Coupling Considerations in Critical Infrastructure Resilience

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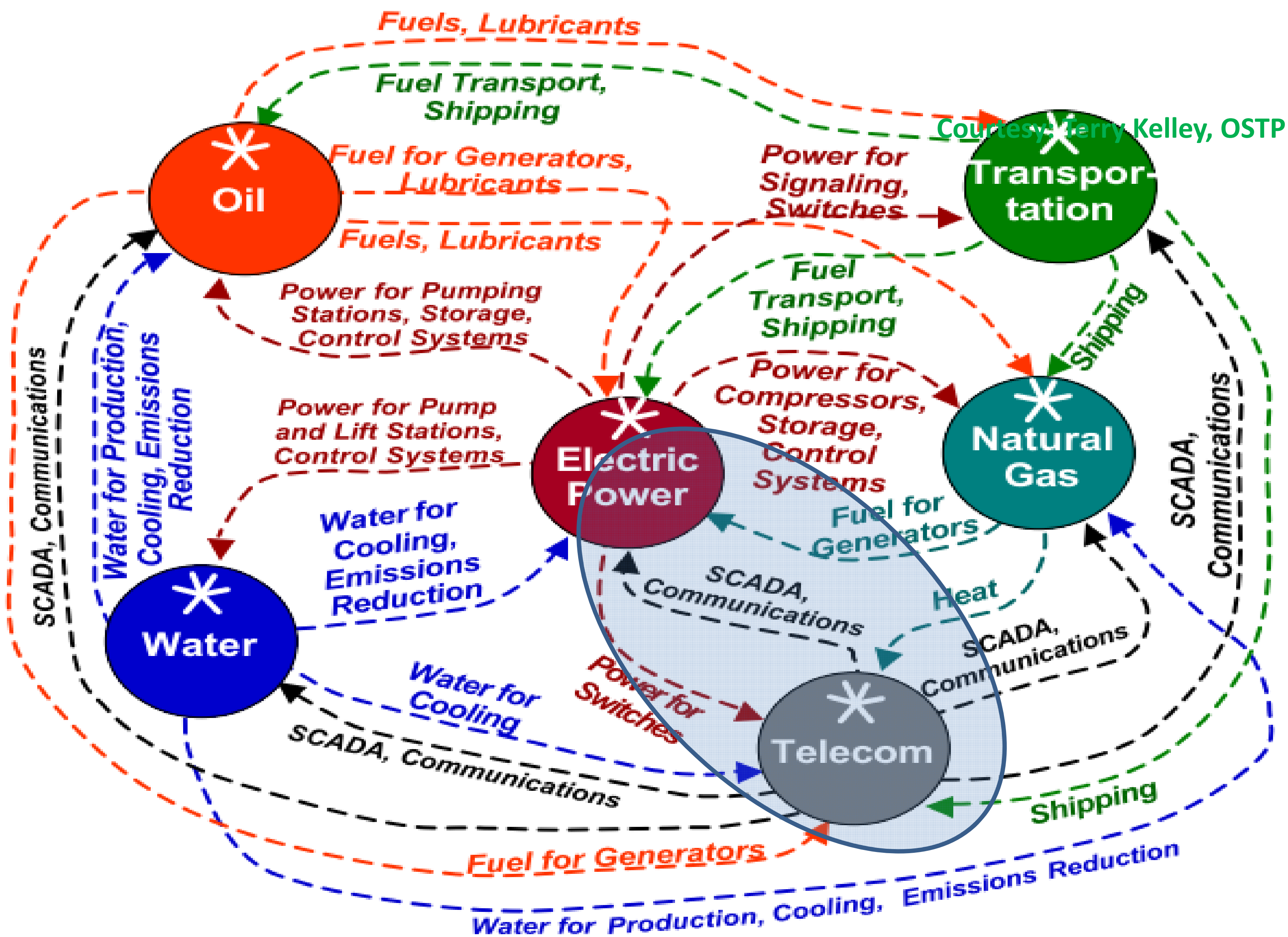
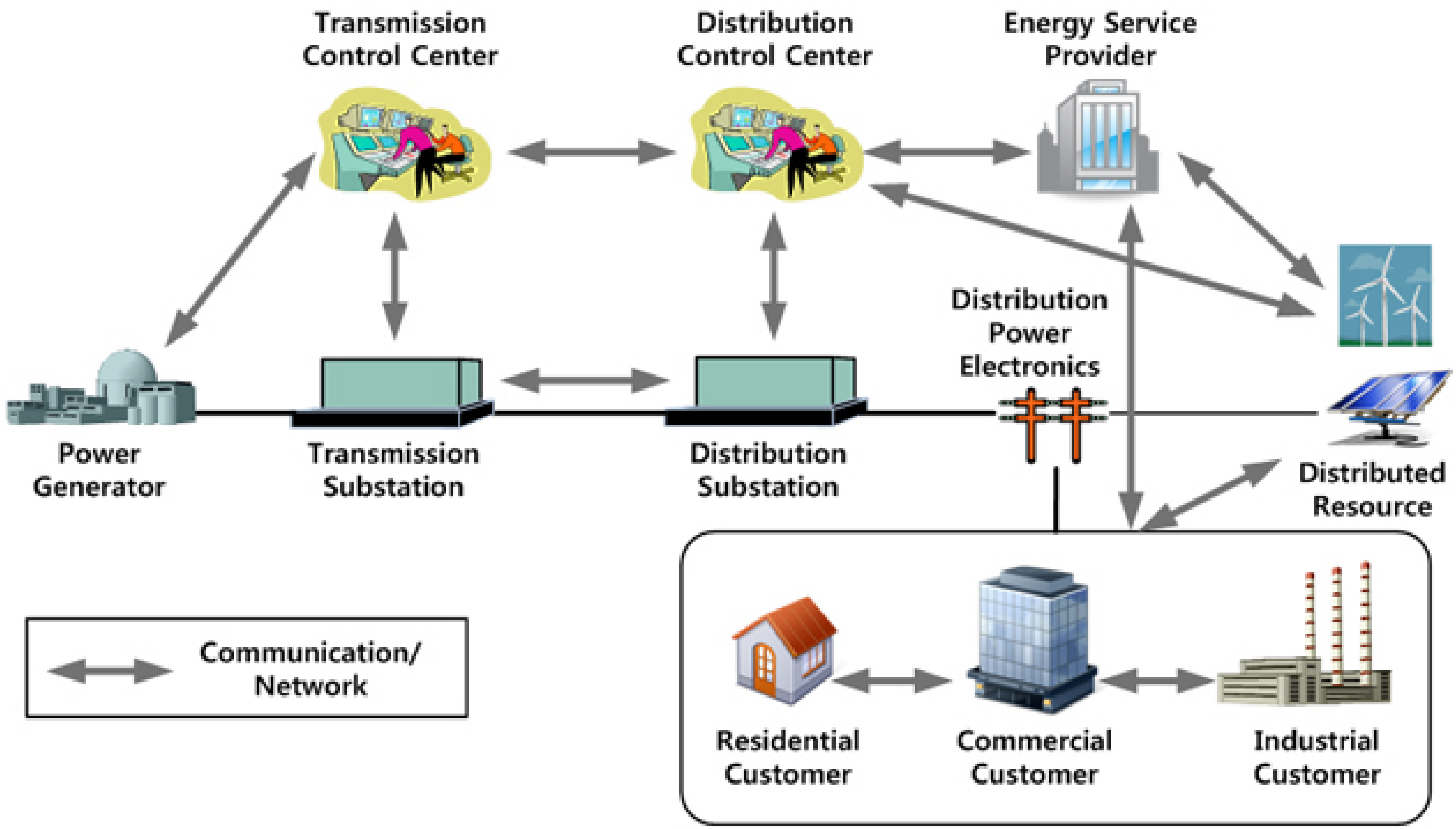
Critical Infrastructure Coupling

- Critical Infrastructure
  - Power, Communications (including Internet), Water, Transportation, Oil/Gas, …
- Many areas of coupling
  - Geographic: Physical disaster affects power grid & Comm.
  - Operational: Comm. ⇔ Power Grid
  - Logical:
    - Blackout ➔ Congestion in operational part of the Internet ➔ Overload related failure

Complex Coupled Systems



Smart Grid: Power + IT Infrastructure



Energy/Cyber Coupling

- Many emerging reasons
  - Increasing frequency of extreme events that affects both
  - Cyber infra increasingly a life-line during extreme events (in addition to power)
  - Comm critical to Wide Area Protection Systems (WAPS) for the grid
- Increasing grid stability concerns
  - Local, smaller scale, perhaps less robust power generation, which may drive local cyber-infra.
  - Integration of variable sources reduces stability of power grid.

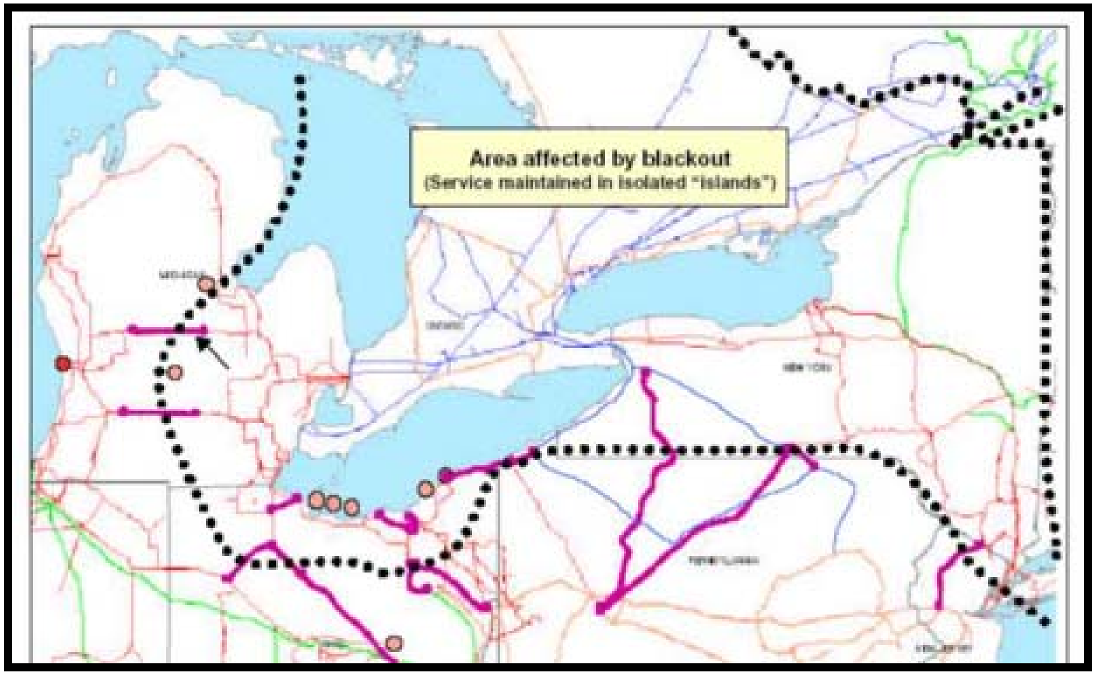
Human Coupling

- Participation of customers as local producers & intelligent consumers creates a new form of coupling
- Each consumer independently decides on mgmt of power consumed & time of day (time shifting)
  - This in turn decides the reverse power flow to utility.
- Creates a 2-way coupling between utility & consumers that play a role in stability of grid

Some Notable Events

- NY and Italy grid failure in 2003
  - Widespread power outage ➔ Internet impact, especially in Italy event
- External event driven
  - Hurricane Katrina ➔ Widspread power/comm damage & feedback
  - Earthquake – Undersea cable damage (Taiwan Dec 2006)
  - Router software update cripples 4000 routers (e.g., May 2007, Japan)
- Comm related Grid failures
  - El Paso Electric (EPE) system
    - Improper isolation of 345KV line by phase angle comparison relays due to incorrect communications latency estimation.
  - Hydro-Québec system
    - Single point of failure in the communications system at the special protection system (SPS)
  - A better understanding of power/comm interactions could have minimized the disruption

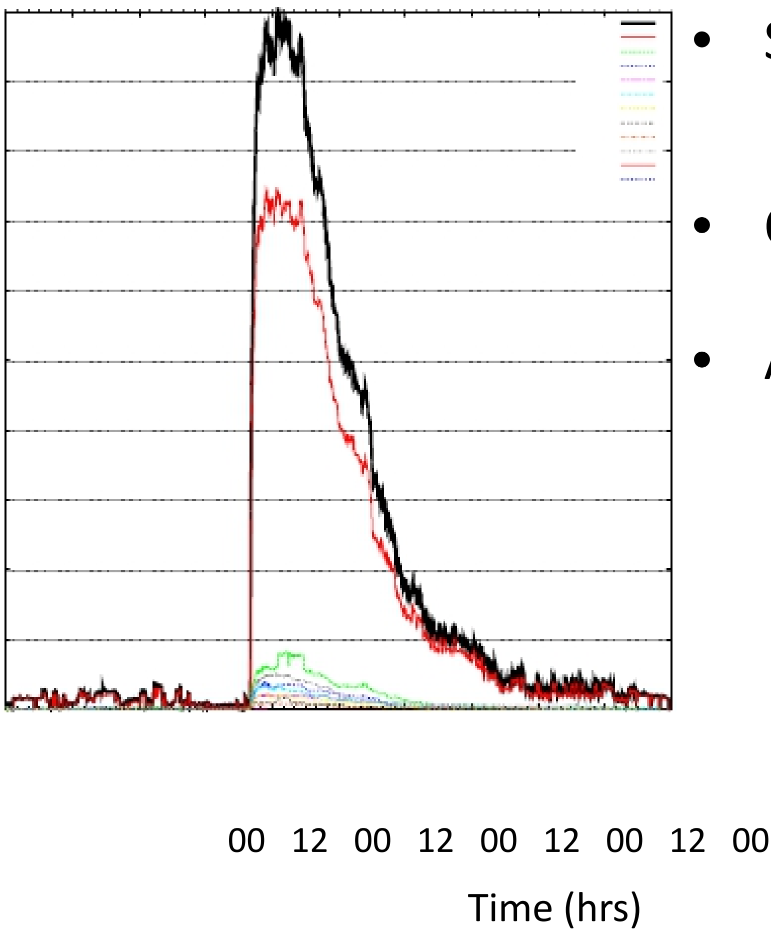
NY Power Outage (Aug 2003)



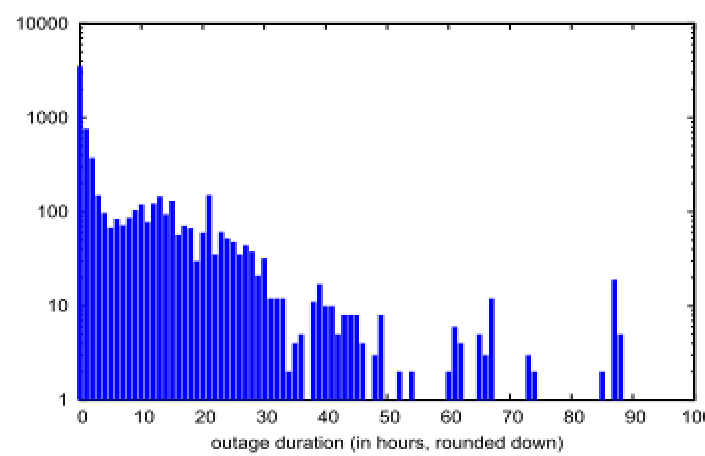
- Outage triggered by a downed tree on Aug 14, 16:10 EDT
- Affects 55M customers (2 mins to spread)
- Restoration by 21:00, Aug 15

Ref: *[www.renesys.com/tech/reports/Renesys_**Blackout**Report.pdf](www.renesys.com/tech/reports/Renesys_BlackoutReport.pdf)*

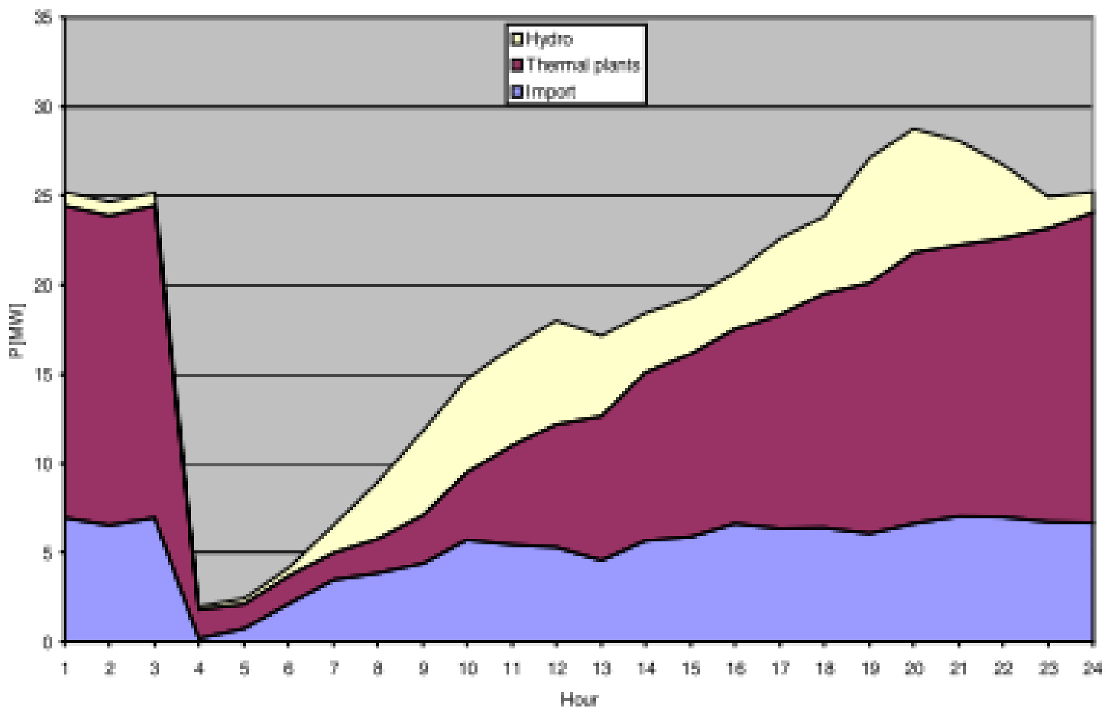
Internet Impact NY Power Outage



- Scope of impact
  - >9,700 customer networks, of which 3,175 suffered outages.
- Outage durations
  - Many hrs, some exceeding 48 hrs
- AS statistics
  - >10% of ASes had outages >4 hrs in ALL of their networks
  - Large AS ➔ smaller loss percentage.



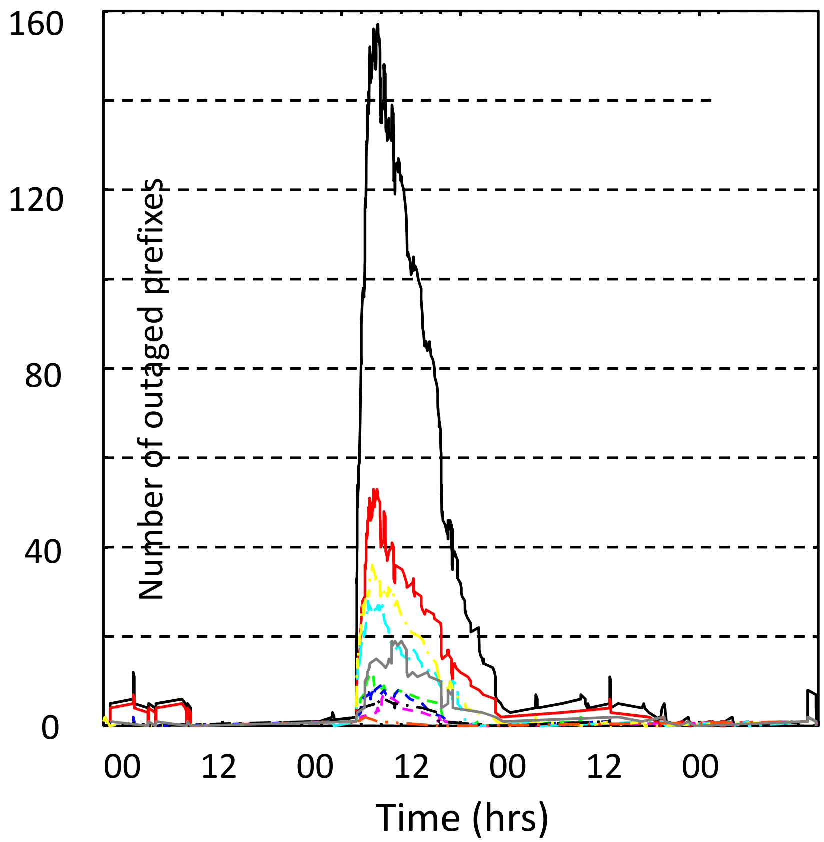
Italy Power Outage: Sept 2003

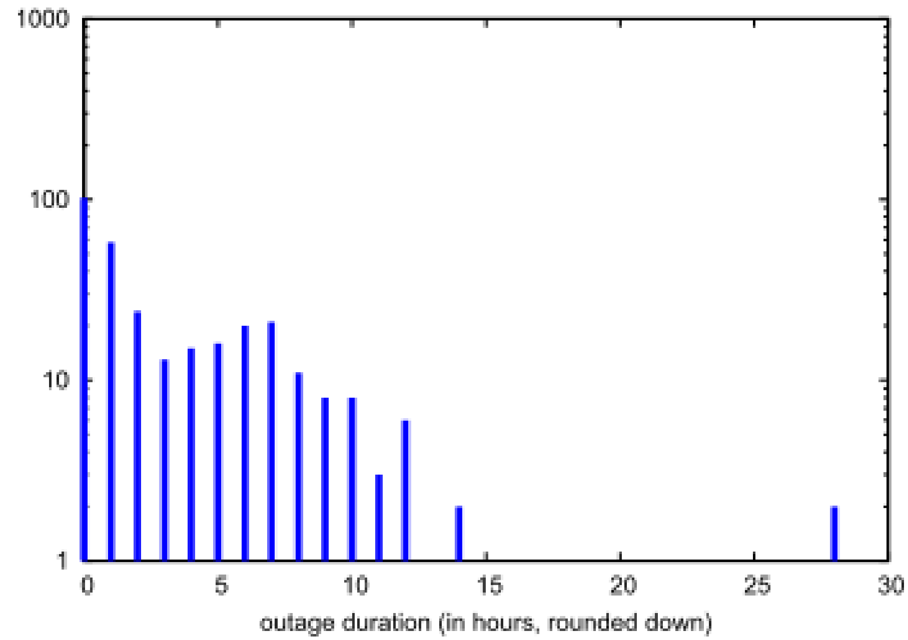


- Similar to NY power outage
  - 59M (entire Italy) affected
  - Started w/ a small outage on Swiss border

Ref: http://crpit.com/abstracts/CRPITV86Johnson.html

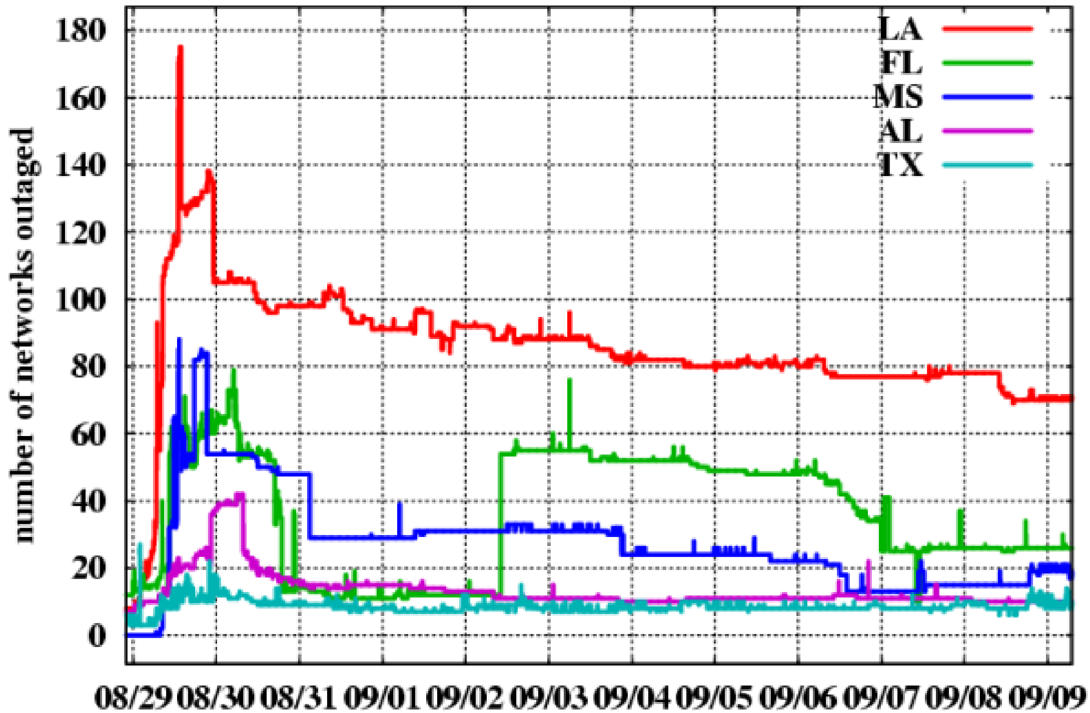
Italy Power Outage: Sept 2003





- Effect on Internet very similar to NY outage.
  - But only 1/14th as many ASes
- Network services completely out for many hrs

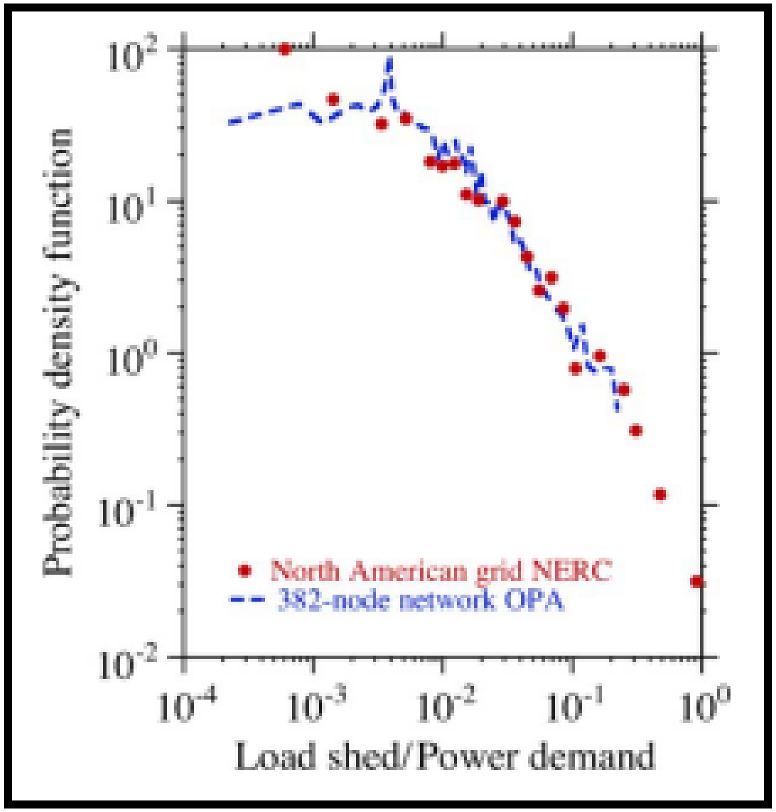
Hurricane Katrina (Aug 2005)



- Induced by major local power outages (1.3M customers)
- No major regional cable routes through the worst affected areas.
- Many instances of secondary failures (e.g, FL 4 days later!)
- Ref: www.renesys.com/tech/presentations/pdf/Renesys-Katrina-Report-9sep2005.pdf

Power Grid – A Complex System

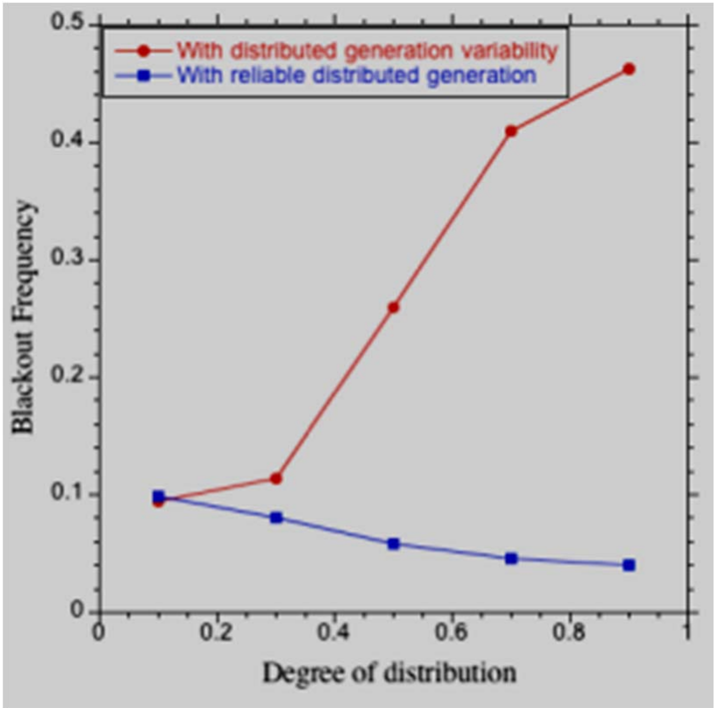
- Dynamics largely independent of individual triggers (e.g., lightning strike)
  - Cascaded failures quite prevalent
- Failures are invariably strongly correlated
  - Heavy tail dist. for failure size (power law)
  - Observed in many power grids

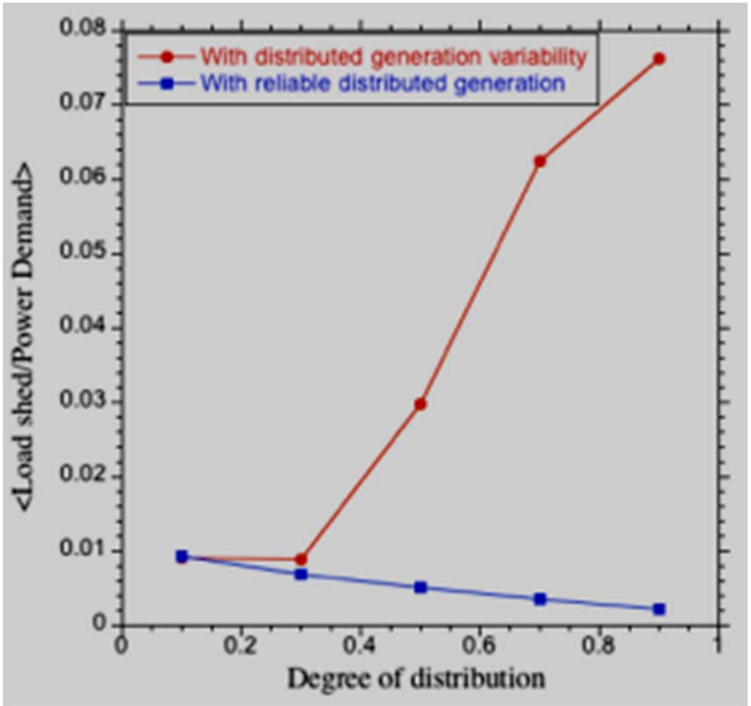


D.E. Newman, B.A. carreras, V.E. Lynch, I. Dobson, Exploring Complex Aspects of Blackout Risk and Mitigation, IEEE trans/Reliability, March 2011

Impact of Variability

- Blackout freq: Freq. of at least 10% transmission lines going down
- Degree of dist: Normalized std dev of power generated by all distributed sources
  - Substantial increase in blackout freq & load shedding w/ degree of dist.





Reducing Coupling

- Key techniques: redundancy, isolation, and diversity
- Redundancy
  - Independently powered comm infra (e.g., Battery & or PV backup)
  - Excess reserve generation capacity
  - Redundant emergency comm (via wireless or other means)
- Reduce dependence on WAPS
  - Apply protection based on local events (e.g., CB trips) or estimate state from surviving comm ability.
  - Time – space tradeoff: Local info. available quickly but incomplete.
- Diversity
  - Direct sourcing of local generation into the computing infra. in addition to grid power (i.e., avoid integration!)
  - Free cooling option (remove electric/water dependence)

Challenges

- Modeling of grid/comm interactions
  - Characterization of relevant effects
  - Huge state space to explore, tractable analytic models
  - Integration of continuous (power instability) & discrete (comm failure) dynamics.
  - Data issues: different formats/semantics, integration of real-time data.
- Redundant emergency comm
  - Technological – what emergency comm are most appropriate
  - Assessment of benefits & dangers of technologies (e.g., wireless)
- Reduce dependence on WAPS
  - Space-time tradeoff in state estimation
    - Use local info quickly & easily, or wait for & analyze global info
- Security Issues:
  - What couplings are most likely to be exploited by malicious entities
  - How do you design decoupling mechanisms to address this

Resilience for Large Cyber-infra

- Engagement of local power sources based on power quality from the grid.
  - Traditionally small diesel capacity, engaged on failure
  - Proactive engagement of local renewable energy source (PV) to protect both the cyberinfra & the grid.
- Lumpy Failures
  - Power related failures likely affect an entire area (e.g., ISP POP) rather than single routers or link interfaces.
  - Modeling and resilience mechanisms
- Indirect coupling
  - Electric faults ➔ Water unavail for cooling ➔ Overheating
- Energy adaptation
  - Soft load shedding in response to grid instability
  - Environmental angle: Maximize use of local renewables

Energy Adaptation

- Dynamic end to end load adjustment
  - Workload adaptation: What & how to run?
  - Infrastructure adaptation: Where & when to run?
- Workload Adaptation
  - Shut down low priority tasks, Lower resolution or precision, partial service, …
  - Pre-compute or pre-communicate during energy plenty periods
  - Reduce number of replicas (reduce reliability/perf)
- Infrastructure Adaptation
  - Load consolidation & migration
  - Managed QoS degradation
    - Batched service, mandatory use of power mgmt controls
  - Limit cooling (both CRAC and fans)
- Challenge: End to end coordination is crucial for acceptable performance.

Thank you!