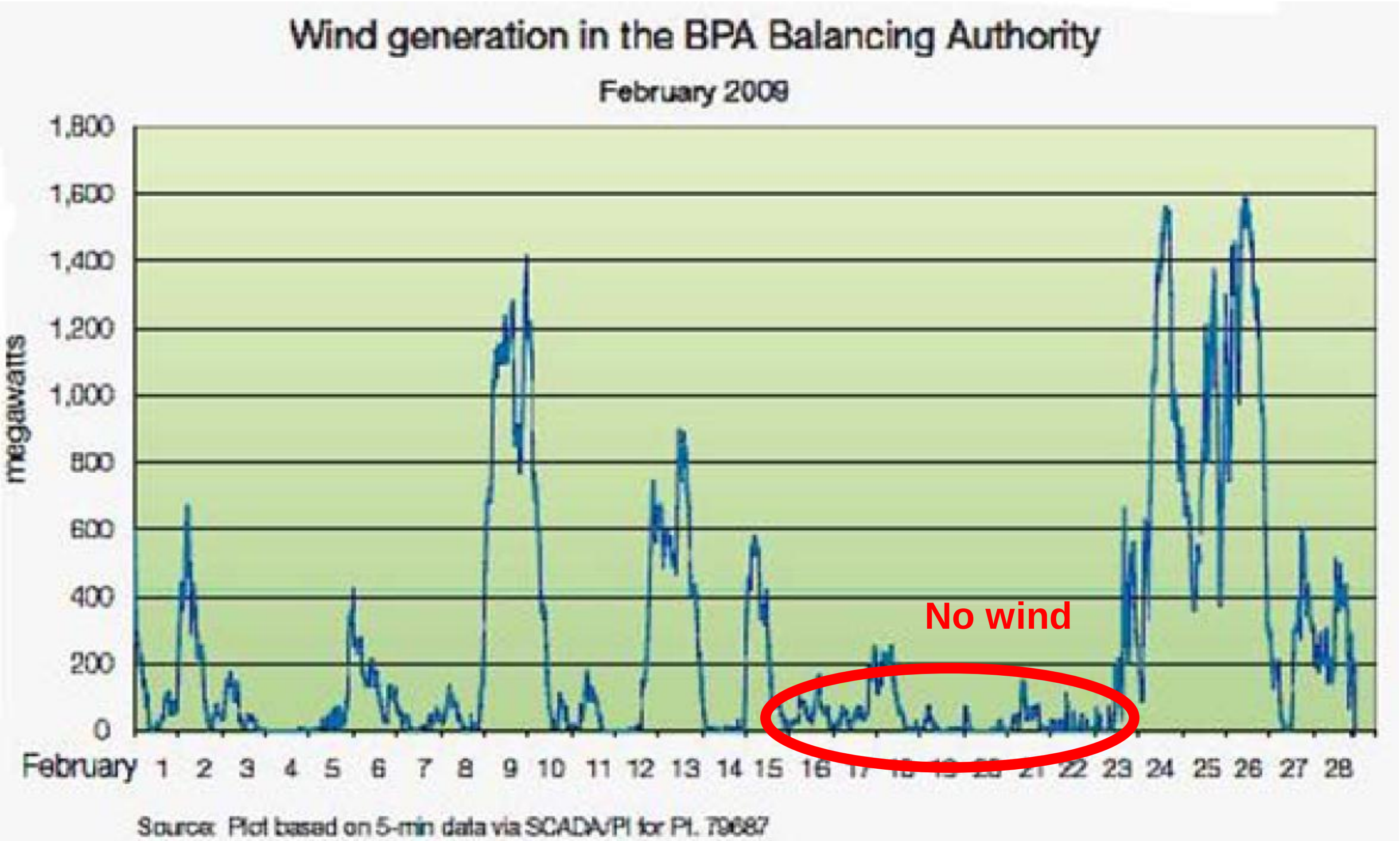


Figure 9. All Individual California Wind Plant Profiles for July 21, 2003.

- Variability not decreased by diversity over 1000 miles

Variability in BPA wind power (5-min)



- Wind power ramps up and down quickly and unpredictably

ERCOT wind power ramps

Figure A-6: 3,039 MW increases (18-Apr-09 23:39 to 19-Apr-09 00:39)

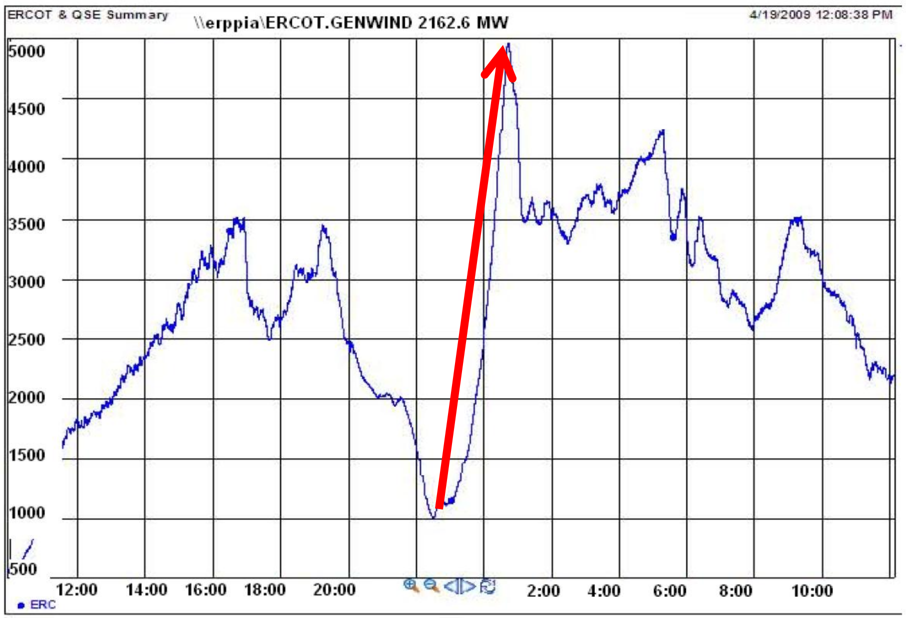
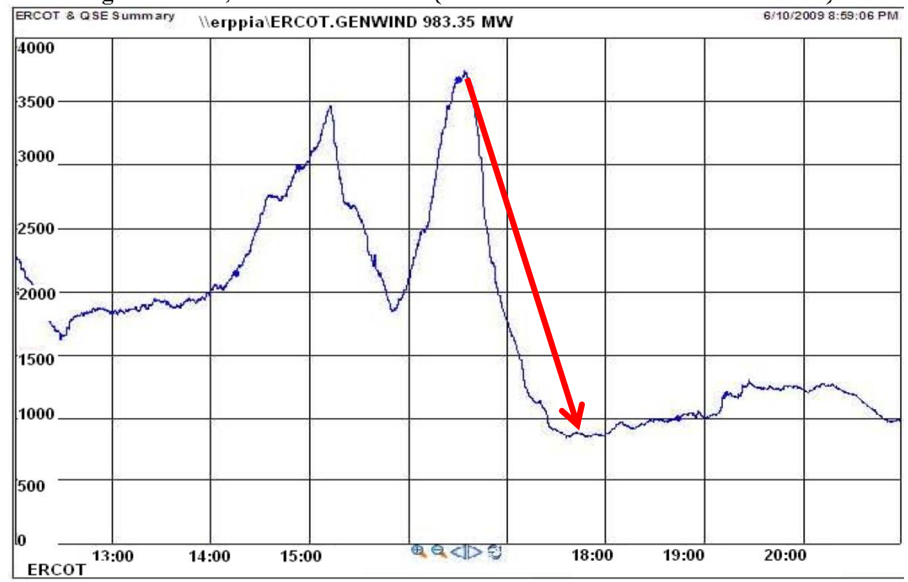


Figure A-7: 2,847 MW decrease (10-Jun-09 16:35 to 10-Jun-09 17:35)



- ERCOT 3,039MW up-ramp in 1 hour (left); 2,847MW down-ramp in 1 hour (right)

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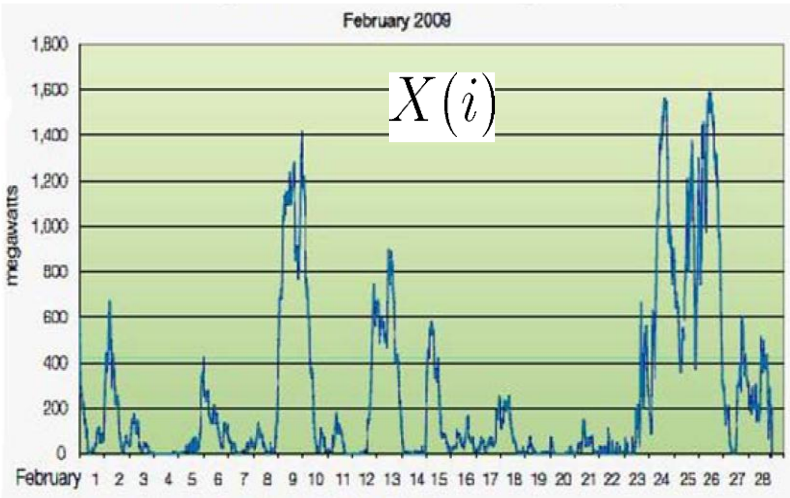
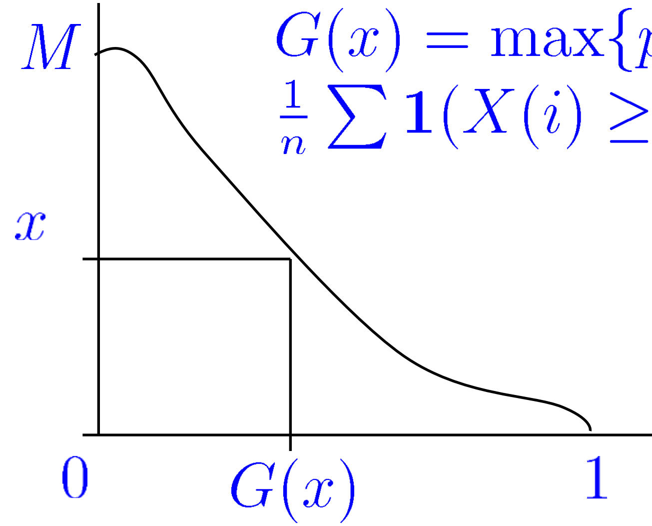
What is wind integration cost?

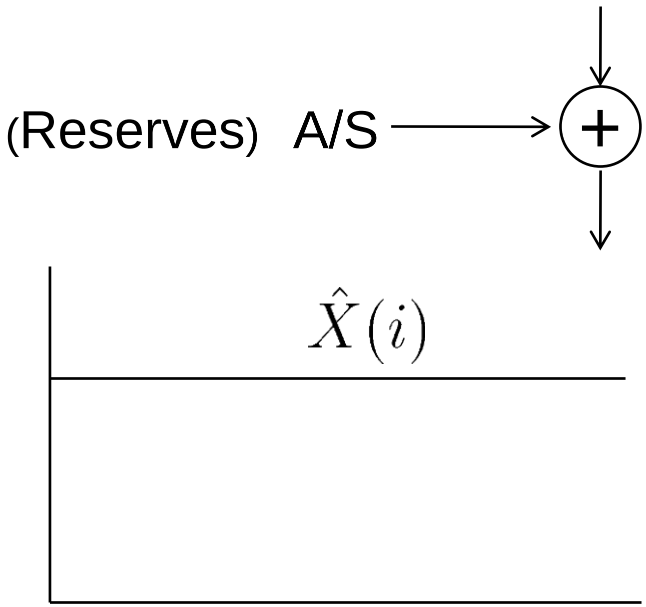
- It is the extra cost of capacity and energy required to make a wind power source behave like firm power source:
  - reserve capacity to counter unpredictable shortfall
  - following and regulation capacity to counter variability
  - energy costs associated with following and regulation

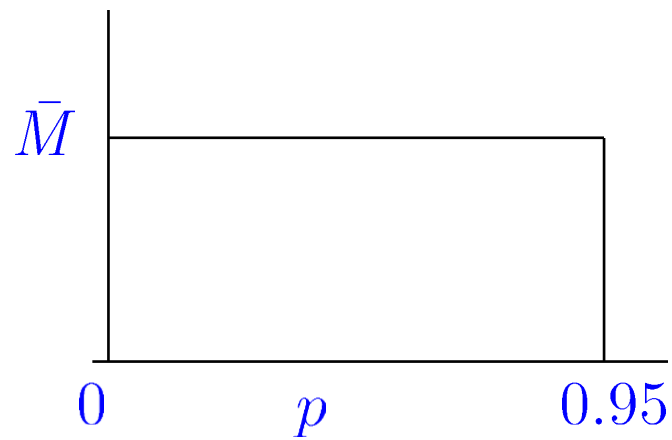
Bounding integration cost (1/4)



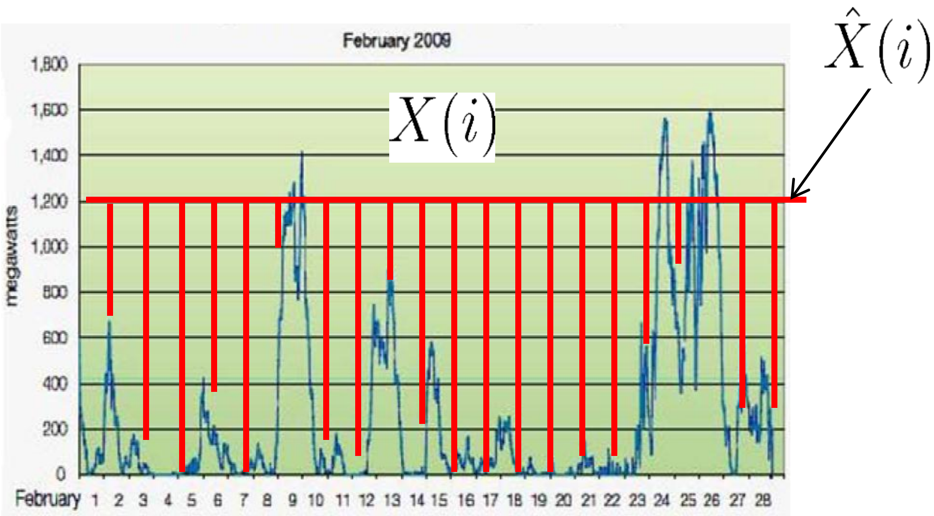


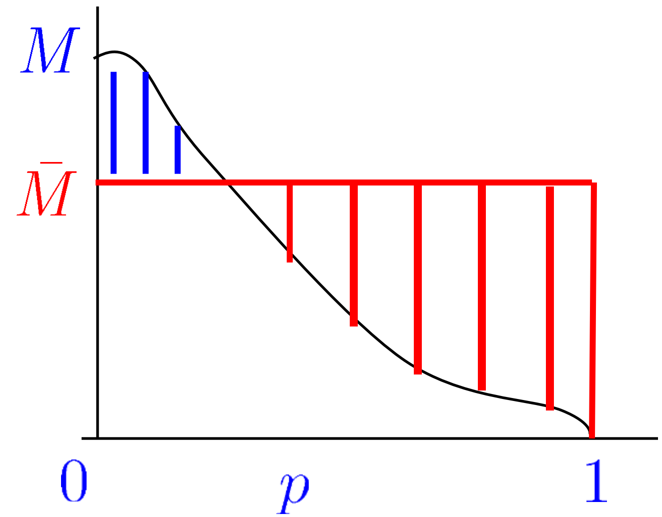
$$G(x) = \max\{p : \frac{1}{n}\sum \mathbf{1}(X(i) \geq x) \geq p\}$$





Bounding integration cost (2/4): Full info





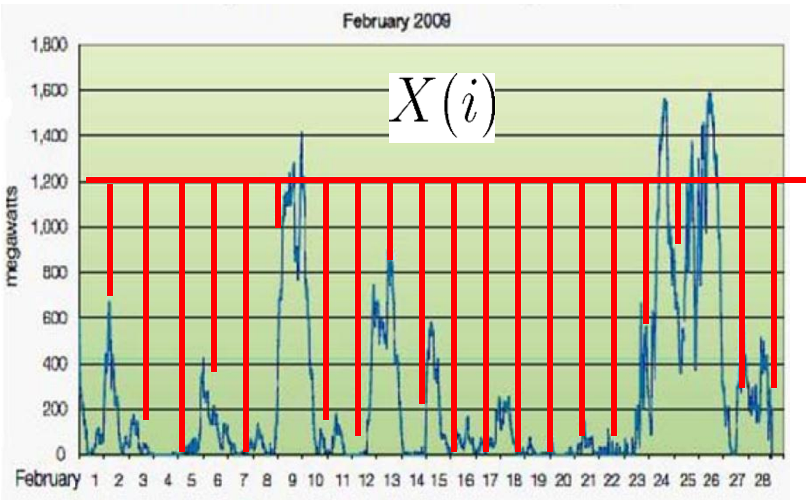
Under full knowledge of future

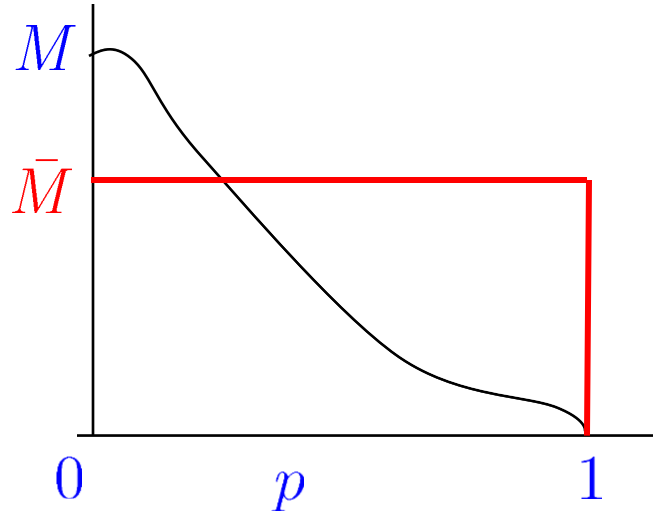
min av real-time energy = min av reserve capacity =

$$E[\bar{M} - X(t)]_+ = \int_0^{\bar{M}} (\bar{M} - x)[-G(dx)]$$

Note: $[X(t) > \bar{M}]_+$ is 'spilled' (wasted). How to choose $\bar{M}$?

Bounding integration cost (3/4): No info





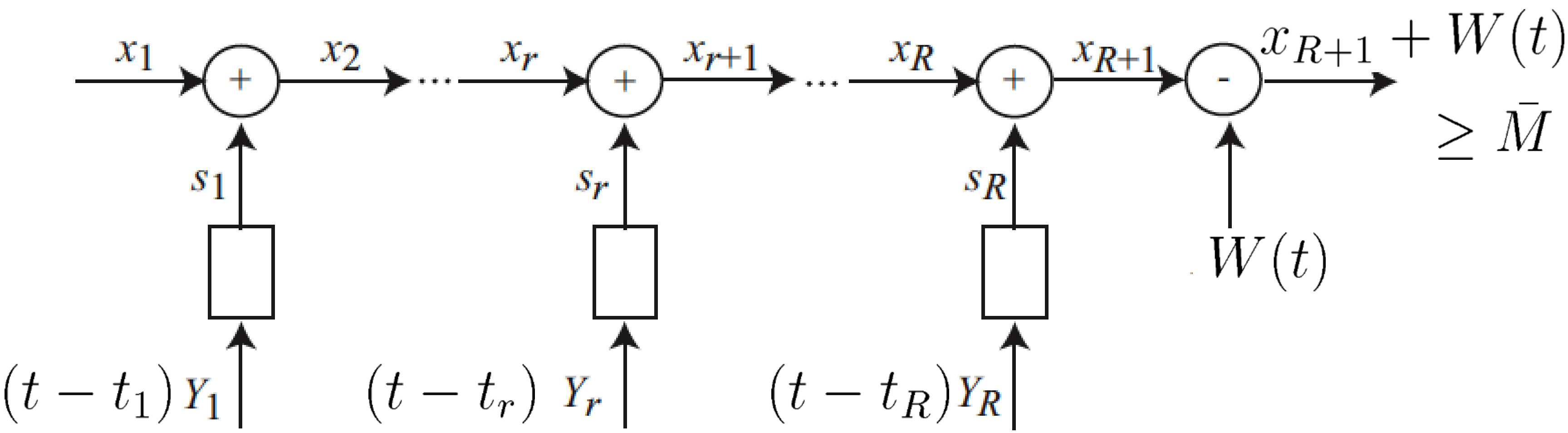
Under no knowledge of future

av real-time energy $= E[\bar{M} - X(t)]_+ = \int_0^{\bar{M}} (\bar{M} - x)[-G(dx)]$

av reserve $= \bar{M} - \min X(i) = \bar{M} >> E[\bar{M} - X(t)]_+$.

Important problem between full and no information

Partial information



$$\min E\{c_1 s_1 \quad + c_r s_r \quad + c_R s_R\}$$

$$\text{s.t. } s_i = s_i(Y_i); \quad x_{R+1} + W(t) \geq \bar{M} \text{ wp } 1$$

Thm There are thresholds $\phi_i = \phi_i(Y_i)$ s.t.

$$s_i^* = [\phi_i - x_i]_+$$

Interpretation: ϕ_i is optimal reserve target at stage i

Summary

- Cost of integrating wind may be very high, especially if prediction of wind is poor
- Why not abandon attempt to make wind power look like gas plant and sell wind power as random power?

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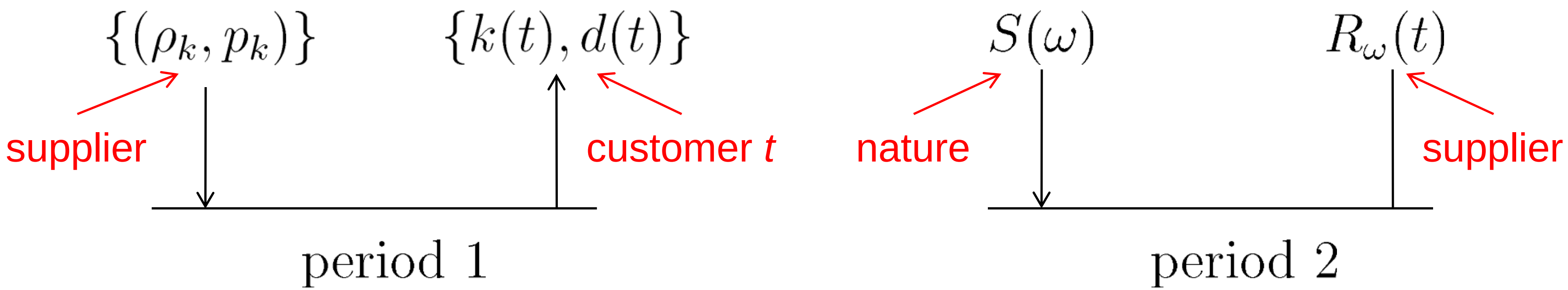
Interruptible power contracts



1. Supplier offers contracts $\{(\rho_k, p_k),\ k = 1, 2, \cdots\}$
2. Consumer t purchases $d(t)$kWh of reliability $\rho_{k(t)}$, price $p_{k(t)}$
3. Wind power $S(\omega)$kW is realized
4. Supplier rations according to $R_\omega(t) \in \{0, 1\}$
6. t receives $d(t)$kWh if $R_\omega(t) = 1$; receives 0 if $R_\omega(t) = 0$
7. Contract guarantee: $P\{\omega \mid R_\omega(t) = 1\} = \rho_{k(t)}$
8. Constraint $\sum d(t) R_\omega(t) \leq S(\omega)$ wp 1.

How to design contracts, rationing

Supply: $P\{S(\omega) = s_i\} = \pi_i; \quad i = 1 \cdots n$, i is random event

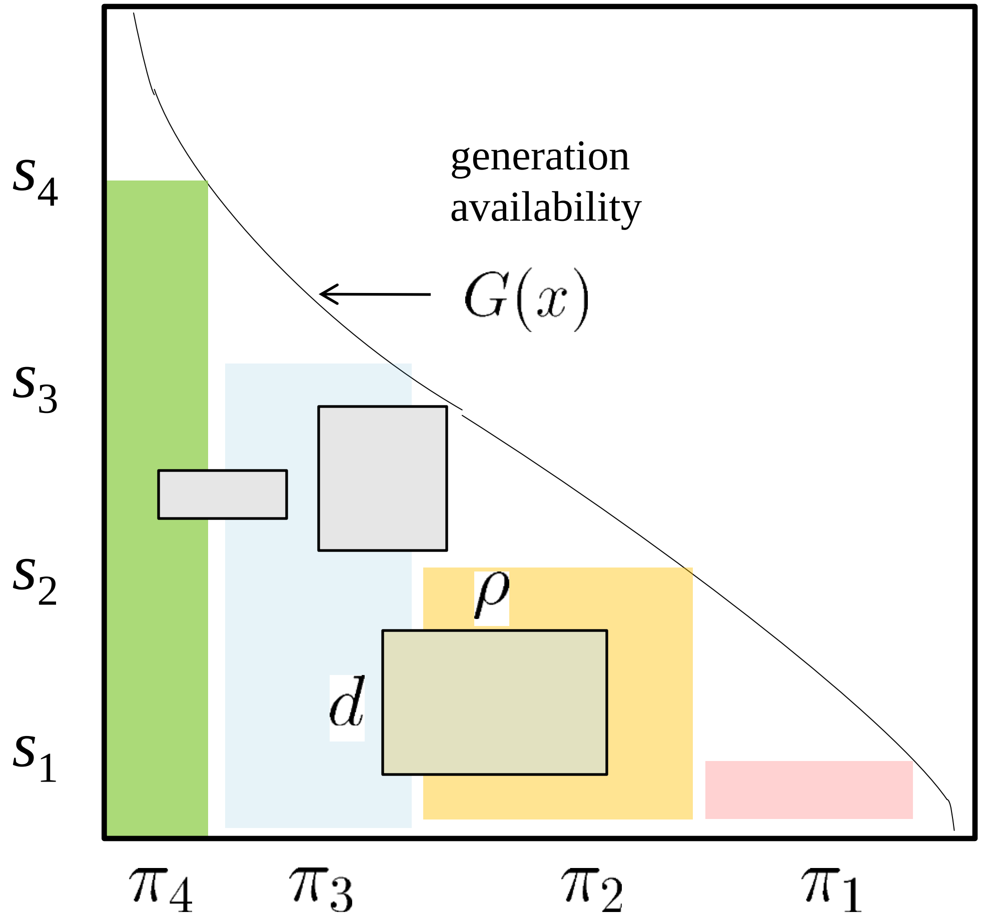
Consumer $t \in [0,1]$ allocated $(\rho(t), d(t))$ gets:
$w(t) = \rho(t)U(d(t)) - [1-\rho(t)]L(d(t))$—welfare.
$U(0) = L(0) = 0$; U concave; L convex.
All consumers have same w.

Problem: Design $t \to (\rho(t), d(t))$ and rationing functions $R_i(t) \in \{0,1\}$, $i = 1 \cdots n$ such that
$\int_0^1 R_i(t)d(t)dt \le s_i$, $i = 1 \cdots n$; $\sum \pi_i R_i(t) \equiv \rho(t)$

$$\max_{\rho, d, R_1 \cdots R_n} W = \int_0^1 w(t)dt$$

Wind generator example

$n = 4$



Problem: Divide available generation into (ρ, d) contracts to max welfare

Optimal control formulation

state $x(t) = (x_1(t) \cdots x_n(t))$, control $(d(t), R(t))$

$$
\begin{aligned}
\dot{x}_i(t) &= R_i(t)d(t), \quad 0 \leq t \leq 1 \\
x_i(0) &= 0, \quad x_i(1) \leq s_i, \\
d(t) &\geq 0, \quad R_i(t) \in \{0, 1\}
\end{aligned}
$$

$\max W = \int_0^1 \{\rho(t)U(d(t)) - [1 - \rho(t)]L(d(t))\}dt$
with $\rho(t) = \sum \pi_i R_i(t)$

Structure of optimal design

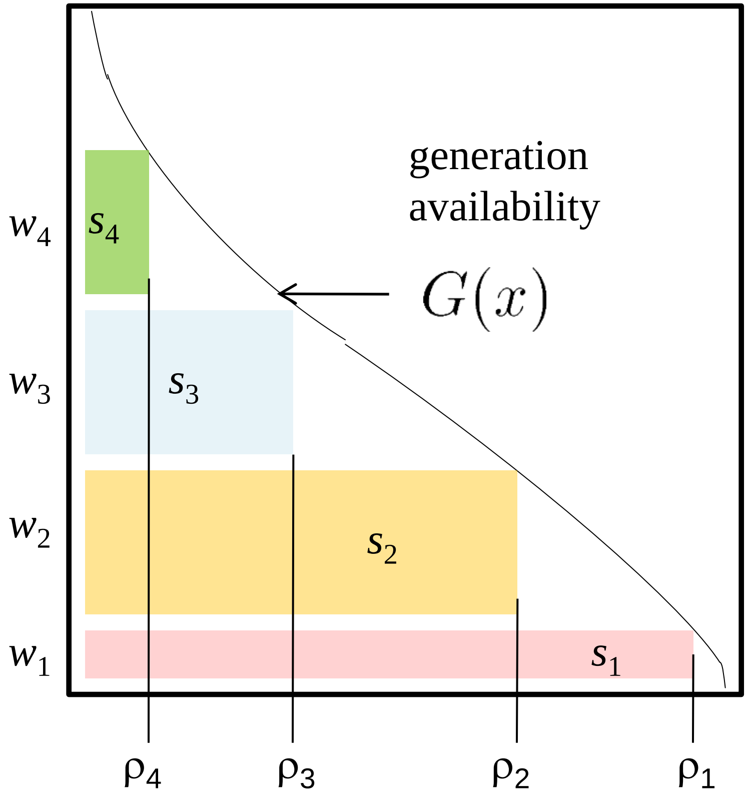
Illustration for $n = 4$

Supplier sells $w_i = s_i - s_{i-1}$kWH
of reliability $\rho_i = \pi_4 + \cdots \pi_i$

At real time s_i is known
Supplier delivers contracts $\rho_1 \cdots \rho_i$

Revenue is $\sum_i p_i w_i$ with no subsidy

Unique prices $\{p_i\}$ maximize welfare



What has this gotten us?

- Integrating wind into current operations means making wind look like firm power
- This may be too expensive and will require subsidies
- Selling random wind requires no subsidy
- May permit innovation to mitigate randomness
- Can be incrementally deployed

Open problems

Discussed one-shot problem. Much more intereting is multi-stage problem.

Wind is stochastic process $W(t)$, with observations $y(t)$.
Contracts are $\{\rho_k, p_k\}$.
Design rationing functions $R_k(\tau, t)$ to meet contract.

What can this mean?

$$\begin{aligned}
\frac{1}{T}\int_0^T R_k(\tau,t)dt &= \rho_k \text{ wp } 1 \\
E\frac{1}{T}\int_0^T R_k(\tau,t)dt &= \rho_k \\
P\{R_k(\tau,t)=1\} &= \rho_k \text{ all } t
\end{aligned}$$