Keeping it Together

Transient stability in a world fully electrified by wind & solar generation

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CAUTION CONCERNING FORWARD-LOOKING STATEMENTS:

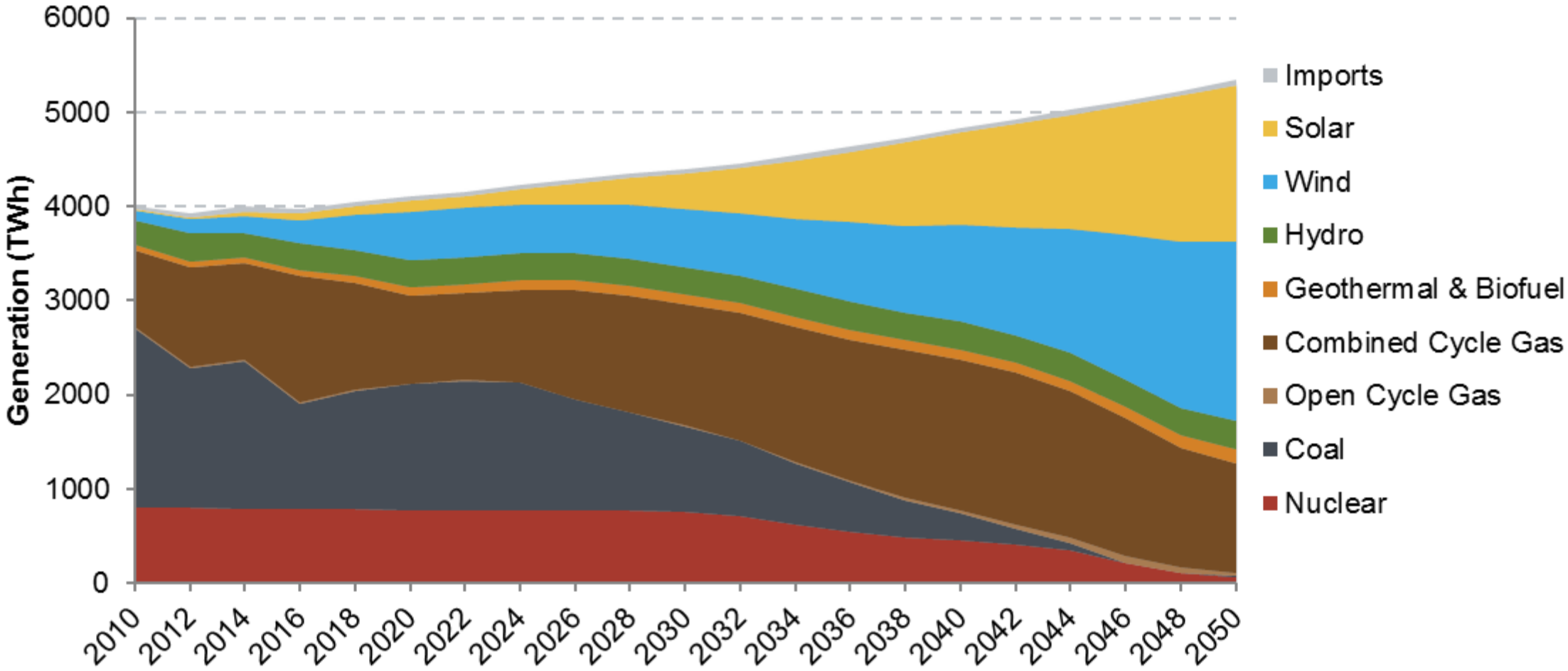
This document contains "forward-looking statements" – that is, statements related to future events that by their nature address matters that are, to different degrees, uncertain. For details on the uncertainties that may cause our actual future results to be materially different than those expressed in our forward-looking statements, see http://www.ge.com/investor-relations/disclaimer-caution-concerning-forwardlooking-statements as well as our annual reports on Form 10-K and quarterly reports on Form 10-Q. We do not undertake to update our forward-looking statements. This document also includes certain forward-looking projected financial information that is based on current estimates and forecasts. Actual results could differ materially. to total risk-weighted assets.]

NON-GAAP FINANCIAL MEASURES:

In this document, we sometimes use information derived from consolidated financial data but not presented in our financial statements prepared in accordance with U.S. generally accepted accounting principles (GAAP). Certain of these data are considered "non-GAAP financial measures" under the U.S. Securities and Exchange Commission rules. These non-GAAP financial measures supplement our GAAP disclosures and should not be considered an alternative to the GAAP measure. The reasons we use these non-GAAP financial measures and the reconciliations to their most directly comparable GAAP financial measures are posted to the investor relations section of our website at www.ge.com. [We use non-GAAP financial measures including the following:

- Operating earnings and EPS, which is earnings from continuing operations excluding non-service-related pension costs of our principal pension plans.
- GE Industrial operating & Verticals earnings and EPS, which is operating earnings of our industrial businesses and the GE Capital businesses that we expect to retain.
- GE Industrial & Verticals revenues, which is revenue of our industrial businesses and the GE Capital businesses that we expect to retain.
- Industrial segment organic revenue, which is the sum of revenue from all of our industrial segments less the effects of acquisitions/dispositions and currency exchange.
- Industrial segment organic operating profit, which is the sum of segment profit from all of our industrial segments less the effects of acquisitions/dispositions and currency exchange.
- Industrial cash flows from operating activities (Industrial CFOA), which is GE's cash flow from operating activities excluding dividends received from GE Capital.
- Capital ending net investment (ENI), excluding liquidity, which is a measure we use to measure the size of our Capital segment.
- GE Capital Tier 1 Common ratio estimate is a ratio of equity

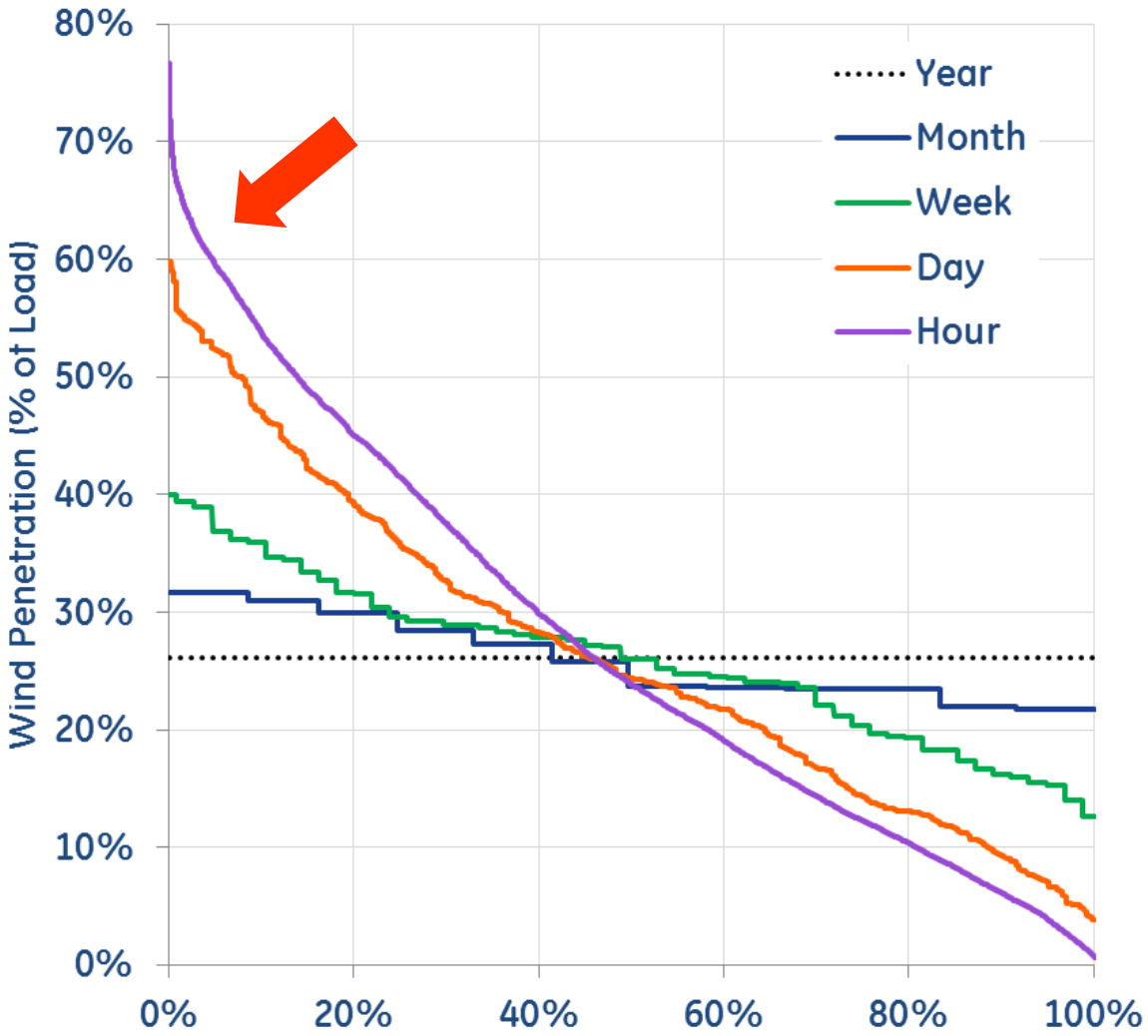
What the policy people see



Source: NREL

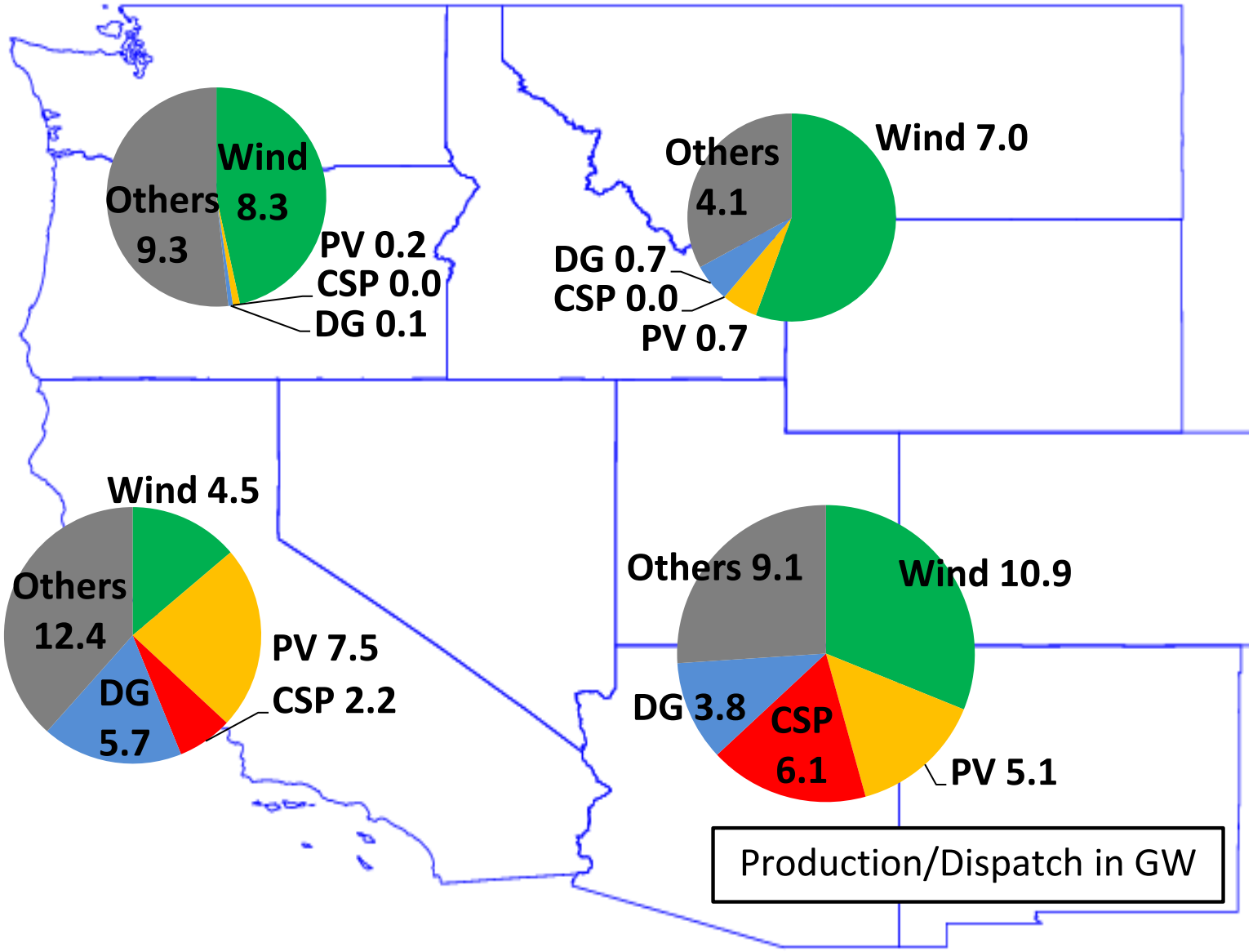
But, the grid people need to keep the lights on ALL the time

Enough wind to meet 30% annual energy penetration



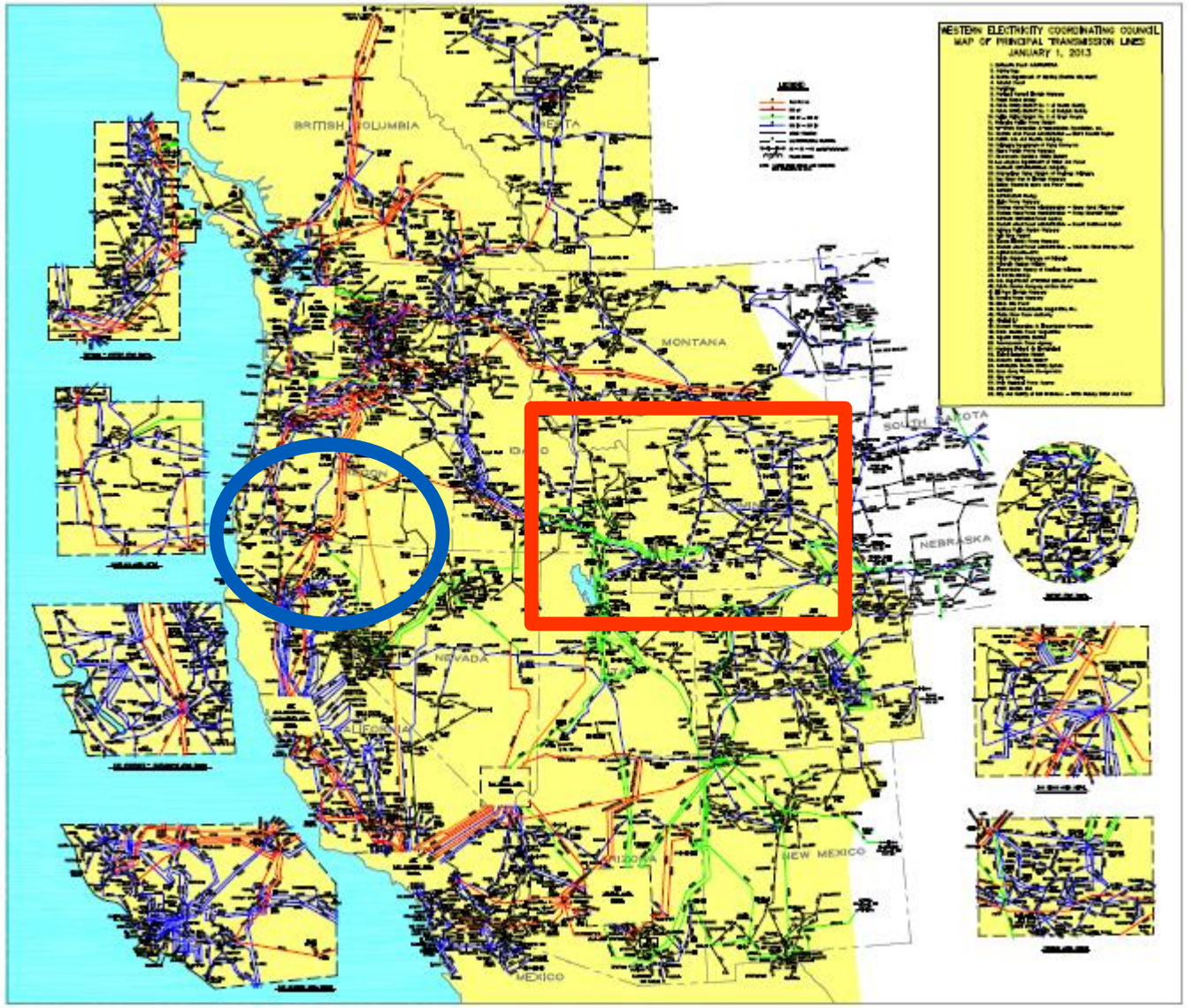
Source: GE NSPI Study

At periods of high instantaneous penetration, things get interesting



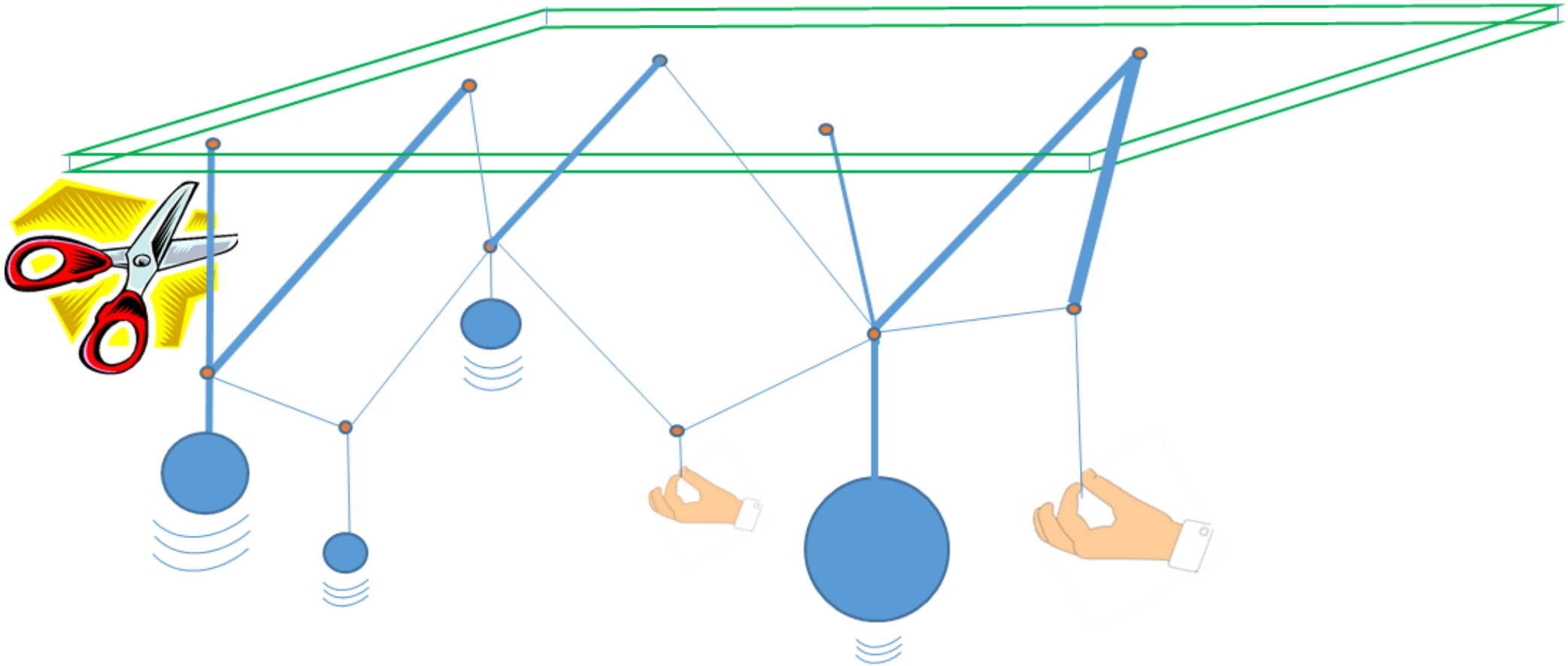
Source: NREL/GE WWSIS 3a

What the grid people see



- ~10000 nodes
- 38 balancing authorities
- ~120,000 circuit miles of transmission
- ~4000 generators- ~265GW
- ~5000 loads
- ~100,000 state variables

Is it stable?



Derived from original figure by Elgerd

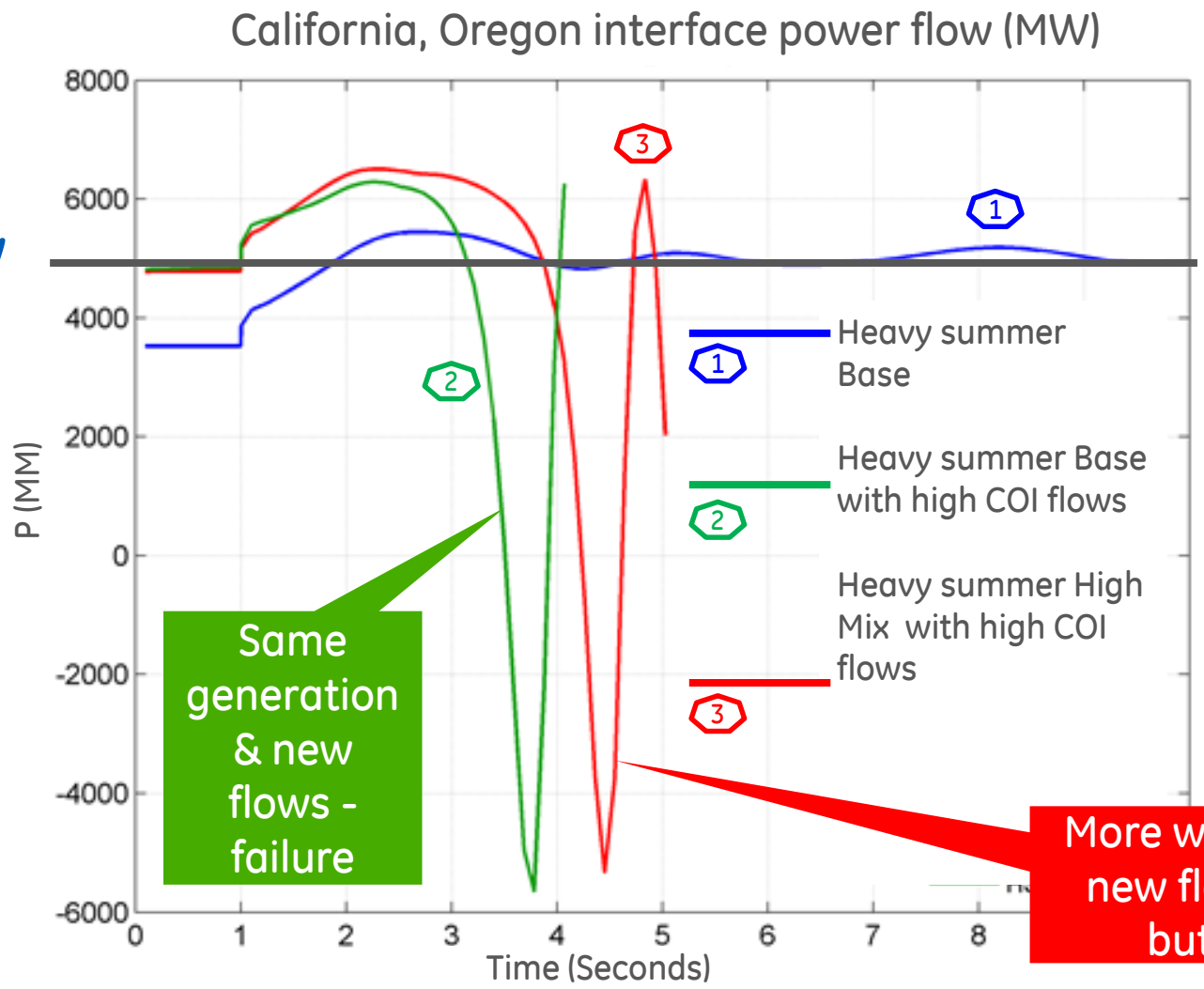
Elgerd, Olle, I. 1971. "Electric Energy Systems Theory: An Introduction" McGraw-Hill, pg 478.

What happens when the flow patterns change?

A disturbance on the north-south corridor between Oregon and California

(Trip of the Pacific DC Intertie)

4,800 MW

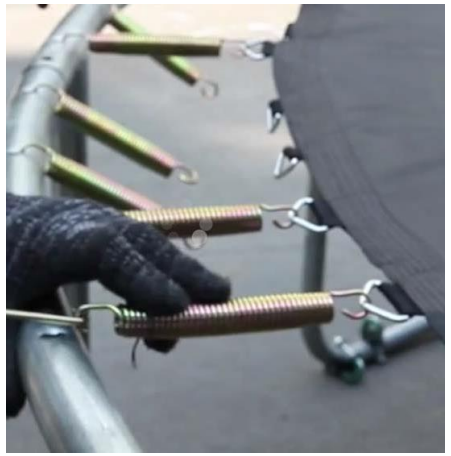


Source: NREL/GE WWSIS 3a

What about “weak grids”? What is Grid Strength?

- Grid strength is like a “stiffness” of a power system
- It is specifically for voltage (not frequency)
- Unlike frequency stability, location matters
- In a strong grid, bus voltages do not change much when the system is ‘whacked’ by a disturbance like a fault
- In a weak grid, bus voltages change a lot during disturbances like faults

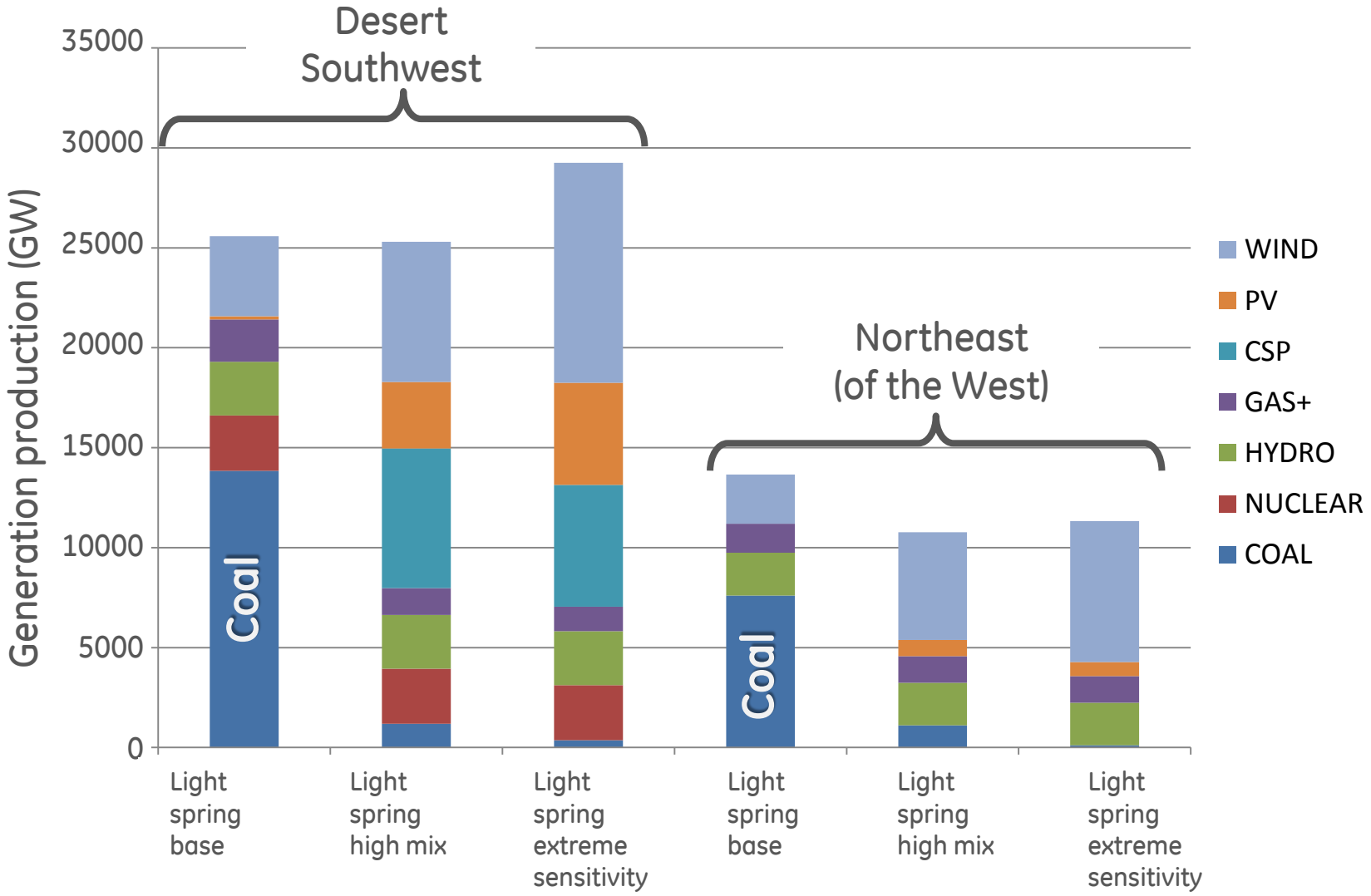
“Strong Grid”



“Weak Grid”

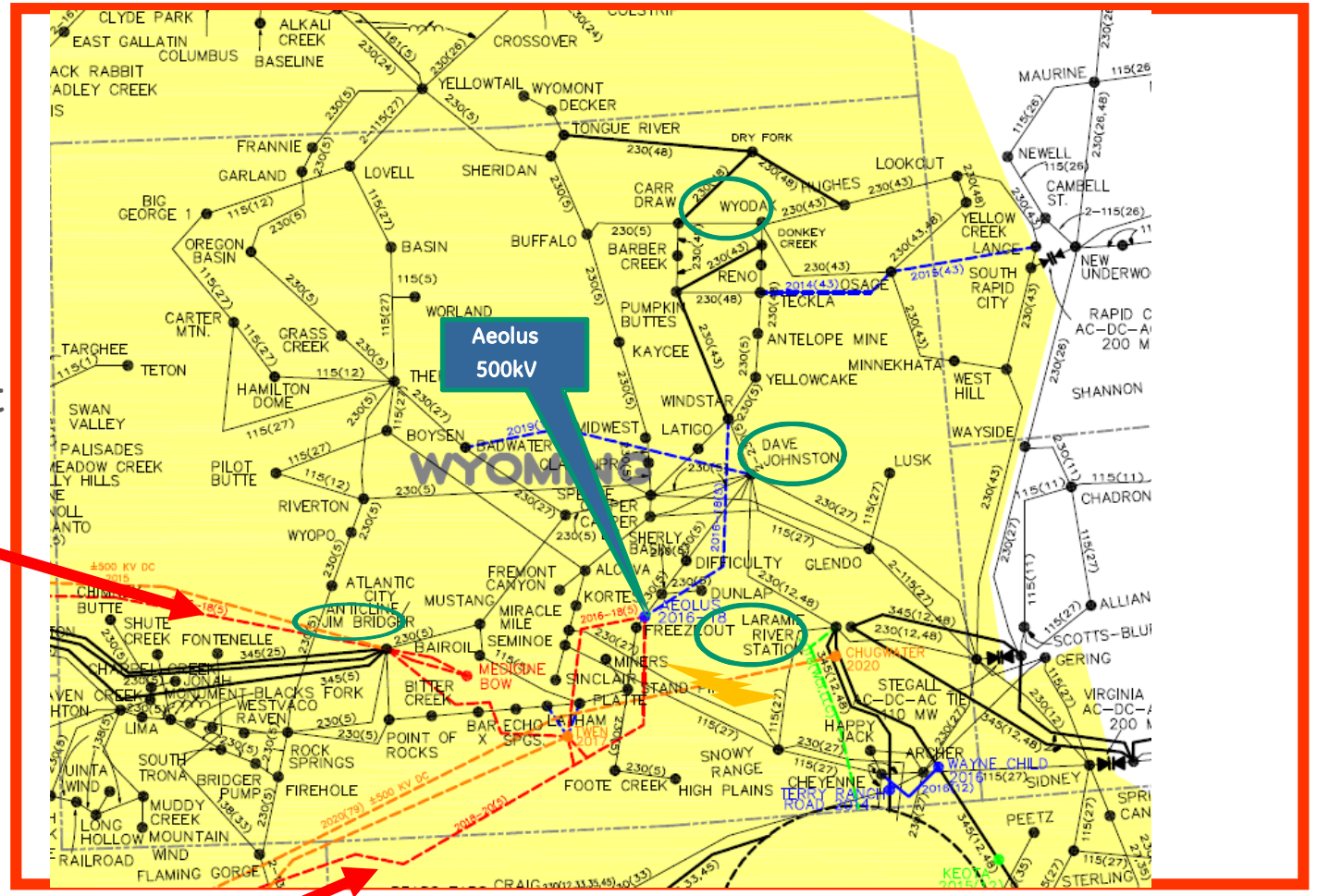
“Impending Fault”

Wind and Solar Displacement of Thermal (East portion of the Western Interconnection)



Weak Grid Example: Transient Stability in Northeastern Western Interconnection

Gateway West 500kV transmission project



Gateway South 500kV transmission project

Large Coal Plants

It depends on how stressed the system is:

Source: NREL/GE WWSIS 3a

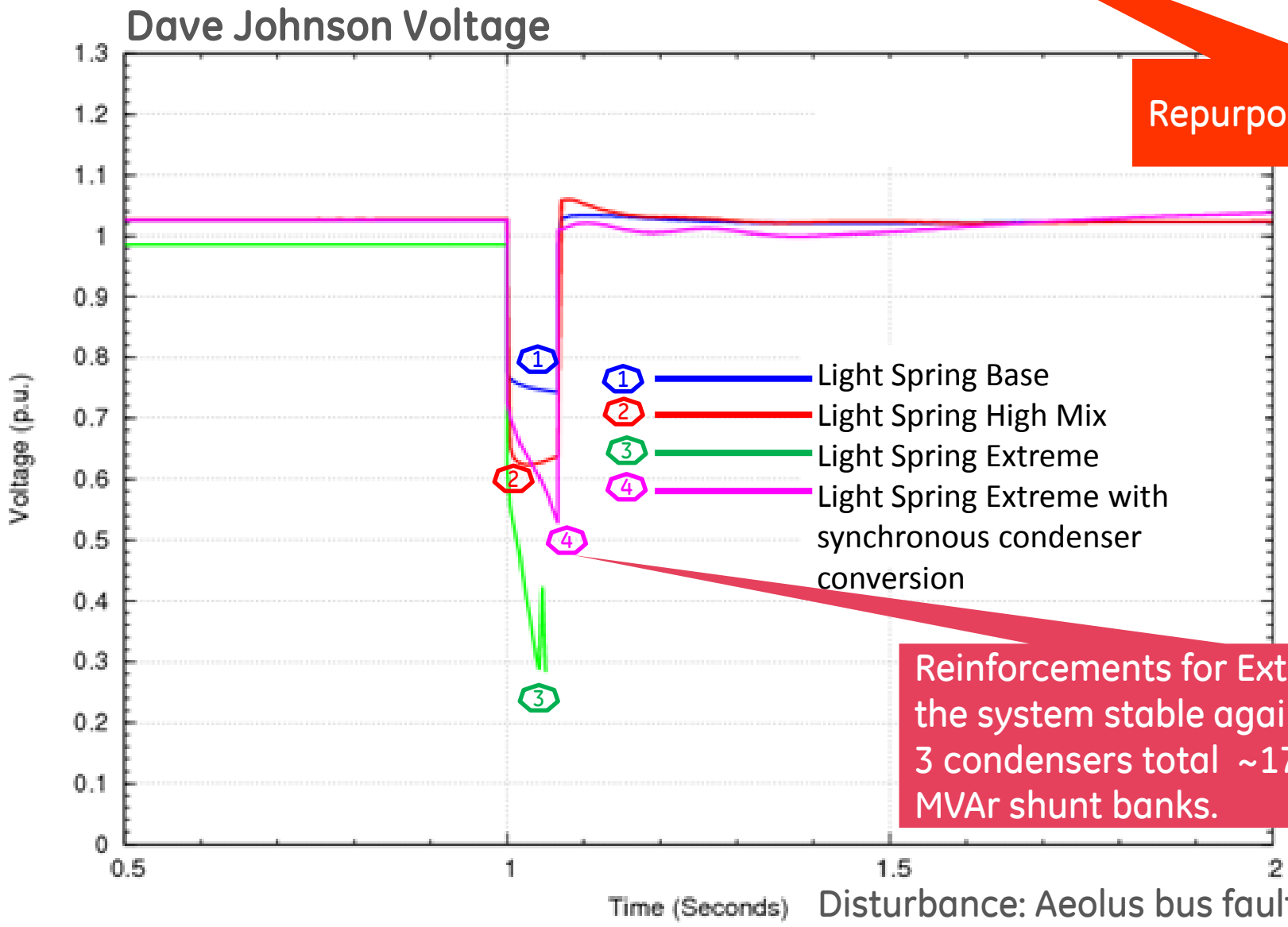
What Contributes to Grid Strength?

- Synchronous machines (generators, condensers)
- Motor Loads

And what does not (today)?

- Most of today's power electronic-based generation (PV, Wind, HVDC)
- Battery storage
- Other Loads

Synchronous Condenser Conversion Results in Acceptable Performance even under extreme stress



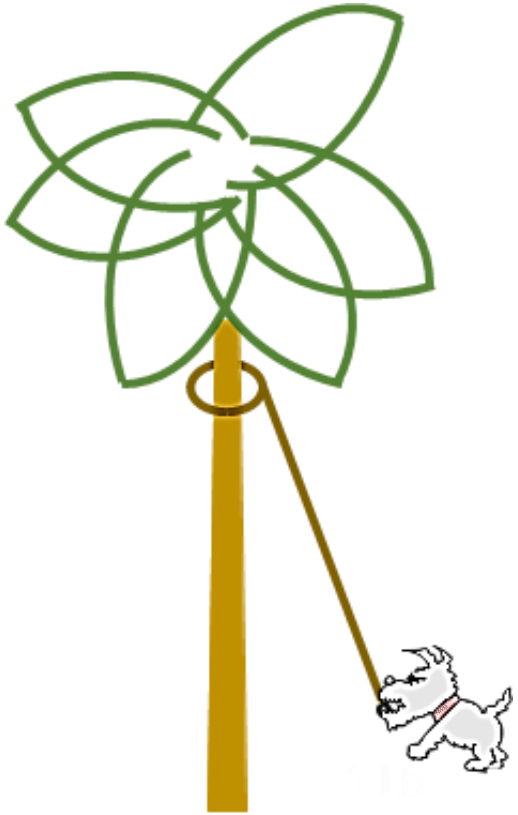
Repurpose the old stuff!

Reinforcements for Extreme sensitivity makes the system stable again:
3 condensers total ~1700MVA plus ~500 MVAr shunt banks.

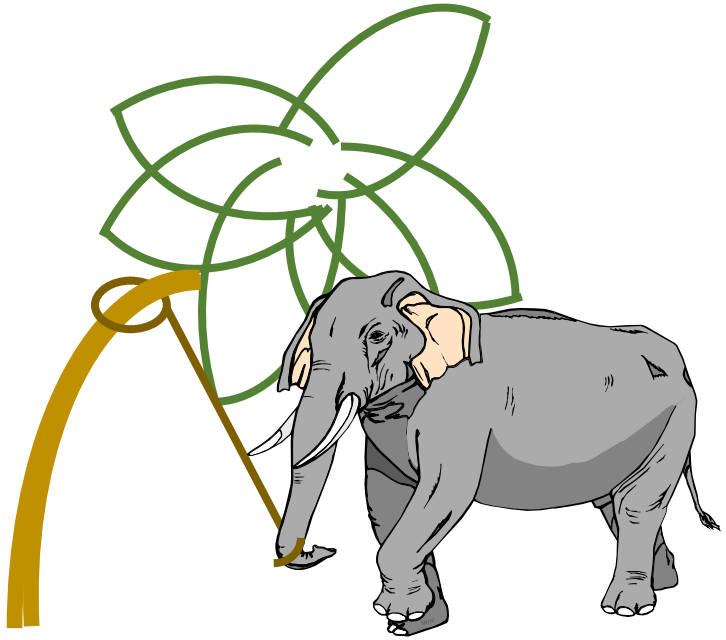
Disturbance: Aeolus bus fault and line trip

Source: NREL/GE WWSIS 3a

Weak Grid – why the wind & solar need to keep improving



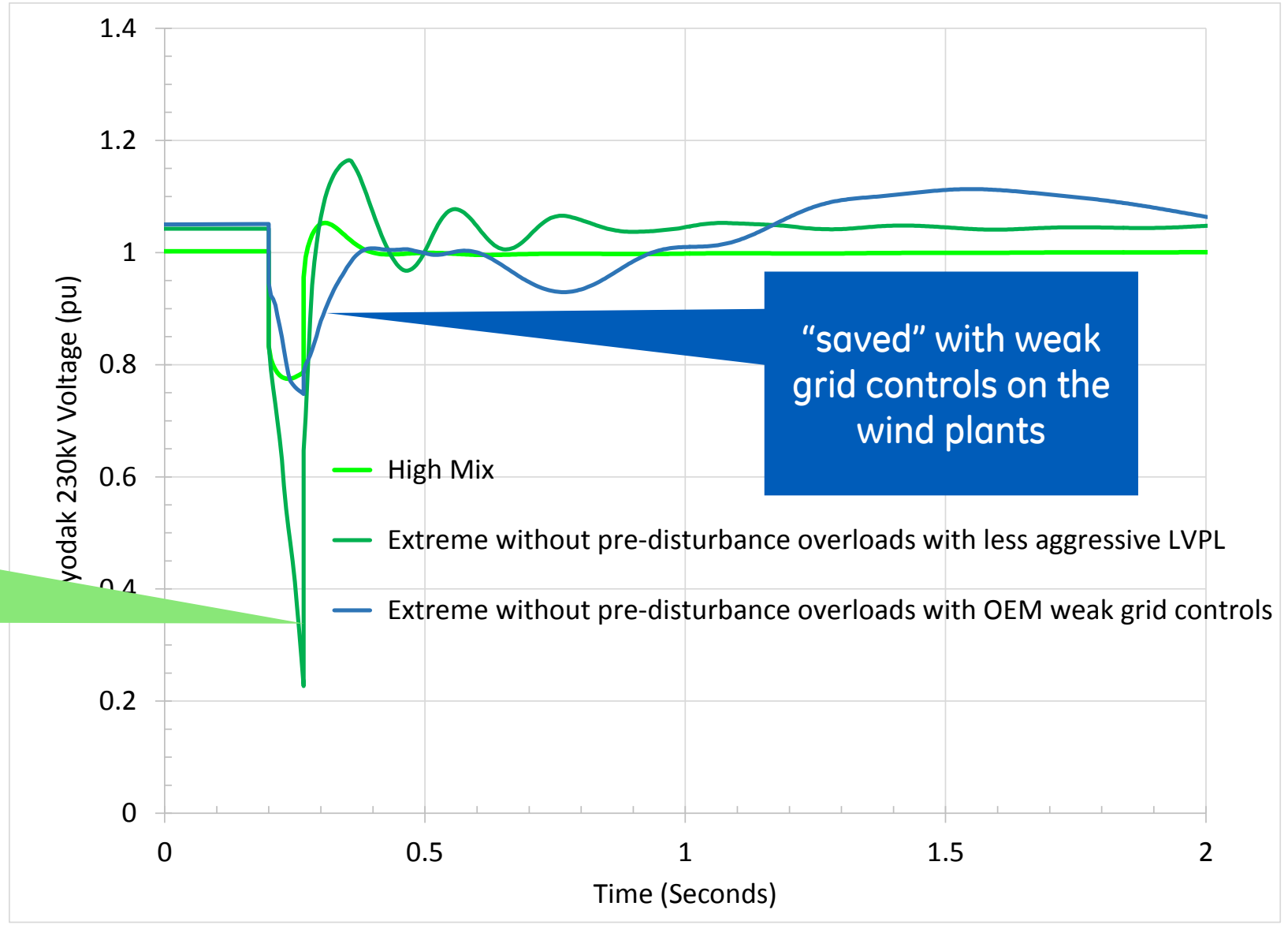
Small wind plant relative to grid



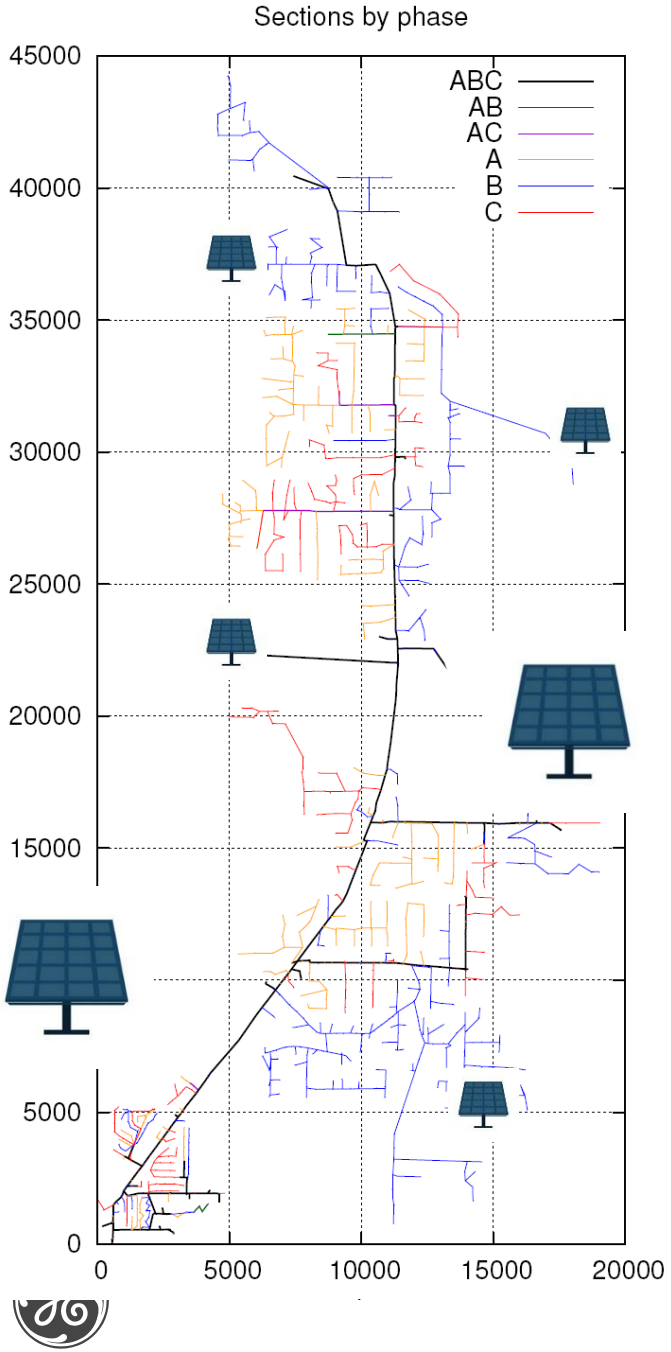
Large wind plant relative to grid

Source: NREL/GE WWSIS 3a

Better controls can make a huge difference:



Source: NREL/GE WWSIS 3a



"Load Netting" isn't adequate anymore

General practice is for "load netting":

What is lost when distributed PV is "buried" in net load:

- Load shedding is wrong.
- Vulnerability to common mode tripping of dPV is lost.
- Weather impacts can't be captured.
- Dynamics of dPV are lost.

Today: we simplify to this!!!!

$P + jQ$

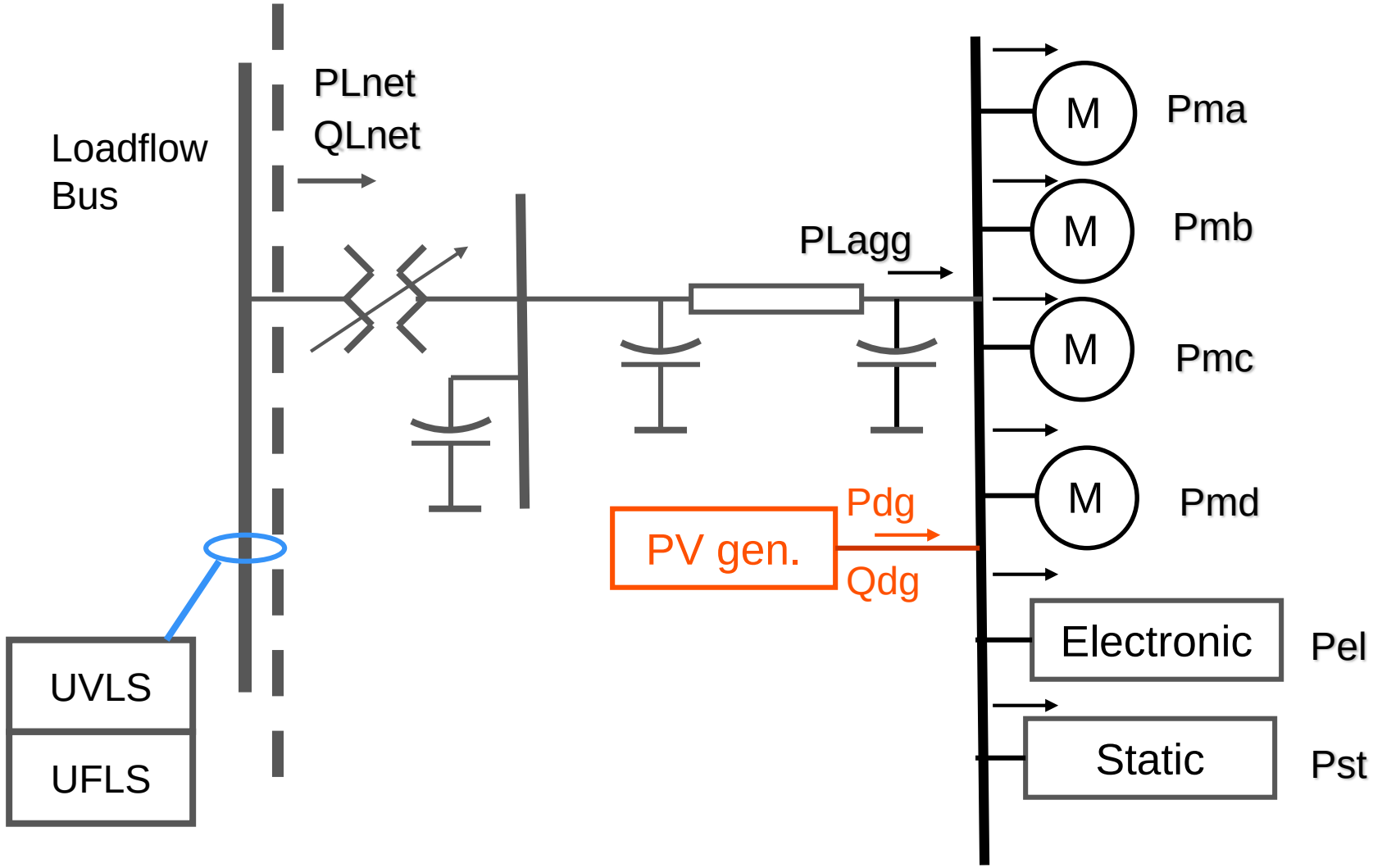
$$P = P_0((a_p + b_p V + c_p V^2) \times (1 + k_{pf} F))$$

$$Q = Q_0((a_q + b_q V + c_q V^2) \times (1 + k_{qf} F))$$

"ZIP" load model

Composite Load Model: "CMPLWG"* Structure with Distributed Generation

*WECC's Composite Load Model Working Group"



The behavior of the load can dominate the system dynamics

Same disturbance* - very different outcome

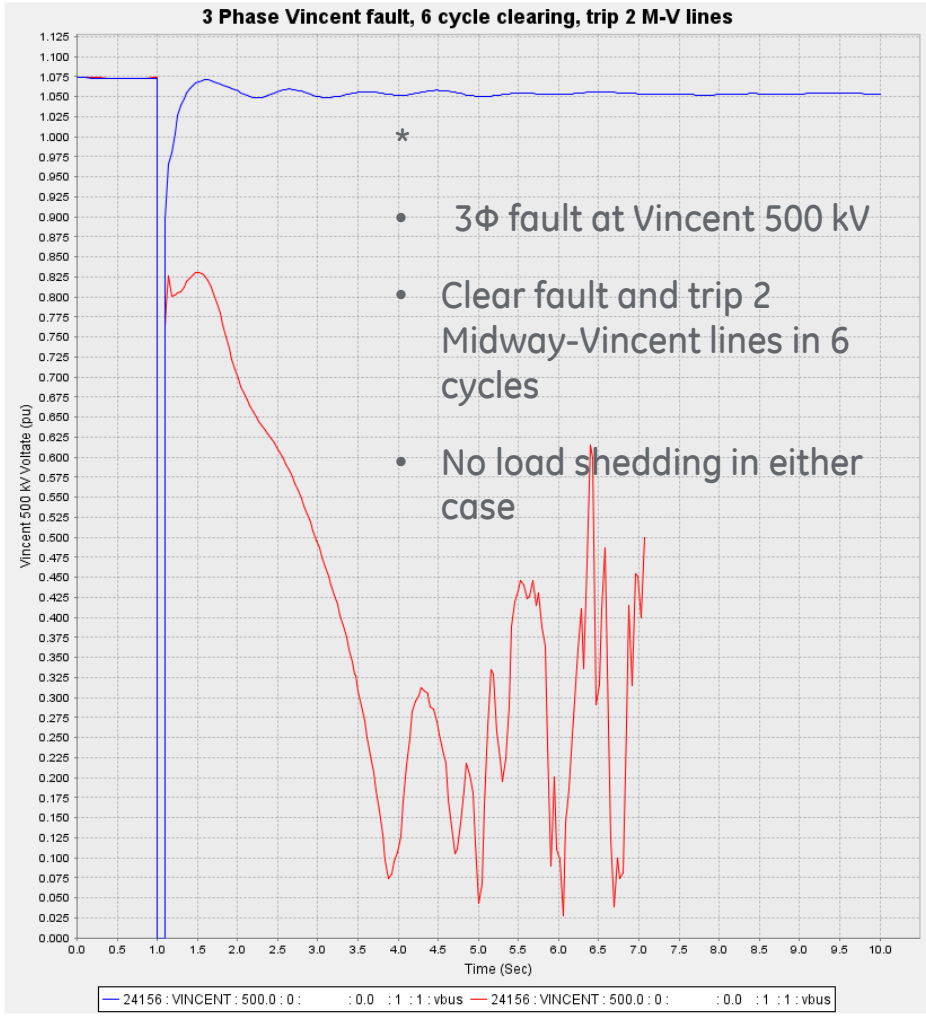
Std WECC load model (blue)

192GW total load modeled as induction motor (18% overall) + static – fast voltage recovery, very stable response

Composite load model (red)

143.9 GW modeled as composite load – fails to recover

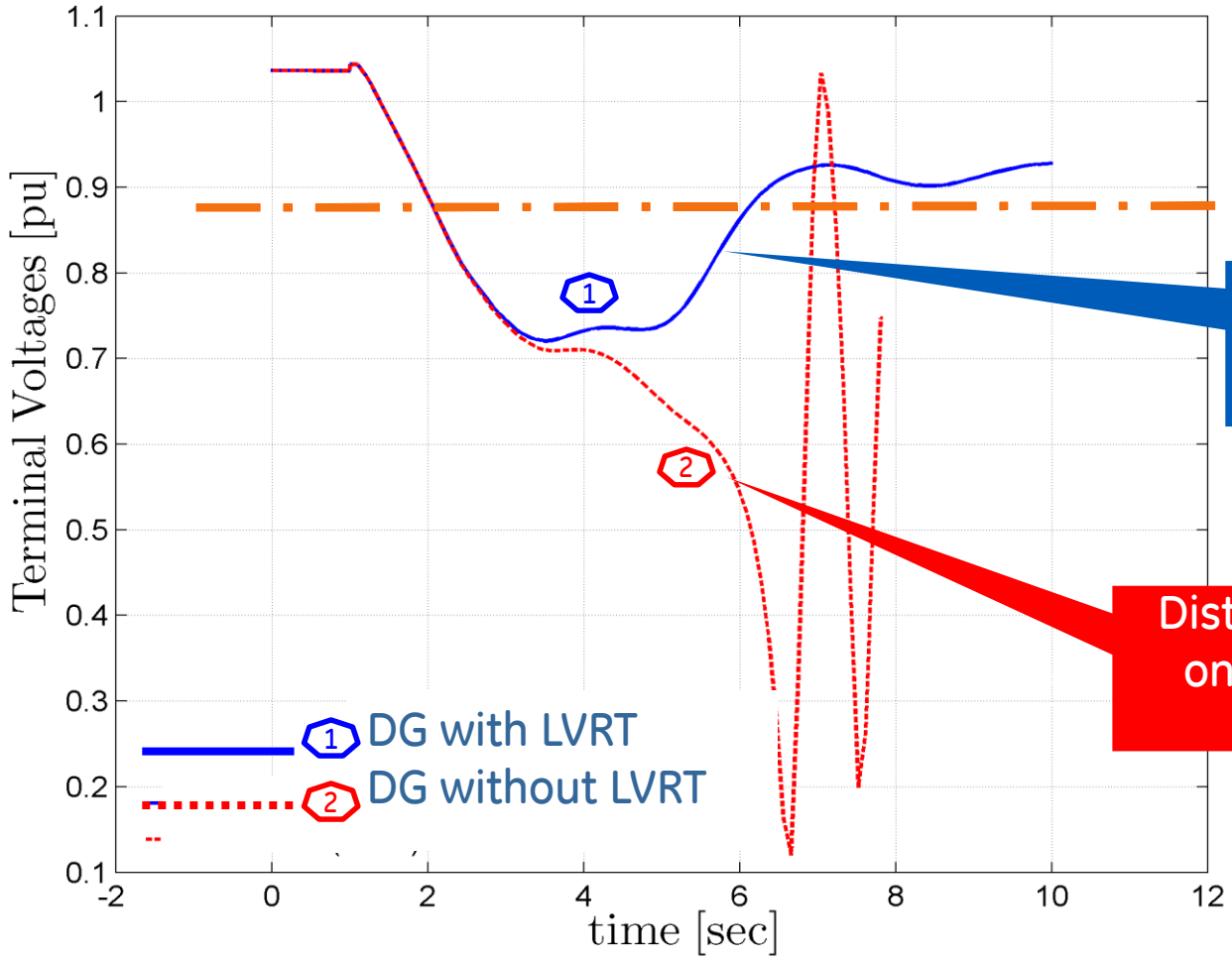
There's a shocking dearth of actual supporting data!!!



Load behavior dominates system response – what will ESI "loads" look like?

Source: NREL/GE WWSIS 3

Fault ride-through is critical: Impact of common-mode tripping of DG without low-voltage ride-through

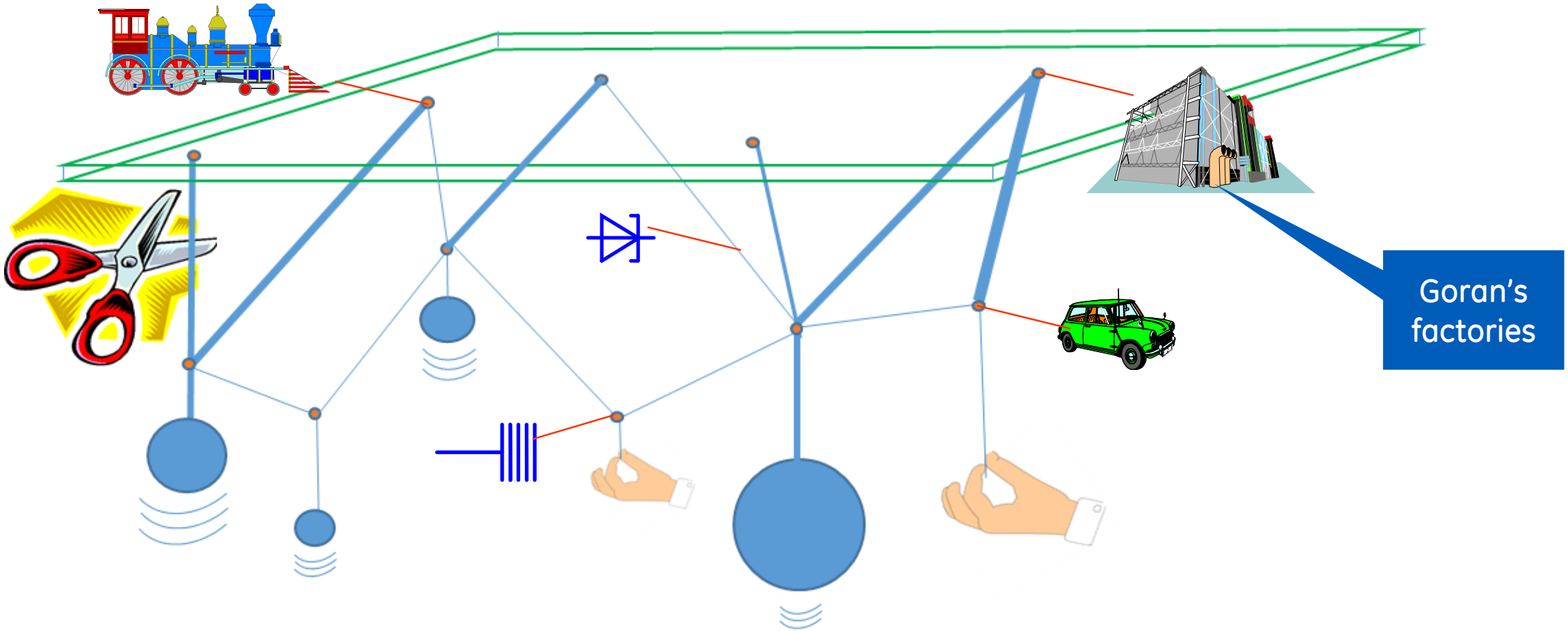


Distributed PV behaved well on fault: recovery satisfactory

Distributed PV tripped on fault: took entire system down.

Source: NREL/GE WWSIS 3

Is it stable with ESI?



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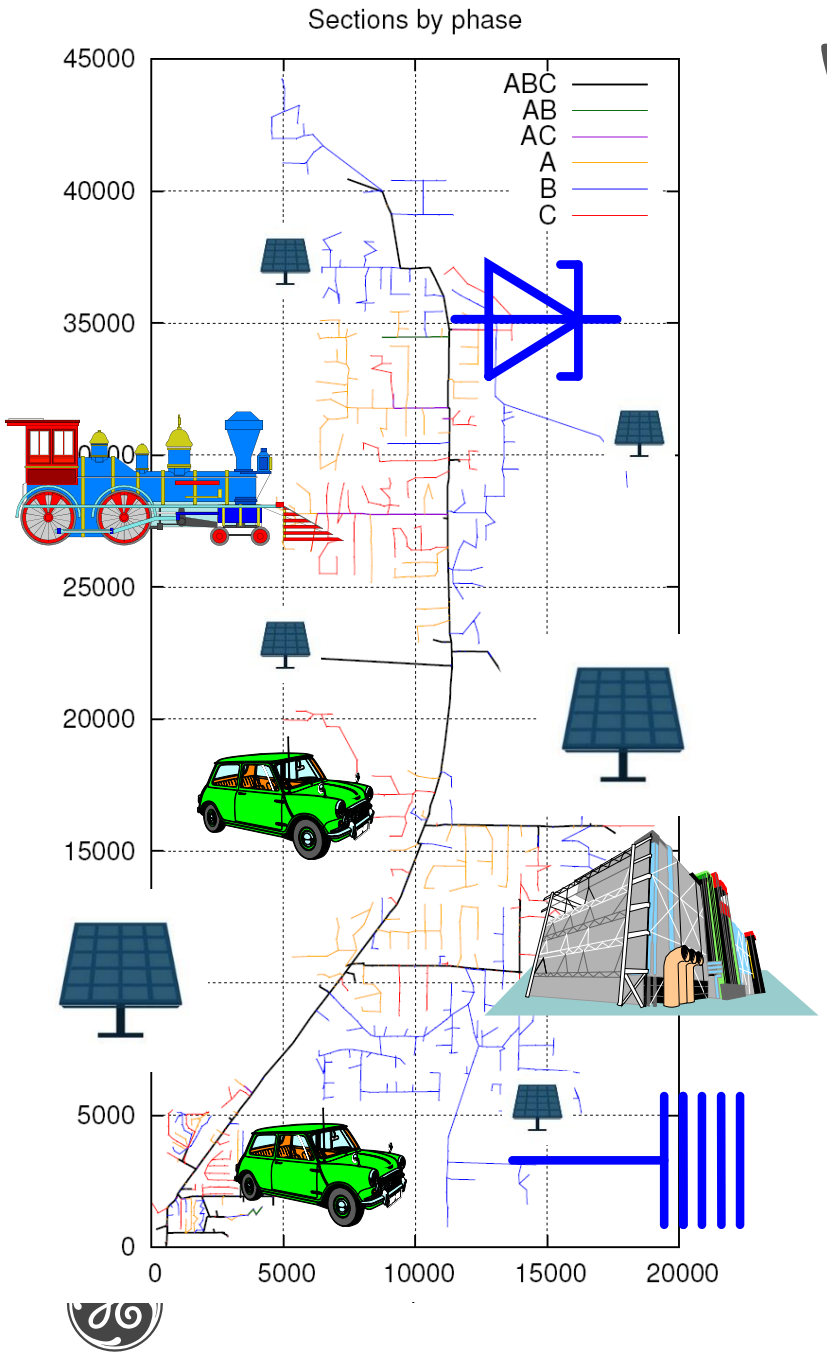


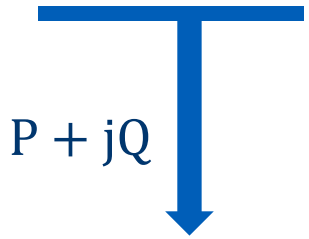
What happens in an ESI world?

The "load" becomes an even more complex and active element

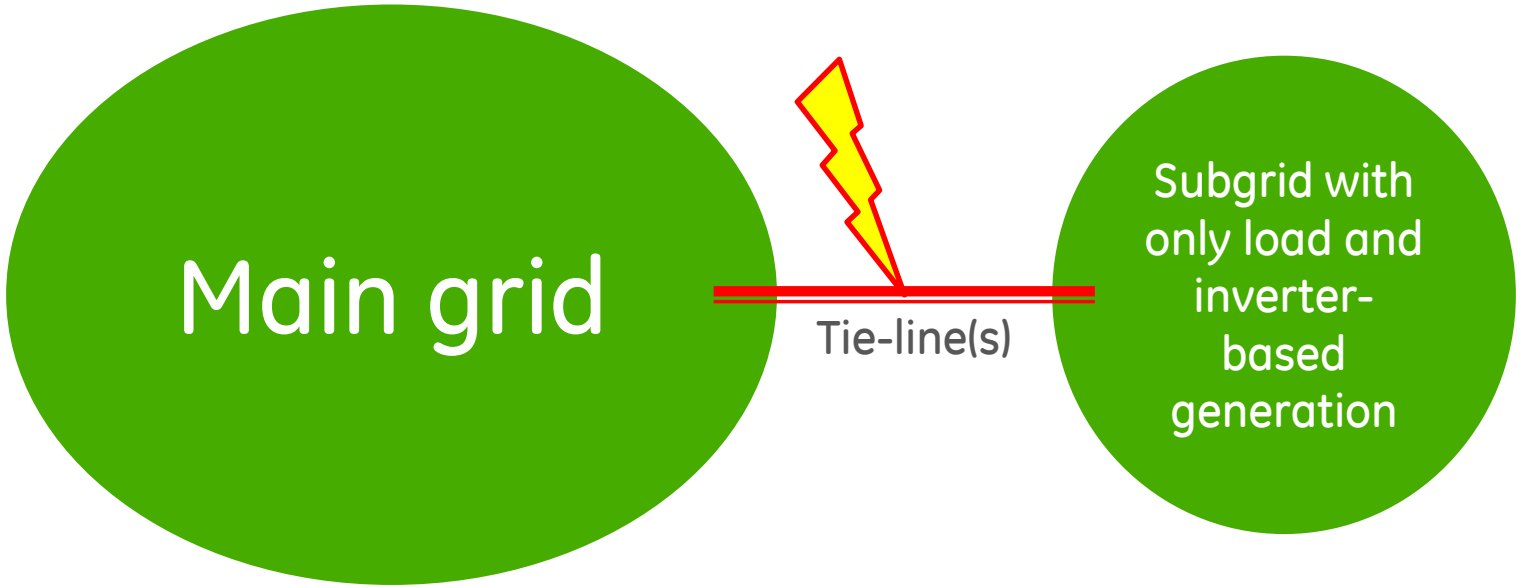
What might bite us?

- "Prosumer" fault ride-through
- Vehicle to Grid; Grid to Vehicle dynamics.
- Active thermal loads; new load dynamics
- Embedded energy storage.
- Load dynamics driven by weather or externalities (that we ignore today).

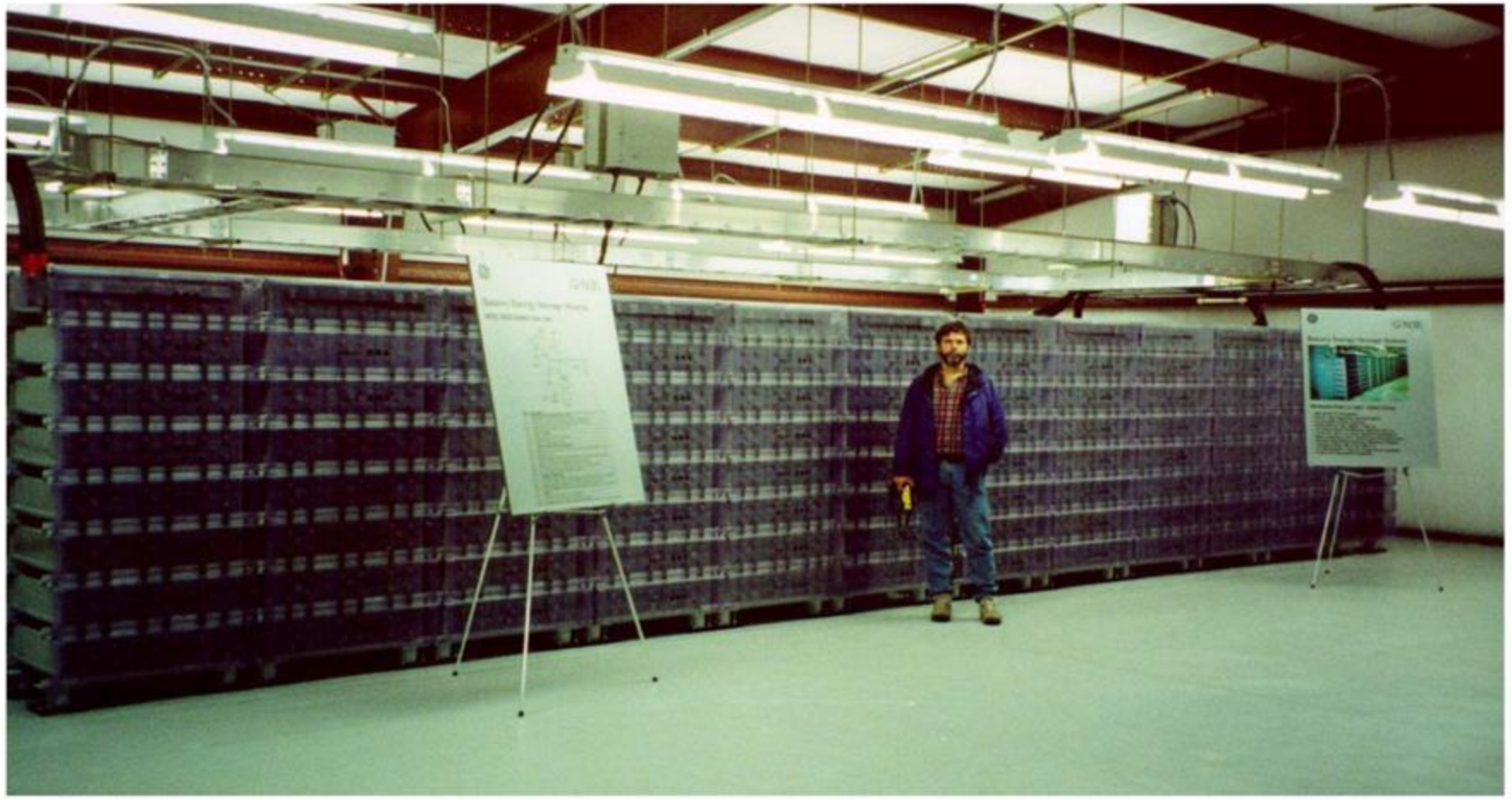
It seems inevitable that this simplification will be wildly inadequate



What happens when the grid breaks up? Consequences in an ESI World are even more dire.....



We'll need grid forming inverters…and a lot of other brains



Metlakatla 1MW/1.4MWhr BESS. C 1996

Take aways

The Grid and ESI future is only as reliable as it is stable

- Reliability must be and can be as good or better, with well designed systems.
- Flexibility, flexibility, flexibility
- Transmission is (still) needed.

System Dynamics are already complex, and getting more so.

- Understanding and tools must evolve
- ESI brings a whole new layer of complexity and opportunity

Using the actual power system as a simulator is uneconomic and irresponsible

- We've got research to do, and we'd better get to it!

Thanks…

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Source: GE Power Marketing, GE Energy Consulting