100% Clean Energy and Distributed Energy Resources

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WIEB/WIRAB Webinar

May 20, 2020

Webinar Outline

- April 15 – Resource Adequacy – long-term reliability
- April 22 – System Balancing – medium-term reliability
- April 29 – System Stability part 1 – short-term reliability
- May 6 – System Stability part 2 – short-term reliability
- May 20 – 100% Clean Energy and Distributed Energy Resources

Acronyms/definitions

- BA – balancing authority
- CCS – carbon capture and storage
- DA – day-ahead
- DER – distributed energy resources
- DG – distributed generation
- DR – demand response
- DS – distributed storage
- DSO – distribution system operator
- GFM – grid-forming (adjective). E.g. Grid-forming inverter = GFM Inverter
- IBR – inverter-based resources
- LOLE – loss of load expectation
- NWA – non-wires alternatives
- Power-to-X is the synthesis of hydrogen or other fuels from electricity and chemical processes
- RT – real-time
- SCR – short circuit ratio is a metric we use to assess grid strength
- V2G – vehicle to grid
- VER – variable energy resources

Today's webinar

- Builds on everything we learned in the last several weeks on grid reliability
- We'll assume we use all those mitigation options to manage variable and inverter-based resources
- And focus on the challenges that are left in getting to 100% clean energy and high penetrations of DERs
- What do we know? What don't we know?
- What's easier? What's harder?
- Much of this is educated speculation on the future. There are many pathways and we don't have a crystal ball, so please take our speculation with a grain of salt…

The key takeaways of this talk

We can do 100% clean energy with what we know today, but it would probably be very expensive, so the challenge is how to do this at a reasonable cost

- Two key challenges that require R&D:
  - Meeting resource adequacy during multiple days-in-a-row of low wind/solar/hydro resources especially during some seasons
  - Maintaining grid stability at 100% instantaneous penetration of inverter-based resources (IBRs) across an interconnection
- Two key challenges that require policy/regulatory support:
  - Transmission is the great enabler.
  - Demand flexibility is the low hanging fruit, especially if we can provide price signals that reflect costs

High penetrations of distributed energy resources (DERs) have different challenges

- Control, communication and automation infrastructure will be needed to enable this future
- A new operational paradigm, with the market to support it, will be necessary – this may be the biggest paradigm shift
- Adapting protection for high inverter-based DG may be a significant effort

100% Clean Energy

Reducing carbon in the electricity and other energy sectors

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You can easily operate a grid with 100% renewables… if you are Iceland

Most regions will depend on high amounts of wind and solar (variable and inverter-based)

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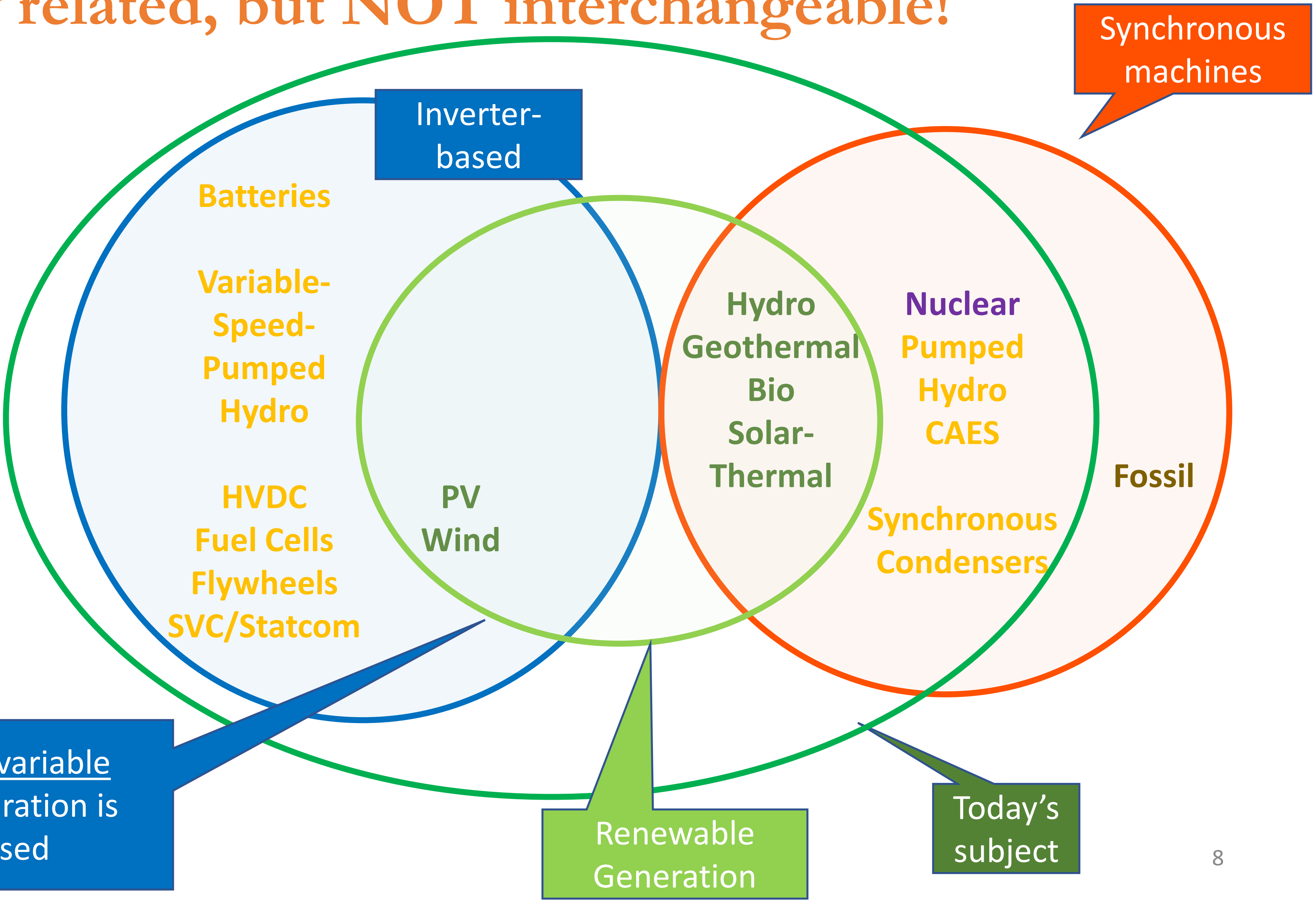
Slide from: D. Lew, GE Energy Consulting, 2018

100% Renewables vs. 100% Inverters

Closely related, but NOT interchangeable!

- *Some slices:*
- Synchronous vs Converter-based
- Renewable Generation vs "Enabler" vs Fossil vs Nuclear



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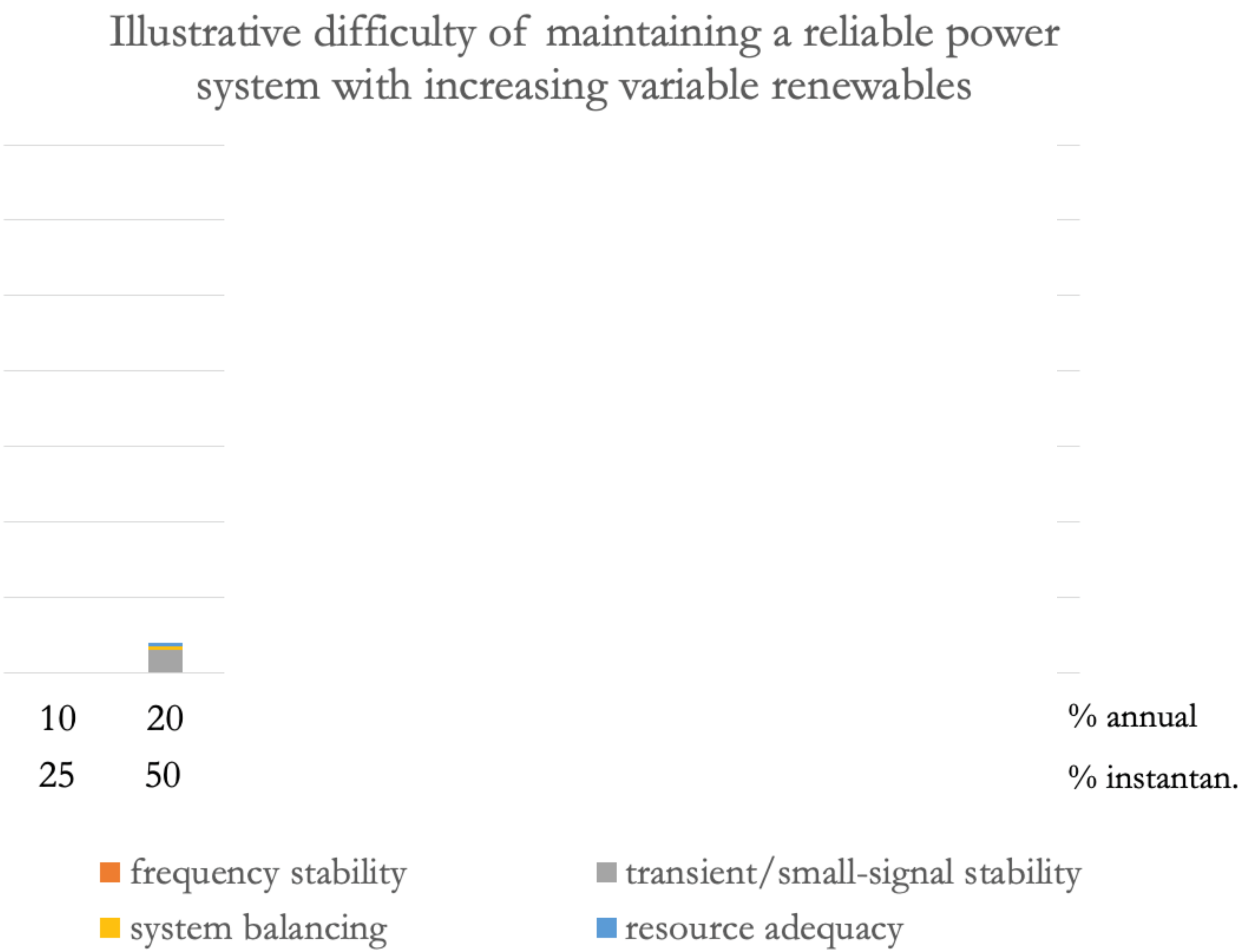
What does 100% clean energy mean?

- Means a lot of things to different people.
- Here we are examining 100% clean electricity all the time, with a focus on high levels of wind/PV, and with 100% inverter-based resource instantaneous penetration at some times across BAs or interconnections.
- Do you include bio-based fuels, carbon capture and sequestration, modular nuclear? We're not excluding anything today but we are focusing on what we think is promising.
- You can question whether the goal is economically sound or whether it gets at carbon reductions in the best way. We don't do that here, but rather examine implications of a grid that is served 100% by clean electricity.

Reliability challenges



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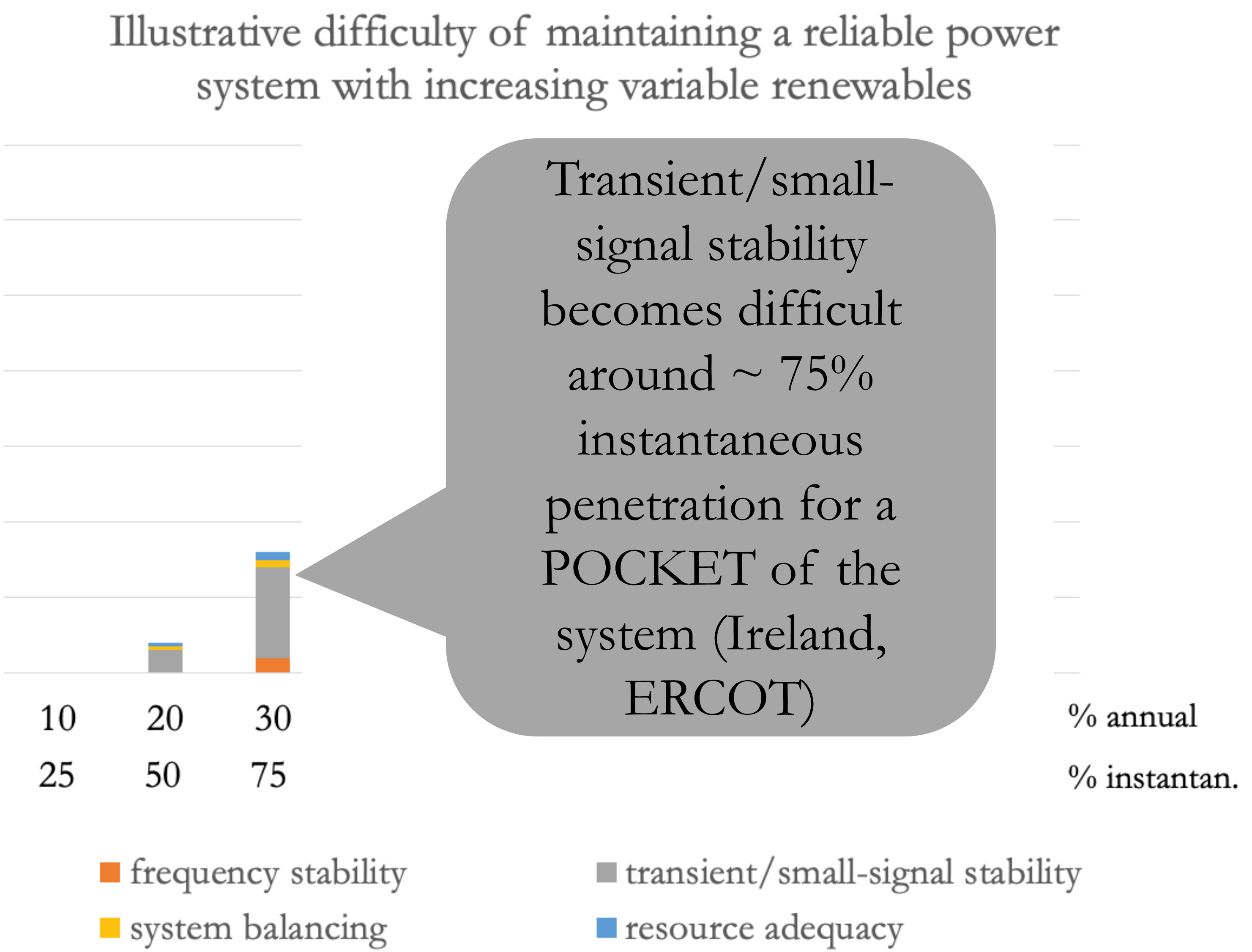
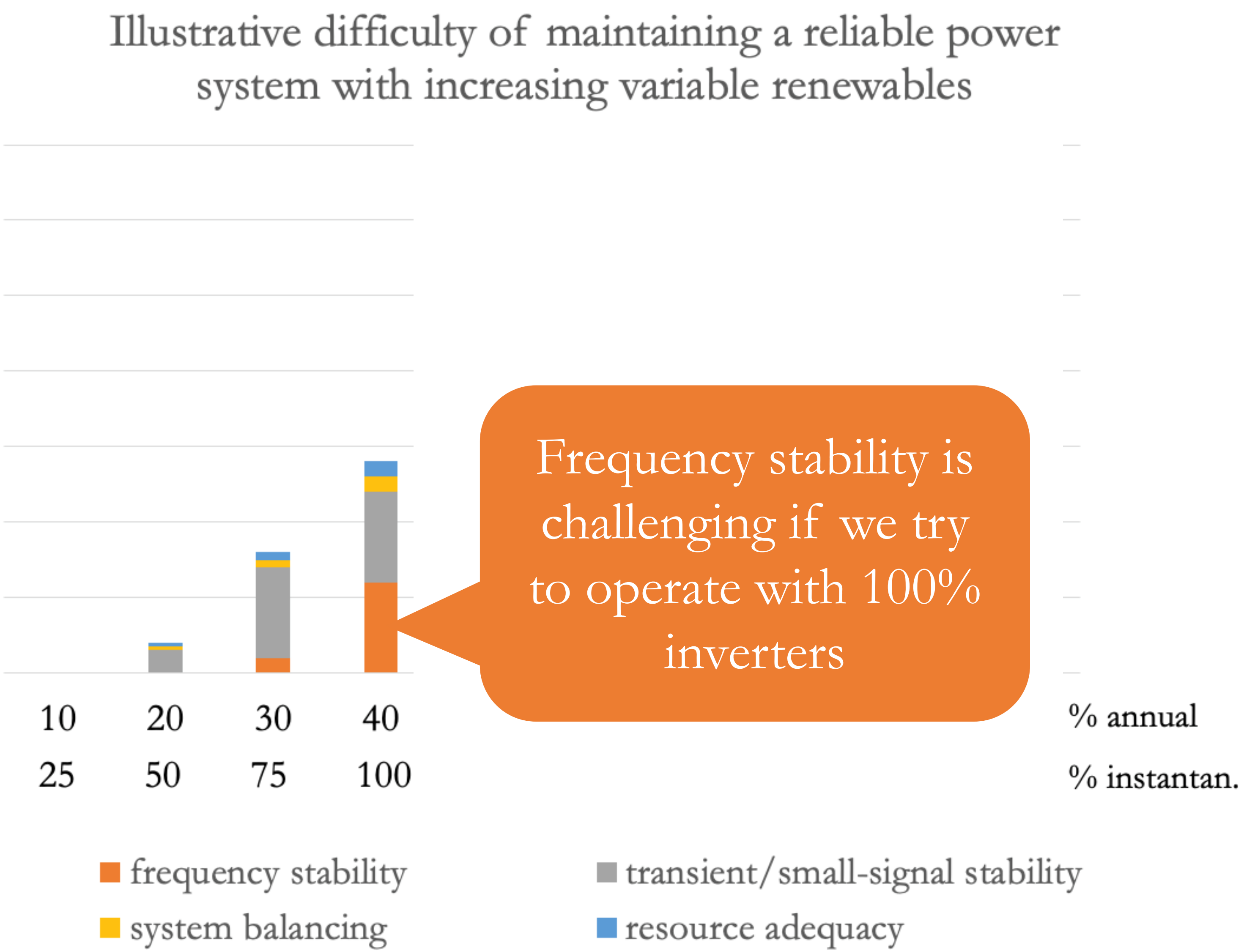
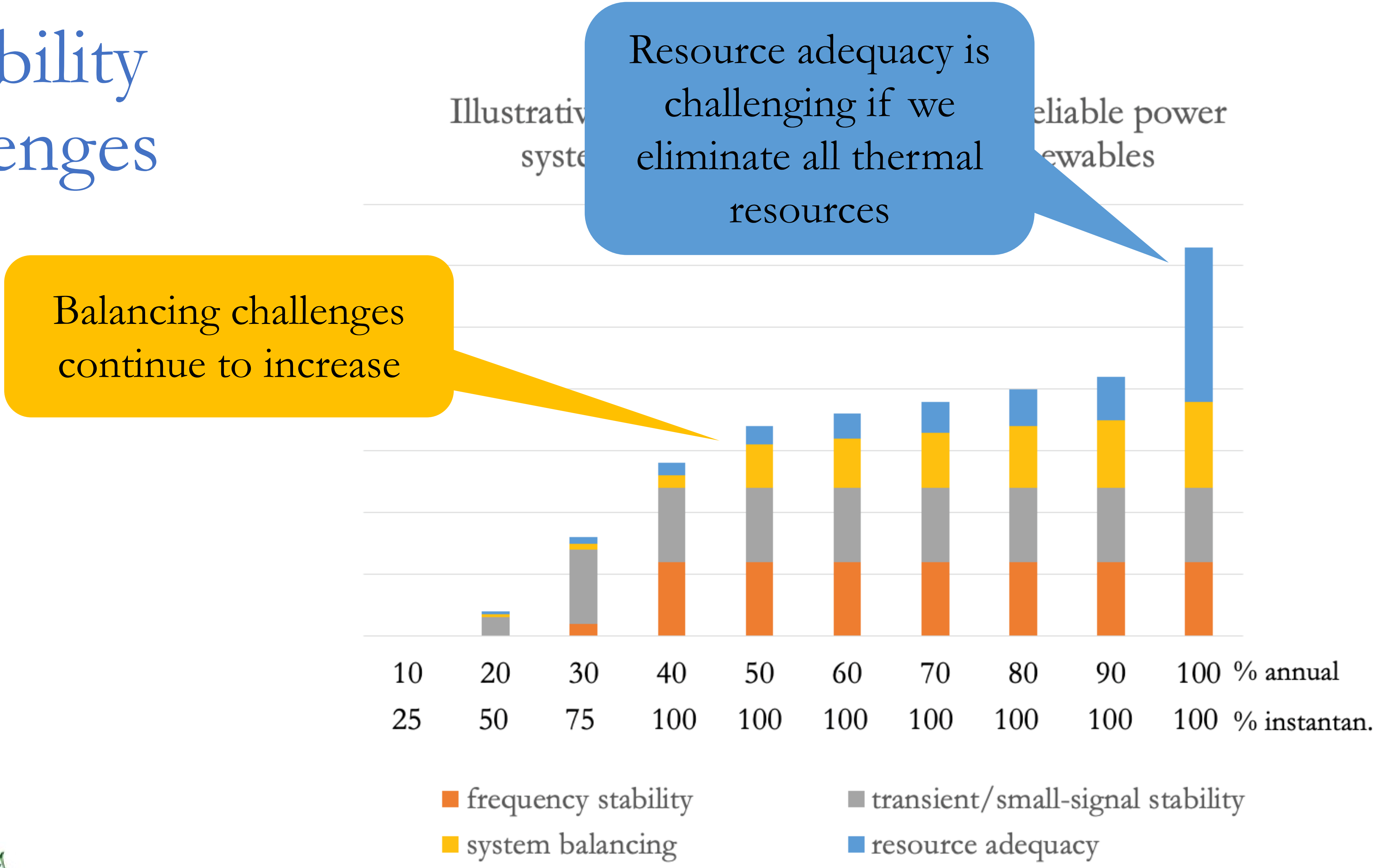
Reliability challenges



Reliability challenges



Reliability challenges



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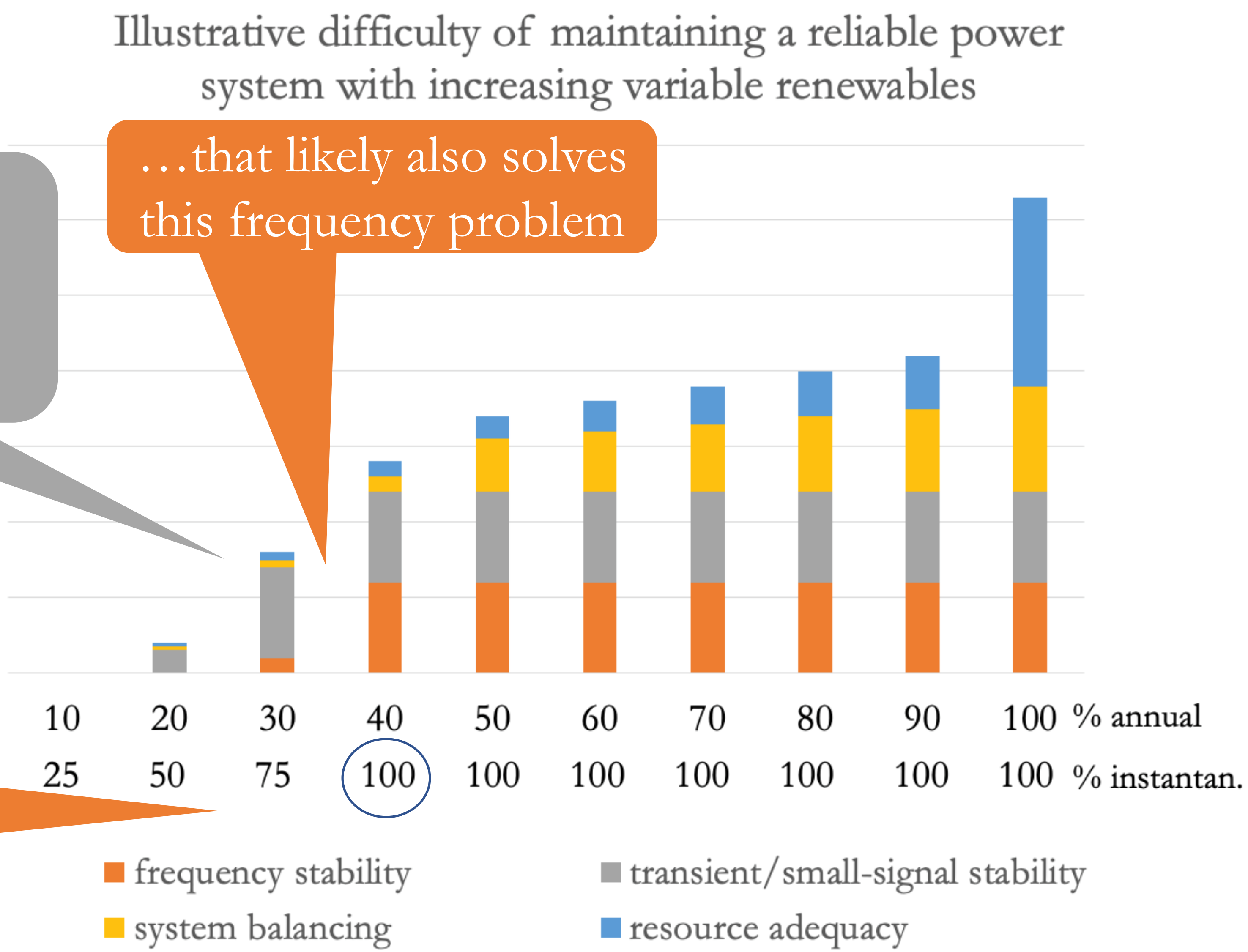
Reliability challenges

However, if we can solve the TS/SS problem…

…that likely also solves this frequency problem

If we can operate at 100% inverters, we should be fine as renewables increase beyond this



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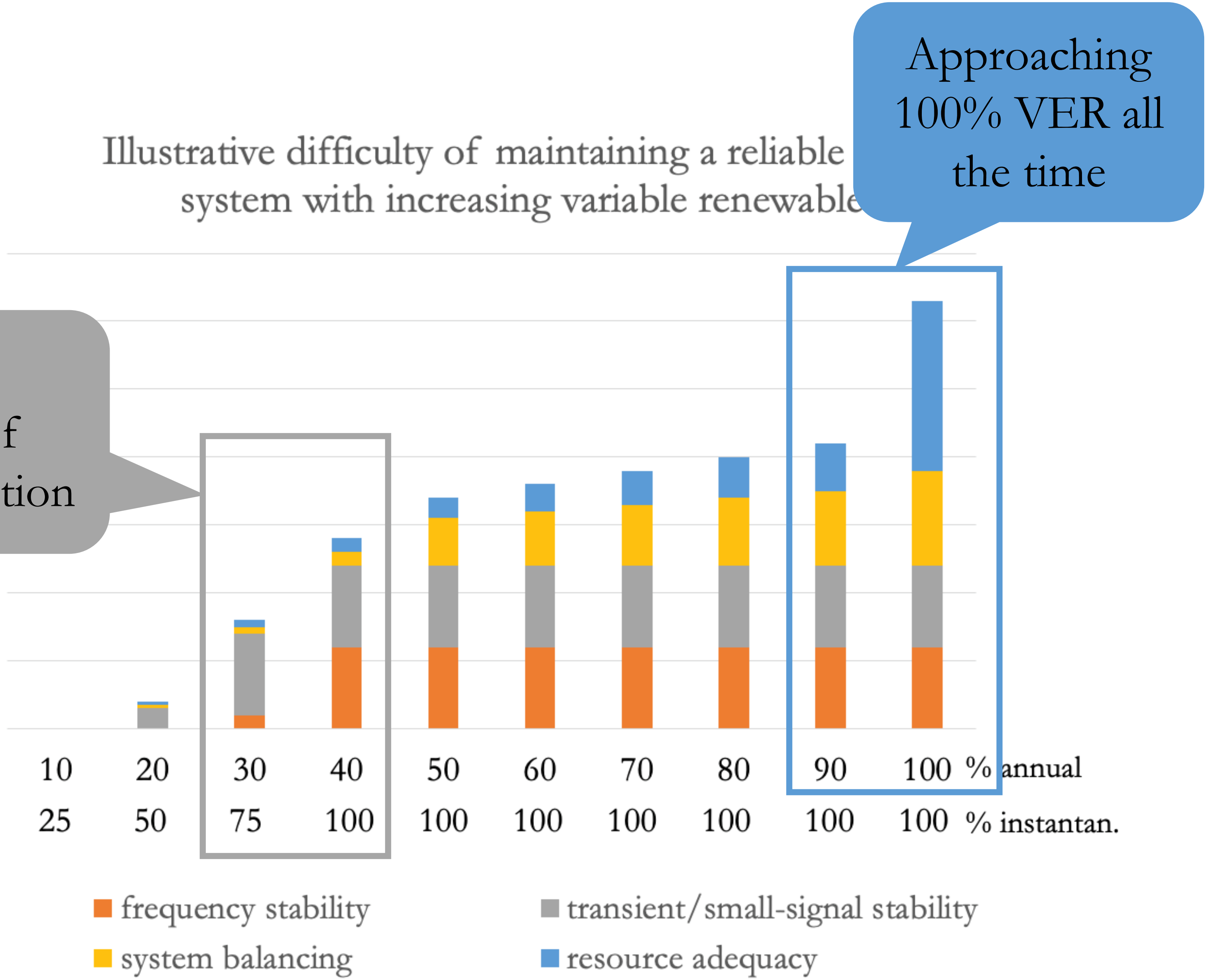
Two major inflection points



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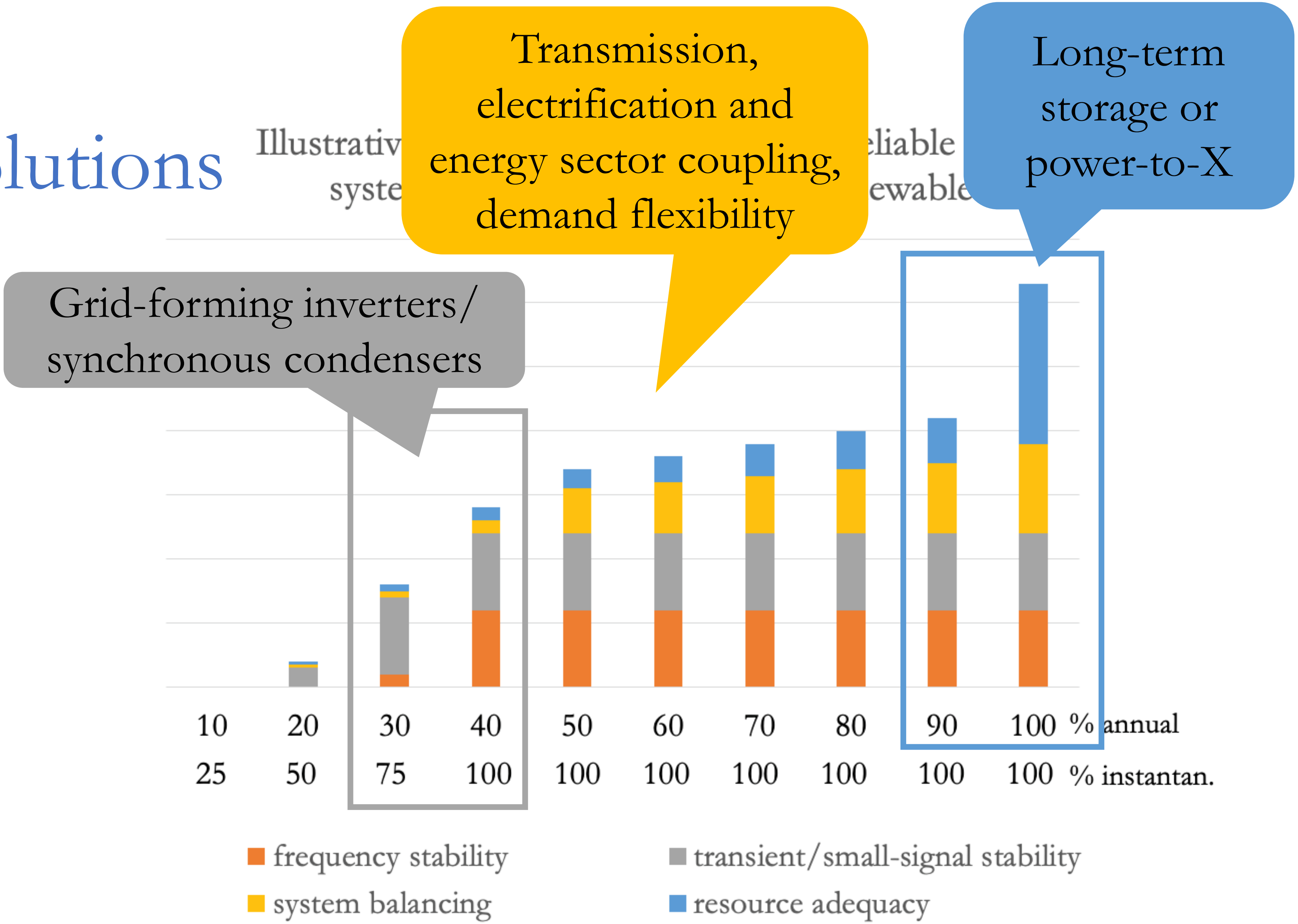
Potential solutions



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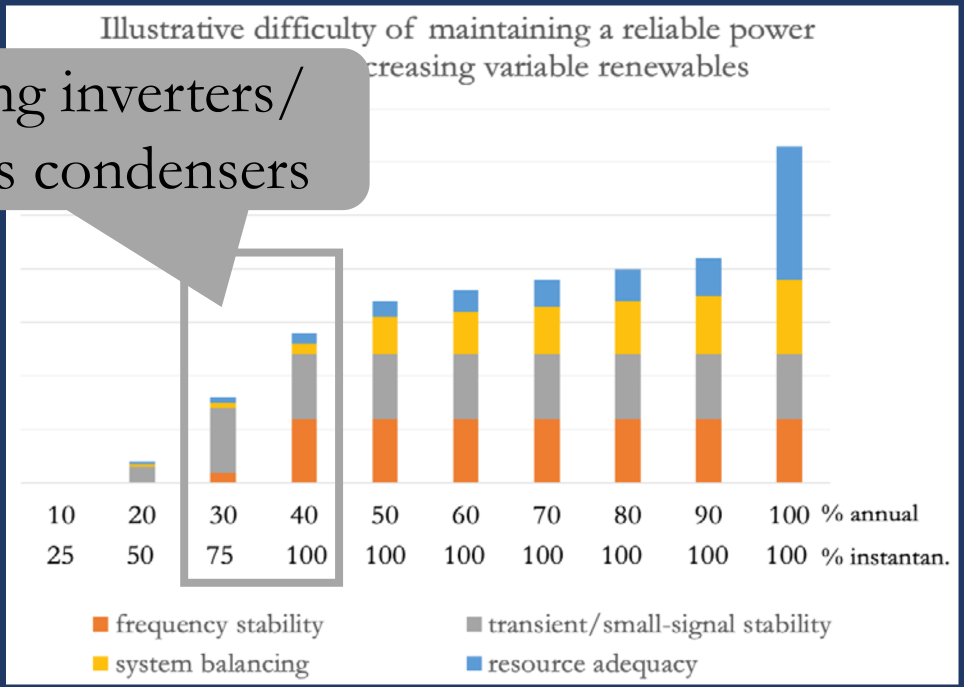
Grid-forming inverters/ synchronous condensers



100%: System Stability

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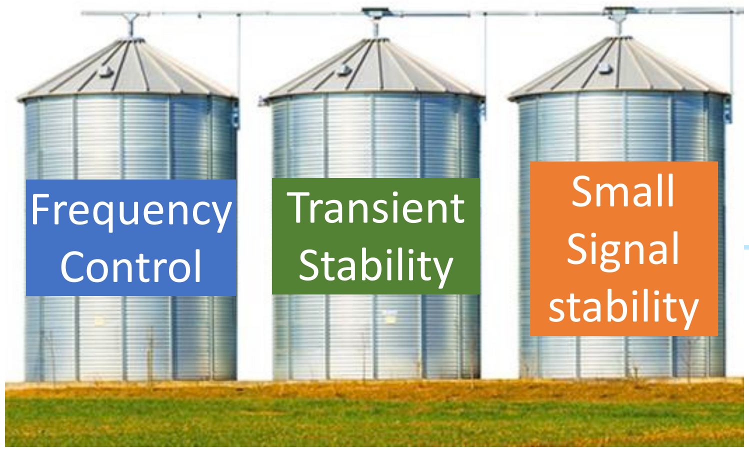
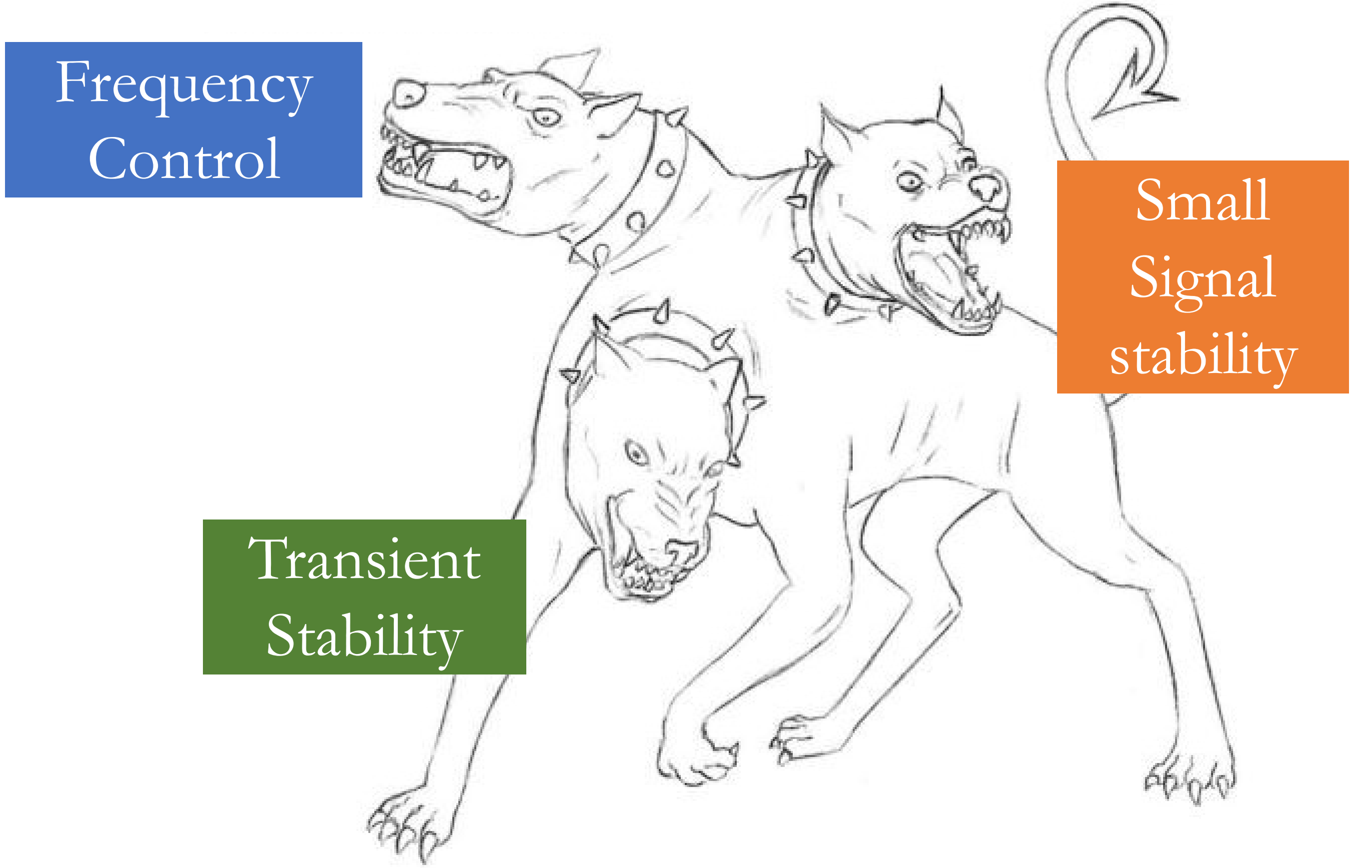
Stability has multiple faces, but it's the same beast



- Systems aren't secure unless they are stable
- All 3 types of stability constraints must be satisfied
- Degree to which each type is constraining varies with each system
- They aren't completely separate



Source: N. Miller, HickoryLedge. ESIG Reliability Working Group, 2019

Dog Image Source: Drawingforall.net

Why do we care about stability limits?

Economic Operation of the Bulk Power System tends to drive the exchange of power from low cost resources to higher cost areas (duh!)

When the exchange is limited by the transmission, there is a cost.

Physical limits come in 2 basic flavors:

1. Thermal Limits
2. Stability Limits

Most major transmission constraints in the Western Interconnection are stability limits.

Stability considerations set most "path limits" in WECC; i.e. the collective ability to transfer across a collection of transmission lines. (e.g. California – Oregon Interface: COI)

2 faces of stability limits on the way to 100%

Changes in the importance of stability limits because of changes in **location** of new renewable resources

- New resources aren't necessarily in the same location as the generation they displace
- Flow patterns change (with dispatch, season, time of day, etc.)
- Existing limits may become operationally/economically important

Changes in stability limits associated with the change to **inverter-based** resources

- Inverter-based resources (IBRs) behave differently
- Existing limits may increase or decrease
- The limits can have fundamentally different physical underpinnings
- IBRs are NOT a single, uniform, monolithic technology

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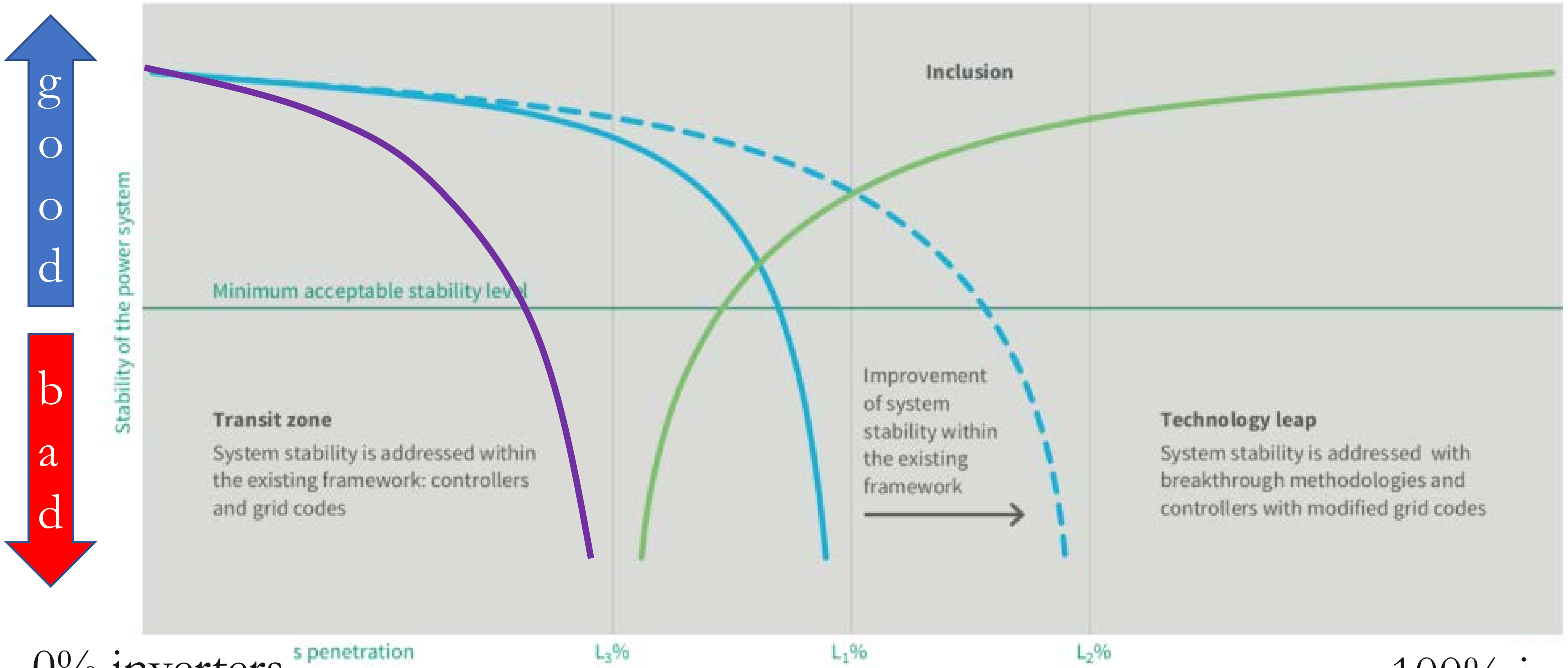
You can't get there from here without a technology leap



0% inverters

100% inverters

When we started the VER revolution, we were on the purple line. Today we are on the blue line and working towards the dashed blue curve. We are still working out what the green curve looks like and how we might get there.

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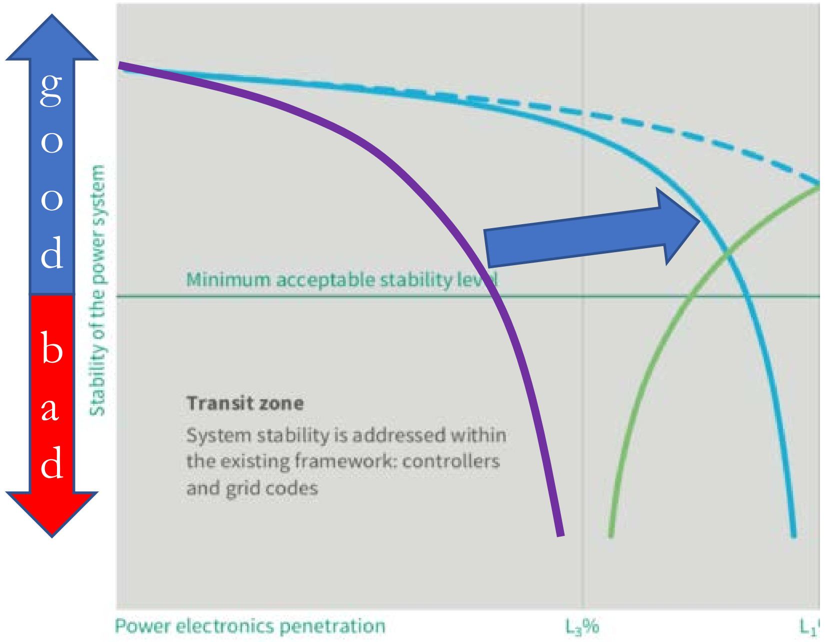
Slide: D. Lew and N. Miller, GE Energy Consulting 2017 with graphic from MIGRATE, 2016

Recap: How we got this far

- Grid Friendly Wind and Solar Plants.
  - Fault-ride through
  - Voltage regulation
  - Primary Frequency Response
  - Synthetic Inertia
- Superior Operations
  - Hugely improved forecasting (fewer surprises)
  - Situational awareness; avoided risks
  - Better PFR from existing generation
- Local and selective transmission
  - E.g. CREZ.



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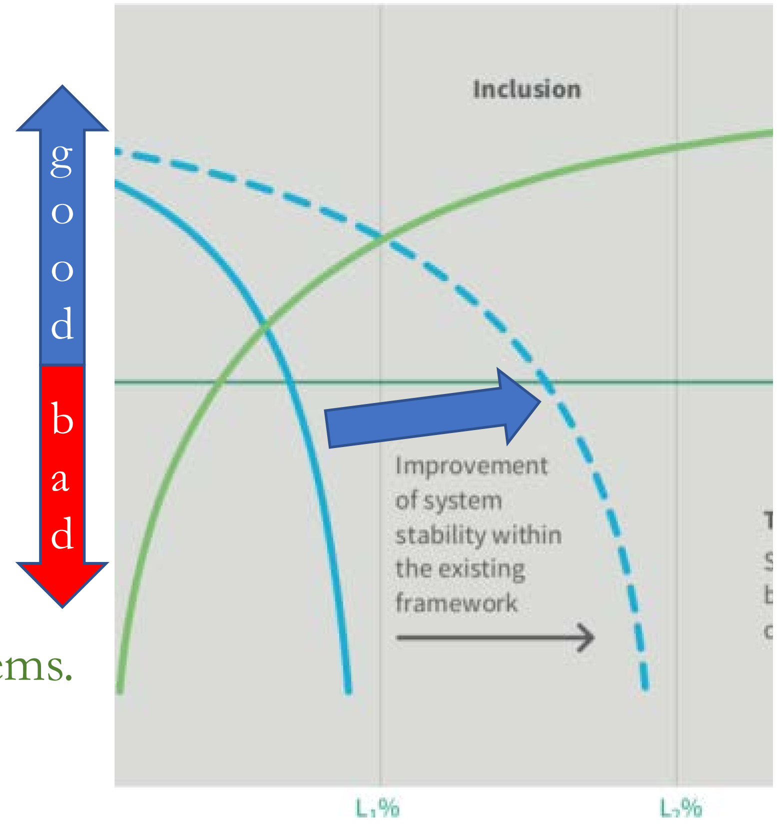
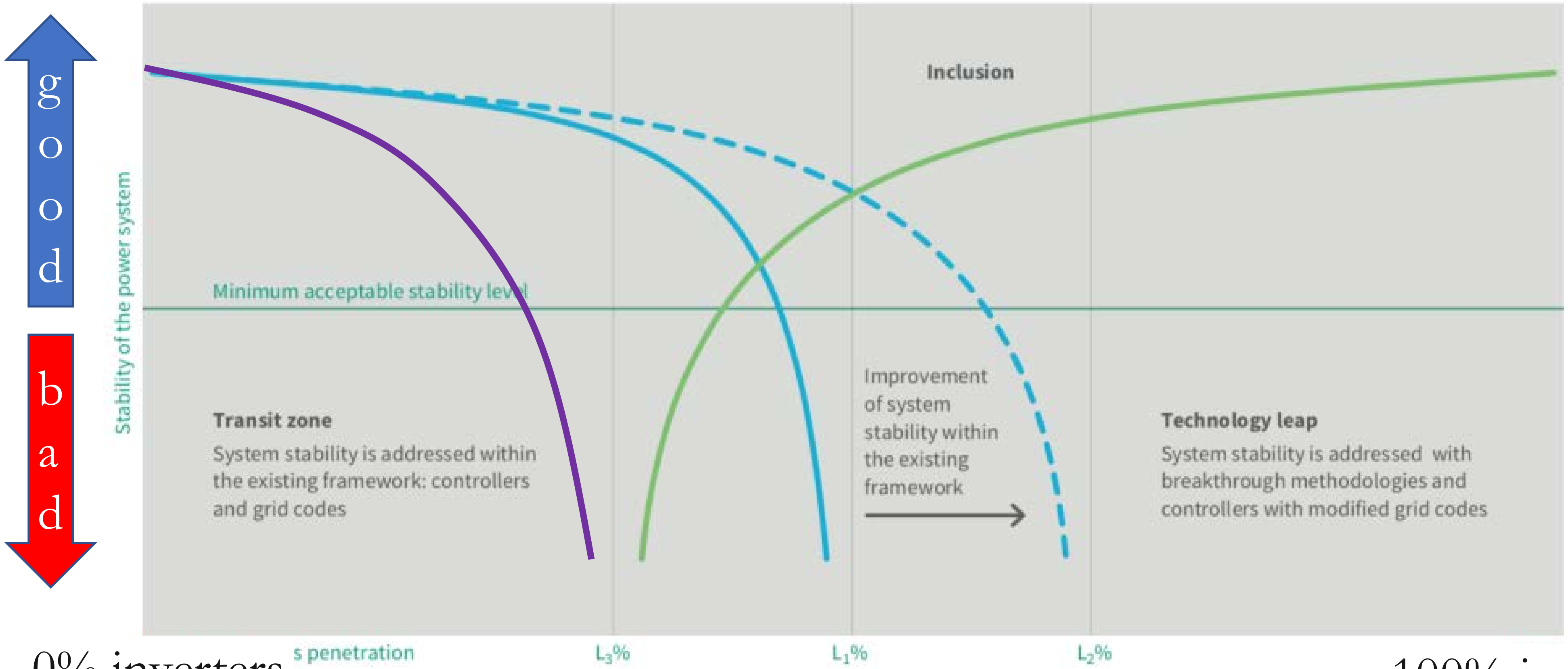
Pushing the limits out with Grid Following Inverters: today's toolbox

- Better inverter controls. ("more robust controls")
  - Grid following inverters have gotten spectacularly better for high penetration and weak grids in recent years. Tolerate weaker grids
  - This trend of improvement will continue, though a degree of diminishing return is expected.
- Additional transmission ("more wires").
  - New AC or DC lines
  - More power, additional circuits on existing right-of-way
- Synchronous condensers ("stiffer grid")
  - Improve all faces of weak grid. BUT, watch for new stability problems.
- Grid Enhancing Technologies ("use the wires better")
  - power flow control, dynamic line ratings, and topology optimization
  - Series and advanced compensation



Technology Leap:



0% inverters

100% inverters

Grid-Forming (GFM) Inverters are a necessary component

Slide: D. Lew and N. Miller, GE Energy Consulting 2017 with graphic from MIGRATE, 2016

Grid-following vs Grid-forming Inverters

- Grid following (Inverter follows): Inverters measure the grid voltage and frequency, and then try to inject the correct real and reactive power.
- Grid forming (Inverter leads): Inverters create a local voltage and frequency, and then try to move that voltage to cause the correct real and reactive power to flow into the system

A bit oversimplified, but close enough - the point is this behavior is fundamentally different.

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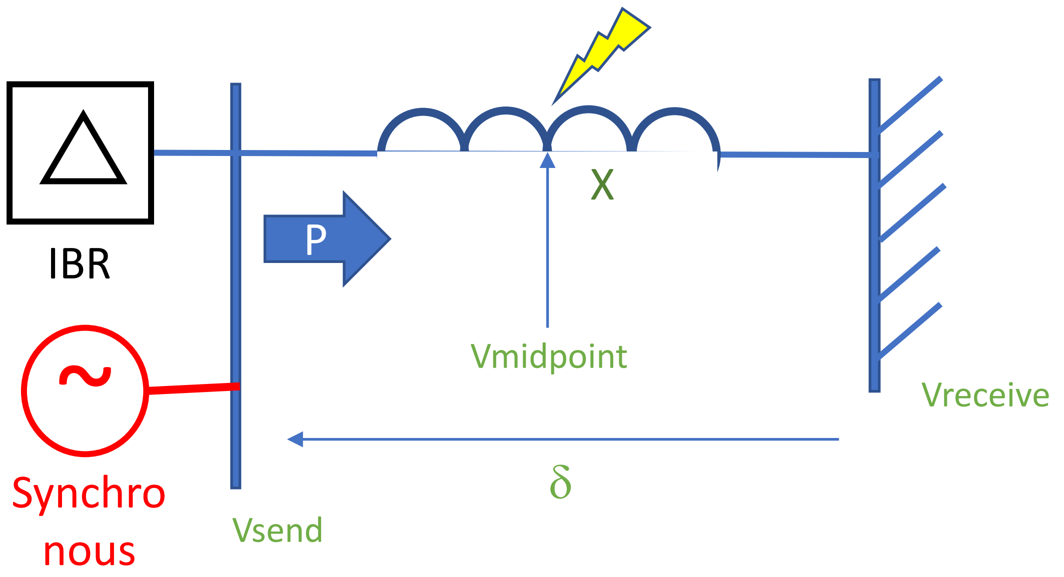
Getting the Power Out

- Wind (especially) and Solar PV (sometimes) are developed relatively remote from load centers.
- Exporting large amounts of power has always presented stability problems
- The problems look different with inverter-based resources compared to synchronous machines



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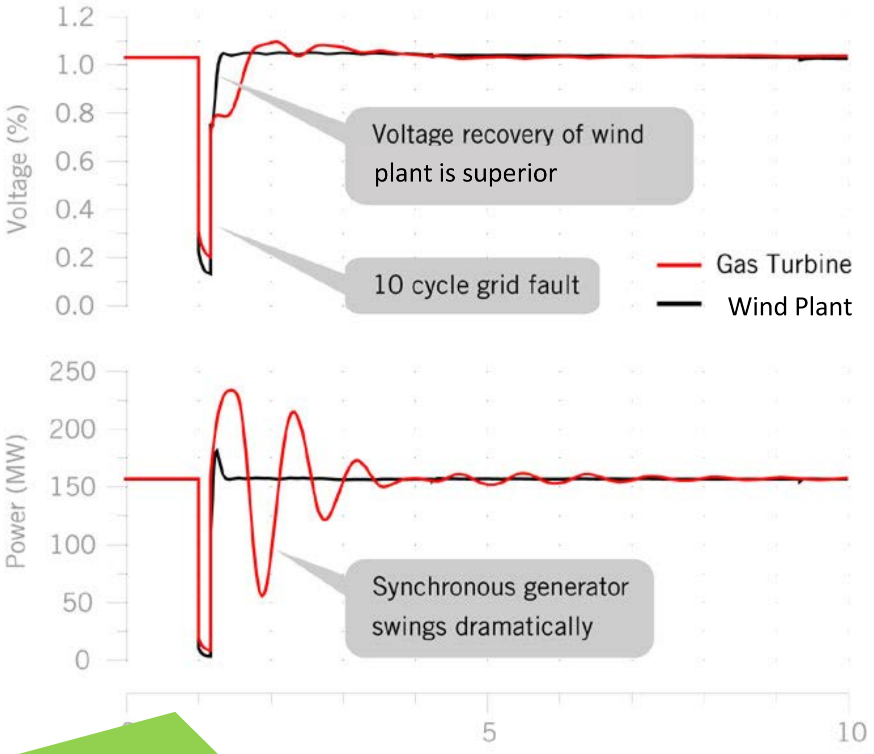
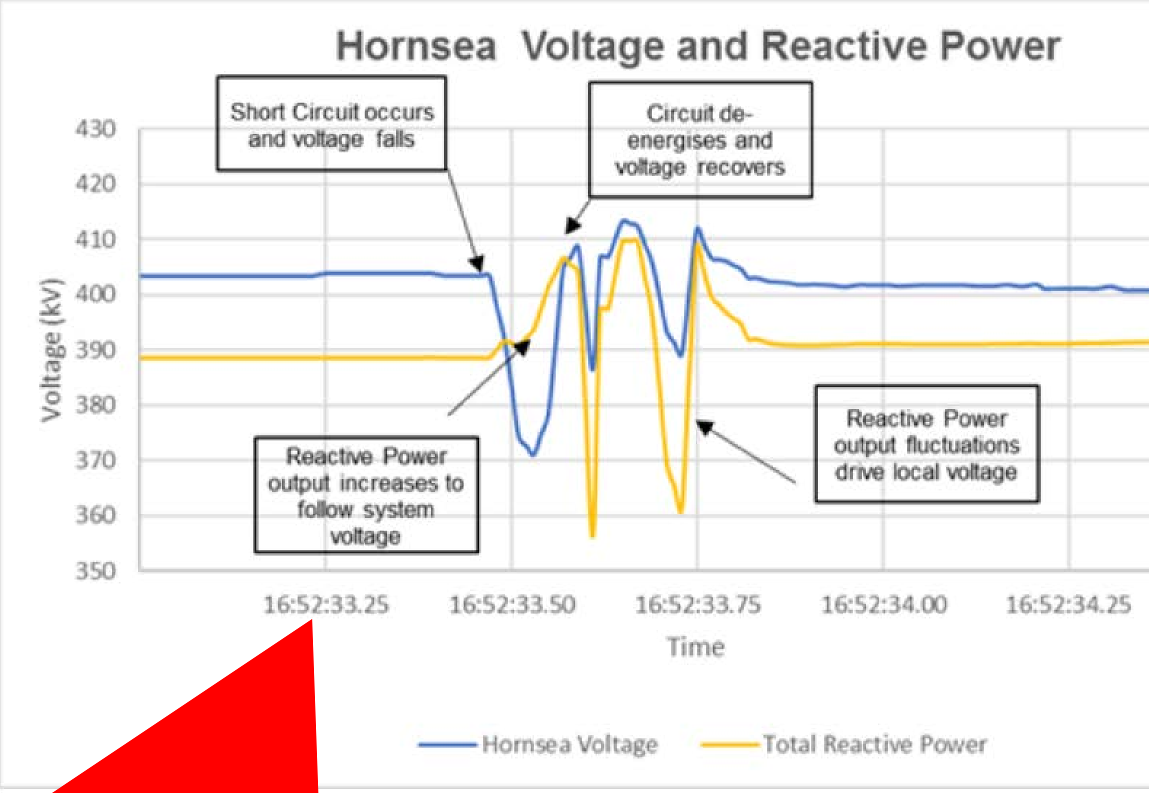
Today's Wind and PV plants are more stable than conventional synchronous generators… But weak grid imposes limits on them, too



Good news: IBR more stable

Push harder



Bad news: IBR experiences weak grid instability (fast and ugly)

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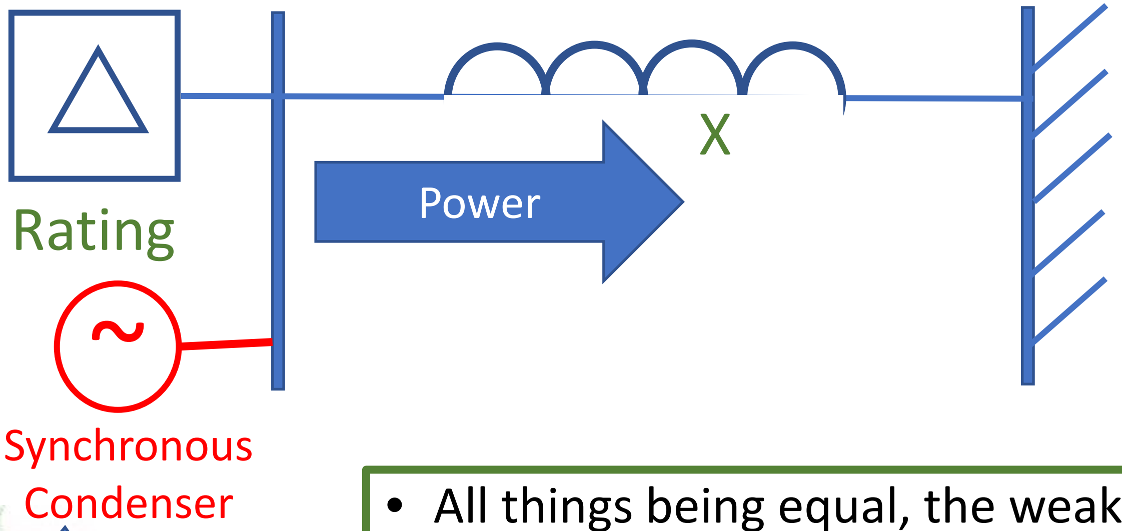
Source: GE Energy Consulting c.2005;

Source: National Grid ESO LFDD 09/08/2019 Incident Report
https://www.ofgem.gov.uk/system/files/docs/2019/09/eso_technical_report_-_appendices_-_final.pdf

Grid Strength & The Simple Export Problem

A few fundamentals:

1. Grid gets weaker with distance
2. Grid gets stronger with more transmission; higher voltage ratings
3. “weak” is relative:
4. If the devices are big, i.e. “rating” is large, relative to the strength, the grid is weak
5. If the grid is too weak, grid-following inverters don’t work properly
6. **Adding synchronous condensers in the electrical vicinity of the IBRs improves the grid strength – reducing the risk of weak grid control instability**



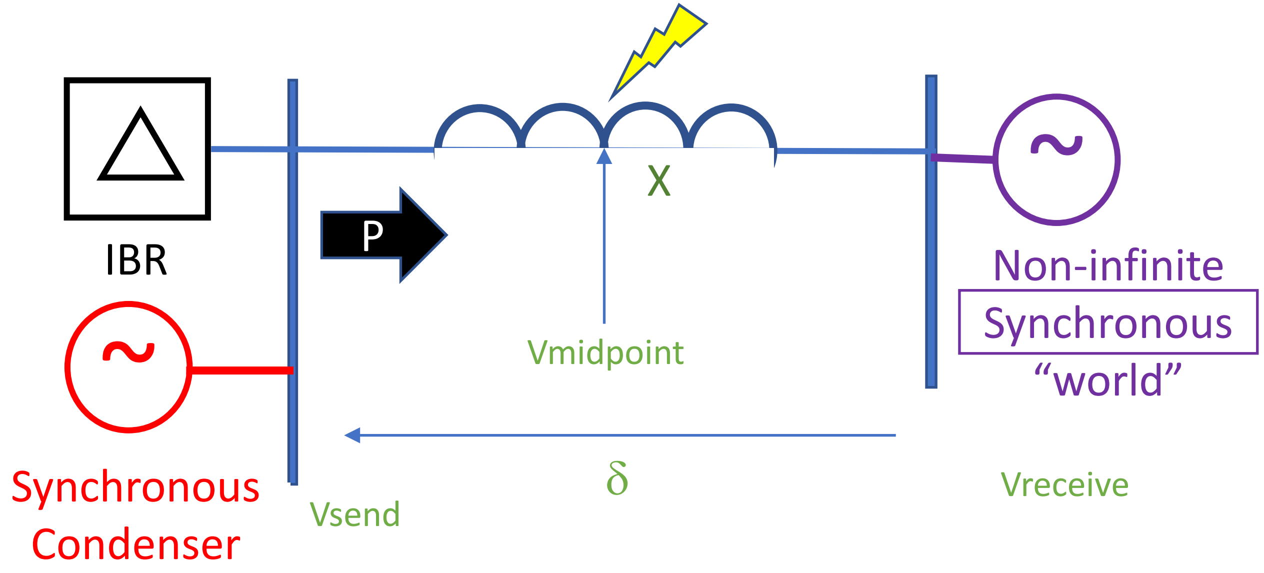
Woohoo! A simple, proven technology, that is commercially available and not stupid expensive. What’s not to like?

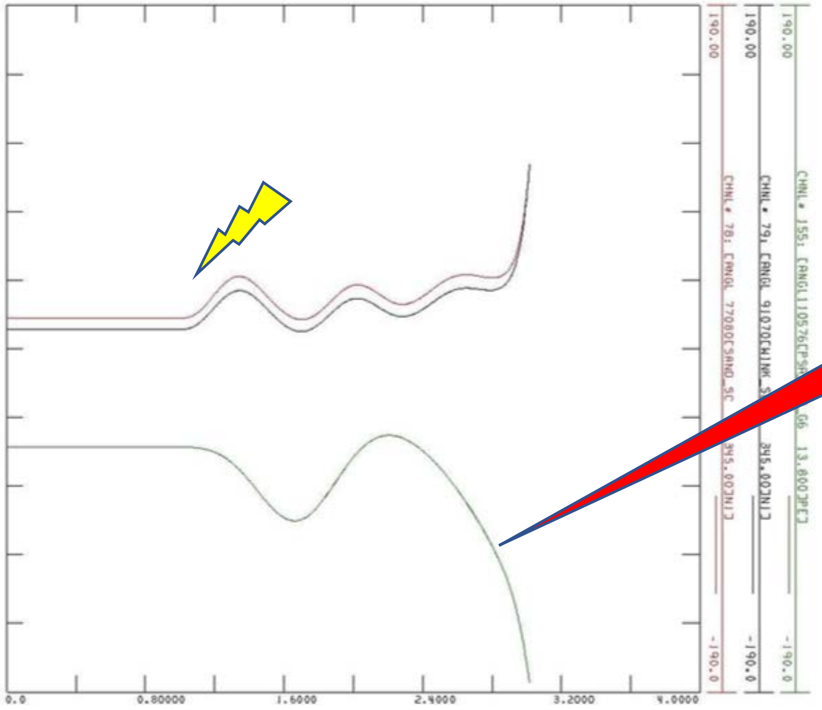
- All things being equal, the weaker the grid, the harder it is to stay stable.
- All things are never equal.

Stability – when we add a synchronous condenser for weak grid, we introduce a different stability risk

When there's a disturbance, IBR follows, if it can, keeping P relatively steady

But the condenser is anchored to its inertia. It gets left behind!





If pushed too hard, it breaks loose

This is a case where inertia is not helpful.

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Graphics: ERCOT, Dynamic Stability Assessment of High Penetration of Renewable Generation in the ERCOT Grid Version 1.0, ERCOT, 2018

Then, how about using Grid-forming (GFM) technology?

- By "creating" its own voltage, GFM inverters **should** remove (or reduce) the weak grid driven need for the synchronous condenser **at the exporting end**.
- This reduces the exposure to the condenser transient stability risk just outlined.
- We could make the GFM just look like a synchronous machine, but we'd give up the big stability benefit of IBRs
- GFM control is much more flexible, and it **should** be possible to keep or improve on the stability benefit we already get with grid-following IBR.
- If the control <u>does not</u> mimic the synchronous machines, the power swing **could be designed** to be less severe.
- The transient problem is not eliminated, but might be eased.

The middle of the span needs support

This is not a new problem for WECC

If you don't support the middle, the system is unstable, no matter how healthy the sending and receiving ends are

Synchronous condensers were used decades ago to solve support problems

They fell out of favor for new inverter-based compensation, like SVCs and STATCOM

But, because of the weak grid issues just outlined, we need to consider them again for this function

There are Pros and Cons to each:

Synchronous Condensers

+ Help the weak grid stability problem
+ Soft limits on Q support
+ Adds inertia (especially with flywheels)

- Slower than SVC/STATCOM
- Inertia related stability issues created
- More physical constraints on control options

SVC/STATCOM

+ Fast, agile, customizable
+ Lower losses (possibly)
+ No inertia related stability problems introduced

- Hard Q limits
- Exacerbate weak grid problem
- Don't contribute to inertia

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Getting the Power Out: Observations on Condensers and GFM Inverters

There are two related but distinct stability concerns

(a) Low SCR/weak grid in vicinity of IBRs that are exporting power

(b) Poor support between export region and receiving region (the middle)

Synchronous Condensers

1. Help with (a), but should be less necessary or eliminated with GFM resources
2. Help with (b), but may have fewer advantages over SVC/STATCOM as GFM resources are deployed

The best solution may include both technologies

As always: we've got more homework to do!

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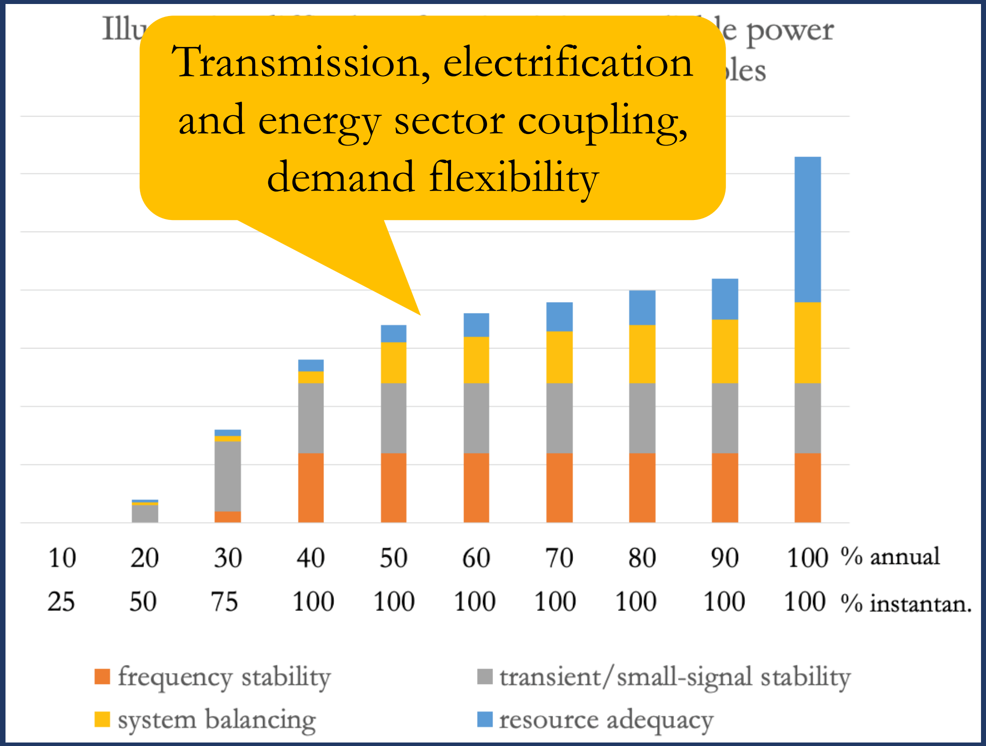
Grid Forming Inverters: Action Check List

- There isn't a (single) "GFM" available.
    - OEMs and researchers making progress; Not all the technical issues resolved.
    - Yes, GFM can reasonably be expected to produce substantial benefits in some regards.
    - Yes, GFM performance can be worse than grid-following, especially if you're not careful.
    - No, we can't expect GFM to make all the grid problems go away
- There is every reason to expect good outcomes (excellent experience with grid-following supports this expectation)

- **What can regulators, policy makers, market designers do to help move things along?**
    - Don't panic. (don't hit the brakes!)
    - OEMs are not seeing enough demand for GFM to make the big investments – chicken-and-egg:
    - Promote policies, tariffs, interconnection rules, incentives, that will encourage R&D to commercialization faster.
    - More studies, more demonstrations, more lab work, more investment!

System stability: Towards 100%

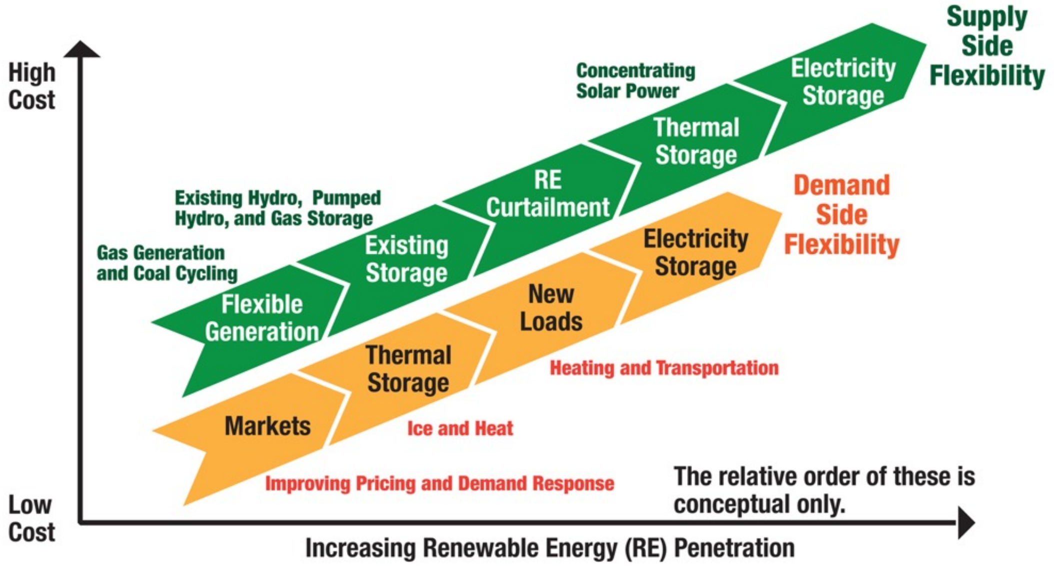
- What we know
  - Wind and solar need to provide frequency and voltage reliability services that can replace many provided by displaced synchronous generation
  - IBR deployment must recognize weak grid limitations
  - Build more transmission to alleviate weak grid issues
  - Synchronous condensers can maintain grid strength but also introduce other challenges
- Challenges
  - Even before you get to 100%, in pockets of high penetrations of IBR, transient and small signal stability can suffer
- Opportunities
  - Grid-forming inverters are a likely part of the solution portfolio
  - Use grid-enhancing transmission technologies to get the most out of existing and new circuits (and Right-of-Ways!)



100%: System balancing

We know how to find flexibility

- Transmission, larger markets, wider trading
- Faster trading, scheduling closer to real-time
- Forecasting
- Extract flexibility from variable resources – dispatch and ancillary services
- Extract flexibility from non-variable resources
- Storage of different durations; thermal and electricity
- Demand-side flexibility of different types



Source: US Dept of Energy Wind Program

Eventually there are diminishing returns from mitigation options

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Transmission is a key enabler

In addition to bringing resources to load:

- Smooths loads, resources, and enables resource diversity
- Reduces peak capacity needs
- Facilitates balancing (reduced curtailment or need for storage)
- Saves money!
- Mitigates weak grid issues
- Maximize use of existing transmission and right-of-ways (eg, grid enhancing technologies)

Transmission Enabled ½ of US Wind Capacity

~105 GW installed in US

Transmission plan	Wind Capacity Enabled (GW)
Tehachapi CA	4.5
Texas CREZ	14.5
MISO MVP	14
SPP Priority Projects, Balanced Portfolio	6
CO+ME+NV+PAC+BPA	10
Total	49

12

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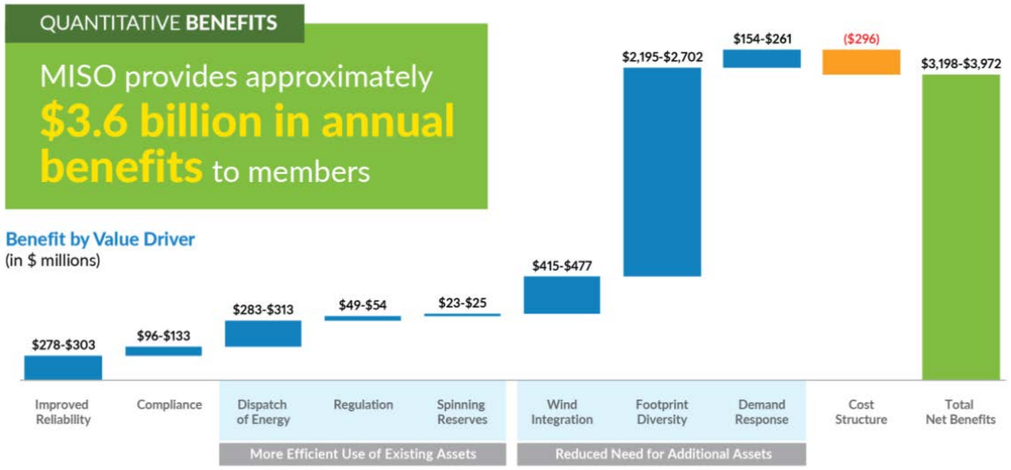

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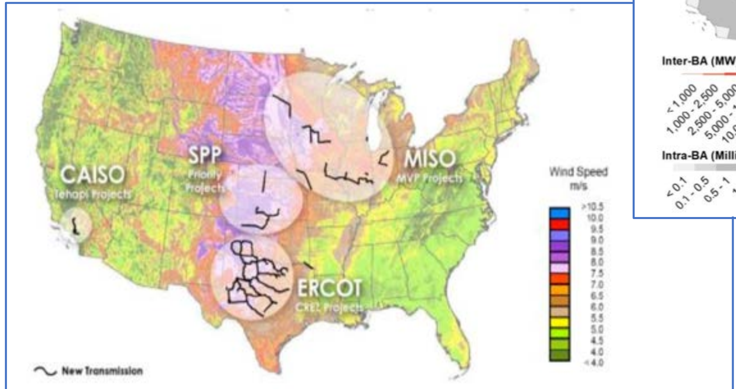
Graphics: Gramlich, "Transmission Planning for the Future," ESIG Spring workshop, Apr 2020; MISO, 2019

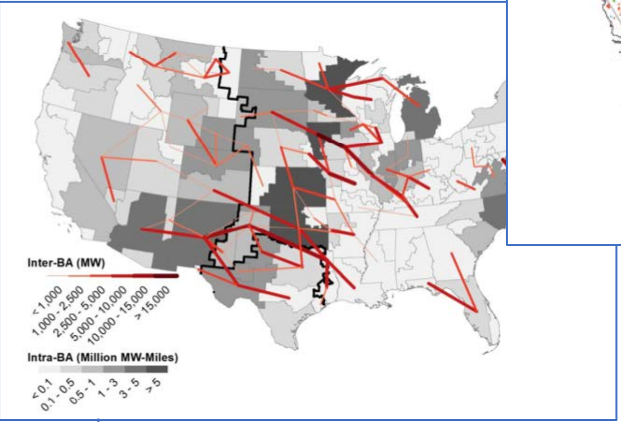
Stages of transmission needed

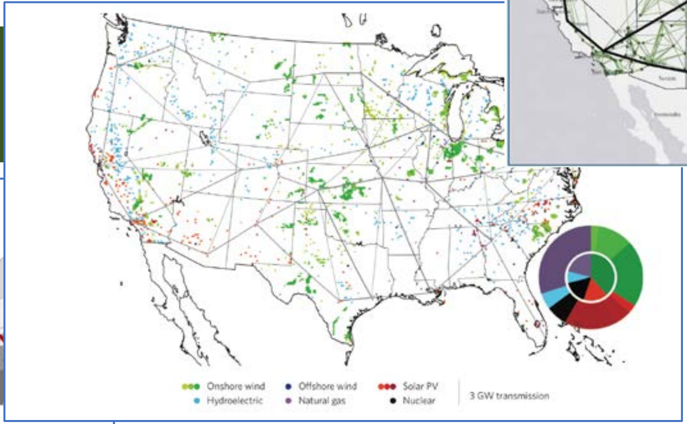
MW-miles of transmission

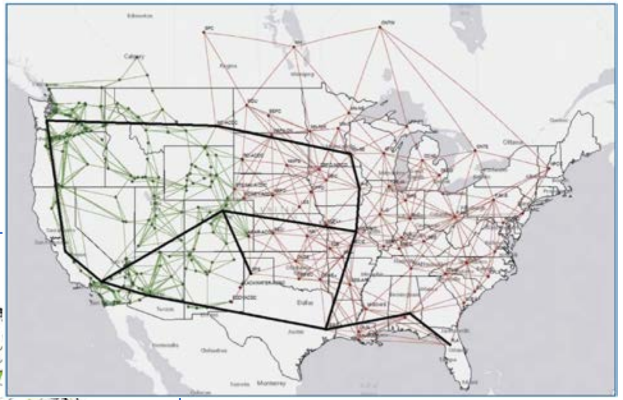
Transmission within a state or BA



Transmission between states or BAs







Transmission between interconnections

Increasing VER penetration

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Graphics: MacDonald, "Future cost-competititive electricity systems and their impact on US CO_2 emissions, Nature climate change Jan 25, 2016; Gramlich, "Transmission Planning for the Future," ESIG Spring workshop, Apr 2020; J. McCalley, "Wide-Area Planning of Electric Infrastructure, IEEE PES Magazine, Nov/Dec 2017

Flexibility in demand is the low hanging fruit

DERs unlock the power of electrification and some energy sector coupling

DERs are not one thing

- What kind of resource is it?
  - Distributed generation (DG)
  - Distributed storage (DS)
  - Demand response (DR) – flexibility in demand
- Who controls it?
  - Aggregator
  - Utility
  - Customer
- How is it deployed?
  - Pricing
  - Programs
  - Procurement

By high penetrations of DERs, we mean the level at which DERs influence commitment and dispatch, influence power flows on the bulk power system, and/or have significant instantaneous penetration across the BA

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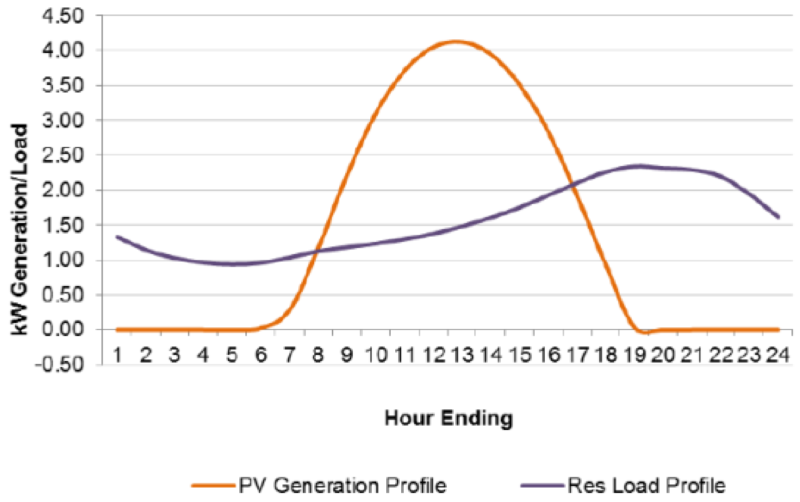
DG can impact system costs and reliability

- Impacts on the distribution system
  - Depends on DG profile compared to feeder loading
  - Depends on location (feeder characteristics, existing DG)
  - Depends on DG capabilities and functionalities
  - Impacts of IBR DG on protection
- Impacts on the bulk power system
  - Variability and uncertainty of wind and solar
  - Generation not aligned with demand
  - May lead to overbuilding of capacity
  - May lead to oversupply, but DG can't be easily curtailed
  - Typically provision of energy only (may not include capacity or ancillary services)
  - Operational reliability – visibility, controls and communications



Graphic: PG&E, Distribution Resources Plan Webinar, Aug. 3, 2015

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Mitigating impacts of high DG penetrations will require communications and control

We aren't getting the best value out of most of our DERs

Simultaneously gave customers choice and incorrect price signals

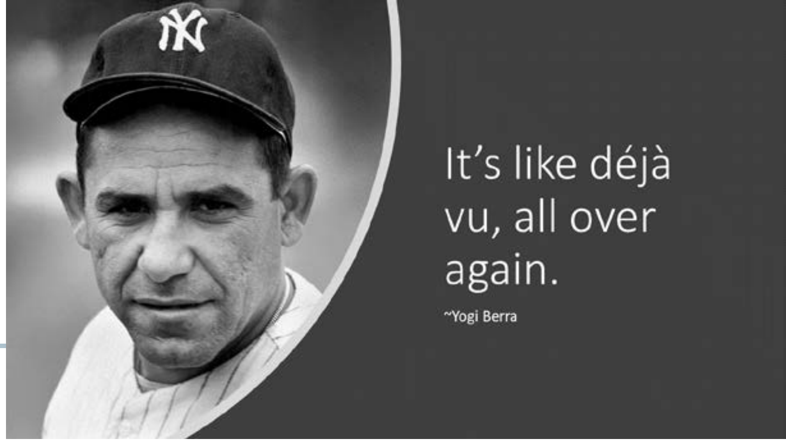
- Deployment is optimized on customer economics. Customer rates typically don't reflect utility cost structures.
- Results in host of issues on distribution system, bulk power system, economics, and equity.
- Can erode trust between public and the utility

Chasing problems from DERs rather than exploiting benefits of DERs

- Industry is reacting to DER issues on the distribution system, bulk power system and utility cost recovery
- Instead of "how can we get ahead of the issues", how about **"What do I need DERs for? What can they do cheaper, better, more efficiently than other resources?"**
- And use that to guide how to establish prices, programs, procurement and systems
- Eg., Defer distribution upgrades; demand-side flexibility to integrate VER; manage electrification to avoid increasing distribution capacity; meet peak demand

Where are we going?

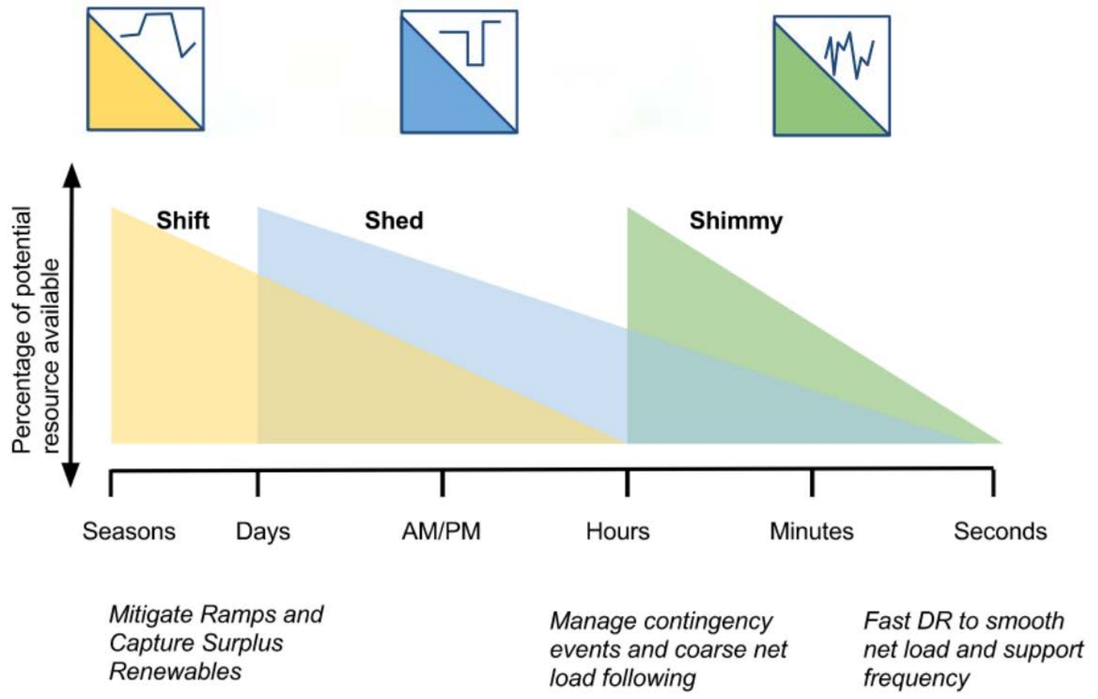
One vision for a high penetration DER future



- A dynamic, open "marketplace" where DERs are treated on a level playing field with centralized generators or infrastructure investments during the **planning** process
- DERs are treated on a level playing field with other resources when they are **compensated** for the services they provide to the system
- During **operations**, DERs are good citizens of the grid and provide essential reliability services when appropriate including ride-through, curtailment/down-dispatch, voltage regulation, frequency response. DERs respond to security-constrained economic dispatch like any other resource
- Just as we moved away from 'must-take' VER, we will move away from 'must-take' DG. Just as we required reliability services from VER, we'll **require essential reliability services from DG**.

Demand is not homogenous

- There is 'must-take' demand like your stove or lighting
- There is demand that has small amounts of thermal storage like HVAC or longer duration thermal storage like water heating/cooling – shimmy
- There is demand that is shiftable over the day like EV charging – shift
- There are prices at which customers may be willing to curtail even 'must-take' demand – shed
- Can model demand response like different types of generators



Graphic: Alstone, P, "2025 California DR Potential Study," Oct 9, 2017

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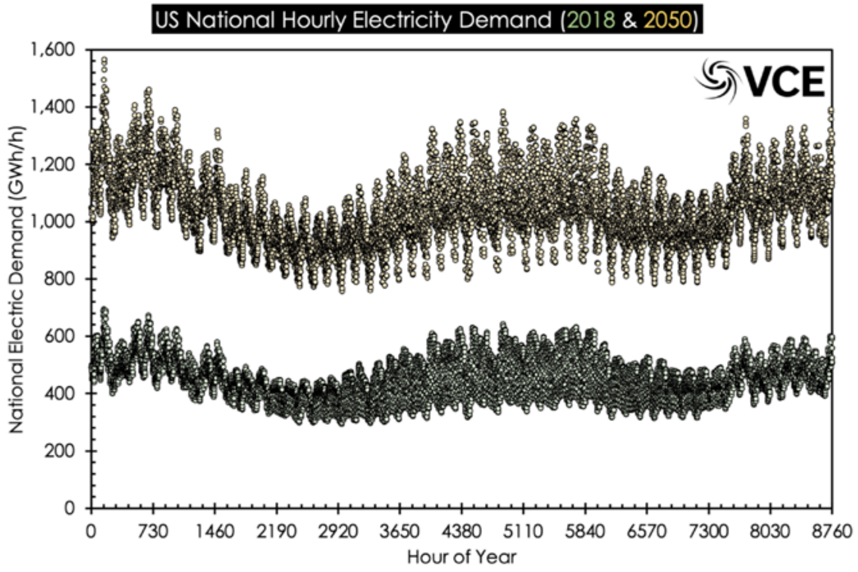
Electrification is a double-edged sword

- Electrification and integration of other energy sectors will increase load and volatility. Can change system from summer to winter peaking
- This needs to be scalable because we will need a lot of this resource. Therefore, pricing needs to be rational.
- Costs of upgrading the distribution system for increased electrification could be very significant if these new electrified loads are not controlled. Therefore, underpinning this is at least AMI and communications and control infrastructure.



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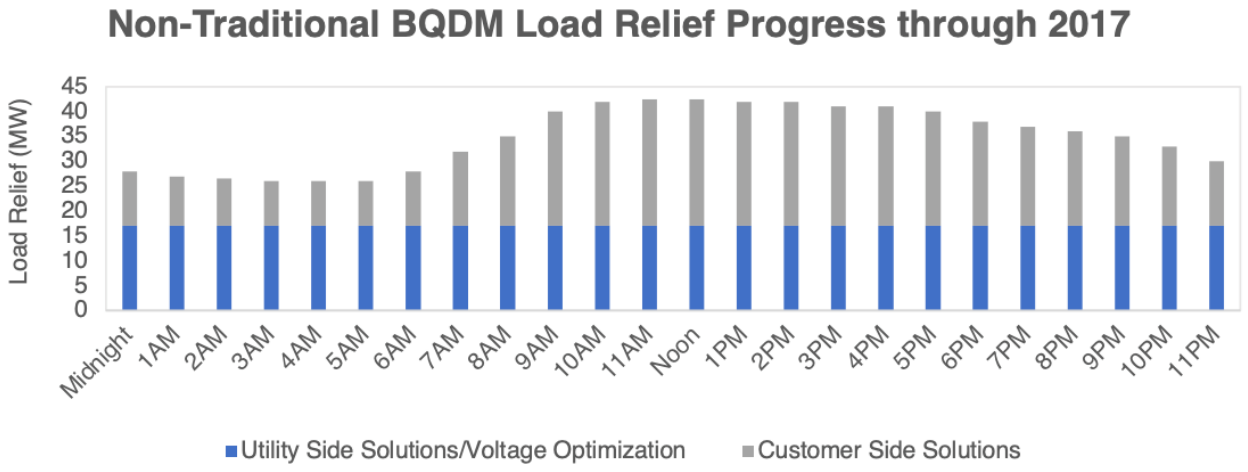
Graphic: Clack, VCE, "Integrated Planning for the Electric Vehicle Surge," 2nd Int. Conf. on Energy Systems Integration, Mar. 25, 2019

Non-wires alternatives (NWAs) are another alternative to expensive distribution upgrades



- Solicitations for solutions to provide load relief, or other services like voltage regulation
- Transparent processes such as California's grid needs assessment and distribution deferral investment framework

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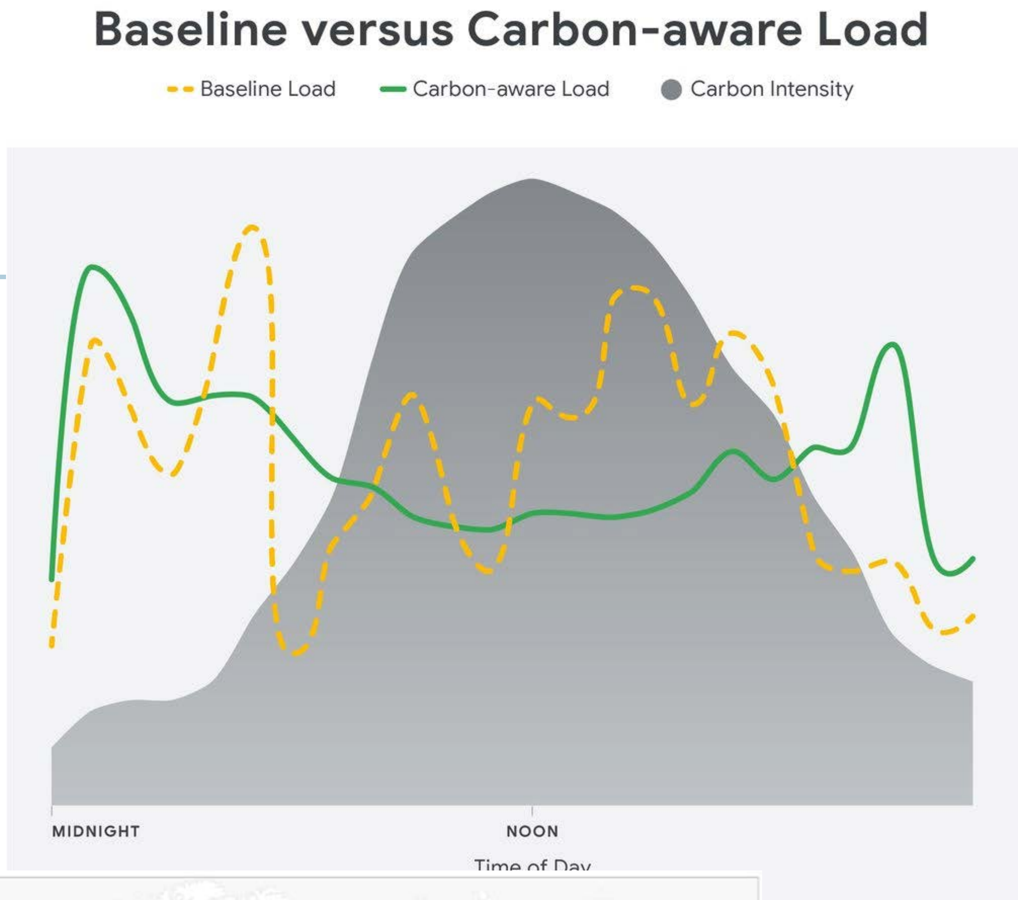
AEE BQDM Case study https://info.aee.net/hubfs/NY%20BQDM%20Final.pdf

Loads are getting more sophisticated

- Google 24/7
  - Shift load during the day. Shift load from continent to continent. Could chase renewables production around the globe
- Nest thermostats providing 700 MW of load relief during solar eclipse
- ERCOT loads on ½ second underfrequency relays
- Vehicle-to-grid is a game-changer



Google data centers

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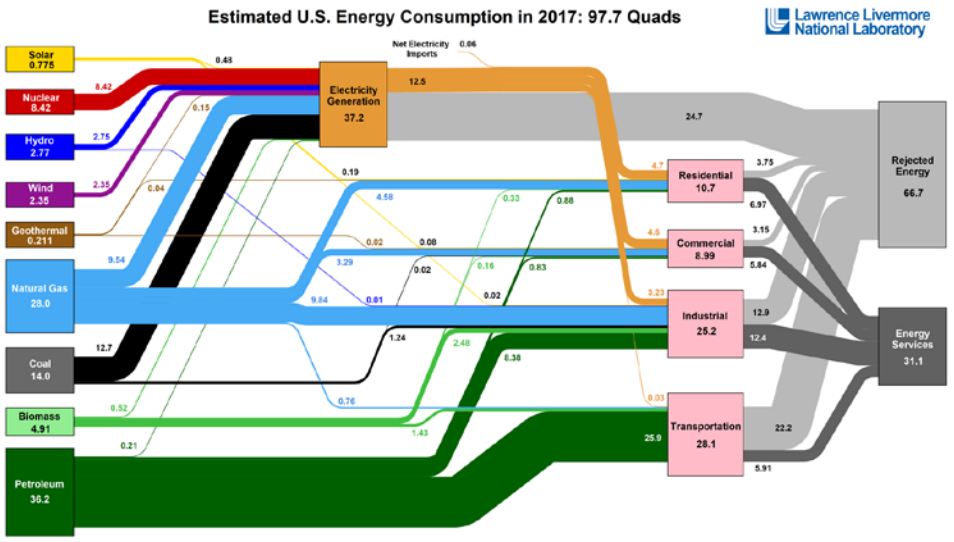
Google 24/7, Apr 2020 https://blog.google/inside-google/infrastructure/data-centers-work-harder-sun-shines-wind-blows

Energy systems integration

Linkages to other energy sectors aid integration; also add to future uncertainty in electricity pathways.

- EVs: Will there be charging infrastructure at work? Parking garages and streets? Or will we have self-driving cars with centralized charging infrastructure outside cities?
- Fuels: Will we pursue a bio-based fuel path? If we make renewably generated fuels (bio-based or power-to-X), will we use that for electricity or only for heating/industrial uses? Can we use existing pipeline and storage infrastructure?



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Graphics: LLNL, 2017

What happens to rates?

- Rates would need to reflect system cost drivers much better than today, if we want to most effectively exploit demand-flexibility
  - Coincident peak demand charges
  - Time-varying rates
- Does this mean everyone has to move to RT prices? Can probably do a lot with some loads on TOU+demand charges, some loads on DA prices, and some loads on RT prices (similar to how generation is managed today)
- Match rates to reflect cost drivers of resource mix and operations
  - If many hours are 'balancing by curtailing', you might have free energy for many hours
  - TOU rates are great match for solar because they act like storage

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High penetrations of DG need IEEE 1547-2018 or similar interconnection standard

IEEE 1547-2003

- A traditional DG paradigm
- DG is passive
- DG provides only energy
- Owners are incentivized to provide as much energy as they can
- No communications
- No control

IEEE 1547-2018

- Unlocks smart inverter capabilities so that DG can act like conventional, transmission-connected resources
- DG may be active: dispatched, curtailed, and provide essential reliability services
- Mitigate impacts of DG on distribution system (voltage, power quality etc) and increase hosting capacity of DG on a feeder
- Two-way communications: DG is visible to operators
- Supports bulk system reliability

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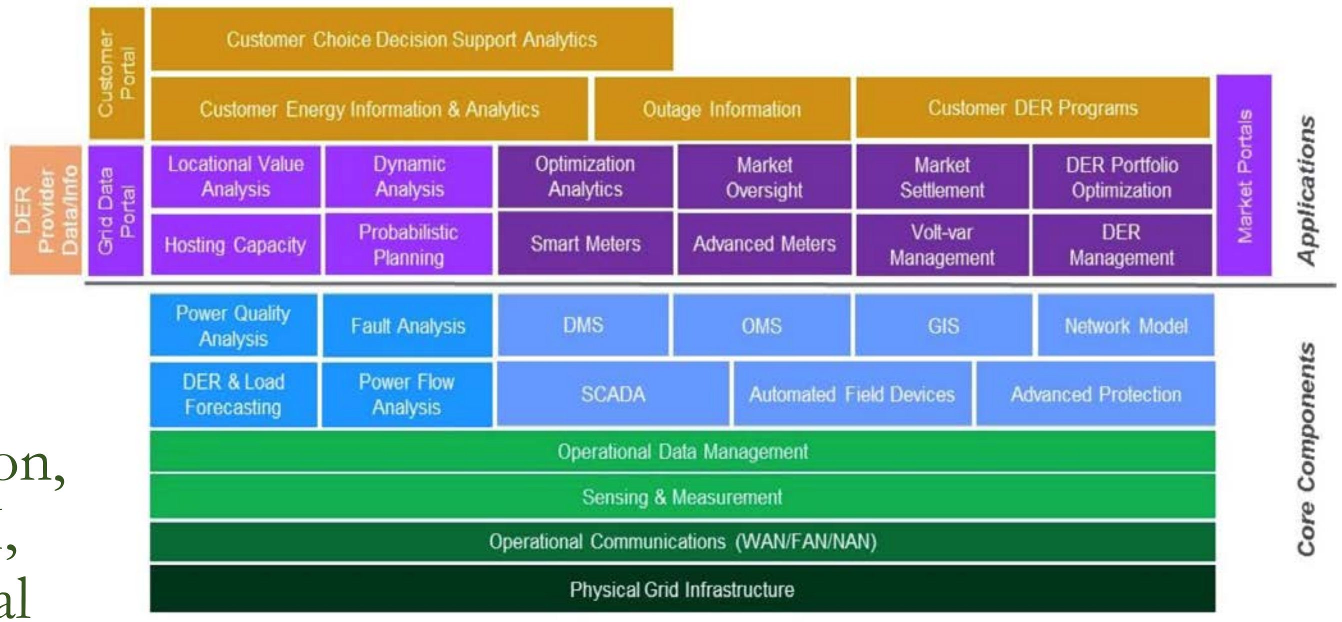
Slide: Lew, GE, CREPC 20 April 2018

Grid Mod and High penetrations of DERs are not the same thing but they are related

- Grid mod is not one thing. You invest in components that you need and will use
- Grid mod investments support utility control or customers responding to signals. Aggregators install their own infrastructure to provide services.
- Communications, SCADA, sensing/measurement, data management, GIS, advanced protection, automated field devices, ADMS, AMI, hosting capacity, DERMS are potential needs in a high DER future

Figure 8: Next Generation Distribution System Platform & Applications



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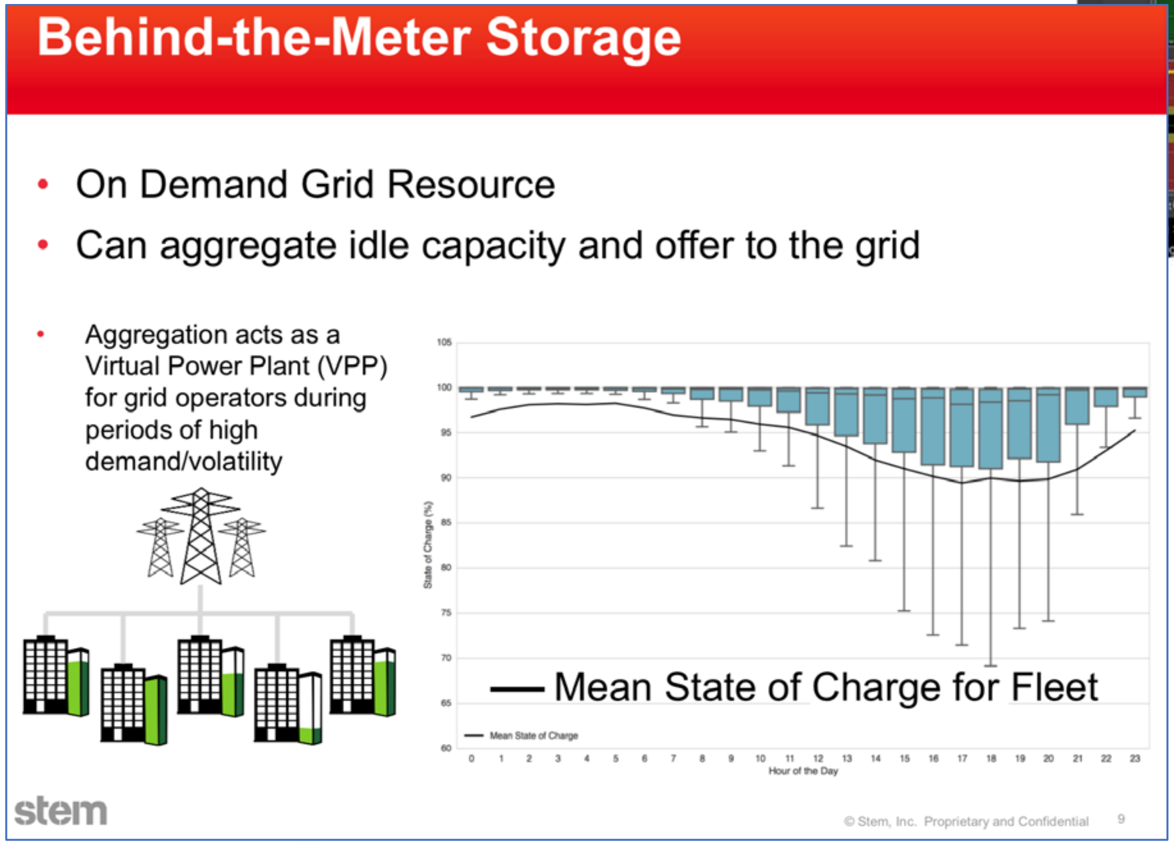
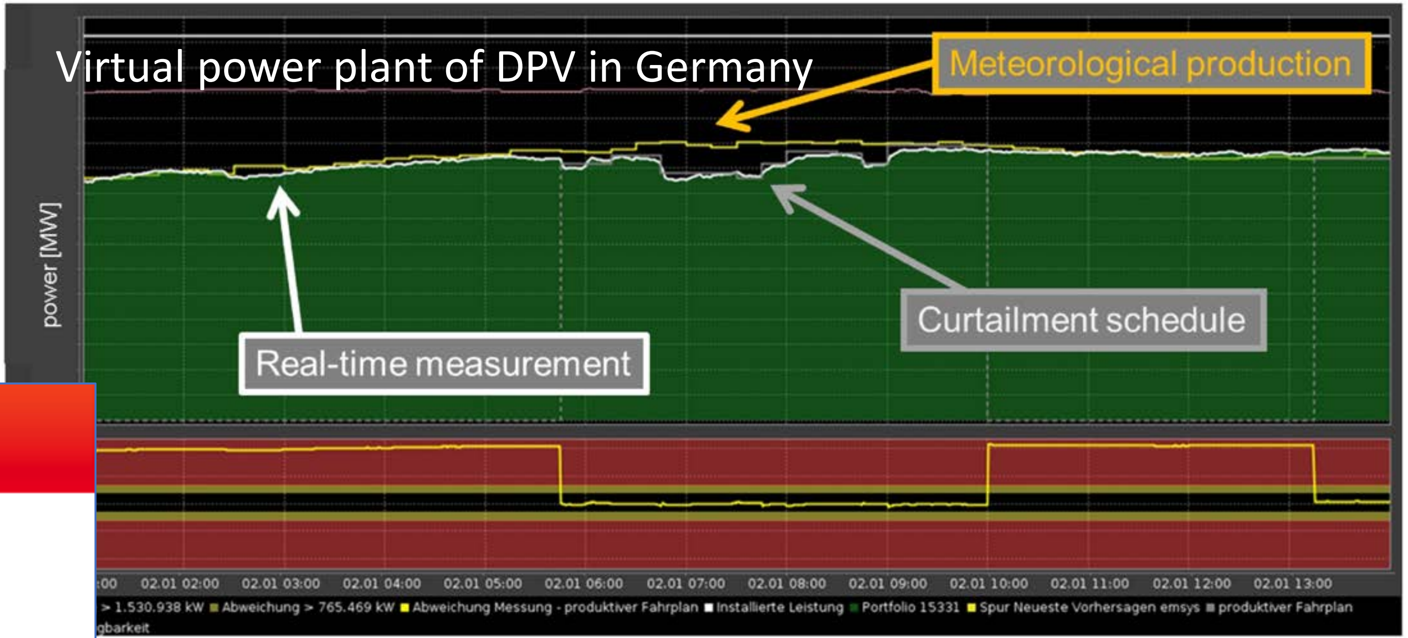
DOE, Modern Distirbution Grid Vol. III, 2017
https://gridarchitecture.pnnl.gov/media/Modern-Distribution-Grid-Volume-III.pdf

Aggregator approach

Best of both worlds or transitional strategy?





- Utility/ISO retains control
- Customers have more dynamic resources to meet their needs
- Third party provides needed services to utility/ISO and shares economic benefits with customers

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D. Erhart, STEM, ESIG Spring Workshop, 2018; Lew, et al, IEEE PES Magazine Nov/Dec 2017

Each distribution feeder has to satisfy power system criteria

Power System Criteria

- **Thermal**
  - Substation transformer
  - Primary conductor
  - Service Transformer
  - Secondary Conductor
- **Power Quality/ Voltage**
  - Sudden (fast) voltage change
  - Steady-state voltage
  - Line regulator or substation LTC
  - Capacitor switching
- **Protection**
  - Relay reduction of reach
  - Sympathetic tripping
  - Element fault current
  - Reverse power flow (backfeed)
- **Reliability/ Safety**
  - Unintentional islanding
  - Operational flexibility
  - Successful intentional islanding

NWAs and Controlled electrification

Smart inverters

Future microgrids

New protection schemes? Maintain fault current?

Adapted from *Integration of Hosting Capacity Analysis into Distribution Planning Tools*, EPRI, Palo Alto, CA: 2015. 3002005793

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How will we balance the system with significant DERs?

Centralized control

- Economic dispatch of DER by distribution system operator (DSO) with overall system optimation at the ISO/BA level
- Distribution locational marginal prices
- Dynamic 'hosting capacity'; real-time security assessment at distribution level
- DER need controls/communications
- There are many variants of this general approach

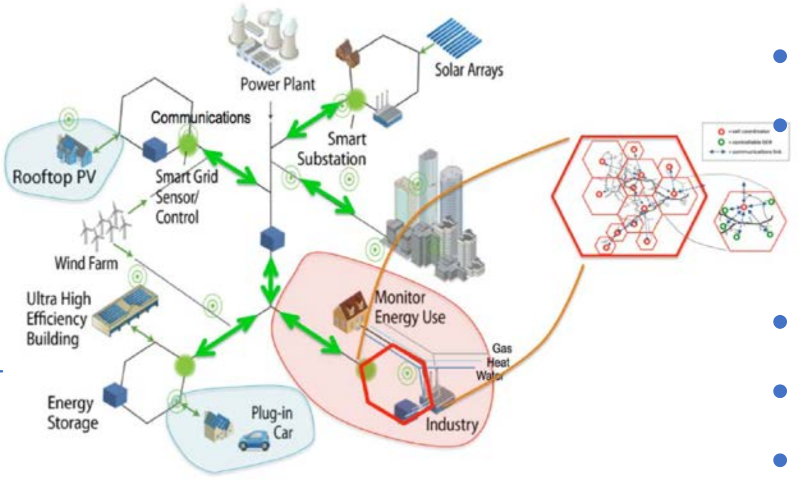

Figure 1. Autonomous energy grids organized into self-optimizing cells

Decentralized control

- E.g, NREL's Autonomous Energy Grid
- Approach to solve the problem of controlling hundreds of millions of nodes instead of the 10,000 that we control today
- Hierarchical cellular structure
- Operate without communications
- Can island and re-connect - resilience
- There are other approaches
- Decentralized control of power systems is in the research stage

Still need security for credible contingencies and operational flexibility to isolate faults and maintain service to rest of system.

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Kroposki, NREL, Basic Research Needs for Autonomous Energy Grids, Sep 13-14, 2017

System balancing and DERs: Towards 100%

- Transmission is a key enabler for 100% clean and there will be different levels of transmission needed
- A truly dynamic distribution system with very high penetrations of DERs, and the marketplace to manage them, is likely a larger paradigm shift than the transition to 100% clean energy.
  - It will require significant infrastructure and investment beyond how we think of grid mod investments today
  - "No-brainer" items: NWAs to defer expensive upgrades; control of flexible loads to defer upgrades or flatten feeder loads; voltage regulation from smart inverters
  - R&D items: seamless islanding of third-party microgrids; decentralized power system operations in autonomous energy grids

Prices need to reflect costs!

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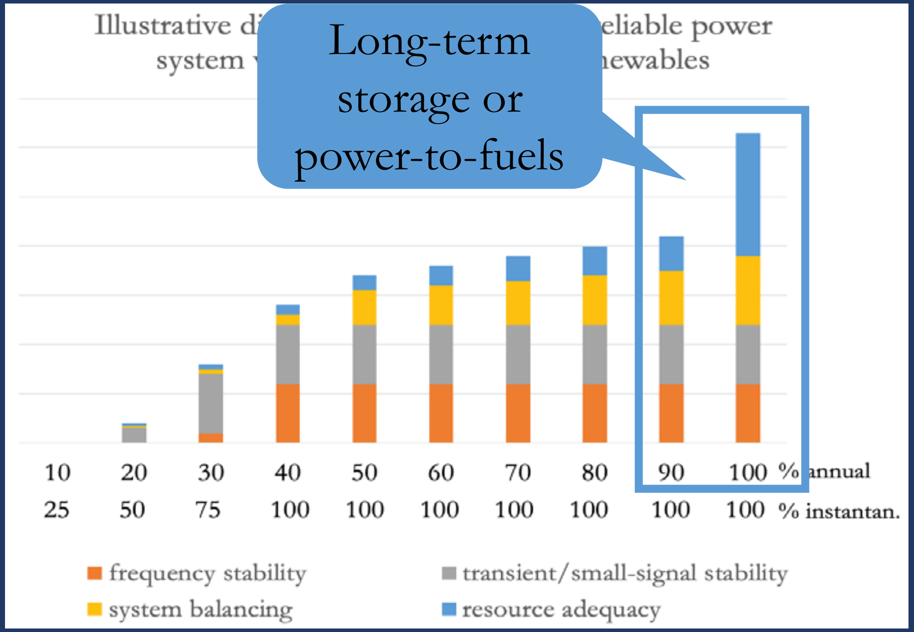

100%: Resource Adequacy

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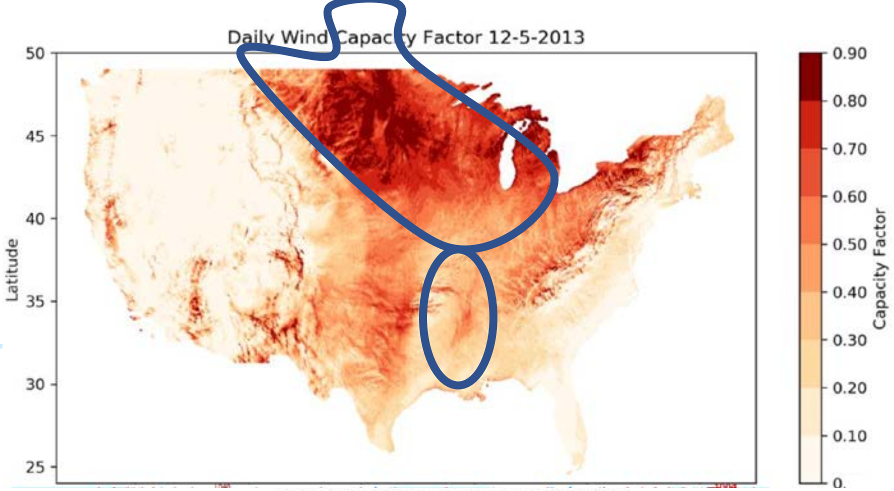
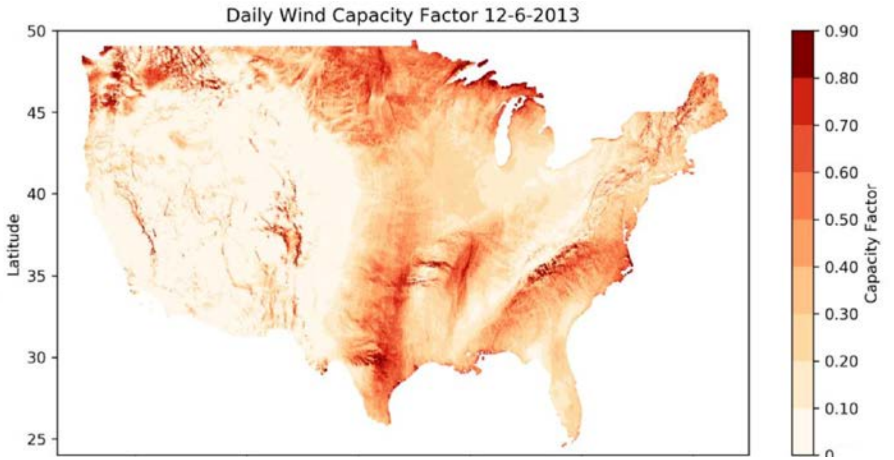
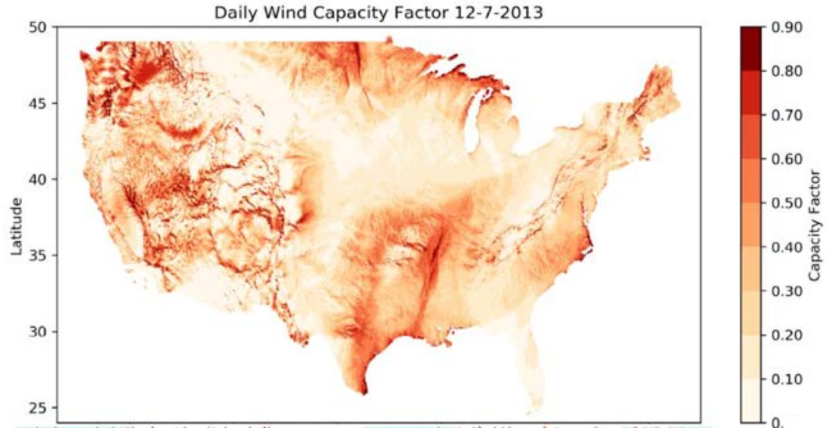
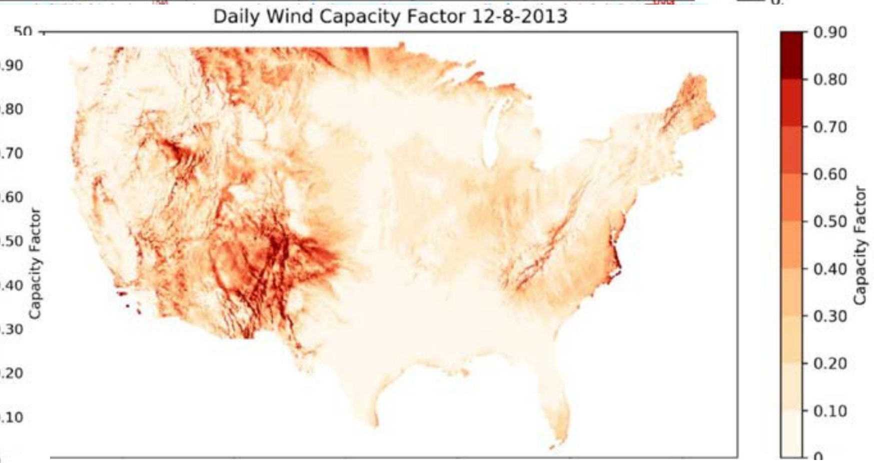
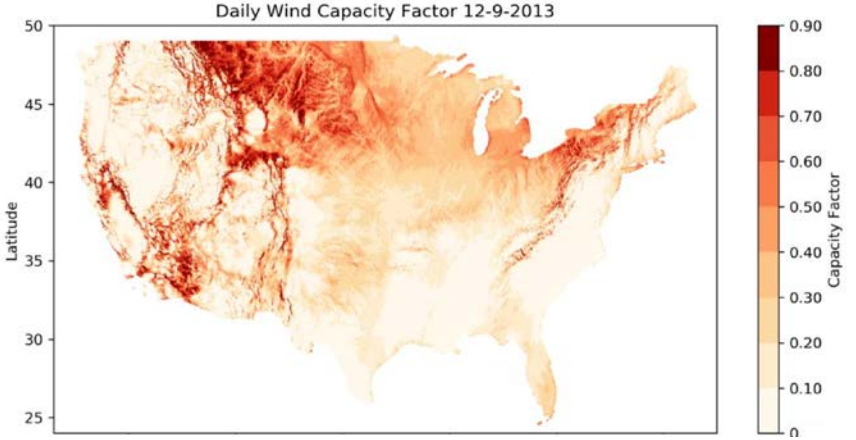
Multiple days in a row

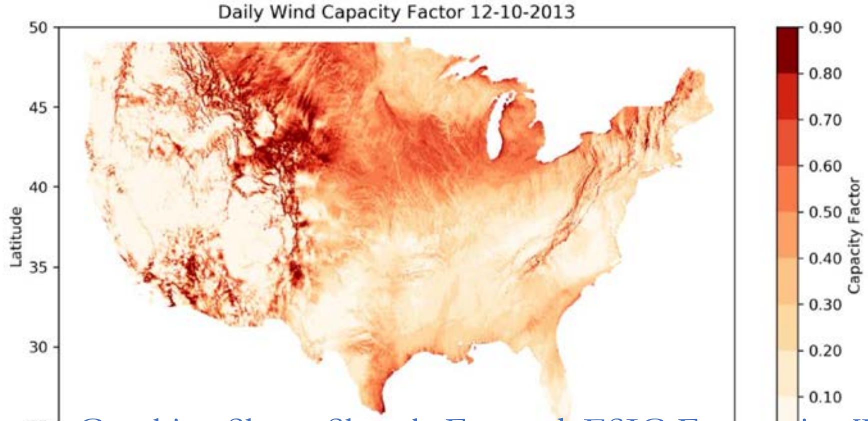


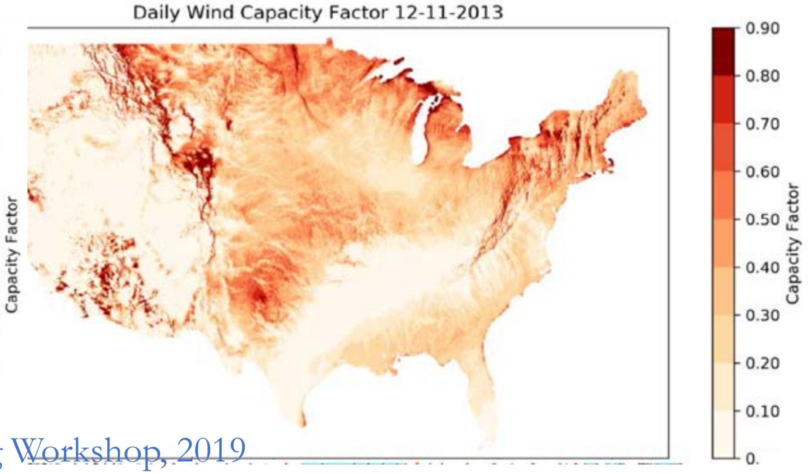


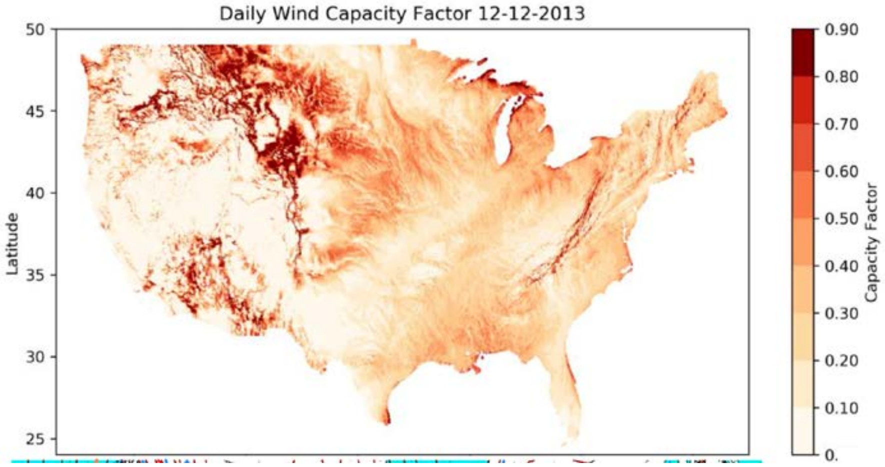












Graphics: Sharp, Sharply Focused, ESIG Forecasting Workshop, 2019

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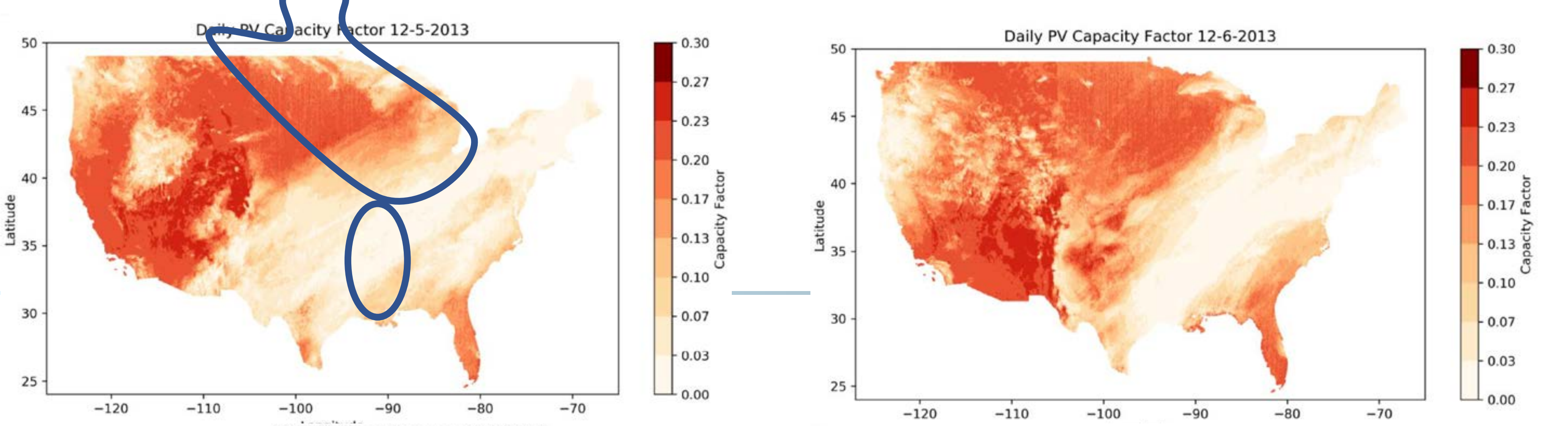
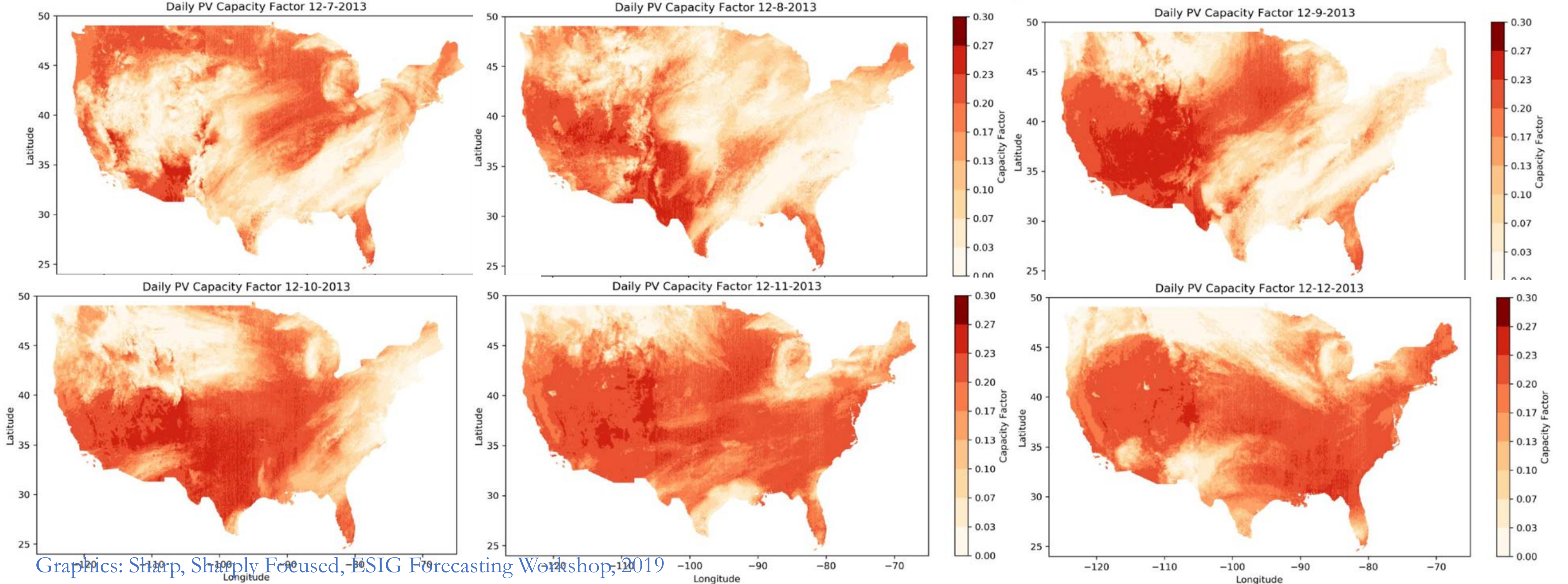
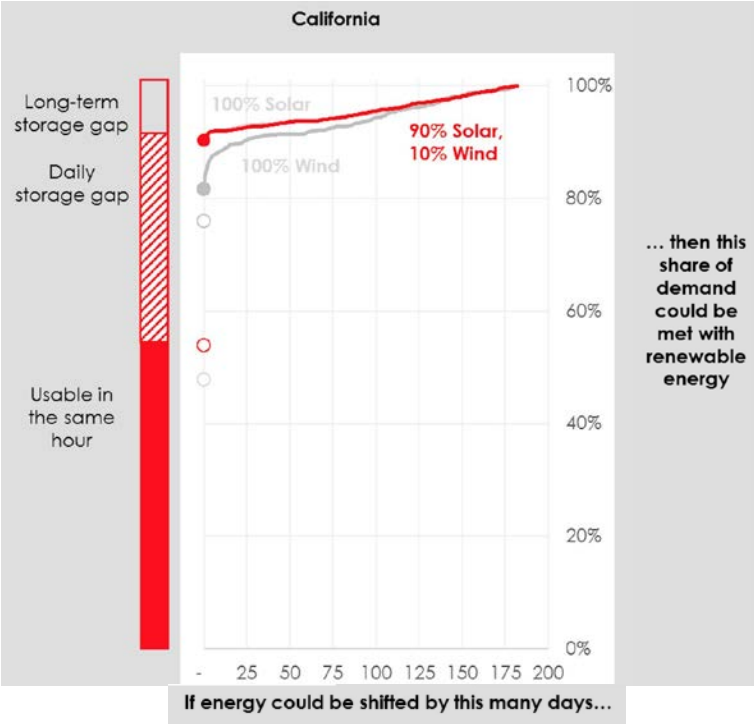


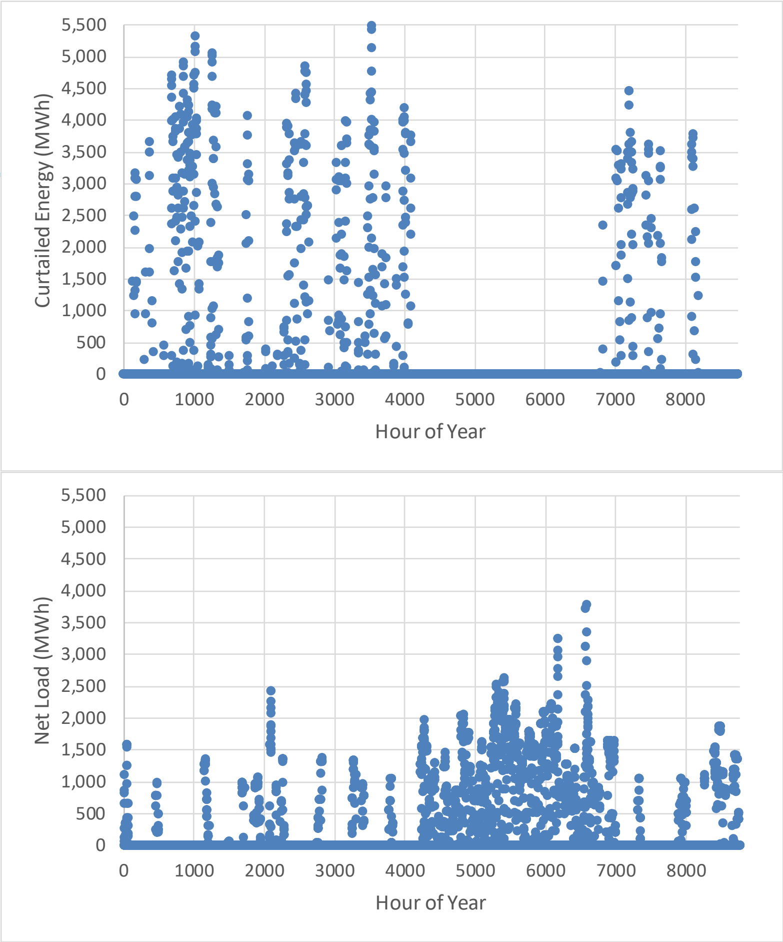


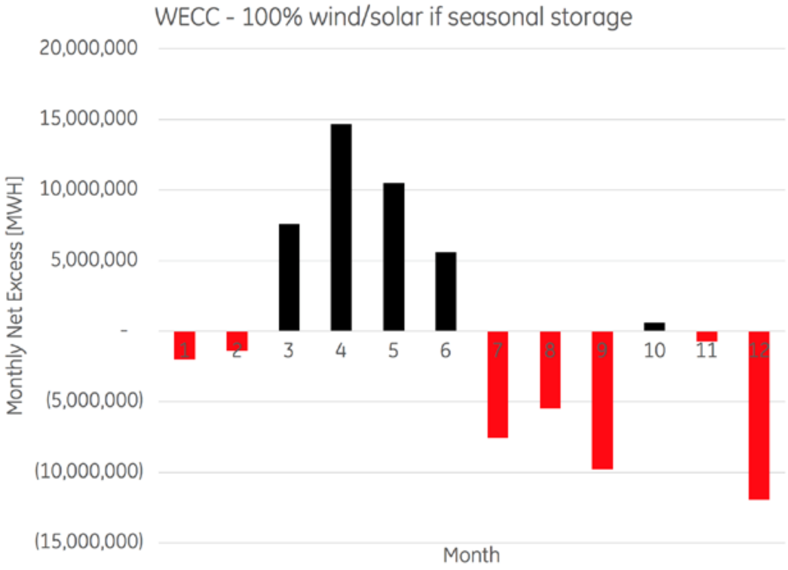
Graphics: Sharp, Sharply Focused, ESIG Forecasting Workshop, 2019

Seasonal mismatch

Illustrative thought experiments







- For many hours, there will likely be excess generation
  - Are there be new loads that don't need high capacity factor (low capital cost) to soak up excess energy in the spring?
- How much do we need to overbuild capacity?
  - Seasonal storage options? Power-to-X?

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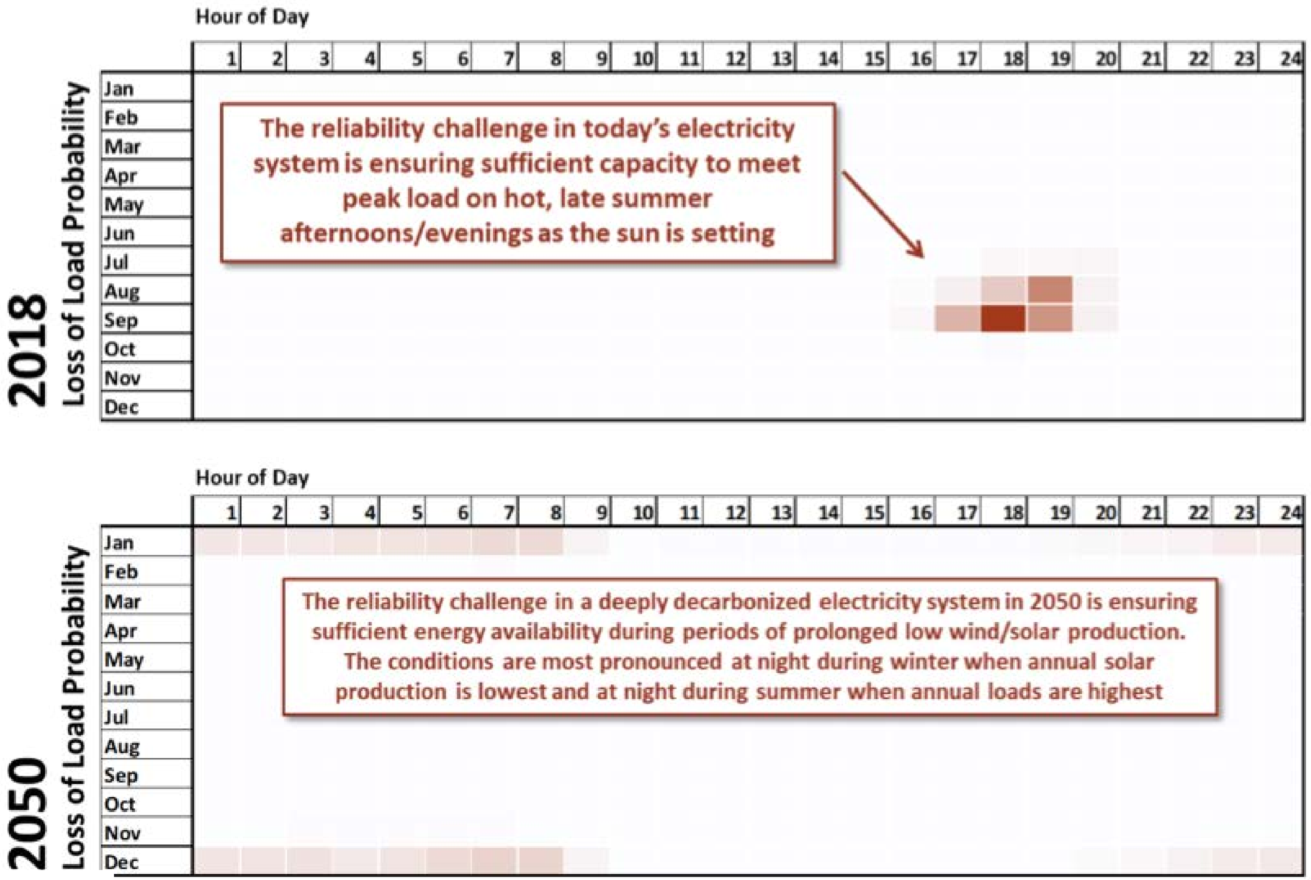
B. Pierpont et al, "Flexibility: The path to low-carbon, low-cost electricity grids," Climate Policy Initiative Analysis, 2017; A. Bloom, Energy Systems Integration Group's Planning WG Oct 2018; Lew, GE, EERA/ESIG/CITIES Workshop, May 2018

High risk hours change

They may no longer be correlated with system peak



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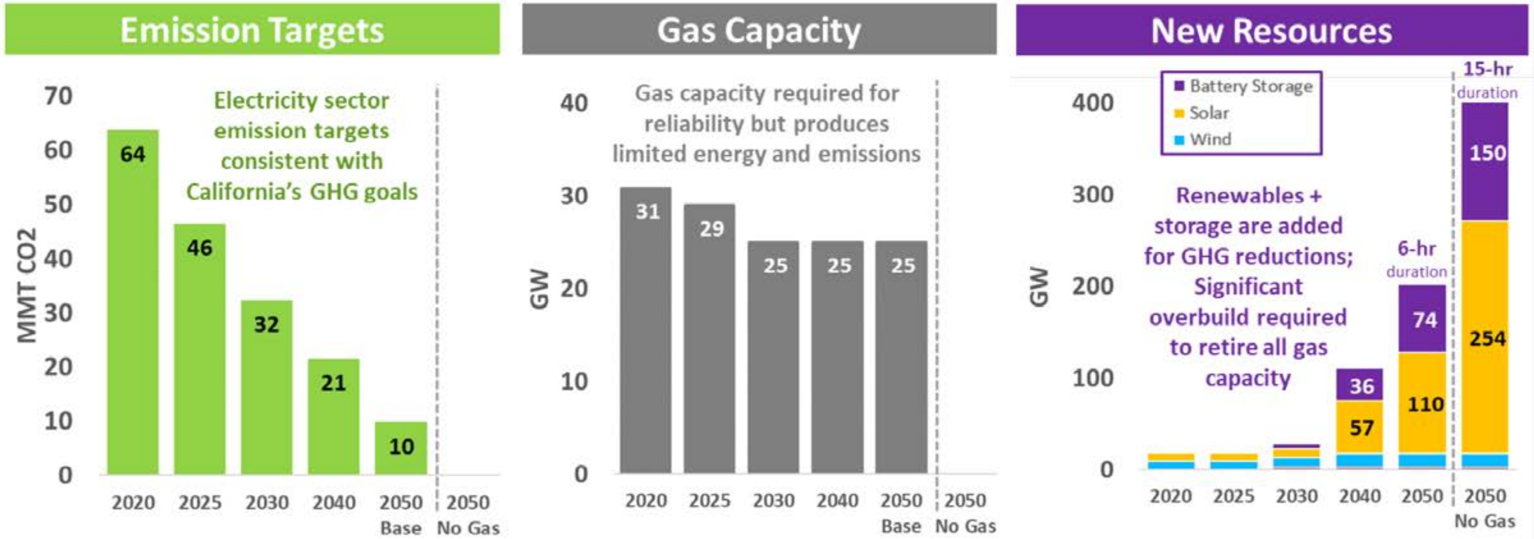
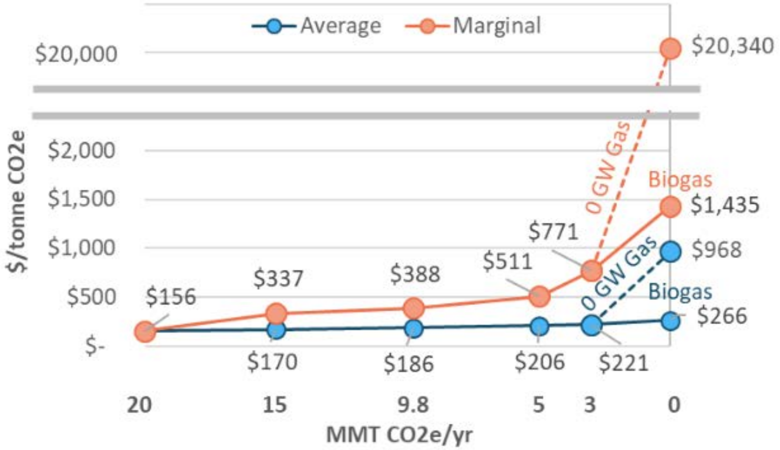
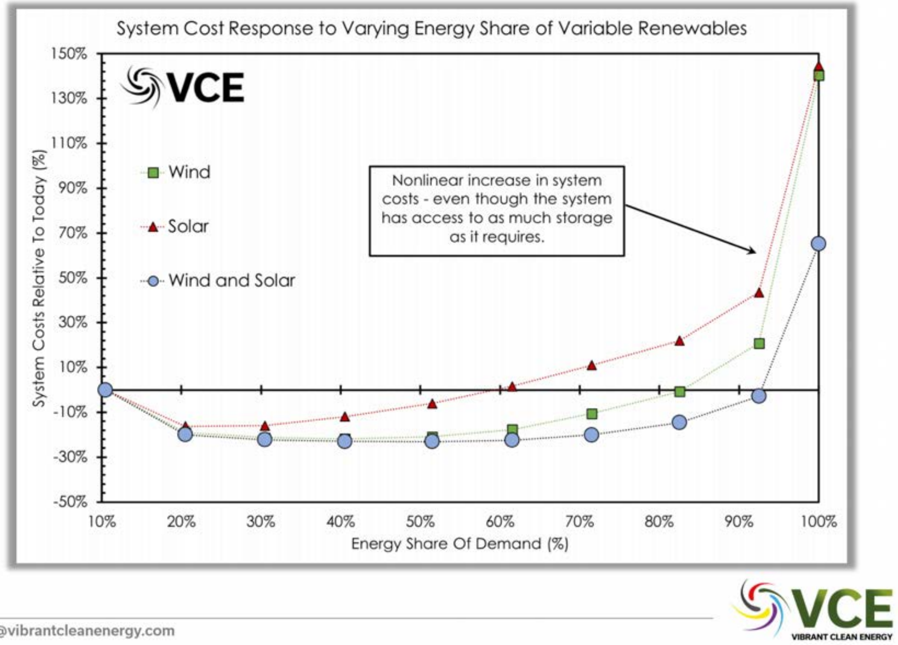
E3, "Long Run Resource Adequacy under Deep Decarbonization Pathways for California," June 2019

The last 20% can be challenging







Sources: E3, "Long Run Resource Adequacy under Deep Decarbonization Pathways for California," June 2019; Clack, VCE, CREPC, Oct 25, 2018

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Resources with very low capacity factor

- Traditional issue: some resources are run very few hours per year but are needed for resource adequacy and need cost recovery.
  - Gas peaking units had cheapest capital costs so cost recovery was not as big an issue
  - Likely to be long-duration storage resources or renewable gas that meets these needs in future (which are likely to driven by multiple-days-in-a-row weather). Unlikely to be cheap
  - Peakier net load duration curves may exacerbate this.
- Transition:
  - As we develop cost-effective solutions to the multiple-days-in-a-row problem, does it make sense to keep some fossil capacity available, but run it very infrequently? (more difficult than it sounds)

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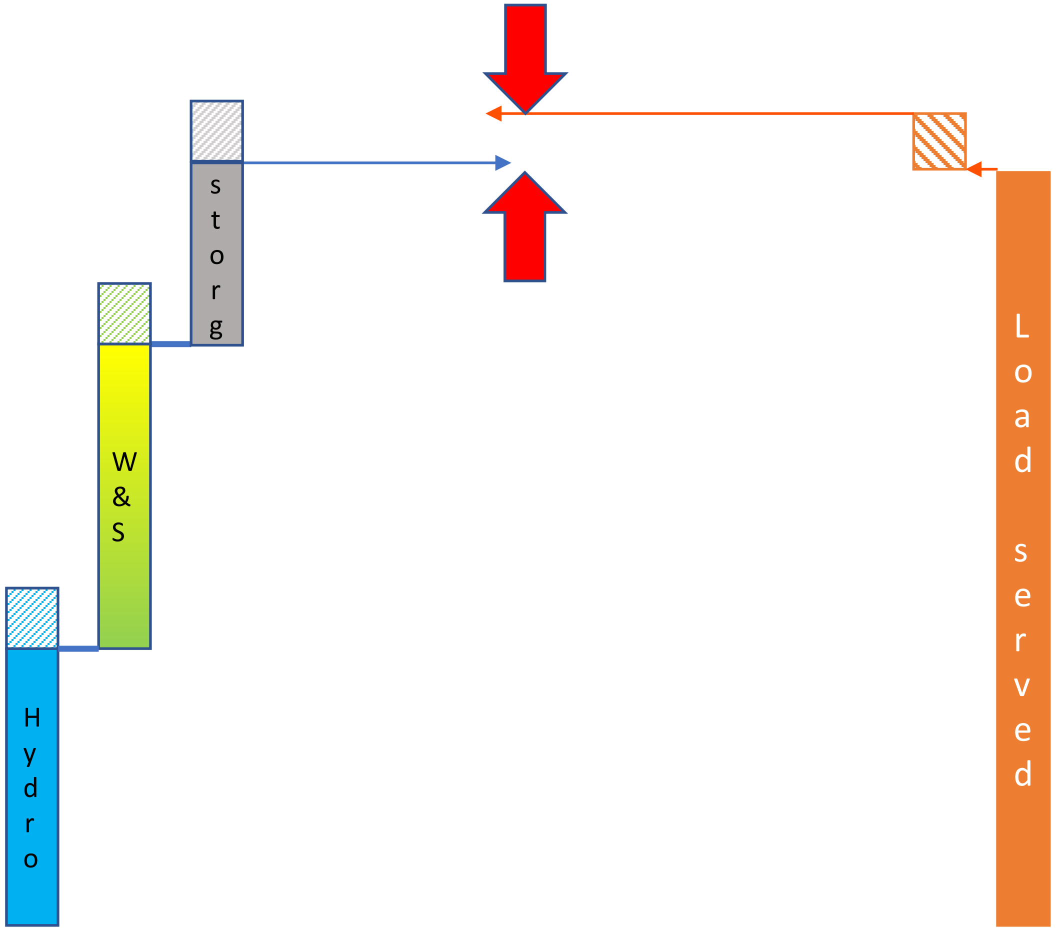
Price-responsive demand is a game-changer



- What used to be an LOLE event is now some amount of load that is compensated for not being served.
- With enough price elasticity in demand, the LOLE metric loses meaning.

Not available
Available

Peak time rebates or some customers pay less (eg 1-day-in-5-year LOLE service)

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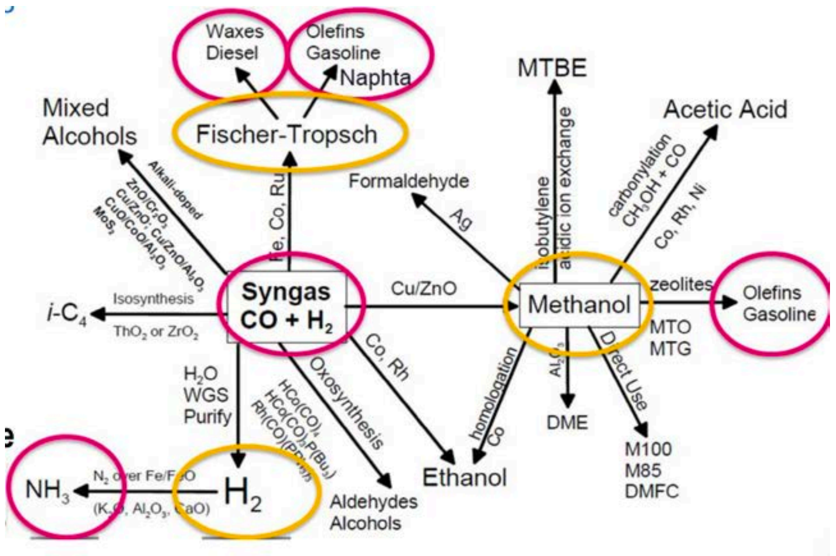
Pathways

- Fuels are how we meet resource adequacy today. There are many power-to-X (in addition to bio-based fuels) pathways and it's not clear what will be most cost-effective, make use of existing infrastructure, and meet other needs. Fuels help separate the need for MW vs MWH. A fuel-based system could also be used in balancing.
- Long duration storage is another option. The LOLE events will likely be due to lack of MWH, not MW. Need to consider how the storage will be operated.



Graphics: Breyer, LUT, 2018

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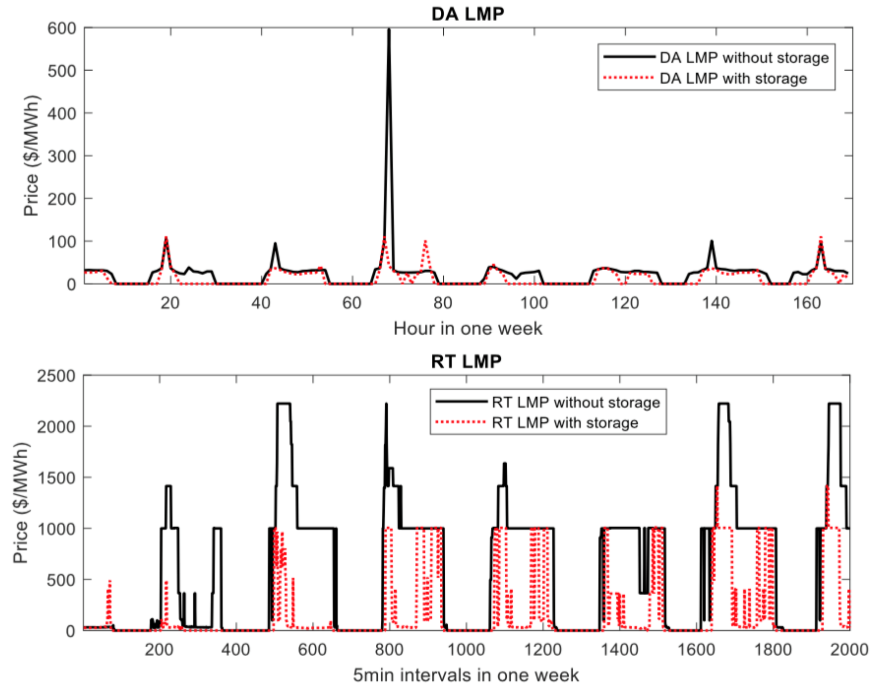
What happens to markets?

- How do you run an energy market with zero marginal cost resources?
- Cost recovery moves to capacity, ancillary services and a few high priced hours. Capacity markets are already challenging.
- Markets (competitive wholesale or vertically integrated)
  - Revise and adapt to changing conditions quickly
  - Set up for long-term needs rather than only seek least cost-solutions for today's needs
  - Recognize and reward when resources are bringing more value

Prices will bounce around and be about determining storage and curtailment



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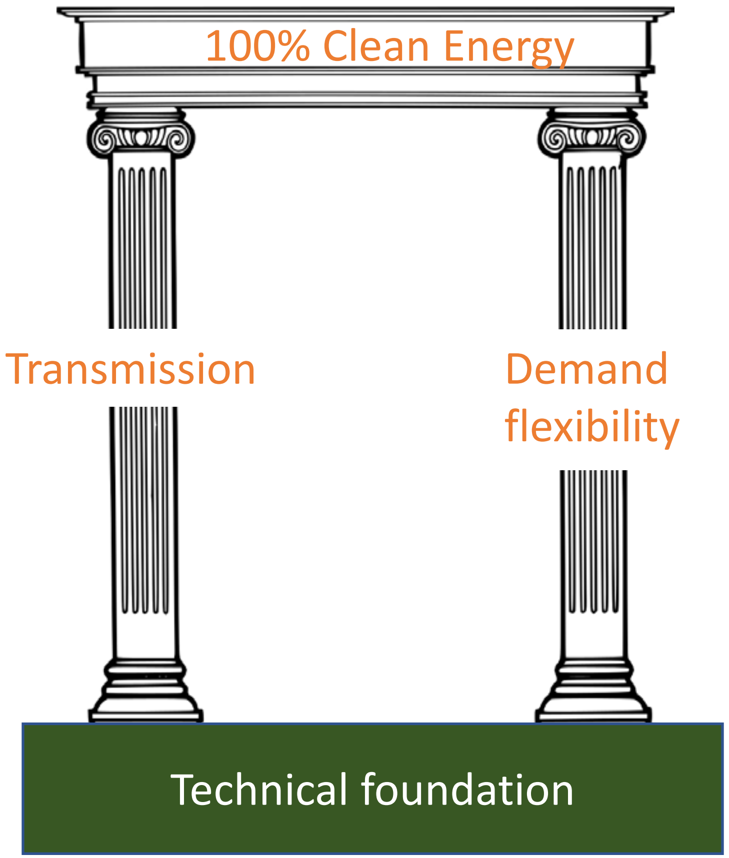
Tuohy, EPRI, ESIG ESI Conference, Mar. 25, 2019

Resource adequacy: Towards 100%

- What we know
  - Generators are not the only resource that contributes to resource adequacy
- Challenges
  - Seasonal mismatch of supply and demand
  - "Boring" weather events of multiple calm, cloudy days or multiple cold, calm days after a snowstorm
  - Likely to be energy (MWH) limited, not demand (MW) limited
- Opportunities
  - Clean fuels: Hydrogen or other power-to-X; bio-based fuels
  - Long duration storage (may need storage portfolio)
  - Controllable/Price-responsive load; does 1-day-in-10-years continue to exist?
  - Rapidly falling price of batteries; V2G
  - Electrification of other sectors AND optimization of interactions between these energy systems
  - Other technologies that may become commercial: CCS, advanced nuclear…

Key points: 100% Clean Energy

- Transmission and demand flexibility are two key pillars that will support 100% clean energy goals. They provide a wide range of grid reliability benefits across all time scales. They are likely some of the most cost-effective mitigation options out there today.
- There's significant technical foundation that underpins these pillars that require analysis, R&D, and commercialization.



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