# Decentralization/centralization in controlling the Internet and the power grid

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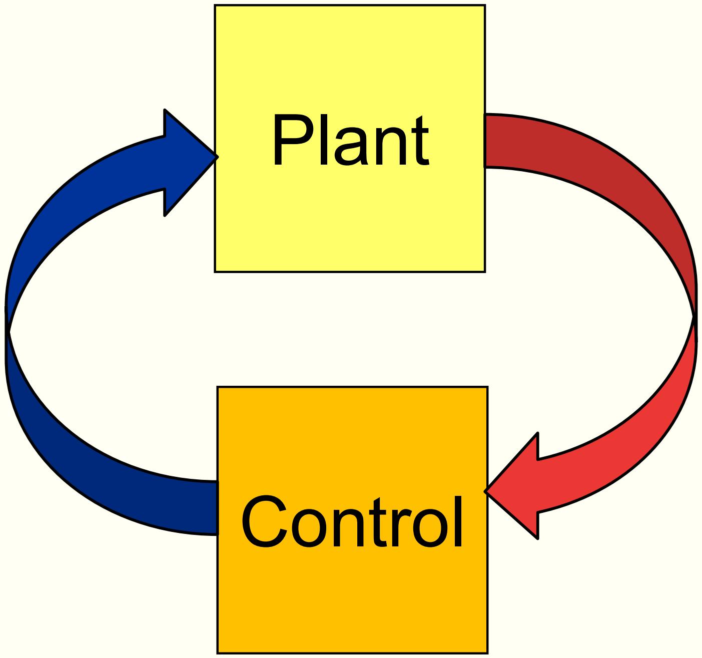
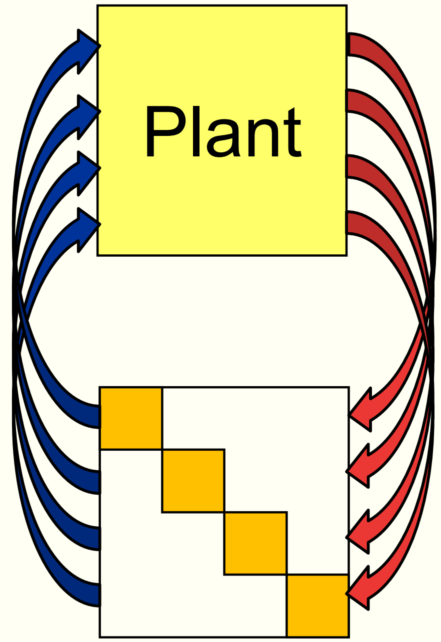
# Is Decentralization good?

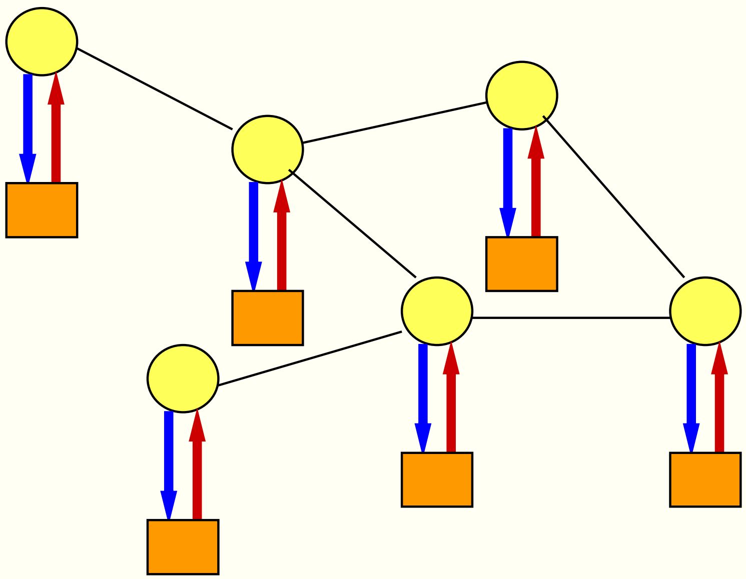
- In economics, the “efficient” market versus the “clumsy” central planner.
- In control, decentralization means information constraints → sacrifice performance, and difficult design.




- “Think globally act locally” is a non trivial mandate.

# Decentralized control under weak coupling



- Design “thinking locally”
  e.g: home thermostat
- Works if coupling is weak.
- Resilience: localized failures.

- What if we allow local comm between neighboring controllers? Less trivial design, but recent progress (SLS).
- Decentralized/localized control for Internet/Powergrid?
  – Not obvious, depends on function.
  – Exploit special structure, interpret notion of “neighbor”.

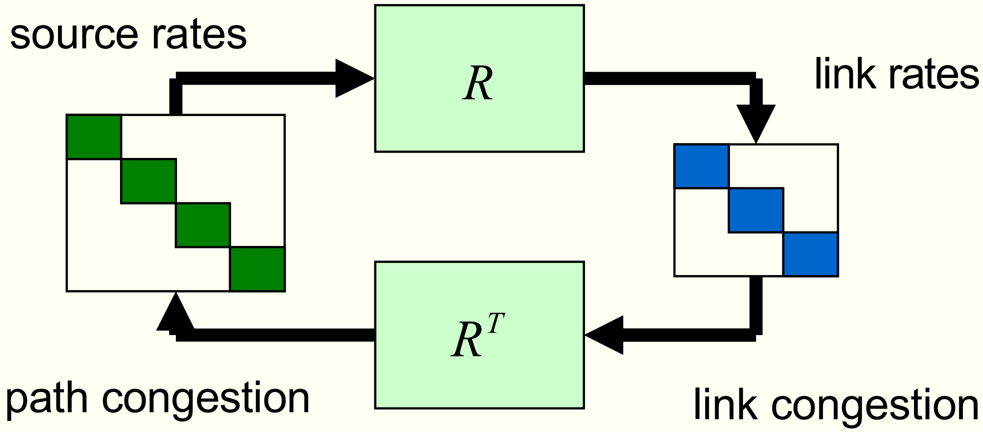
# Decentralization in the Internet

- Original architecture favors local control, plug & play.
  - Successful to achieve global connectivity.
  - Best effort, less worried about performance.

- Performance is highly coupled: sharing scarce resources.

- Kelly/Low (late 90s):
  - microeconomic models
  - convex optimization
  - Resource prices enable “decentralized” control.

Congestion control loop
(Low-P´- Doyle, 01-02)



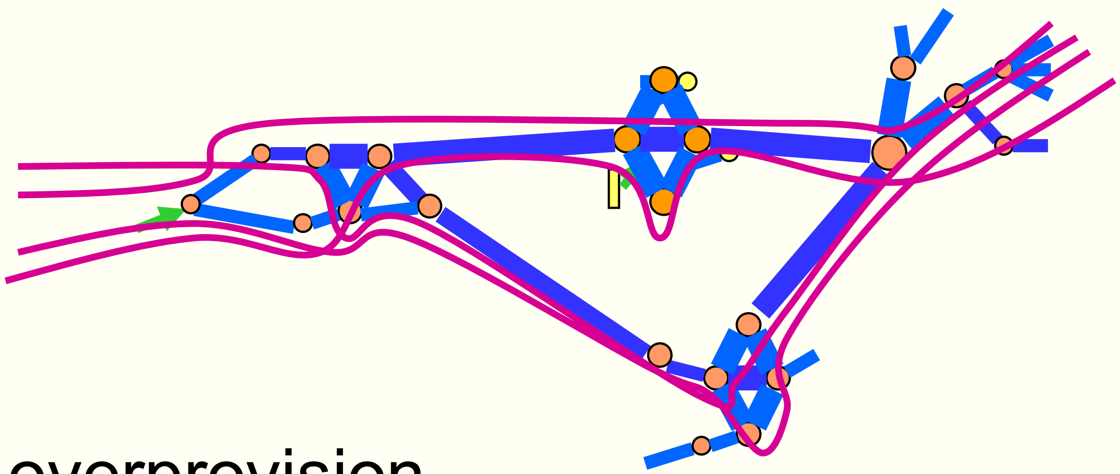

- To implement:
  - Exploit inbuilt information path.
  - **Buffering** allows transient mismatch.

Characterized equilibrium
& dynamic stability resulting
from decentralized actions

# Internet – theory and practice

- Approach extends to other layers (routing, wireless MAC,…). Layering As Optimization Decomposition.

  Practical impact? nonzero, but not significant:
  - Protocols are hard to modify.
  - Cheap fiber optics trumps smart resource allocation.



- At the network core,
  - Less buffering, need to overprovision.
  - Less tolerance to malfunction.

  →Traffic Engineering, centralized multicommodity flow

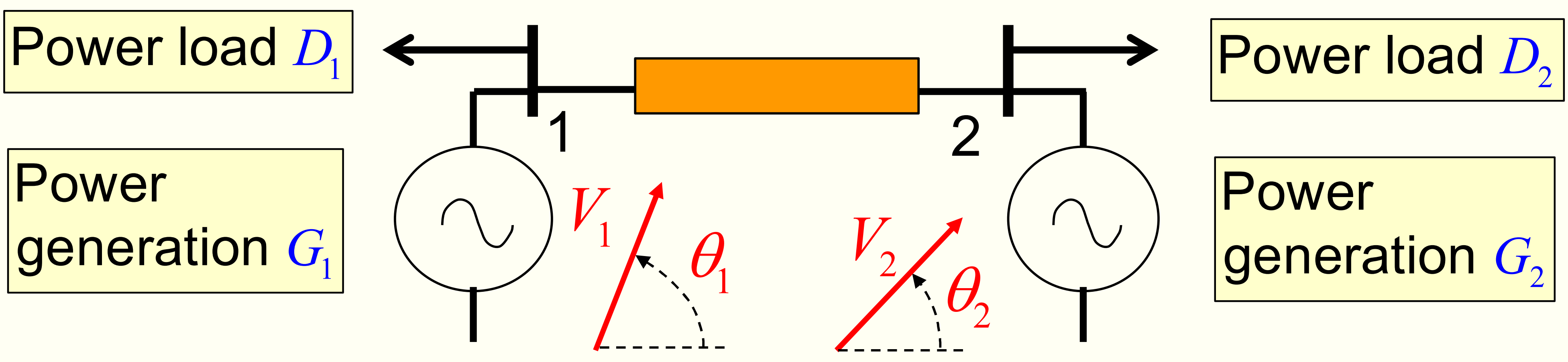
# Power transfer in Alternating Current

Grid Interconnection arose early on (1880s) to mutualize generation, exploit economies of scale in power plants.

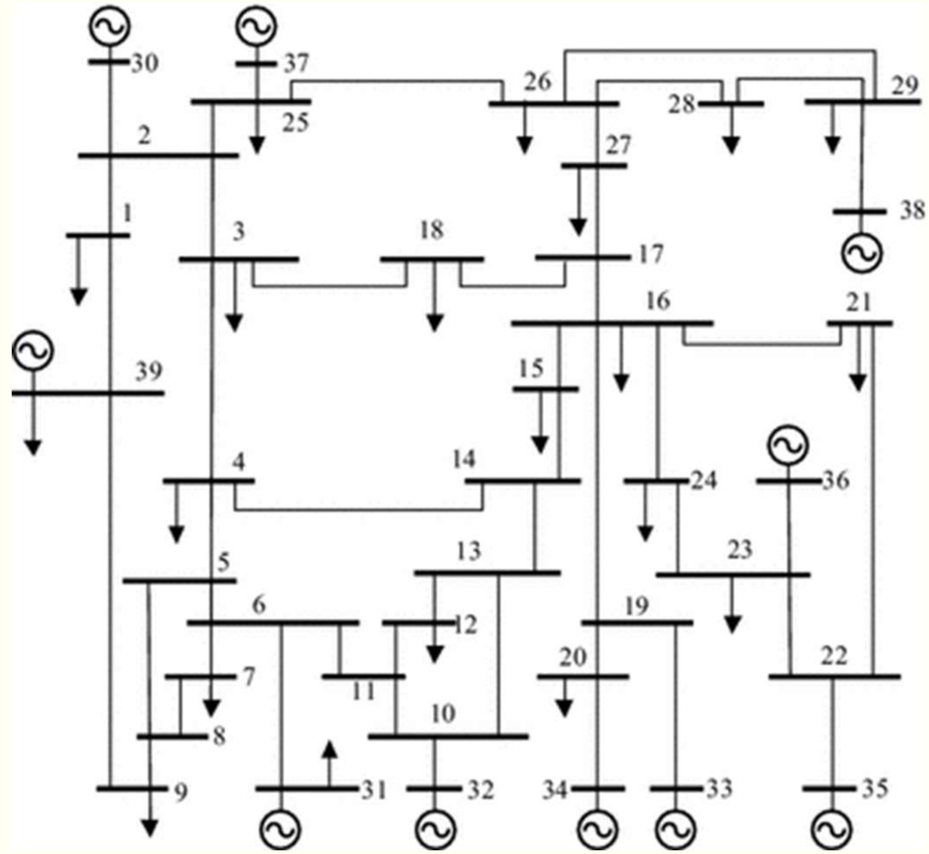
AC became dominant: sinusoidal waveform $V\,\mathrm{sen}(2\pi f \cdot t + \theta)$:

- Frequency $f$. e.g., 60 Hz.
- Amplitude $V$.
- Phase $\theta$

Exchanged power depends on phase (angle) differences between rotating machines: $P_{12} = b_{12} V_1 V_2 \,\sin(\theta_1 - \theta_2)$.



# Power network




Equilibrium:

- Same frequency $f$ overall.
- Approx nominal voltages: $V_i \approx V_{0i}$
- Different phases per node ("bus"):

$$\theta_i,\ i = 1, \ldots, N$$

"Power Flow" (PF) conditions, in simplified form:

- power balance at each node.
- line powers within limits $\left|P_{ij}\right| \leq \bar{P}_{ij}$
- Phases $\theta_i$ consistent with line power flows $P_{ij} = b_{ij} V_i V_j \sin(\theta_i - \theta_j)$.

Non-trivial to satisfy, even if global power balance holds.

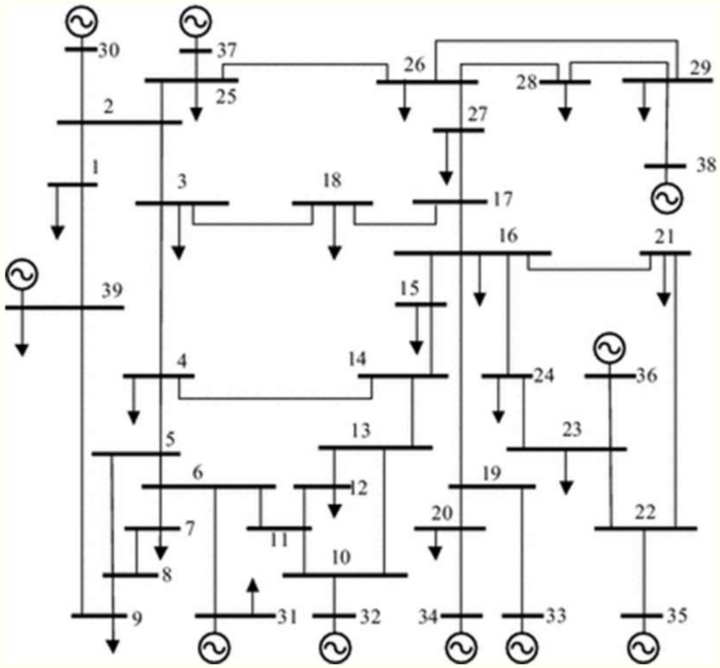
Essentially no buffering $\Rightarrow$ Little tolerance for imbalance.

# At slow time-scales (minutes to hours)

Economic dispatch: minimize generation cost to cover demand.

- PF restrictions matter, not feasible to overprovision network.
- PF rules out naive market solutions (pairwise transactions)

$\Rightarrow$ centralized optimization required.



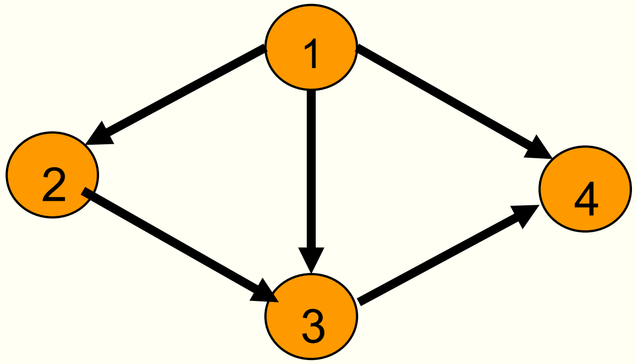

System Operator (SO):

- closes market under PF.
- imposes security constraints.
- solves for nodal prices.

Remarks:

- Economic intuitions from transport networks may fail under PF.
- Less transparent solution, exacerbates market power.

# Transport Network




min $\sum_{n \in G} c_n(g_n)$, (gen. cost).

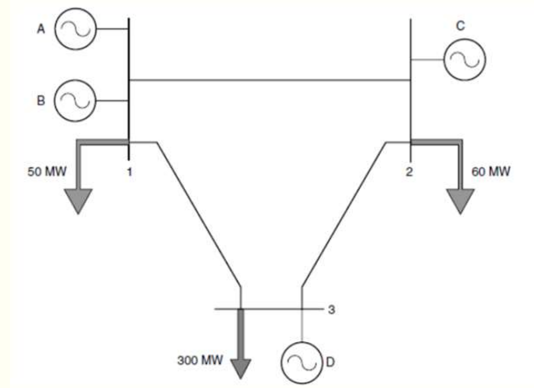
s.t. flow balance at nodes.

line limits. Meet demand.

Properties:

- Non saturated link $\Rightarrow$ equal price nodes.
- flow goes "uphill in price".
- node prices $\in [c'_{\min}, c'_{\max}]$.

# Power Network



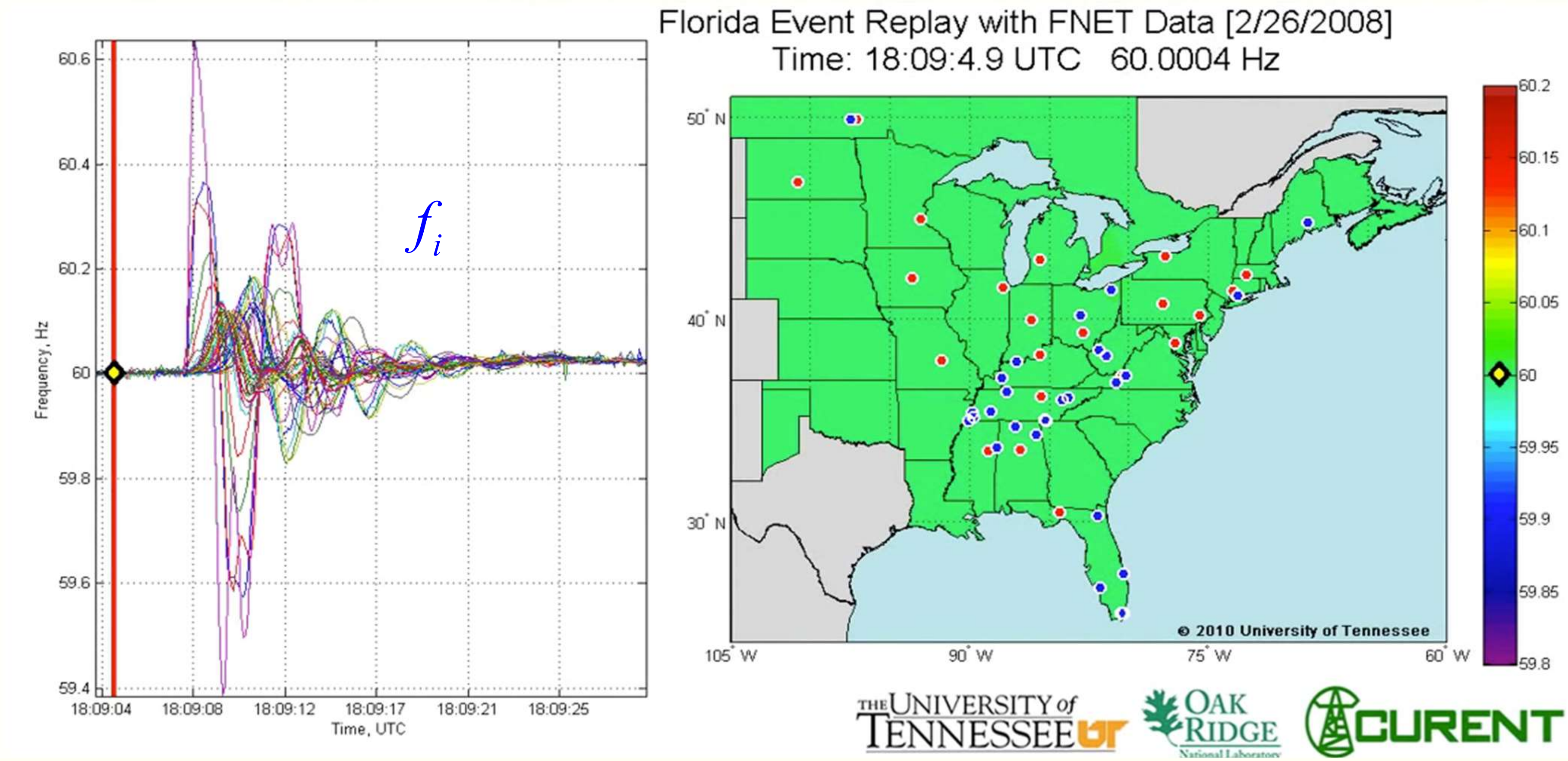

Add constraint between line flows $\leftrightarrow$ node angles.

Eliminates routing as a degree of freedom.

May observe:

- Price differences without local saturation. Downhill flows.
- Prices out of range, even <0 !
- "Braess"-like paradoxes.

# Fast time-scales (seconds)




- Short term imbalance triggers global “swing” oscillations.
- Machine inertia + decentralized “droop” control at machines determines evolution. Coupled oscillators, fragile dynamics.
- Global metrics in P´-Mallada ´00.

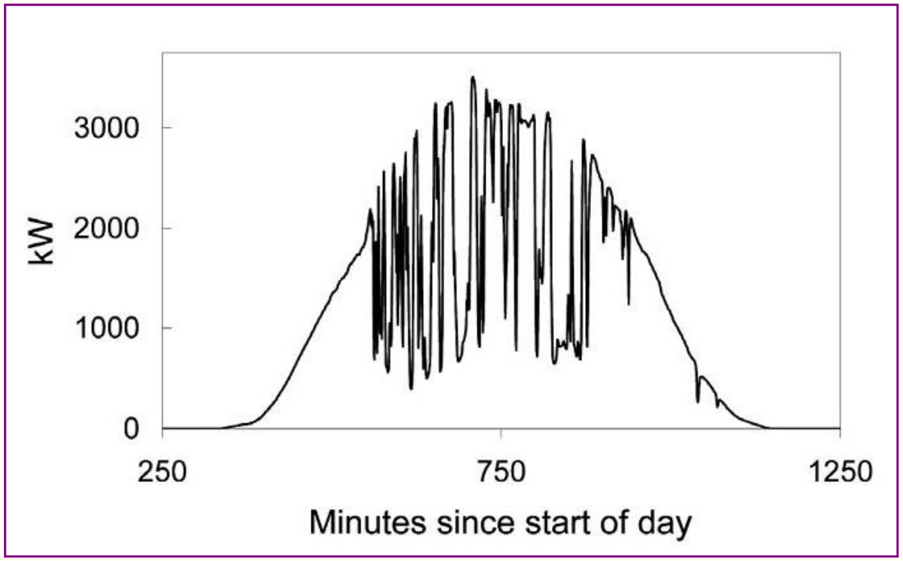
# Challenges of real-time balancing.

- Decentralized control may stabilize (at best) to a different frequency *f.*
- Slower control loop, with SO intervention to restore nominal *f,* and power flows of economic dispatch.
- Overall, combination of centralized/decentralized control.

- Has served us better than expected, but:
  - The opposite of "plug and play". Unit changes are "events".
  - Difficult to rule out cascading events. Costly failures.
  - Survivable? Dynamic fragility, SO dependency.

- And the grid is changing: renewables, DERs, storage,…

# A changing grid




1) Renewable sources (solar, wind):
- Non-dispatchable, exogenous.
- Subject to short term variations.

Impact in resource allocation:
- Slow time-scale: more challenging Economic Dispatch.
- Fast time-scale: power electronics connection (inverters) with no inertia. But also provide faster possibilities for control.

2) Distributed Energy Resources (DERs): Rooftop solar, EVs, ....
- Centralized dispatch infeasible, too many variables.
  Radial topology: simpler to manage locally

3) Network storage (batteries, etc. ): more buffering

# Discussion

Power grid control.

- More centralized: SO susceptible to failures/attacks.
- More fragile: fast dynamics of coupled oscillators.
- AC is partly to blame for both. Unlikely to change.
- Power electronics or DC microgrids to the rescue?

Internet control.

- Decentralized protocols can sustain basic connectivity.
- Performance: bandwidth scarcity has not been an issue, but new demands arise (e.g. from AI).
- Centralization appears inside ISPs, or in cloud computing infrastructures. New challenges to survivability.

Mutual inter-dependence:

- Internet runs on power. Power markets rely on telecom.
- Not clear to what degree control should be coordinated.