Modern GRID and Hybrid Systems Resilience, Sustainability, Protection and Operation

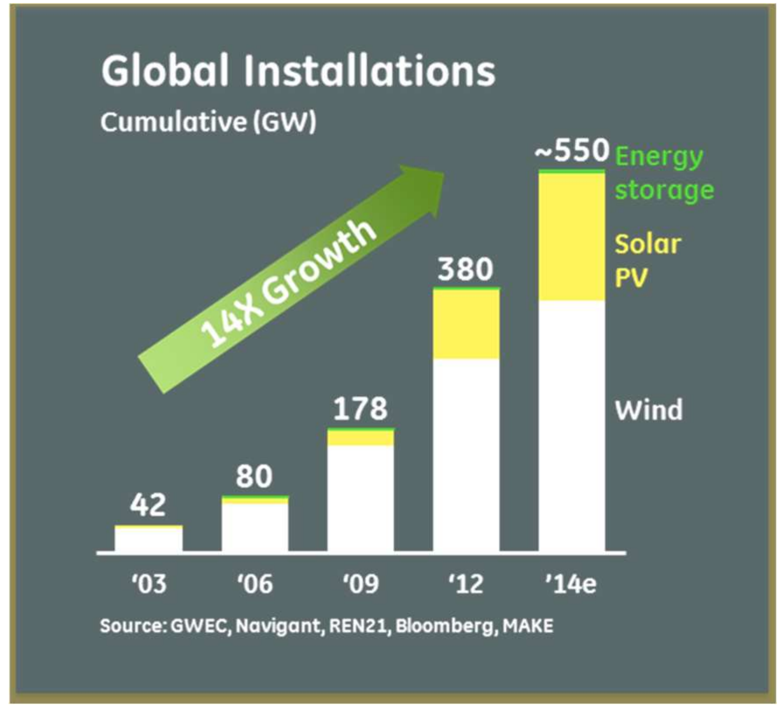
Dr. **Vahid Madani**, PE, Fellow IEEE
Executive Engineer, GridTology LLC.
www.GridTology.com

IEEE Fellow, Main Committee Member
PES Distinguished Lecturer (2010 - present)
PES Major Awards Chair (2016-2018)
PES Fellows Committee Chair (2011-2015)
US DOE and NERC/ NASPI Representative to IEEE (2007-2017)
NSF Site Visit Advisor – Major Grants
Utility and Consulting (40+ Years)
Adjunct Faculty and Research Affiliate – Mississippi State University, Starkville (2012 – Present)

IEEE DLP Webinar
Region 3, Knoxville Chapter, Eastern Tennessee
July 14, 2020
https://events.vtools.ieee.org/m/234570

Topics

- Energy and Technology Transformation Highlights
- Resilience & Reliability
- Changing Energy / Demand Landscape
- Challenges industry is addressing in large scale deployment of power electronics based technologies
  - Characteristics and behavior of the system
  - RES intermittency and resource balancing
  - Strategies and operational aspects of managing the grid system, i.e. exposure to Cascading Events, Oscillations, Damping modes (before, today, and future)
  - Business Models, Transmission Investment
- Sensors and Data Tsunami
- Machine Learning for Energy and Power System



Energy transformation at Incredible speed

- ❑ Demand for bundled load has declined in many parts of the World – Directly affects supply
- ❑ By 2030 - Some projections estimate 75% of northern California load could be served by Clean Power suppliers, or CCA – Consumer Choice Aggregation
- ❑ Electric rates have to be managed through new processes structure and measures for utility industry to remain relevant

IEEE GM Theme, Big Data, Machine Learning and Electric Transportation are Transforming the Grid (August 2020 virtual conference)

Acknowledgments:

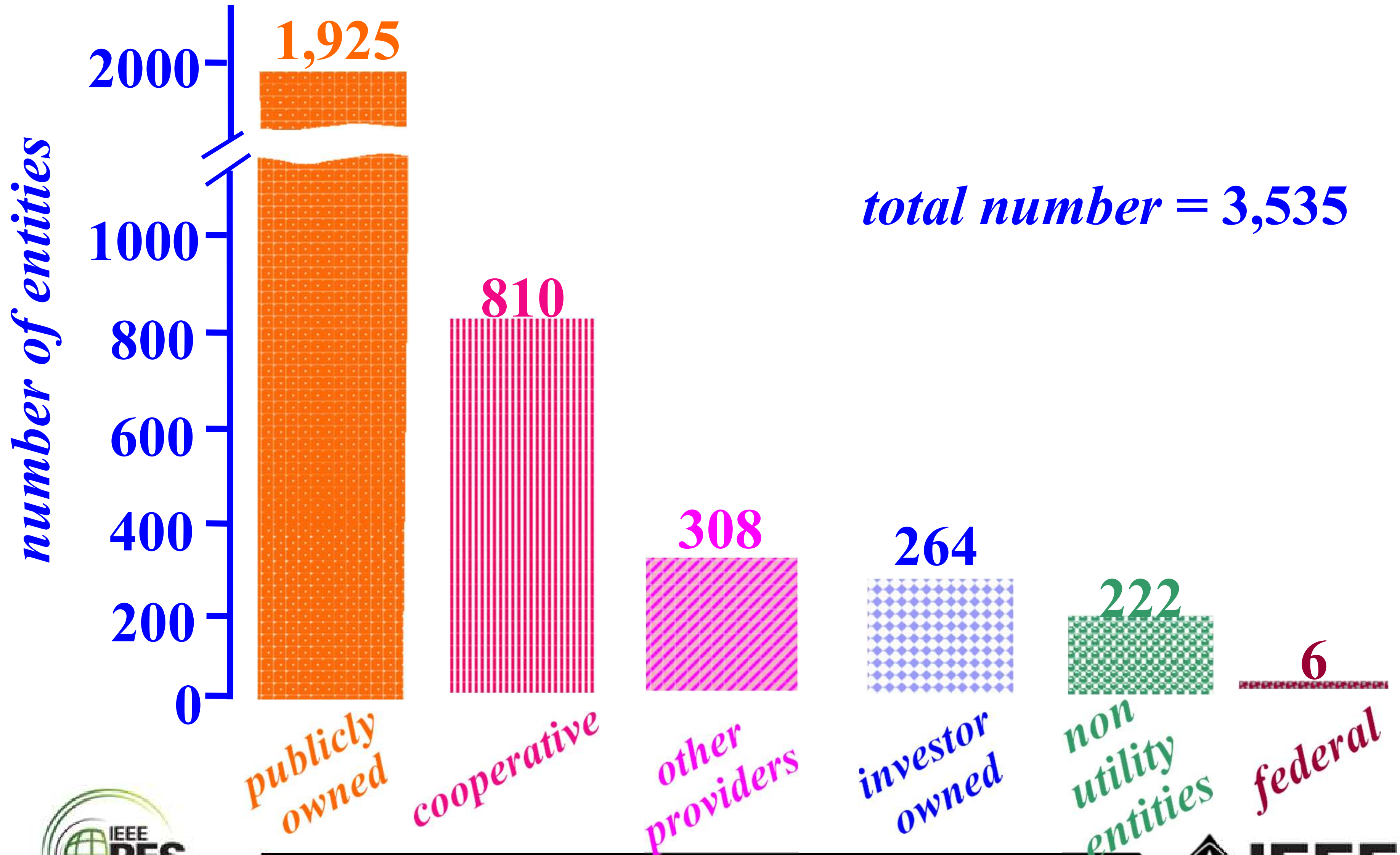
COVID-19 Pandemic

This lecture reviews Energy and Technology trends Worldwide with a prospective outside of the system impact from the global lockdown and shelter in place ordinances (starting late February / early March 2020); implemented to minimize exposure to COVID-19 pandemic. Speaker will reference, on occasion, to operational aspects acknowledging the ongoing pandemic. **The content and topics reviewed in today's session cover the broader Energy and Technology transformation initiatives, lessons and opportunities ahead**.

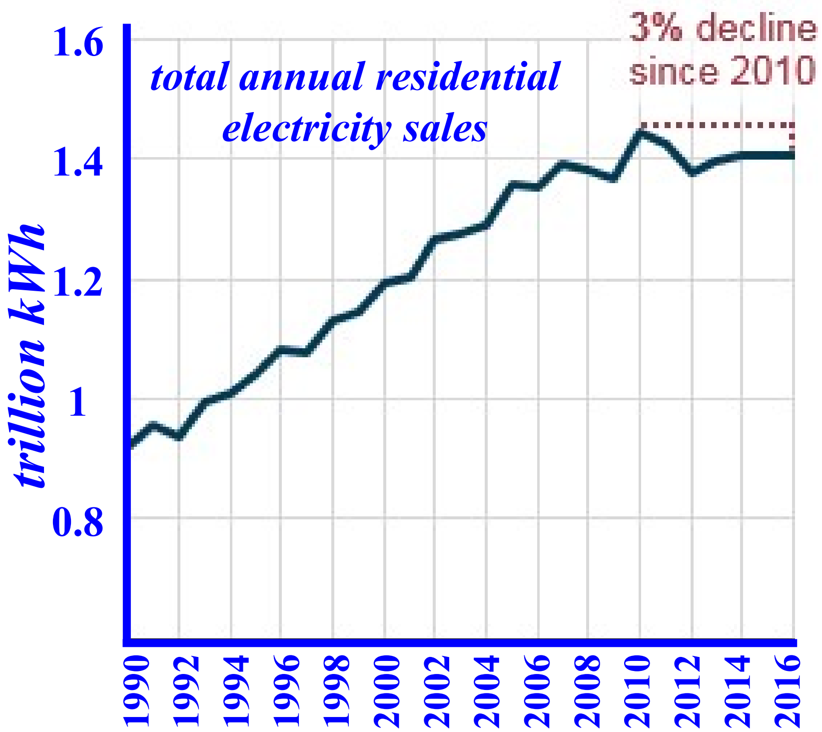
Presentation content:

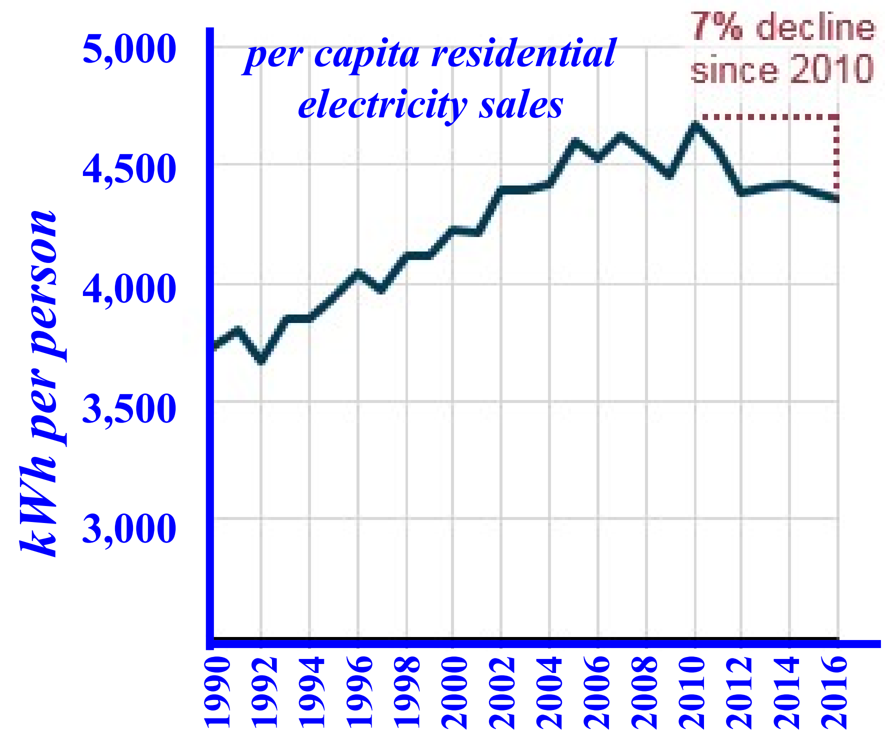
Consider Energy Policy regulations, consumer incentives and behavior may be different due to system topology, regulations, local policies and practices, or business drivers in different regulatory environment, countries, or societies

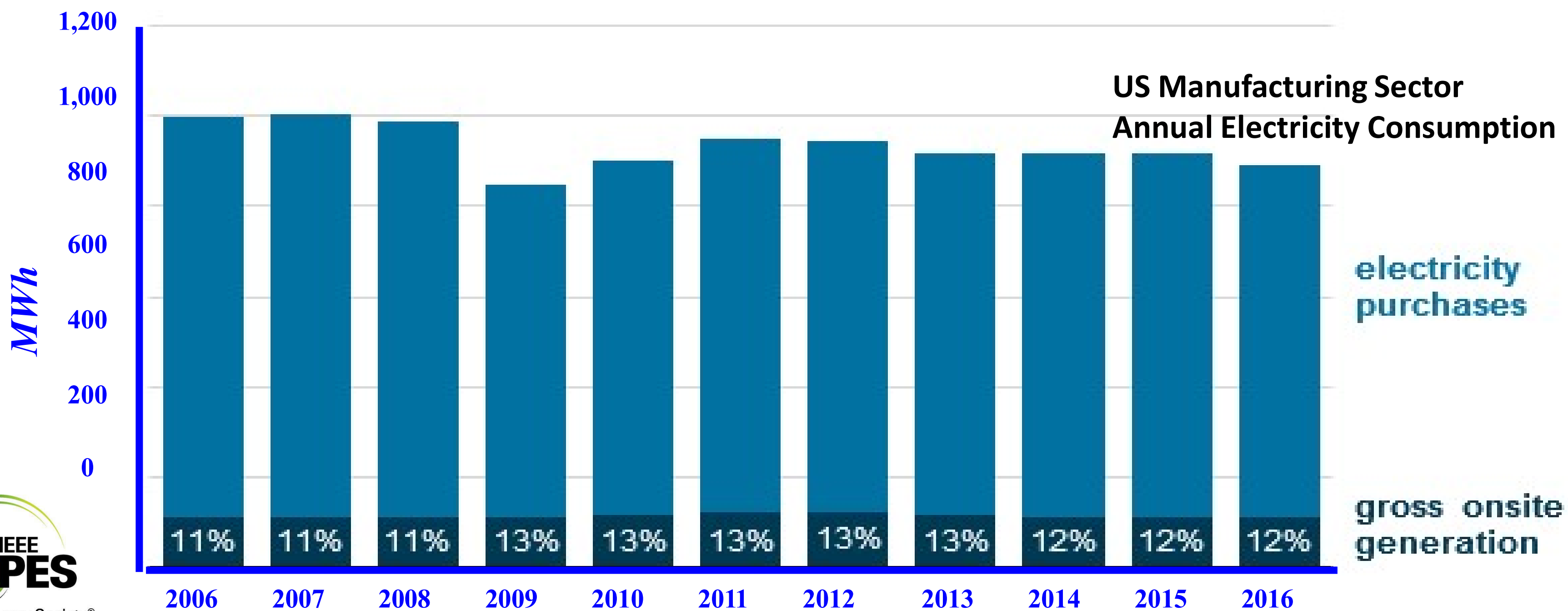
Diversity of The US Electricity Industry



Source: EIA, Mar 2019; www.eia.gov/electricity/state/unitedstates/







Source / Residential: EIA July 26, 2017, https://www.eia.gov/todayinenergy/detail.php?id=32212

Source / Manufacturing: EIA March 23, 2018, https://www.eia.gov/todayinenergy/detail.php?id=35472

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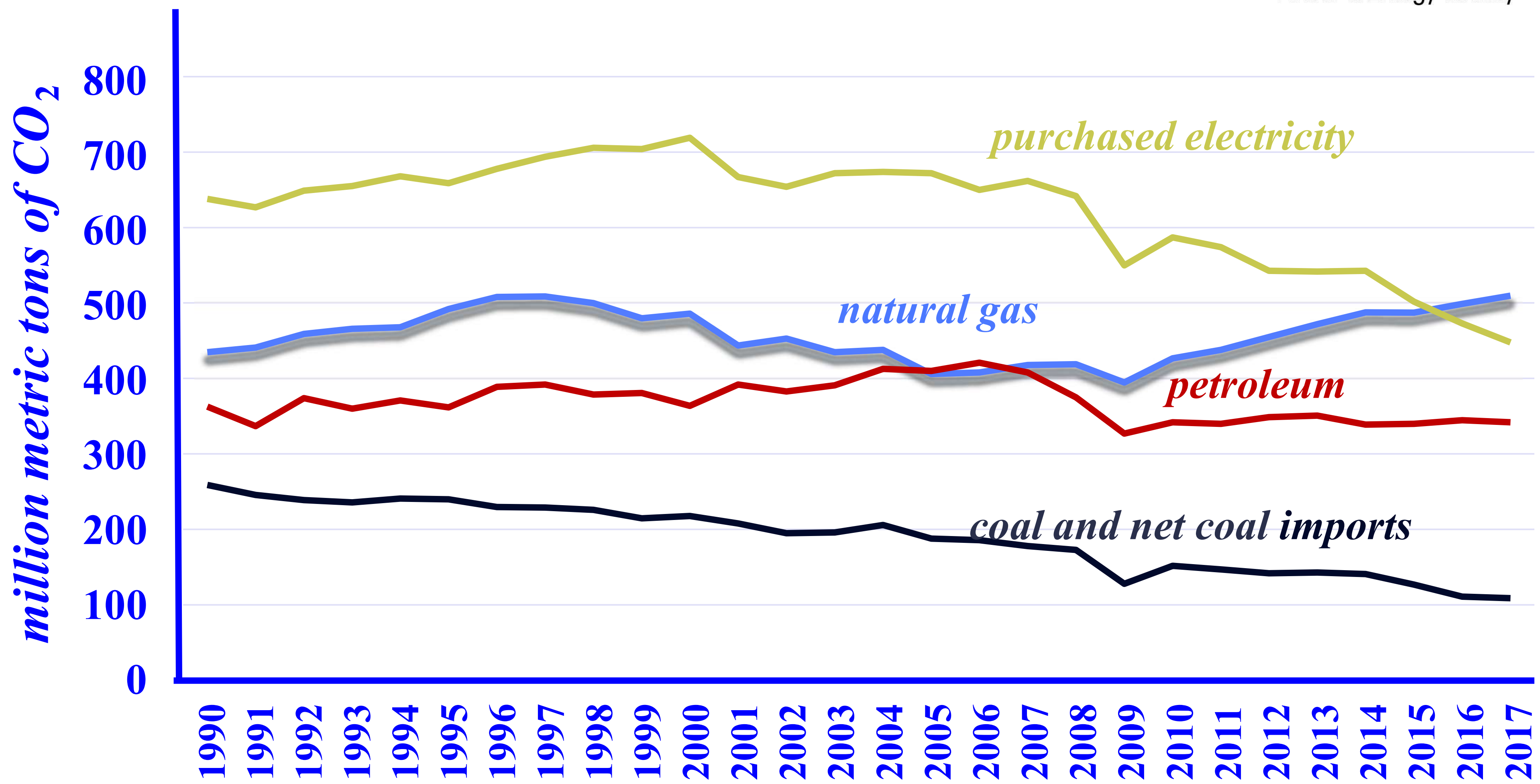
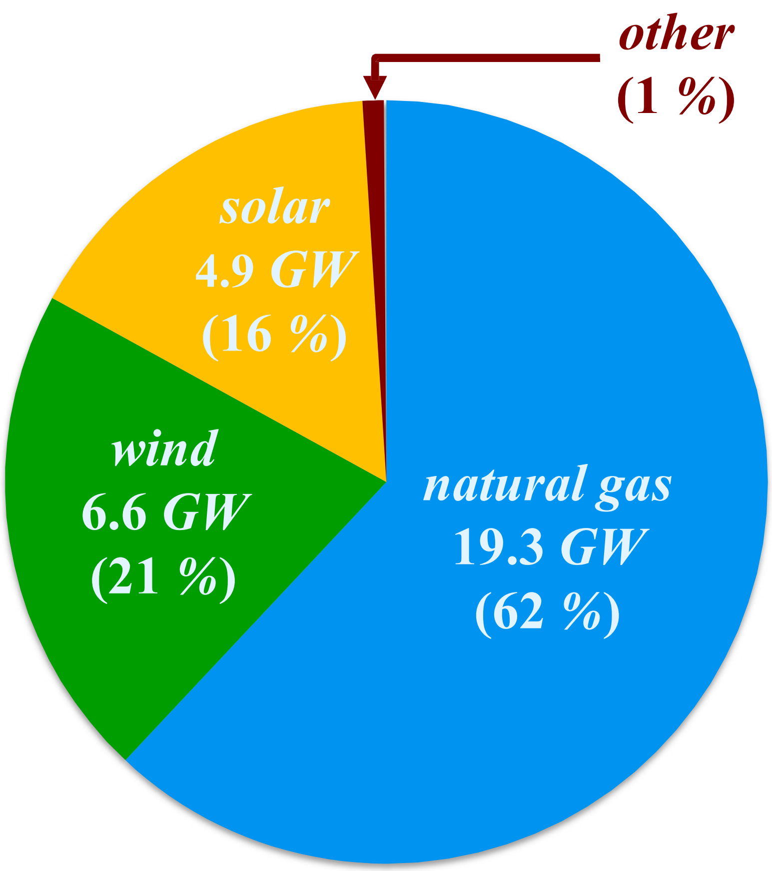
CO_2 Emissions from Industrial Sector Energy Consumption

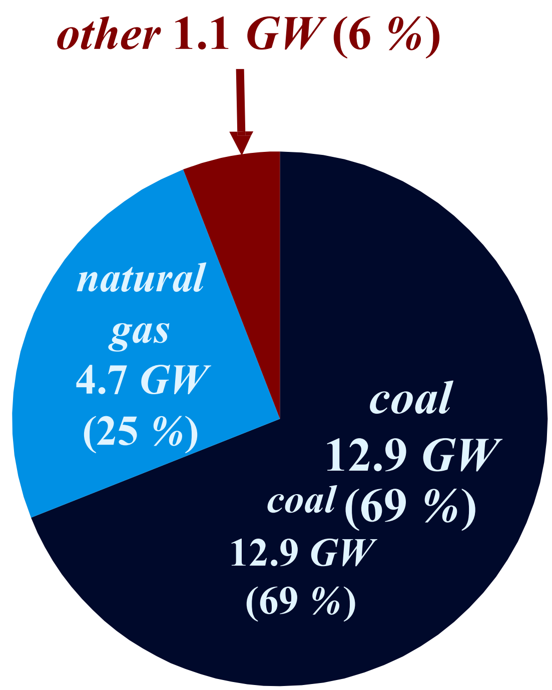


Source: U.S. Energy Information Administration, September 2018 *Monthly Energy Review;* https://www.eia.gov/environment/emissions/carbon/

US 2018 Capacity Additions / Retirements



total = 31.3 *GW*



total = 18.7 *GW*

Source: EIA, Preliminary Monthly Electric Generator Inventory, reported in Today in Energy, March 11, 2019;
*https://www.eia.gov/todayinenergy/detail.php?id=*38632

Regulatory Discretion – US and North America
FERC and NERC to Consider the Impacts of COVID-19 on Registered Entities

March 18, 2020 **July exemption dates under review for extension due to current conditions**

- The effects of COVID-19 will be considered an acceptable basis for non-compliance **with obtaining and maintaining personnel certification**, as required in Reliability Standard PER-003-2, for the period of March 1, 2020 to December 31, 2020. **Registered entities should notify their Regional Entities and Reliability Coordinators** when using system operator personnel that are not NERC-certified.

- The effects of COVID-19 will be considered an acceptable reason for **case-by-case non-compliance with Reliability Standard requirements involving periodic actions that would have been taken** between March 1, 2020 and July 31, 2020. Registered entities should notify their Regional Entities of any **periodic actions that will be missed during this period**.

- Regional Entities will postpone on-site audits, certifications and other on-site activities at least until July 31, 2020. Registered entities should communicate any resource impacts associated with remote activities to their Regional Entities.

https://www.dwt.com/blogs/energy--environmental-law-blog/2020/03/ferc-nerc-covid-19-impact-review

FERC – US, Federal Energy Regulatory Commission
NERC – North American Electric Reliability Corporation

COVID-19 Crisis

Business continuity plans for system operations

Logistics

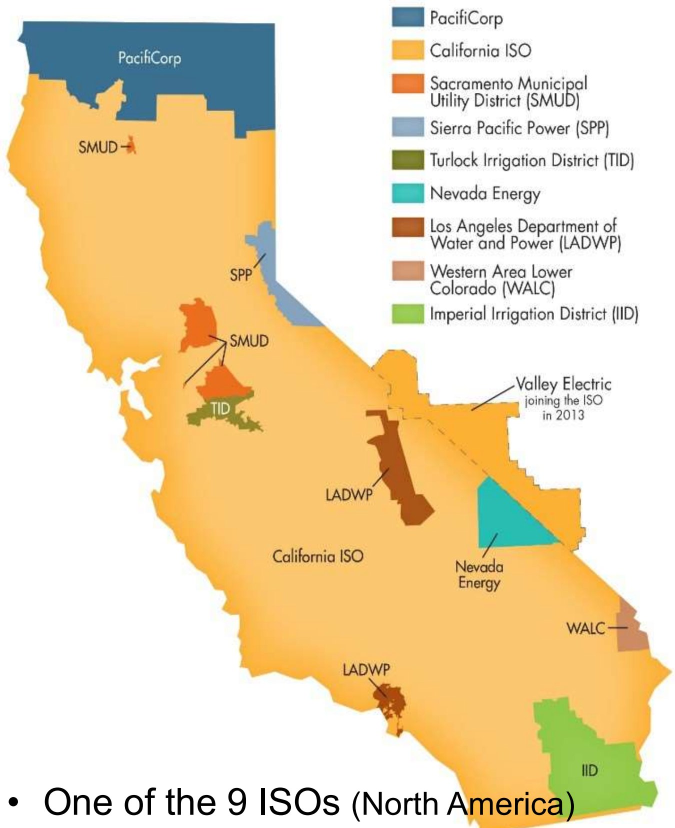
- For each area (National Control Center and 3 Regional Control Centers), the nearby **back up control room** has been activated
- Personnel rotates at each shift from the main control room to the back up one (and vice versa), leaving the elapsed time of a shift for **sanitizing** the site not in use
- **Plexiglass protective panels** between desks
- As a 'last resort' containment measure, in case of 3 regular shifts be quarantined, the control room staff would be segregated in **dorms** for 15-days period
- **Distributed shift crew**, with Operators based in different areas in case 3 crew get infected

Activities

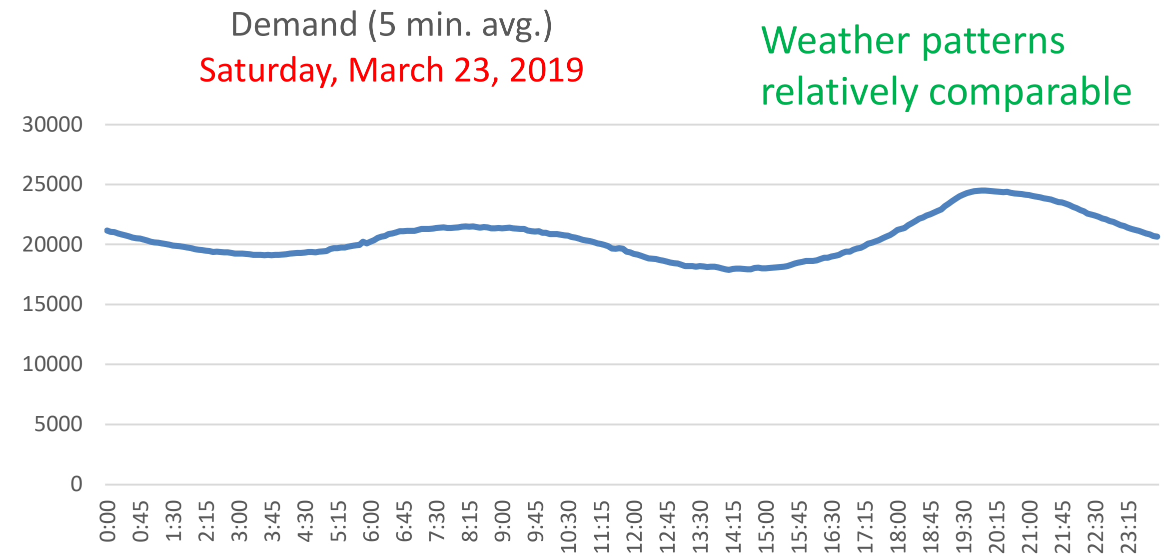
- Crews are **not mixed**
- **Shift turnovers** done via teleconference
- **Training** of new Operators; identification of workers that have previously operated in a Control Room

Source: Terna Power Co., Italy

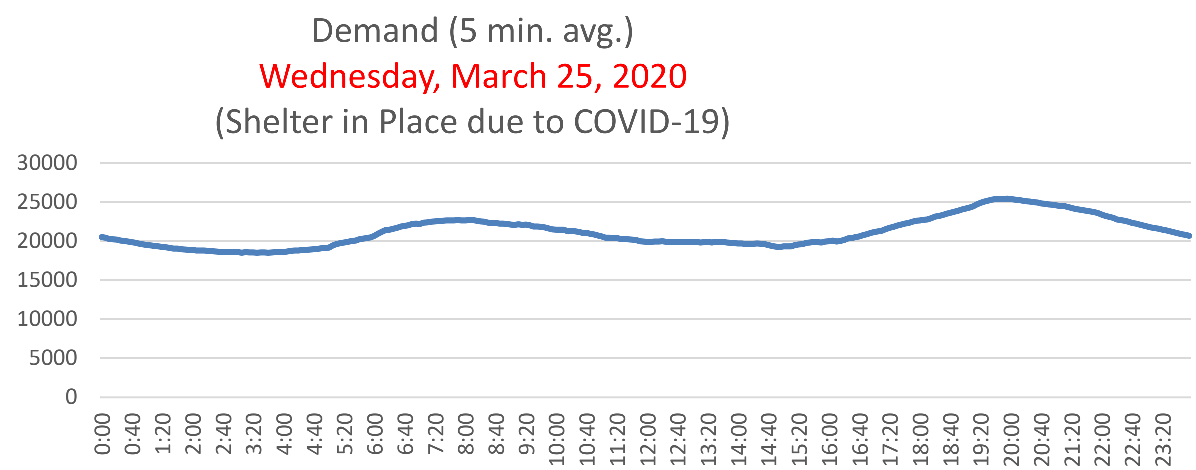
CAISO Energy Demand Trend & Pattern Comparison, 2019 Weekend vs. 2020 Workday (COVID19)



- One of the 9 ISOs (North America)
- Handles 35% of the electric load in the West (78.5 million, 2019)
- Manages load for about 80 percent of California and part of Nevada (over 26000 circuit miles)



Weather patterns relatively comparable



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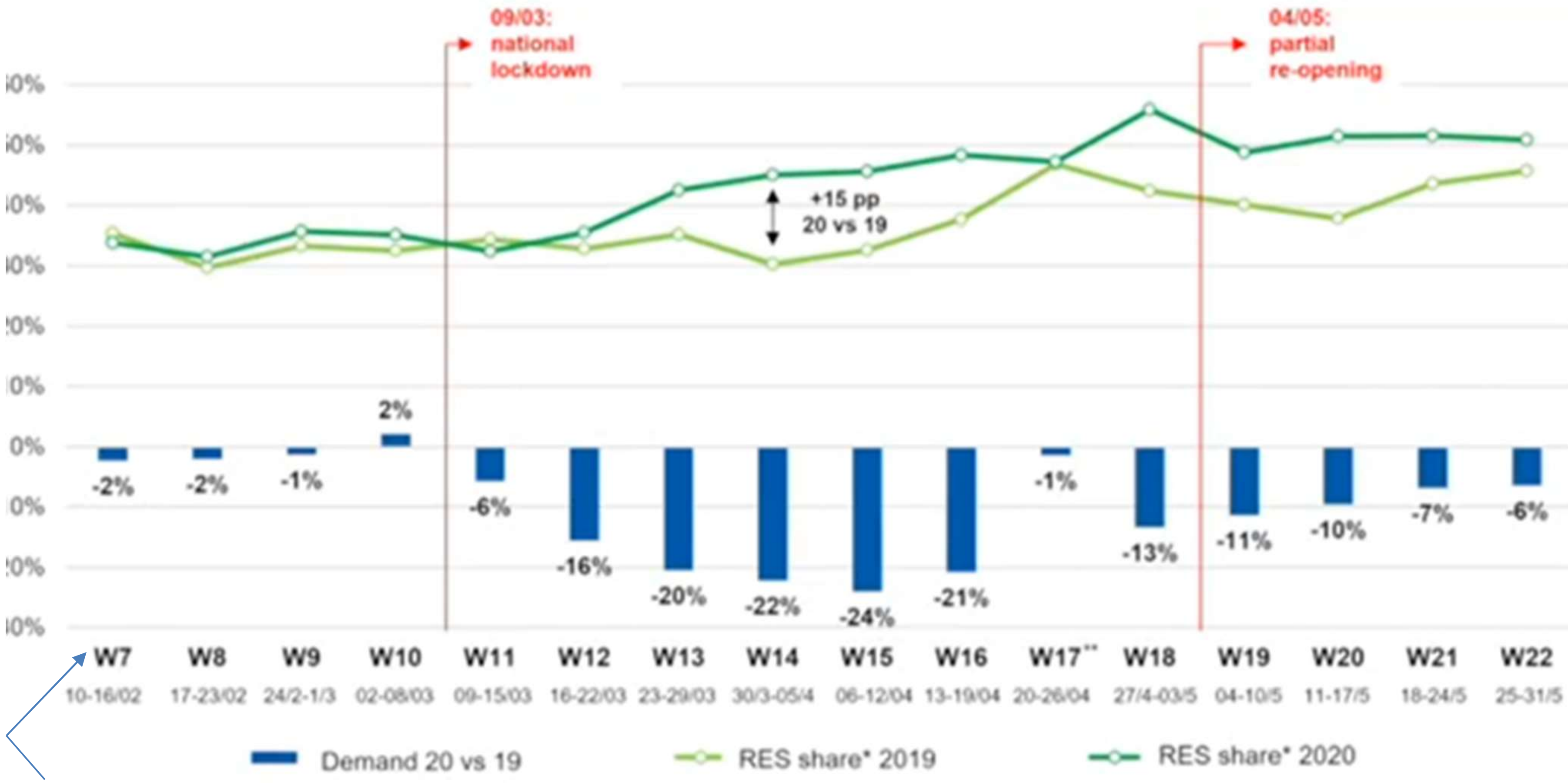
Electricity Demand and Renewable Energy Source (RES) portion 2019 vs. 2020 (to May)



Week 7 in the year, Feb 10-16 2020

COVID-19 Pandemic and Lockdown (Early March 2020 to Partial Industry Opening in Early-May 2020)

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RES includes pumped storage

Figure source: Terna Power Co.

Presidential Policy Directive (PPD21, 2013): Critical Infrastructure Security and Resilience

Energy sector is composed of three interrelated segments: electricity, oil and natural gas. …Many sector owners and operators have extensive experience with infrastructure protection with more recent focus on cybersecurity

National Academy (2017)

"Resilience": Ability to **prepare for and adapt to changing conditions, withstand and recover rapidly from disruptions**. Resilience includes ability to recover from deliberate attacks, accidents, or naturally occurring threats or incidents.

"Resilience" is an emergent property of a system with changing boundary conditions

- Risk Analysis / Pre- Occurrence
- Model for various interconnects may be available for some pre-event assessment, keeping in mind each event may be different and no historical data may be available
    - e.g: Natural Calamity or Pandemic

PPD-21 is infrastructure protection and resilience directive, in the United States, aim to strengthen and secure critical infrastructure.
https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil

National Academy Press: Enhancing the Resilience of the Nation's Electricity System (2017)

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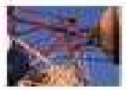
Use of GPS for Timing and Navigation in Critical Infrastructure / Key Resource Sectors in U.S.


Chemical


Commercial Facilities


Communications


Critical Manufacturing


Dams


Defense Industrial Base


Emergency Services

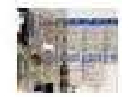

Energy and Power System

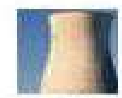
Financial Services


Food and Agriculture

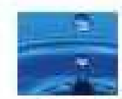

Government Facilities


Healthcare


Information Technology


Nuclear Systems


Transportation Systems


Water Systems


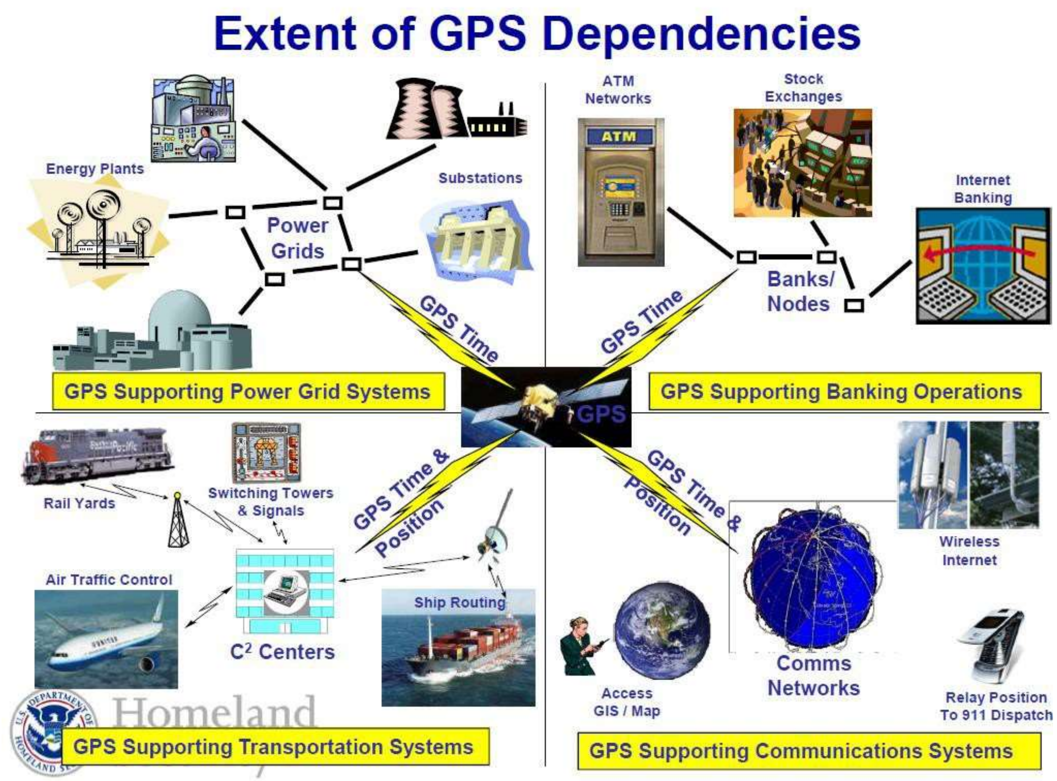
Of the 16 Critical Infrastructure / Key Resource sectors in the U.S., 15 use GPS for timing
GPS timing is deemed essential for 13 of the sectors

DHS – Department of Homeland Security

GPS Operational Need

Critical Infrastructure (CI) reliance on civil GPS and impact of interference largely unknown

- Civil GPS now plays a critical role in modern telecommunications, banking and finance transactions, and electrical power grid operations as a precise and accurate timing source.
- Majority of Nation's16 critical infrastructure sectors would be impacted by an extended GPS signal timing loss



Impacts vary based on threat level

- Transmission line fault detection, synchrophasors, substation control & synchronization
- Protective relays, frequency calculations
- Substation control/re-synchronization
- Disturbance monitoring event recorders
- Metering (Bulk power, customer premise, smart meters)
- Quality of power supply measurement
- EMS / DMS tools
- Distributed energy sources

- Timing requirements throughout the grid vary from 1s to < 1μs
- GPS primary reference for wide-area synchronization at 1μs or less level across the grid
- Few, if any, timing backups with more than a few hours of holdover time at the 1 μs level exist

Source: Homeland Security Advanced Research Projects Agency Science & Technology Directorate, June 2014

NERC Definition of Reliability

A reliable Bulk-Power System (BES) is able to meet the electricity needs of end-use customers even when unexpected equipment failures or other factors reduce the amount of available electricity. **Reliability divided into two categories**:

- **Adequacy**: "…Having sufficient resources to provide continuous supply of electricity at the proper voltage and frequency, virtually all of the time. Resources refer to a combination of electricity generating and transmission facilities that produce and deliver electricity, and demand-response programs … ." Maintaining adequacy requires taking into account scheduled and reasonably expected unscheduled outages of equipment, while maintaining a constant balance between supply and demand.

- **Security**: "…NERC and the bulk power industry have defined system security as the ability of the Bulk-Power System to withstand sudden, unexpected disturbances, such as short circuits or unanticipated loss of system elements due to natural causes. In today's world, the security focus of NERC and the industry has expanded to include withstanding disturbances caused by manmade physical or cyber attacks. …."

https://www.nerc.com/aboutNERC/Documents/NERC%20FAQs%20Aug13.pdf

The electric grid presents a high value target

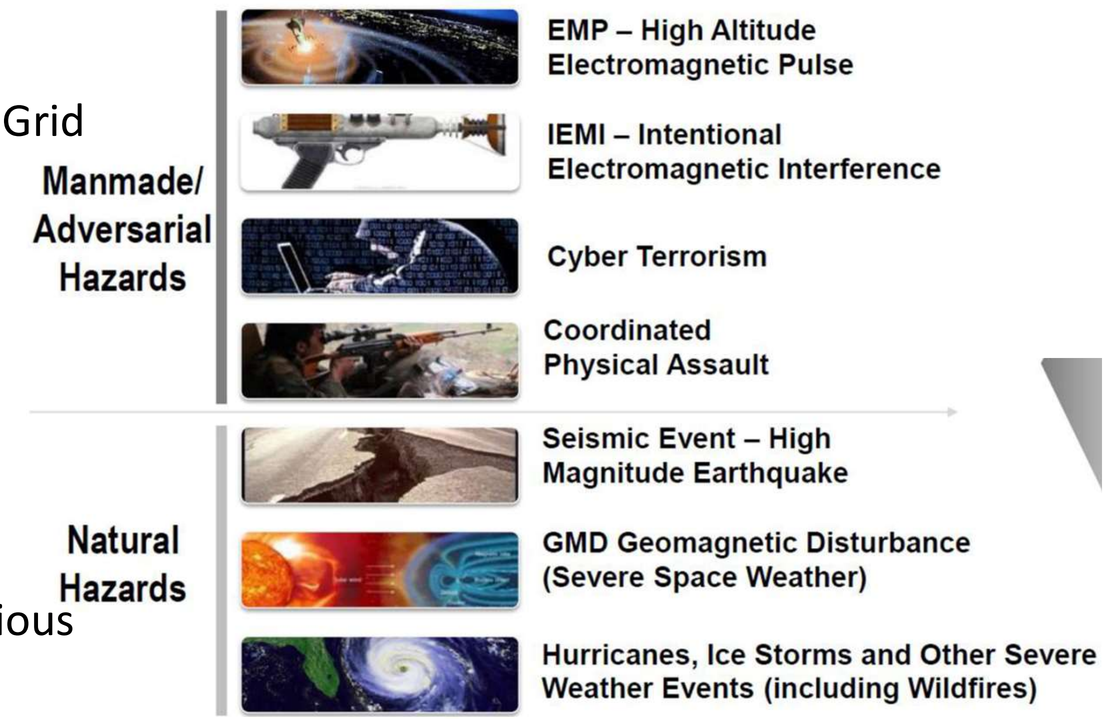
- Most physical assets of the grid are accessible
- Adversaries have capacity to do major damage

❑Reliability

- ➢Metric for operational performance
- ➢Higher probability with lower consequences
- ➢More predictable and repeatable
- ➢Deterministic –It's Yes or No
- ➢Focuses on impact to the Transmission Grid
- ➢Generally dismisses severe events

❑Resilience

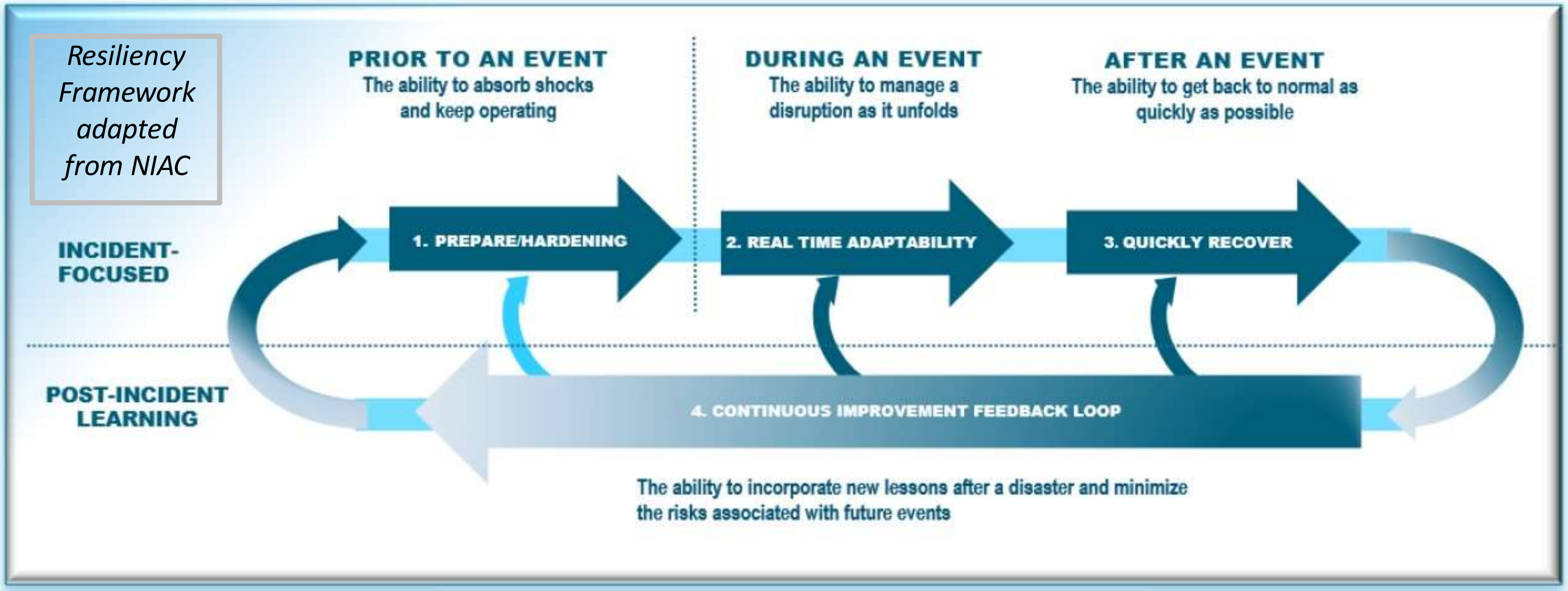
- ➢Ability to withstand and recover from abnormal events
- ➢Greater consequences with unknown probability, less predictable
- ➢Risk based (resilience in the face of various events)
- ➢Confidence level specified (probabilistic vs. deterministic) – not yes/no
- ➢Focuses on impact beyond the grid
- ➢No well established scale of events or metrics



Resilience Framework

- **Readiness**
  - Evaluate risks
  - Develop strategies
  - Harden facilities
  - Plan for continuity
  - Spare strategy
  - Plan to manage event
- **Response**
  - Adapt in real time
  - Ride through
  - Restore rapidly
  - Navigate new normal
  - Reconfigure as needed
  - Manage event
- **Recovery**
  - Replace failed assets
  - Restore full capacity
  - Reestablish reliability
  - Replenish spares
  - Review learning & adapt future plans

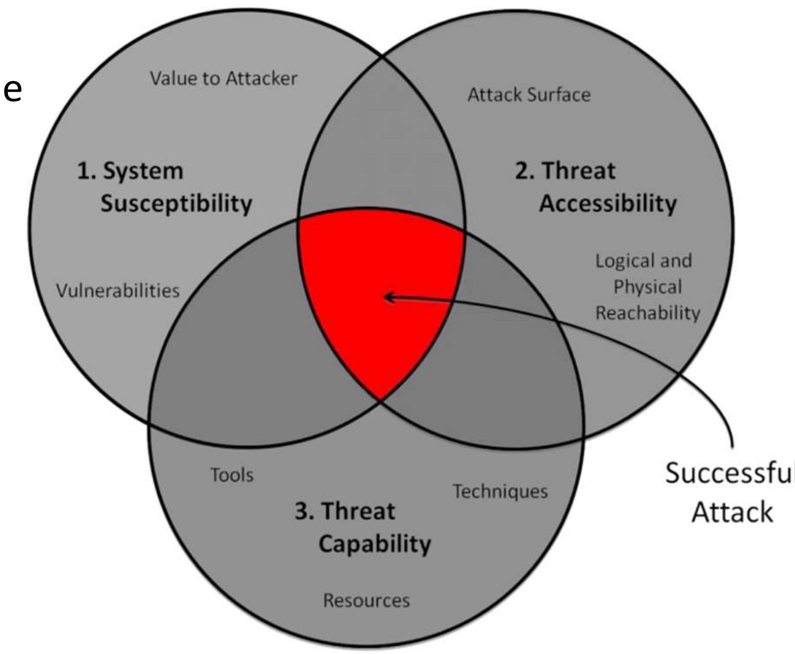
Resiliency Framework adapted from NIAC



NIAC - National Infrastructure Advisory Council, Homeland Security

Transmission System Risks

- **Consequences vary by load served**
  - Probability of consequence is a function of vulnerabilities and threats
  - Requires comprehensive analysis and modeling
  - Innumerable possibilities, assumptions must be made
- **Vulnerabilities vary**
  - Design standards in place when installed
  - Geography and economic factors
  - Assets visible, unattended, exposed to public
- **Threats vary by geography**
  - Natural disaster hazards vary by region
    - Severe terrestrial weather
    - Space weather – geomagnetic storms
    - Earthquakes, wildfires and volcanoes
    - Human threats:
      - Cyber/physical attacks
      - Electromagnetic pulse and interference
- **Impact and Frequency vary**
  - Lower impact and higher frequency – e.g., thunderstorms
  - "HILF" events - High impact low frequency
    e.g., extreme solar storms



Resilience vs. Reliability

- Resilience encompasses hazards and events, including high-impact low-probability events commonly excluded from reliability calculations
- Resilience quantifies the states in which system ends up (like reliability), as well as transition times among the states.
- Resilience aims to capture both the effects on customer (like reliability), effects on the grid operators and staff, and effects on the infrastructure itself (possibly on two or more time horizons).
- Resilience ties with risk-based approaches to power system quantification
- Challenge of obtaining adequate statistical parameters remains a key obstacle.
- From system Planning and Strategy can be significantly different than (N-1), (N-1-1), and (N-2)-based reliability-driven investment decisions.
- Resilience-driven investment decisions require more detailed characterization of the preparation process prior to any events occurring, the operational process during the event, response process after the event.

For distribution systems, it is more resilience-effective to make the system smarter and more responsive to extreme disasters than making the system more redundant in terms of energy flow-level components.

Further reading, IEEE PES TR-65; The Definition and Quantification of Resilience, April 2018

GMD: Impact and Motivation Study

Historic GMD Events:

- Most documented geomagnetic storm for power systems:

  On March 6, 1989, a very large solar flare occurred on the Sun. Then, a coronal mass ejection caused a severe storm which struck Earth on March 13. Caused widespread outages on the Hydro-Québec power system. Nearly 6 million people were without power for 9 hrs. The net cost is about $13 million.

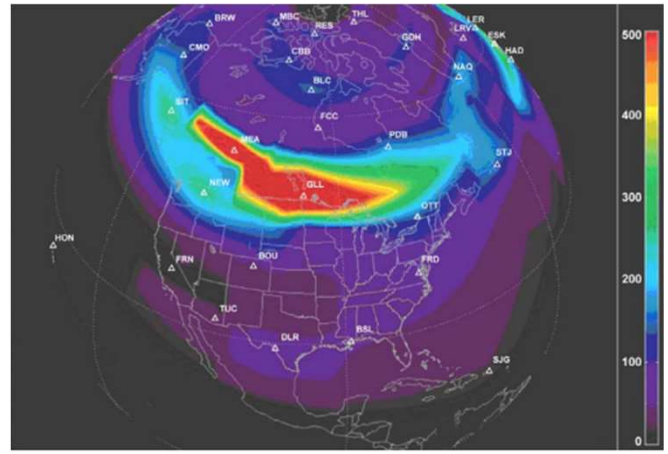
- **Typical event in the 21st century**:

  From mid-October to early November 2003, a series of geomagnetic storms called "Halloween solar storms" affected satellite-based systems and communications. Also, it caused a one-hour-long power outage in Swedish and Scottish power systems and 50,000 people without power.

- NERC considers GMD as a High-Impact, Low Frequency Event (HILF)

- 09/2016, **NERC TPL-007-1**: Transmission System Planned Performance for Geomagnetic Disturbance Events was approved by FERC Order 830:

  (1) Conduct impact assessments of benchmark GMD
  (2) Take actions to mitigate adverse GMD impacts
  (3) Collect GIC and magnetometer data

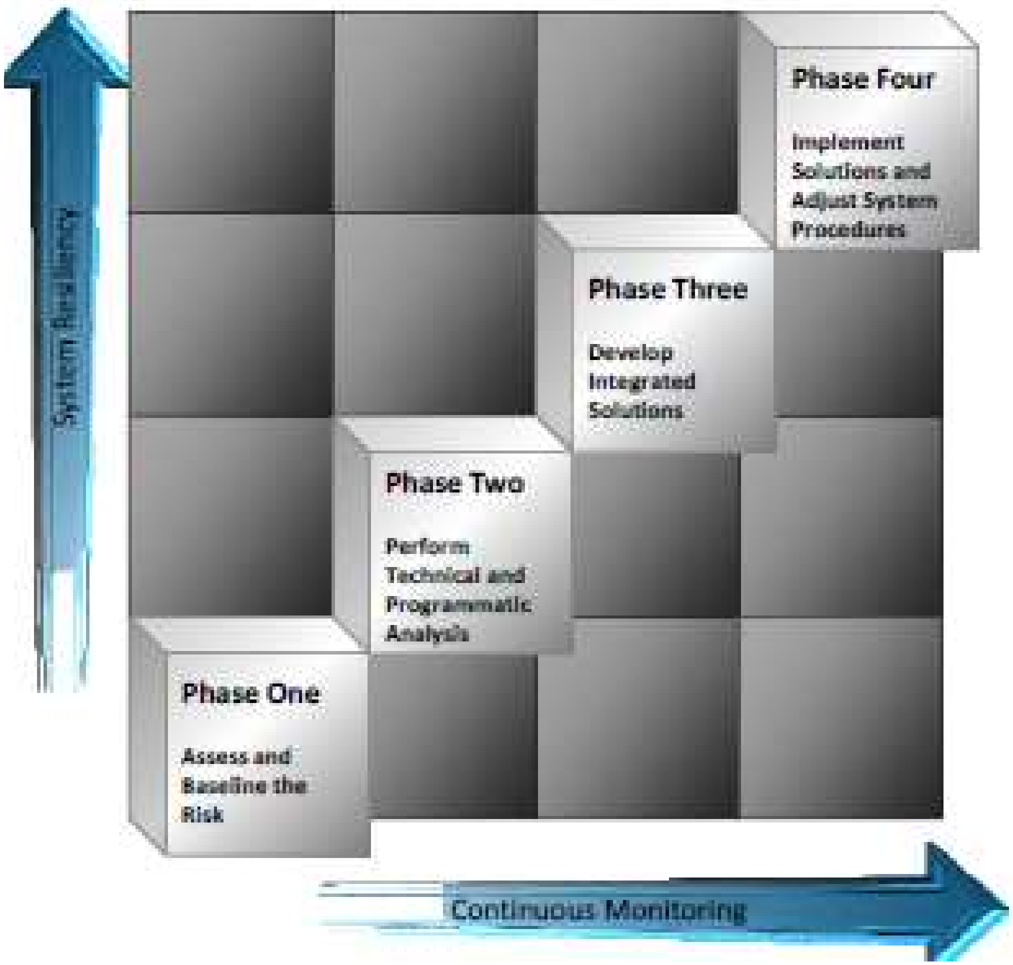


GMD Intensity on March 1989 (Source: Metatech Corp.)

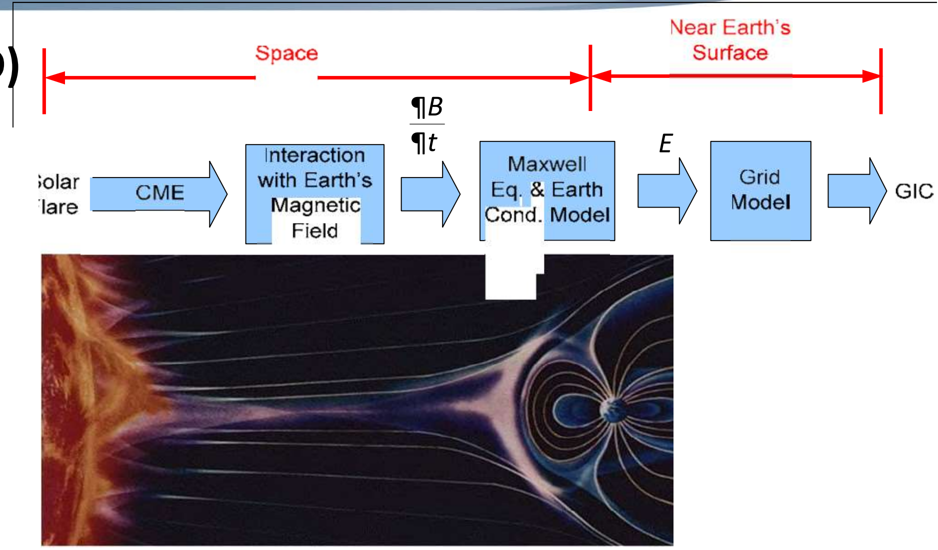
Composite image showing aurorae over northern Europe, taken by DMSP on October 30, 2003

- 09/2016, **FERC Order 830**: Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events

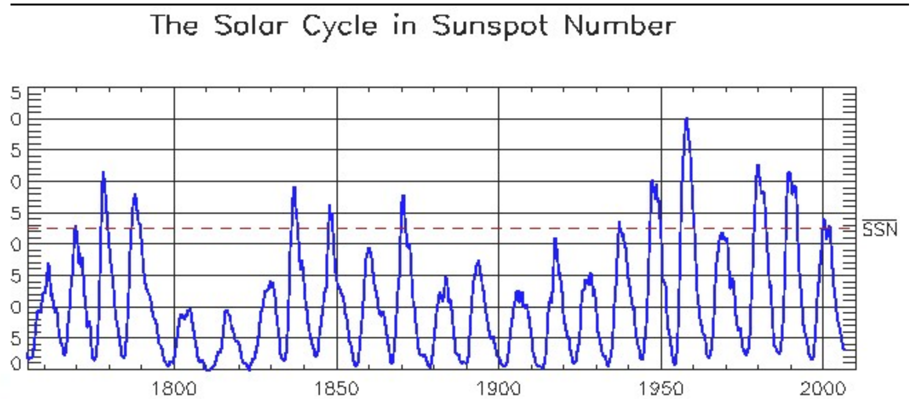
Resilience - Geomagnetic Disturbances (GMD)



Risk Management – Phased Approach



Storm interaction with Earth and transmission System

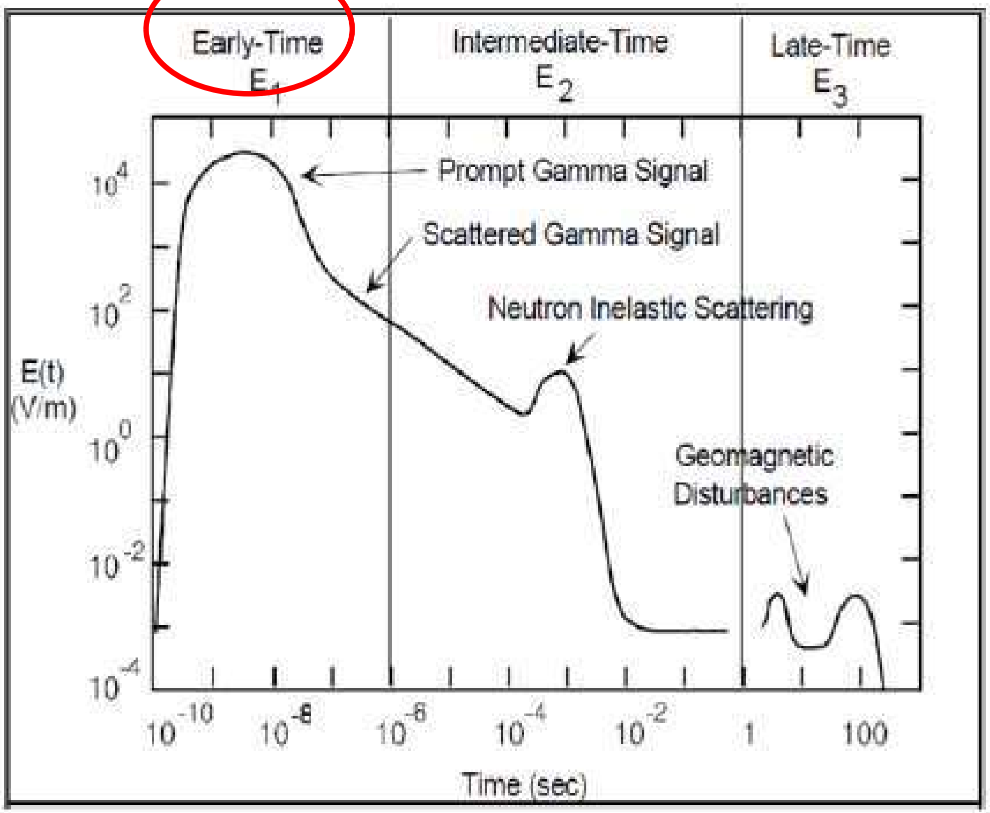


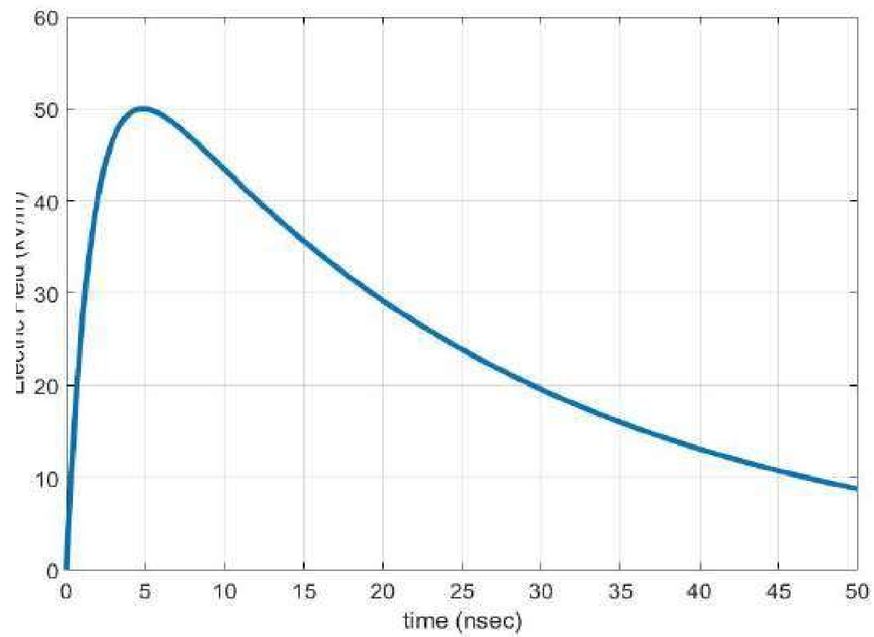
- The Sun undergoes an 11-year cycle, where the polarities of its north and south poles reverse
- Probability of a solar storm occurrence is greater during the peak of the solar cycle. Most solar storms and CMEs occur during a 4-6 year period.
- A number of severe GMD with impact to electric power grids (e.g., 1859, 1921, 1989) have occurred during the peak of the solar cycle with the high sunspot number

GIC – Geomagnetically Induced Current
CME - Coronal Mass Ejections

HEMP – High Altitude Electromagnetic Pulse

- Short burst of electromagnetic energy
- Depending on its source, could occur as a radiated, electric, or magnetic field, or a conducted electric current
- Could be natural or an event detonated at a high altitude by human
- Typically, the higher the altitude, the more HEMP damaging to electrical and electronic components
- Similar Effects as a lightning strike





Main Threat From a HEMP – E1 Pulse

Most common, Double exponential pulse

https://en.wikipedia.org/wiki/Electromagnetic_pulse

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End of Module 1 – Energy Diversity, On-Going COVID-19 Global Pandemic and Operational provisions, Critical Infrastructure / Key Resource Sectors, Reliability, Resilience

Module 2, Hybrid Power Systems

What are the Four R's in Modern Grid?

Reliability

Resiliency

Renewable Resources?

Relevancy / Role as Utility

The energy world continues to evolve

Utilities, ISOs, Manufacturing Play Vital roles in a clean, sustainable future

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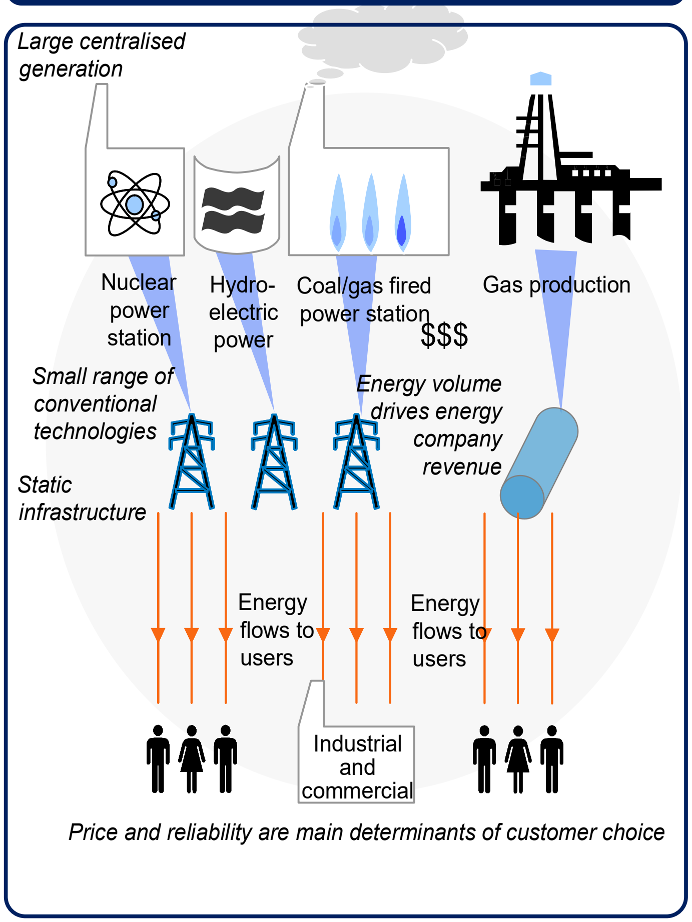
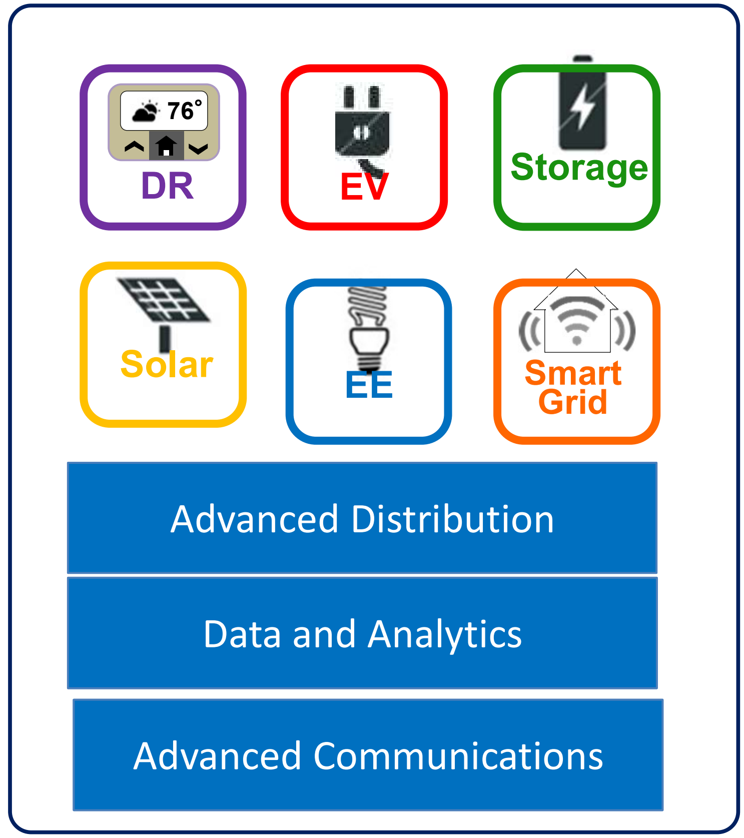
Traditional energy market



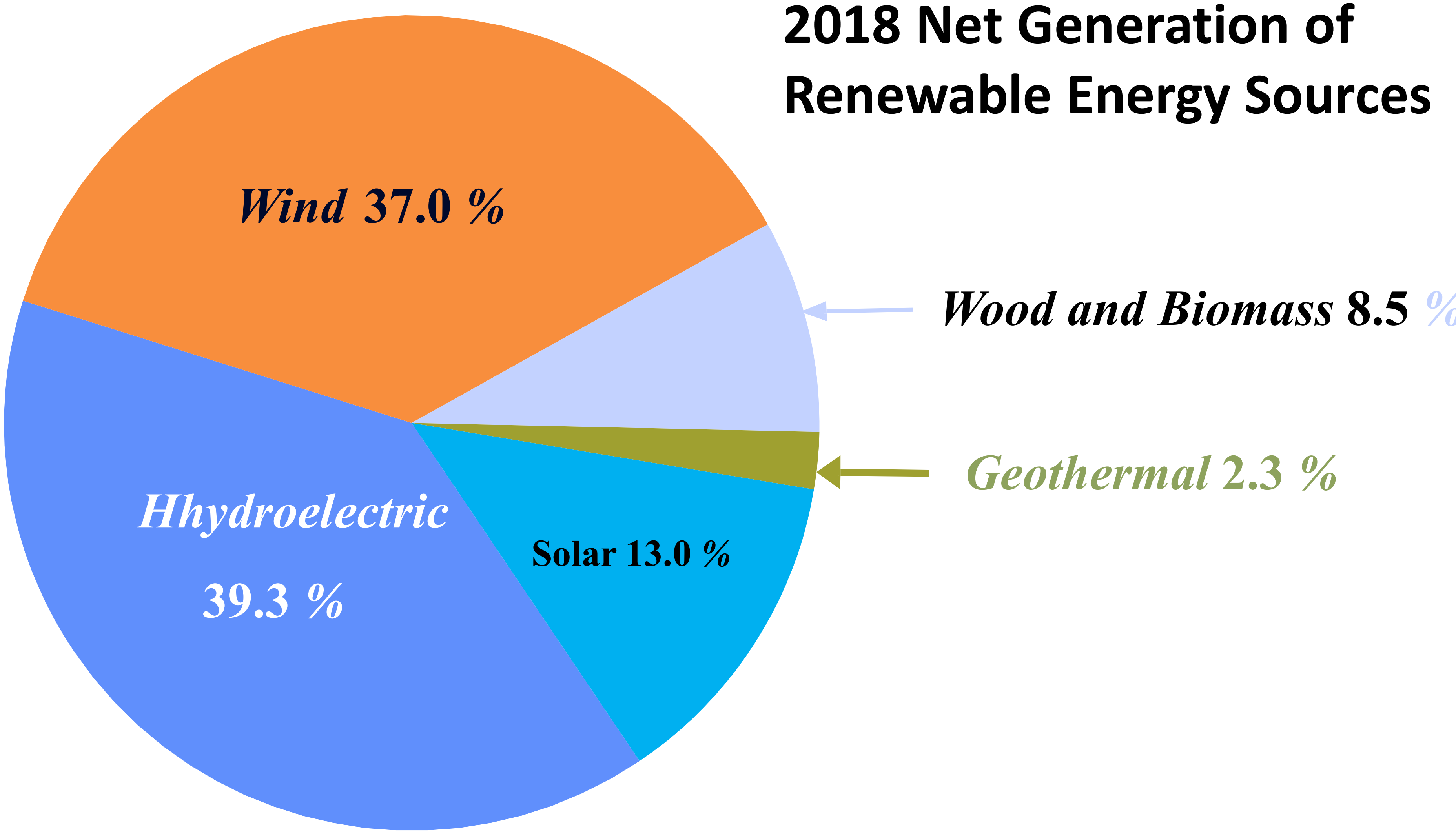
Today's evolving market



The energy landscape transforms more rapidly in the next ten years than in the previous one hundred

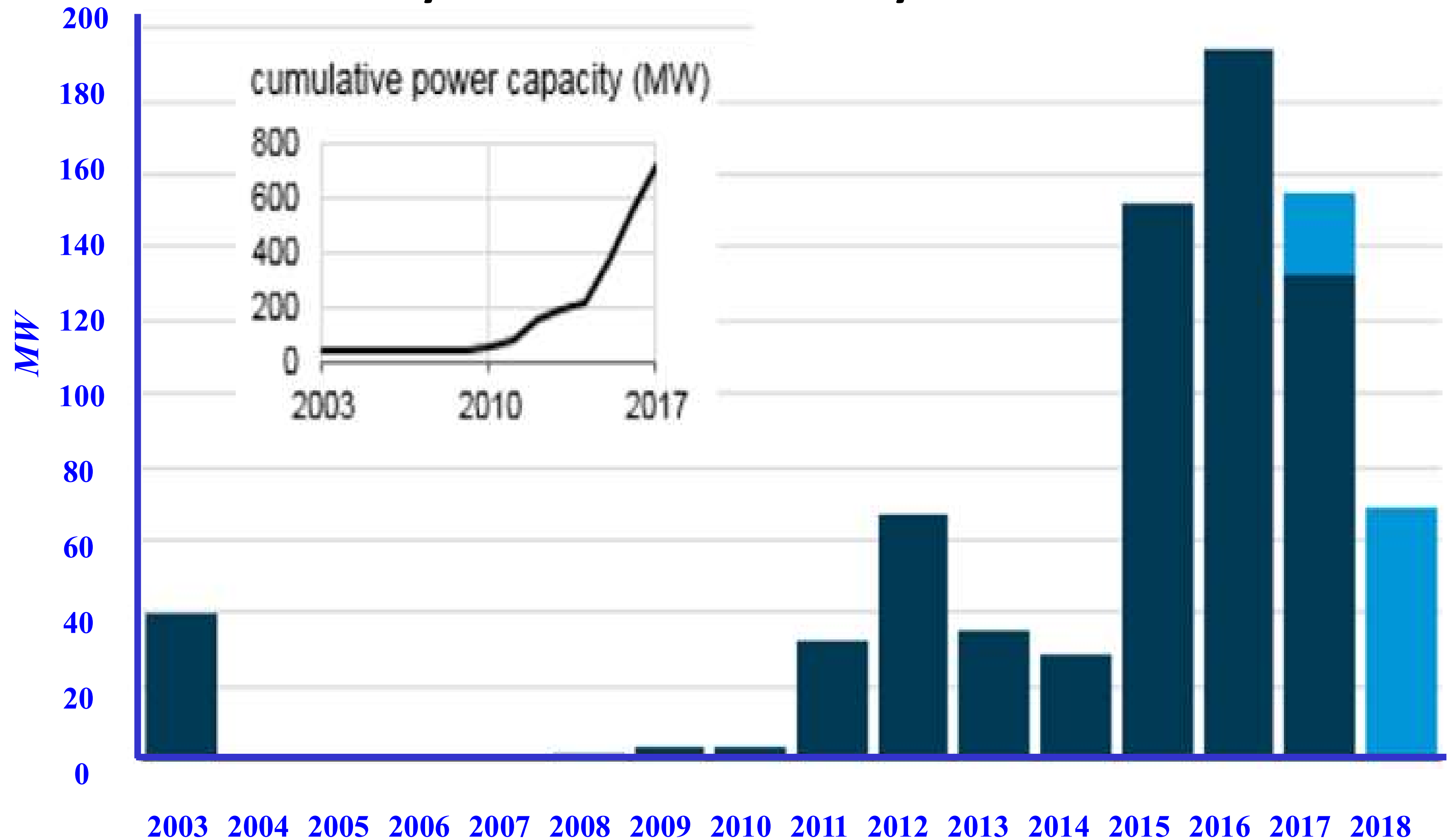
Somehow the utilities have to transform their operations, improve network efficiency, responsive to customer experience, and reduce cost while never letting the lights go out

2018 Net Generation of Renewable Energy Sources



Source: EIA March 29, 2019; https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_1_01_a

US Utility-Scale Annual Battery Installations



Source: EIA January 8, 2018, https://www.eia.gov/todayinenergy/detail.php?id=34432

Battery Energy Storage Systems (BESS), Market Outlook and Risk

Utility Investment Value Proposition and Life Cycle Challenge

Public policies coupled with technological advancements and declining costs

July 10-2020, Federal Appeals Court DC, upheld FERC order 841, Transmission Access Policy Study [1]

- Allows TO in US to open their markets for energy storage including aggregated batteries at the distribution grid or BTM (Behind the meter)
- Ruling includes FERC having jurisdiction over how energy storage interacts with interstate transmission markets under FERC jurisdictions even if those systems are interconnected to the grid under regulations set by the states

Newton-Evans Research Co.[2] , June 2020

- Cumulative 35.5 GW of new energy storage built for critical infrastructure through 2027
- The U.S. energy storage market will grow to more than $5 billion by 2024 - Eight-fold increase from 2019 levels
- Improving reliability is a common concern for mission-critical installations and commercial and industrial (C&I) customers, e.g. Hospitals, large data centers, financial institutions, and complex manufacturing.
- Lithium-ion (Li-ion) batteries are the leading technology for both utility-scale and C&I energy storage
- Li-ion batteries are used in electric vehicles (EVs) and other consumer electronics, results in declining costs
- Risk: Fire, Similar to cell phones and other consumer goods catching fire, the utility sector is no exception
- The fire risk of batteries is monitored by the National Fire Protection Association in the US
    - 2018, South Korea reported 23 fires at utility BESS sites
    - The U.S. has reported at least three significant storage-related fires
        - ✓ 2019 (April), APS (Arizona Public Service), Fire and explosion at a 2MW battery Li-ion BESS
        - ✓ 2012, APS a battery fire in a 1.5MW BESS
        - ✓ 2012, Kahuku wind farm in Hawaii, Fire destroyed a 15MW BESS

1. https://www.cadc.uscourts.gov/internet/opinions.nsf/E12B1903B0477E21852585A1005264D7/%24file/19-1142-1851001.pdf
2. Storage Revolution, T&D World, June 2020

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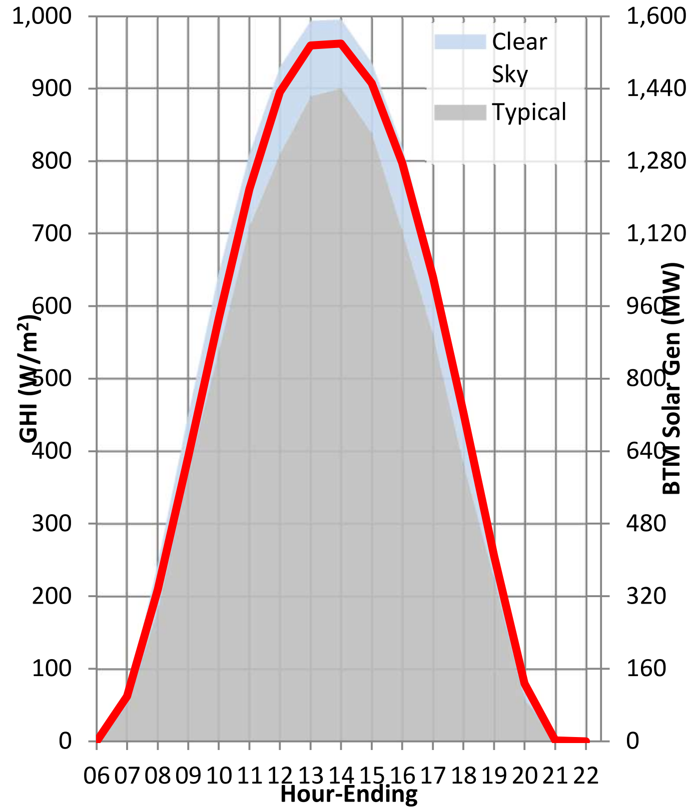
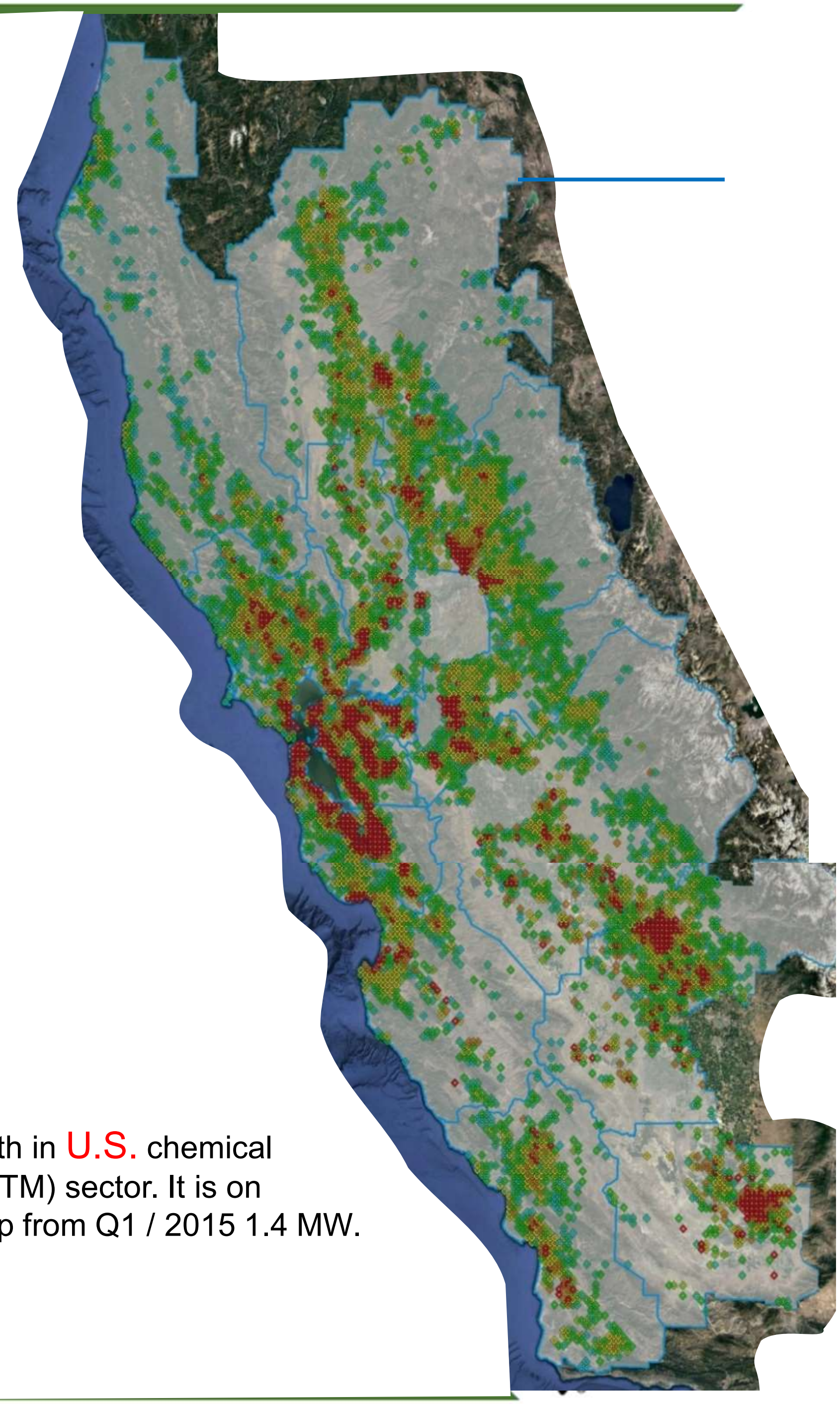
BTM Solar





Northern and Central California Service Territory: The second largest growth in U.S. chemical energy storage in Q2 /2015 was in the non-residential, behind-the-meter (BTM) sector. It is on upward trajectory. Almost 5 MW was the biggest quarter an over 300% jump from Q1 / 2015 1.4 MW.

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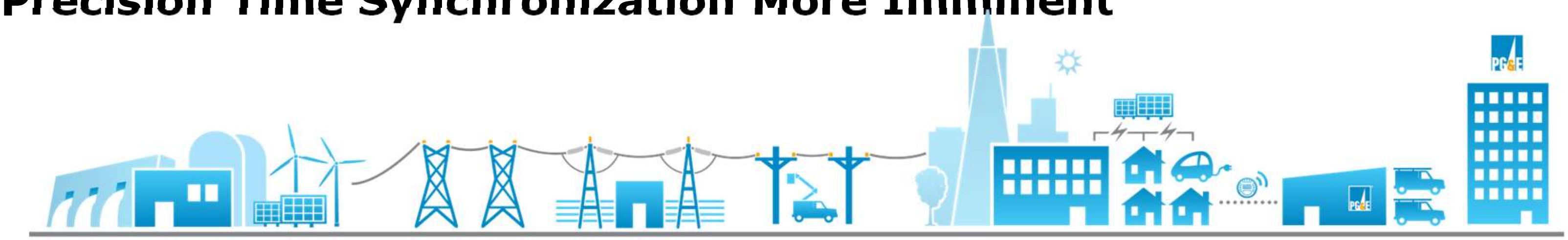
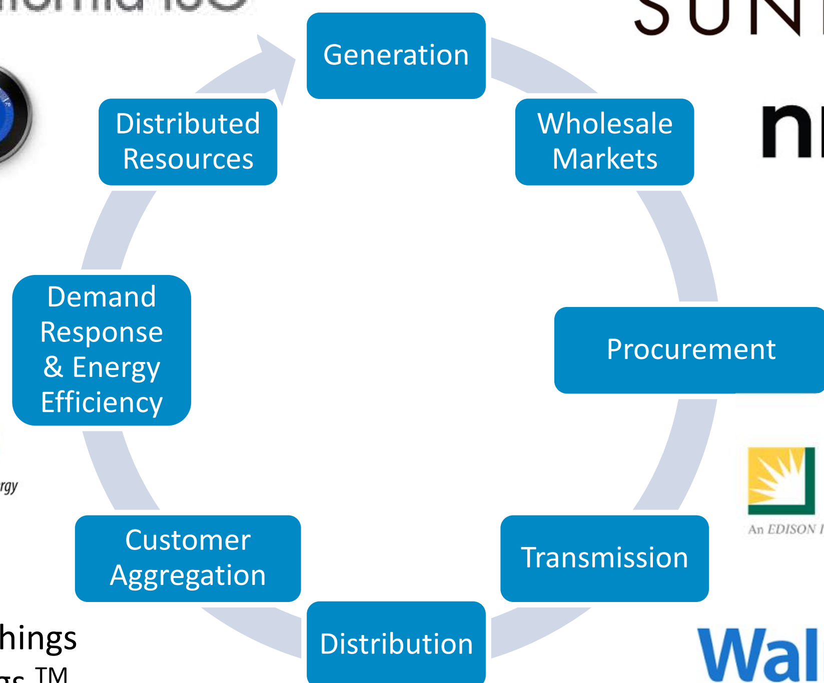
Energy Landscape Transition; More Distributed & Dynamic

Precision Time Synchronization More Imminent



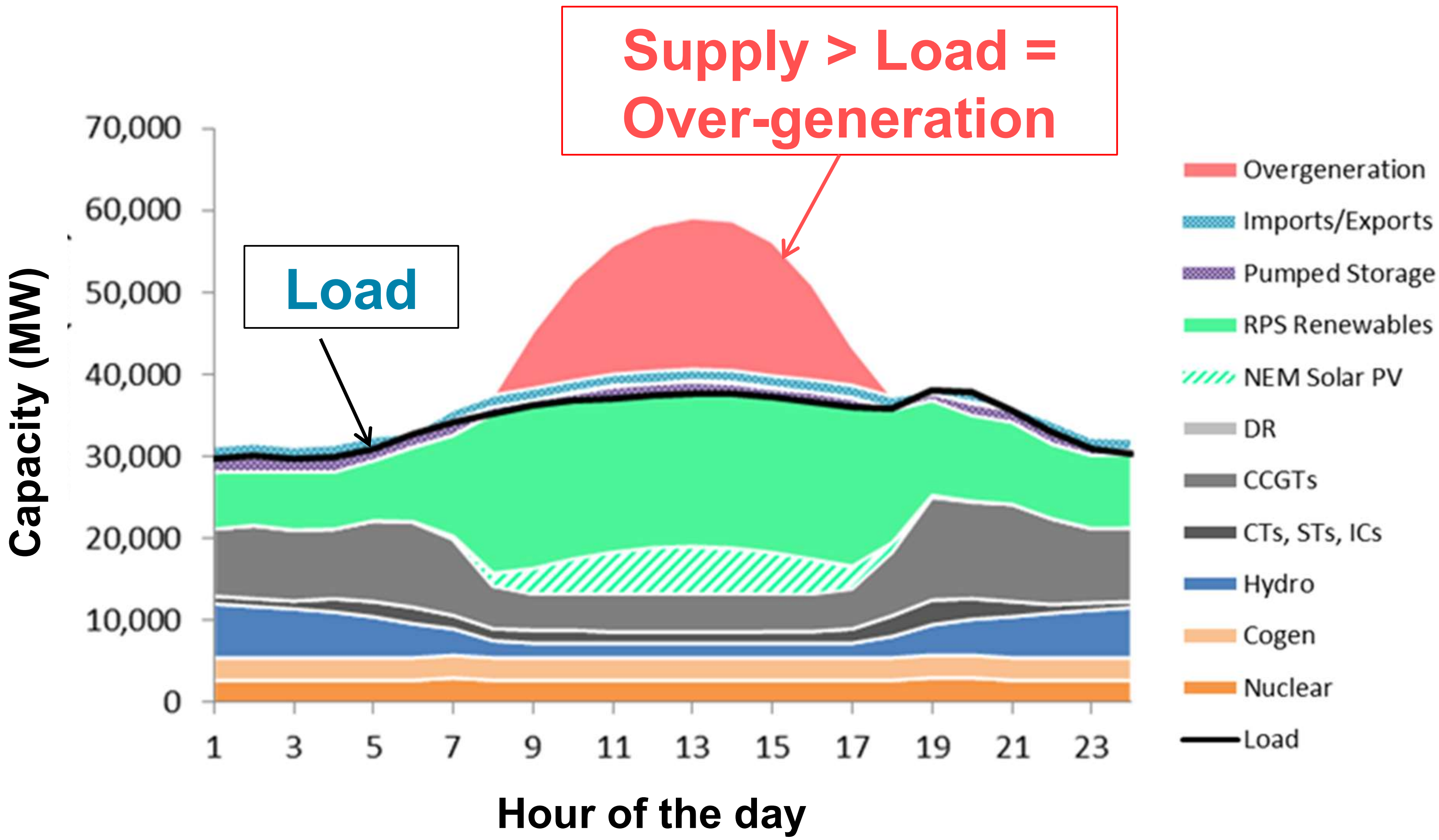
Generation → Wholesale Markets → Procurement → Transmission → Distribution → Customer Aggregation → Demand Response & Energy Efficiency → Distributed Resources



IoT – Internet of Things
GoT - Grid of Things ™

Over-generation

Generation mix calculated for April Day in 2030 with 50% RPS



RPS – Renewable Portfolio Standard

The Control Shift

Distribution | **Bulk-Power System**

10%

90%

- Variability absorbed by load variability
- Operational characteristics do not permeate to BPS

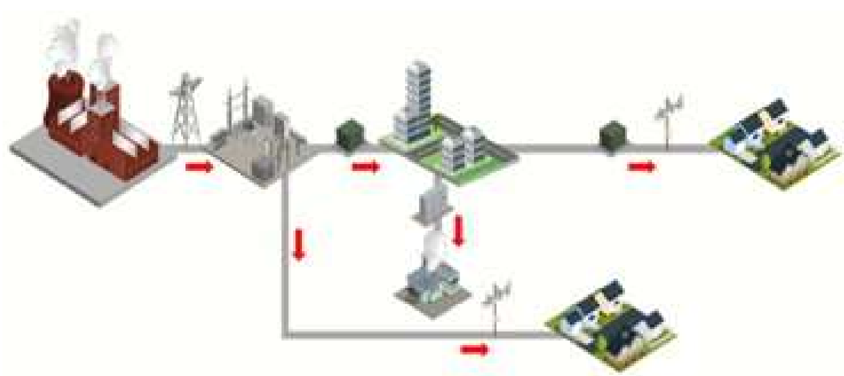
- Supports system inertia and recovery modes
- Dispatchable based on demand
- Centralized to System Operator

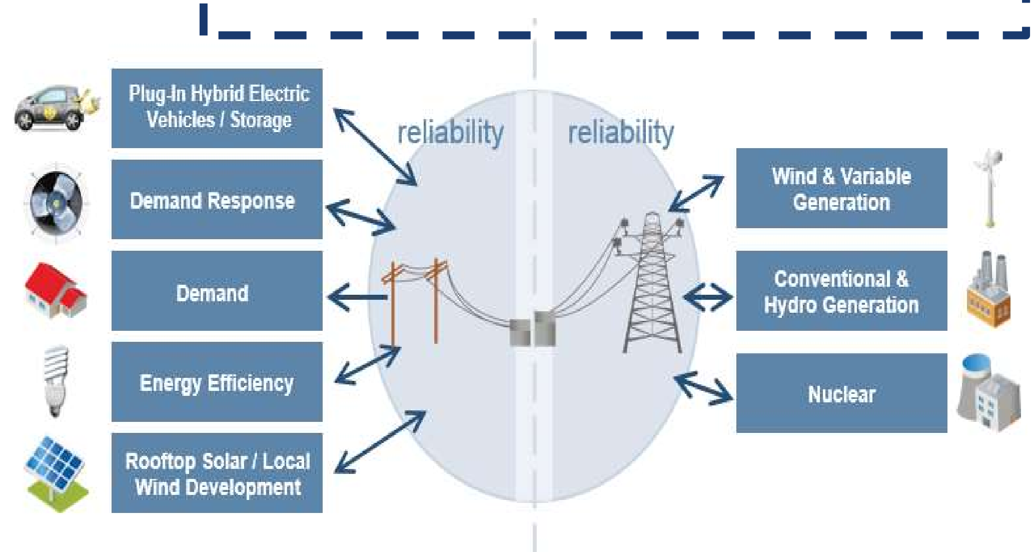
Distribution | **Bulk-Power System**

- Supports electricity services
- Provider of long-haul power transfers
- Reliability backbone

50% 50%

- DERs must act as a system resource
- Storage, curtailment, coordination, grid support, and control
- Operator or aggregator function may be needed





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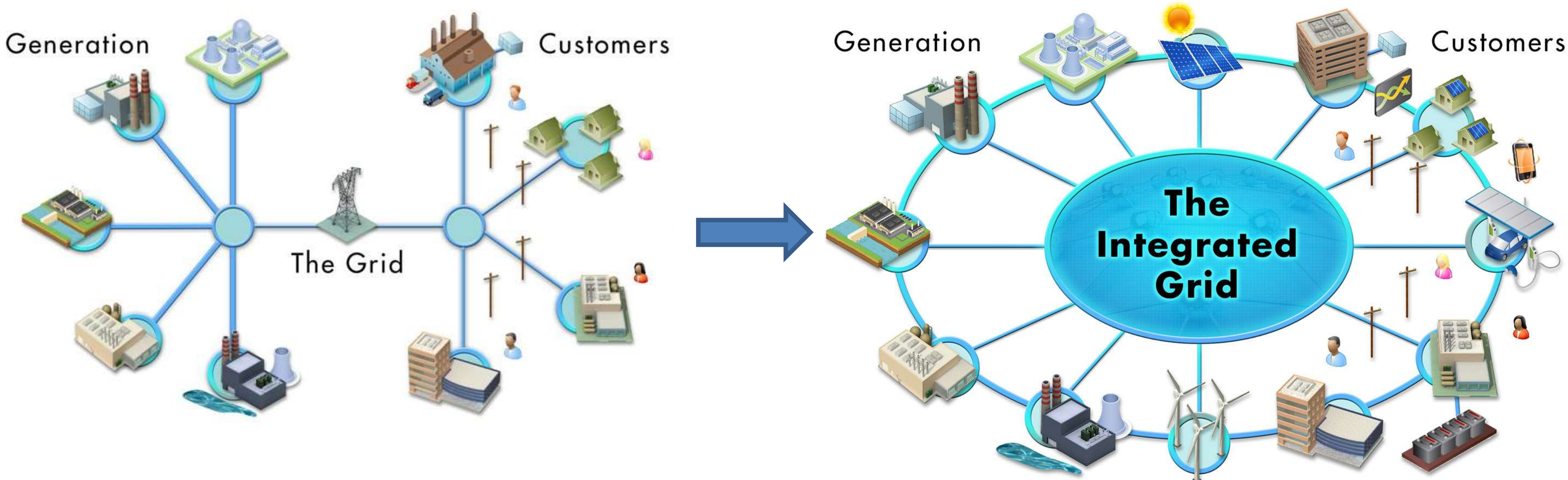
The Electric Grid: Past, Present, and Future

Past

Future
Present Path



Core Mission:

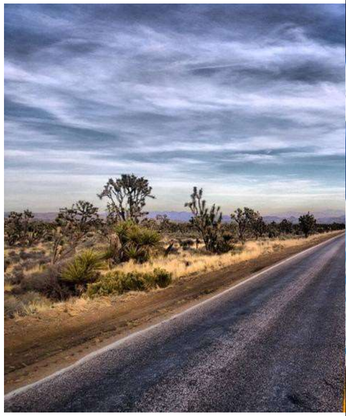
1. Safe
2. Reliable
3. Affordable

Core Mission:

1. Safe
2. Secure
3. Time and Frequency Synchronized
4. Reliable
5. Affordable
6. Environmentally Responsible
7. Integrated
8. Connected, not islanded
9. Resilient
10. Flexible

System Operator Goal: ‘Stay on the Road!’

One of the Past, Rural Roads Today **Transformation to Seamless Access Today**



Transition to Fr

Excludes impact due to Ongoing Pandemic and shelter in place

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Another Example, Air Traffic Controllers (ATC)

Markets for a Grid in Transition

Resource Flexibility

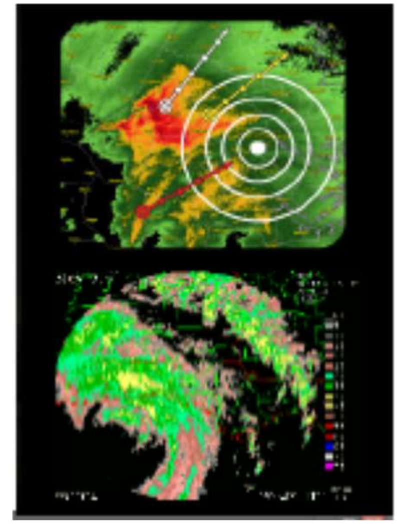
- Qquality of bending easily without breaking
- Incent flexibility through Products, Pricing, and Settlements
- Focus on the integration of DERs and Energy Storage, More Frequent Interchange Scheduling, and Price Formation

Grid Resilience

- Includes: (1) the capacity to recoverquickly from difficulties, and (2) the ability to anticipate, absorb, and adapt to the impacts of disruptive event
- Focusing on ways that markets can incent investments that will support grid resilience

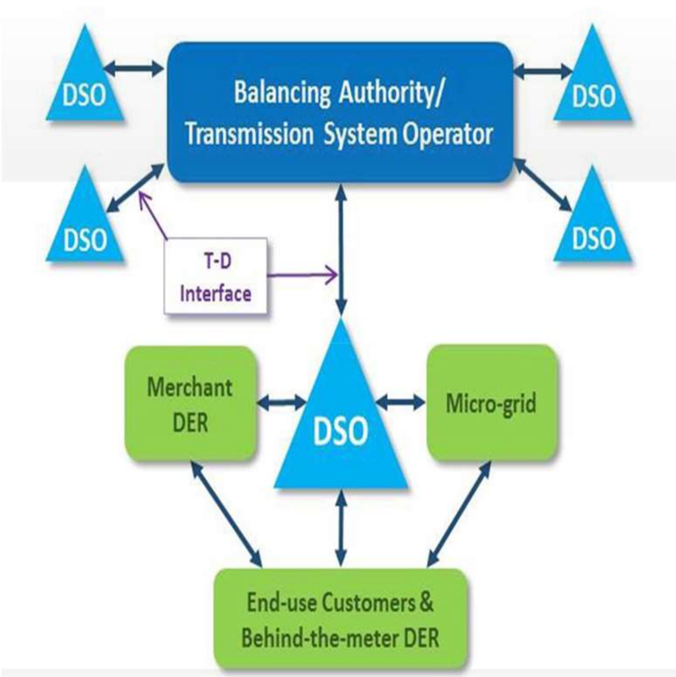
Advanced Real-Time, Analysis, and Ancillary Apps

Distribution Management System (DMS) and DSO Interface



Real-Time:

- Topology Processor (TP)
- Integrated Volt/VAR Control (IVVC)
- Fault Detection / Location, Isolation, Restoration (FDIR/FLISR)
- State Estimation (ES)
- Load Estimation (LS)



Analysis:

- Power Flow (DPF)
- Short Circuit Analysis (SCA)
- Optimal Feeder Reconfiguration (OFR)
- Optimal Capacitor Placement (OCP)
- Feeder Relay Protection Coordination

Ancillary:

- Distribution System Operator (DSO) Support
- Maintenance and Outage Planning (M&OP)
- Power Quality Analysis (PQA)
- Retail Power Marketing (RPMR)
- Coordination with Adjacent Systems
- Distribution Simulation
- …………

Changing Load and Resources

Load composition changing
- Electric vehicle charging
- LED lighting
- Variable speed drive motors

Distributed Energy Resources
- Inverter-based resources
- Roof-top solar panels, Micro turbines, Small wind turbines

Load becoming disorderly?
- Load models no longer adequate for simulation

Changing Resources

Changing Dispatch Mix
High penetration of renewables – variable resources
Minimum generation levels on conventional units
- Generation scheduling

Ramping needs increase for load following

Retirement of large fossil-fired generation plants
Loss of dynamic reactive support for voltage control
Possible reduced system inertia
Lower levels of synchronizing torque

Changing System Inertia
Tradeoff between inertia and Primary Frequency Response

Risk to Reliability

Changing Resource Mix
- Potential for lower inertia with retirement of coal and oil-fired synchronous generators
- Higher penetration of renewables with potentially lower frequency response
- No assurance of adequate inertia or frequency response capability for some resource dispatch scenarios
- Trade-offs between inertia and Primary Frequency Response

Conservative approach
- All resources should have frequency responsive capability to assure that frequency response is available for any resource dispatch.

Inter-related technical areas:

- **Grid Performance and Reliability:** Maintain and enhance efficiency and reliability of electricity T & D grids in a cost-effective, safe manner with hundreds of gigawatts of DERs deployed onto the electricity grid
- **Dispatchability:** Ensure DER is available on-demand, when and where it is needed, in the desired quantities, and in a manner that is comparable to or better than conventional power plants.
- **Address intermittency;** e.g. Storage
- **Power Electronics:** Develop inverters/converters and other devices that maximize the power output from DERs and interface with the electricity grid (or end use circuits), while ensuring overall system performance, safety, reliability, and controllability at minimum cost.

DERs (and PVs) are key drivers for transformation of the electric power grid from today's centralized, static, and rigid system towards a more distributed, dynamic, and flexible system

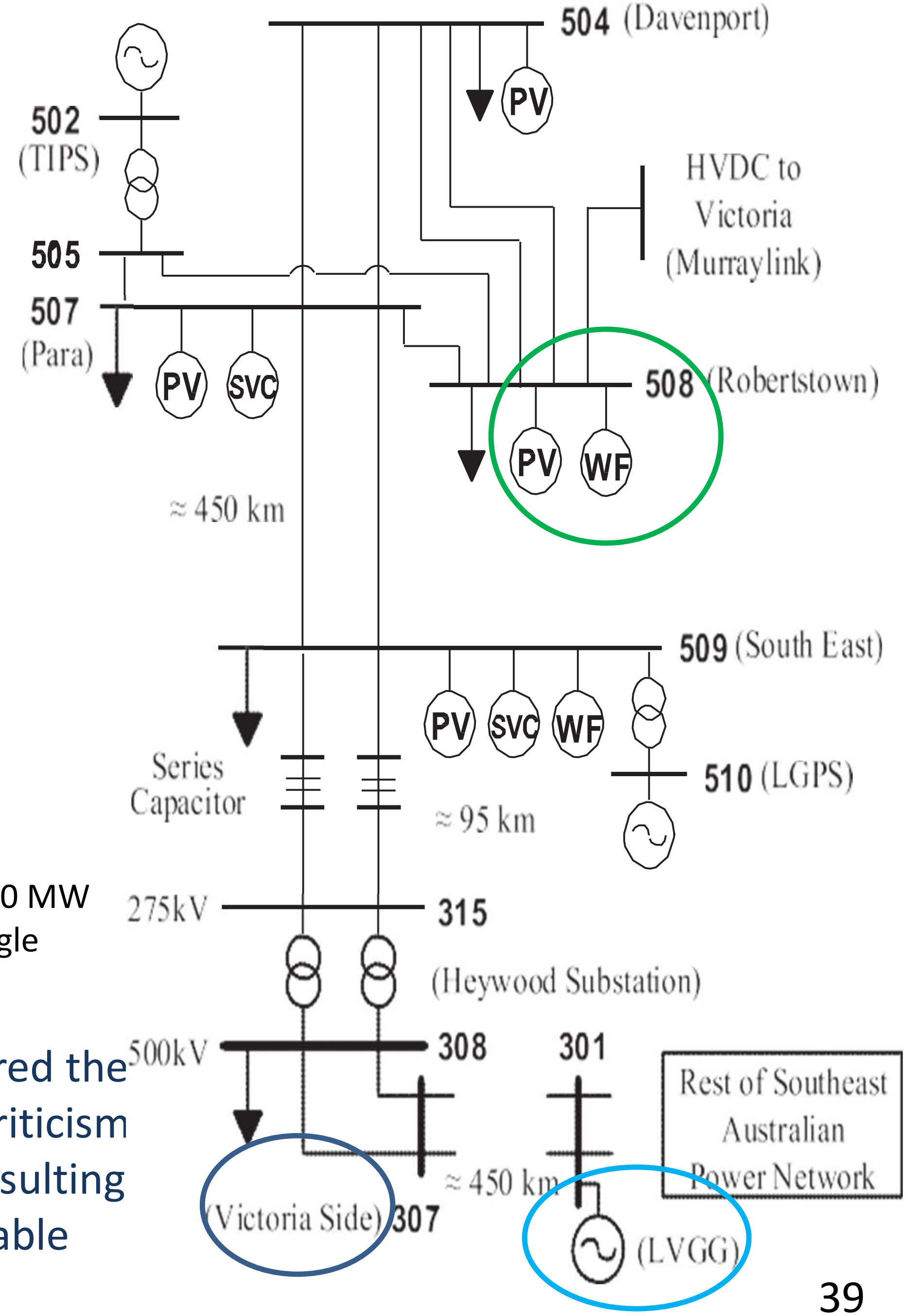
Other Challenges

- Distribution system planning and operations are fundamentally different.
- Bi-Directional Power Flow: Historically, electric power grid has been engineered for power flow in one direction
- The present distribution system's primary voltage control equipment are Voltage regulators (VRs), load tap changers (LTCs), and capacitor banks (CAP banks), which are intended to manage one-way power flow
- Integration of distributed PV may cause excessive (in some cases several times more) operations of these assets compared to baseline operations without PV.

South Australian blackout September 28, 2016

1. Severe storm damaged several remote transmission towers late afternoon in SA
2. A number of wind farms separated (located at Bus 508), because these wind plants had set a limit of two-to-six faults per minute in their control systems
3. A sustained wind power reduction of 456 MW
4. Increased flow beyond the interconnection capability

a) Eventually, the SA grid separated from the rest of the interconnected system, and collapsed soon afterwards resulting in state-wide blackout
   - About 1.7 million people into darkness
   - Financial loss of ~ 367 million Australian Currency



Prior to the Blackout

- Wind and PV power provided ~ 50% of the total demand
- Conventional synchronous generation ~ 18 %
- Imports ~ 32% Power, from the neighboring state, Victoria (VIC) through the Heywood AC interconnection

Following Black start and Restoration

Adjusted Reserves, September 30-October 6

- Increased contingency reserves, Victoria to SA flow limited 350 MW
- Added magin on the Heywood Interconnector - Maximum single credible contingency limited to 240 MW

Proliferation of renewable energy in SA is considered the main reason for this catastrophic blackout. Such criticism will hinder deployment of renewable resources resulting in moving away from meeting the national renewable energy target in Australia

1. Over-voltage issue after network separation: Two units disconnected by operators to mitigate OV resulting in further reduction of available "Sources"

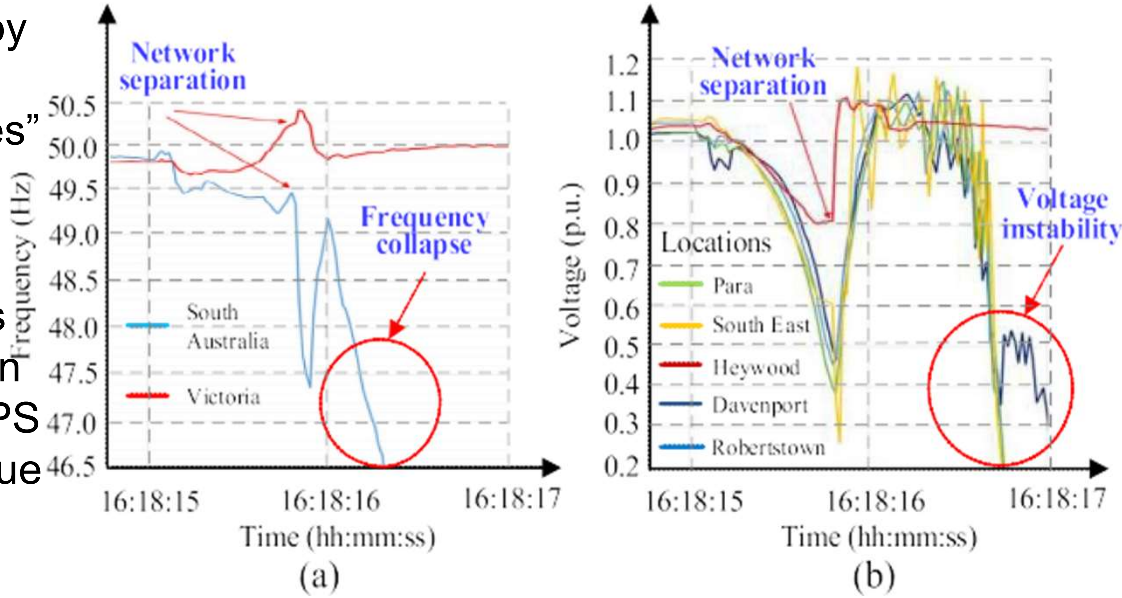
1. High ROCOF induced pole slip concern. The period after system separation, the average ROCOF was as high as 6 Hz/s (3 times higher than test reports), and two out of three TIPS units (Bus 502) were disconnected due to unknown lock-out protection

3. UFLS malfunction due to frequency dip: After the network separation, there is unexplained frequency dip (around 47.5 Hz), and soon afterwards a frequency surge follows.

    - UFLS timer may have initiated and then quickly reset the timer as the measured frequency recovered. Once the frequency drop re-triggered the UFLS timer again, there was not enough time any more for the operation of UFLS to save the SA network. Suspect rapid load variations

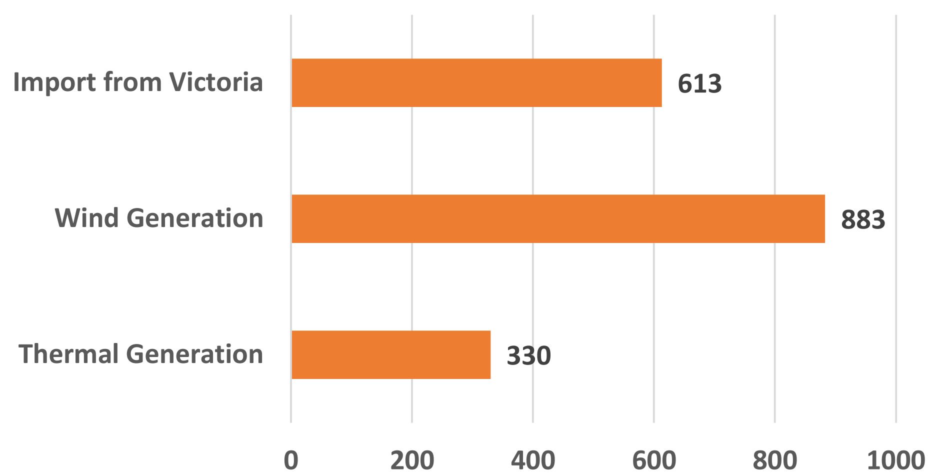
UFLS – Underfrequency Load Shedding
ROCOF – Rate of change of Frequency

South Australian blackout September 28, 2016



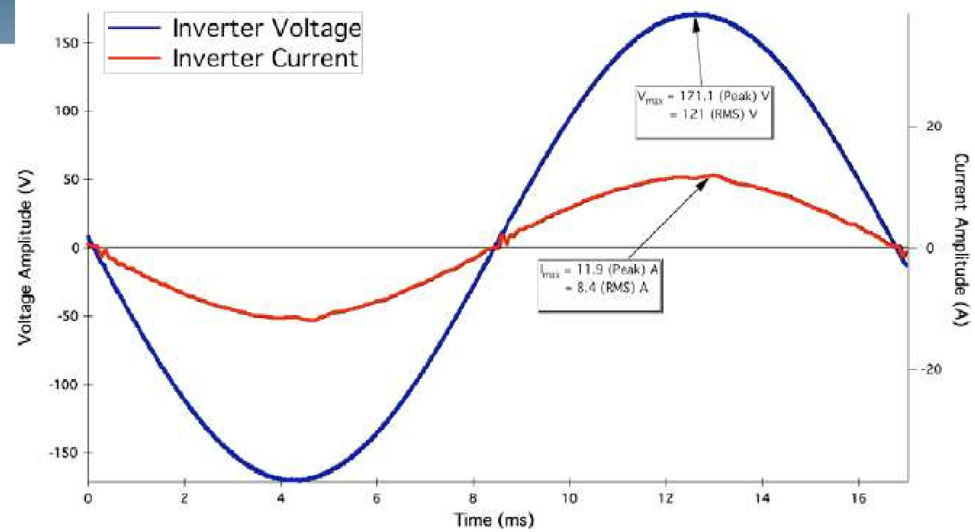
System shutdown at 16:18:16
87 Seconds from start to complete outage

S. Australian Generation Mix, Pre-Event

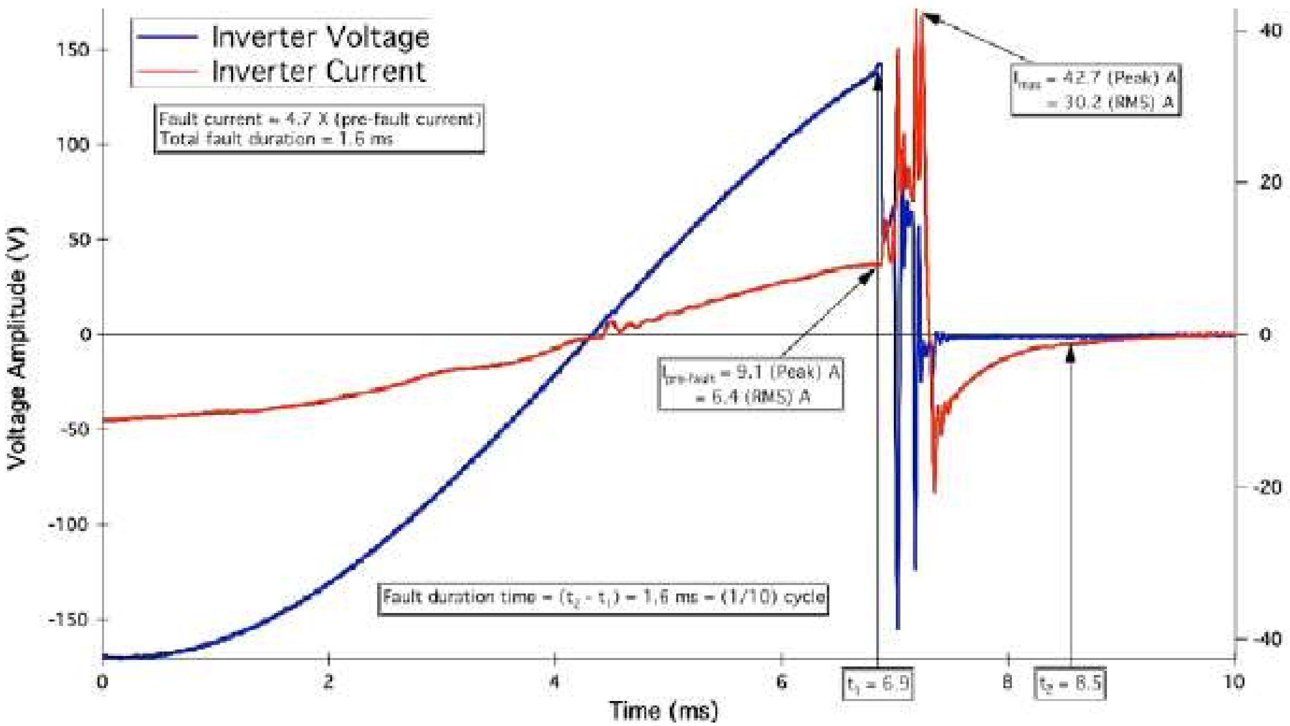


Inverter Output

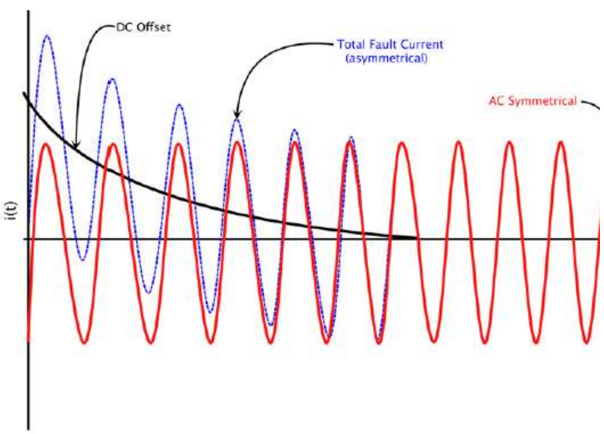
Normal



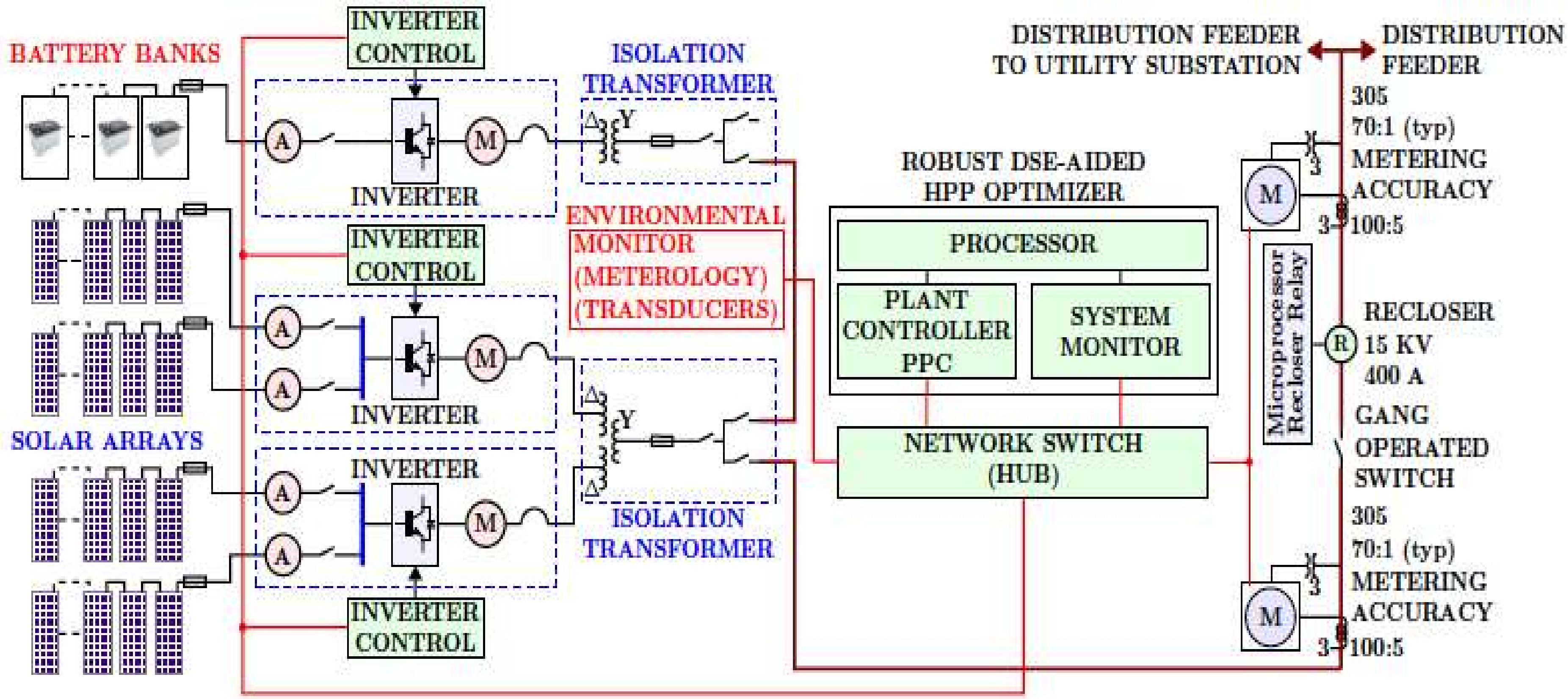
Invertor Response to System Short Circuit



Typical Short circuit fault current for Synchronous Machi



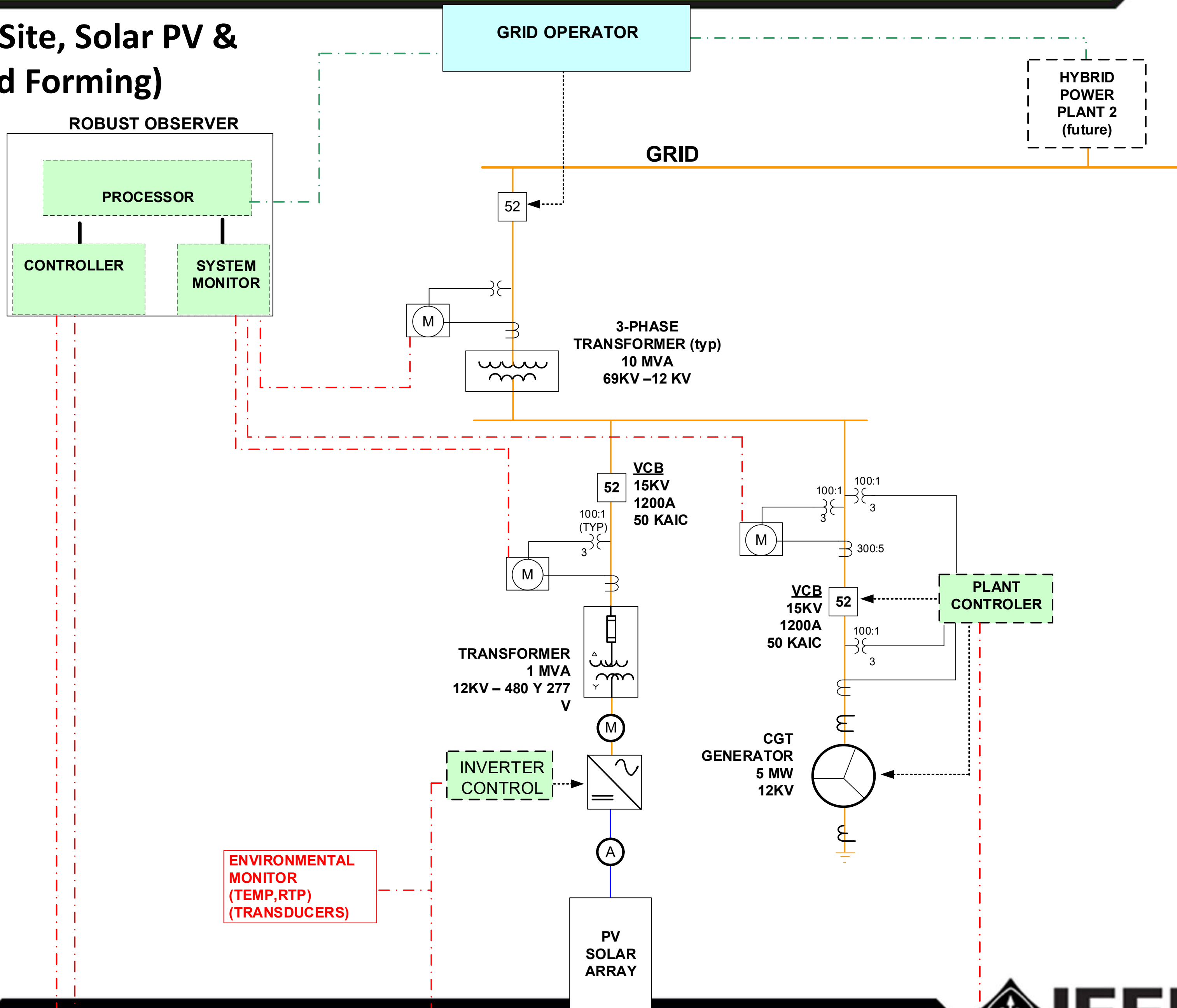
Example of HPP Site, Solar PV inverter and Battery bank



- PV Inverter Dynamic State
- Battery System Dynamic State
- Determine Dispatchable Output of the HPP
- Inertia Emulation – Define Inertia for PV/battery performance
- Mitigate the impact of solar forecasting / Intermittency
- Coordination of Demand Side Resources (requires communication to Demand Side Resources)
- Grid Forming functionality such as Demand response or Direct Load Control
- Respond to AGC signals
- Communication of Real/Reactive power to Upper Grid for Coordinated Control

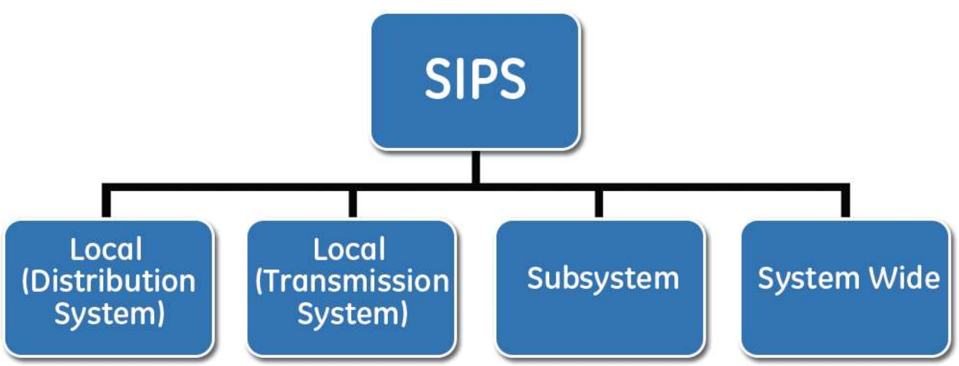
HPP – Hybrid Power Plant

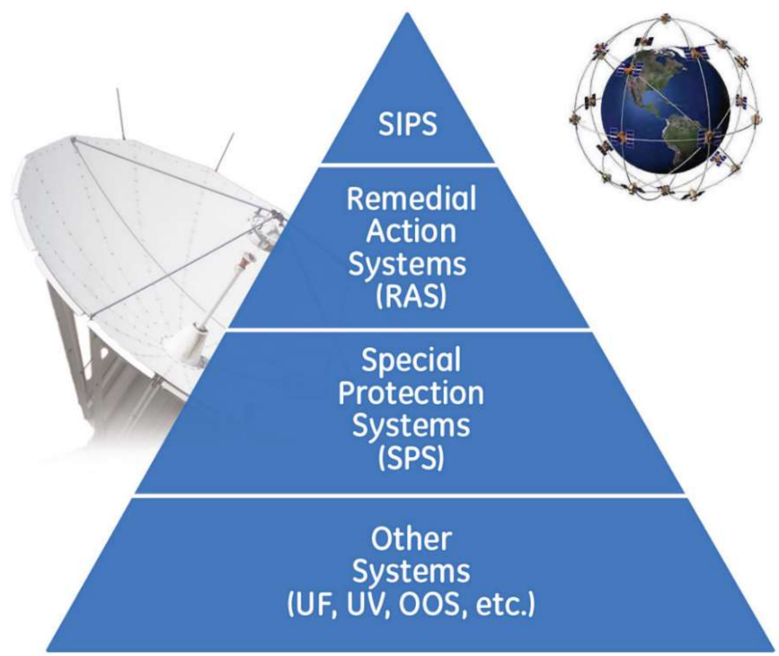
Example of HPP Site, Solar PV & Gas Turbine (Grid Forming)



Wide-Area Systems Technology Enablers

- System Integrity Protection Schemes (SIPS)
  - Remedial Action Schemes (RAS)
  - Special Protection Systems (SPS)
- Integrated systemwide communication infrastructure allowing flexible and secure data collection
- Synchronized Measurements Systems





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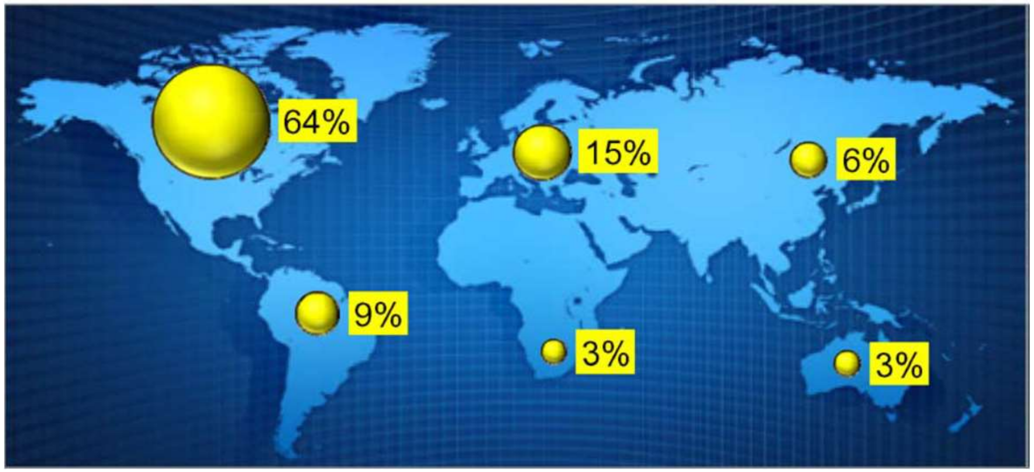
Types of SIPS in Use

1. Generator Rejection
2. Load Rejection
3. Under-Frequency Load Shedding
4. Under-Voltage Load Shedding
5. Adaptive Load Mitigation
6. Out-of-Step Tripping
7. Voltage Instability Advance Warning Scheme
8. Overload Mitigation
9. Congestion Mitigation
10. System Separation
11. Shunt Capacitor Switching
12. Tap-Changer Control
13. SVC/STATCOM Control
15. Turbine Valve Control
16. HVDC Controls
17. Angular Stability Advance Warning Scheme
18. Power System Stabilizer Control
19. Discrete Excitation
20. Dynamic Braking
21. Generator Runback
22. Bypassing Series Capacitor
23. Black-Start or Gas-Turbine Start-Up
24. AGC Actions
25. Busbar Splitting

Global Participants

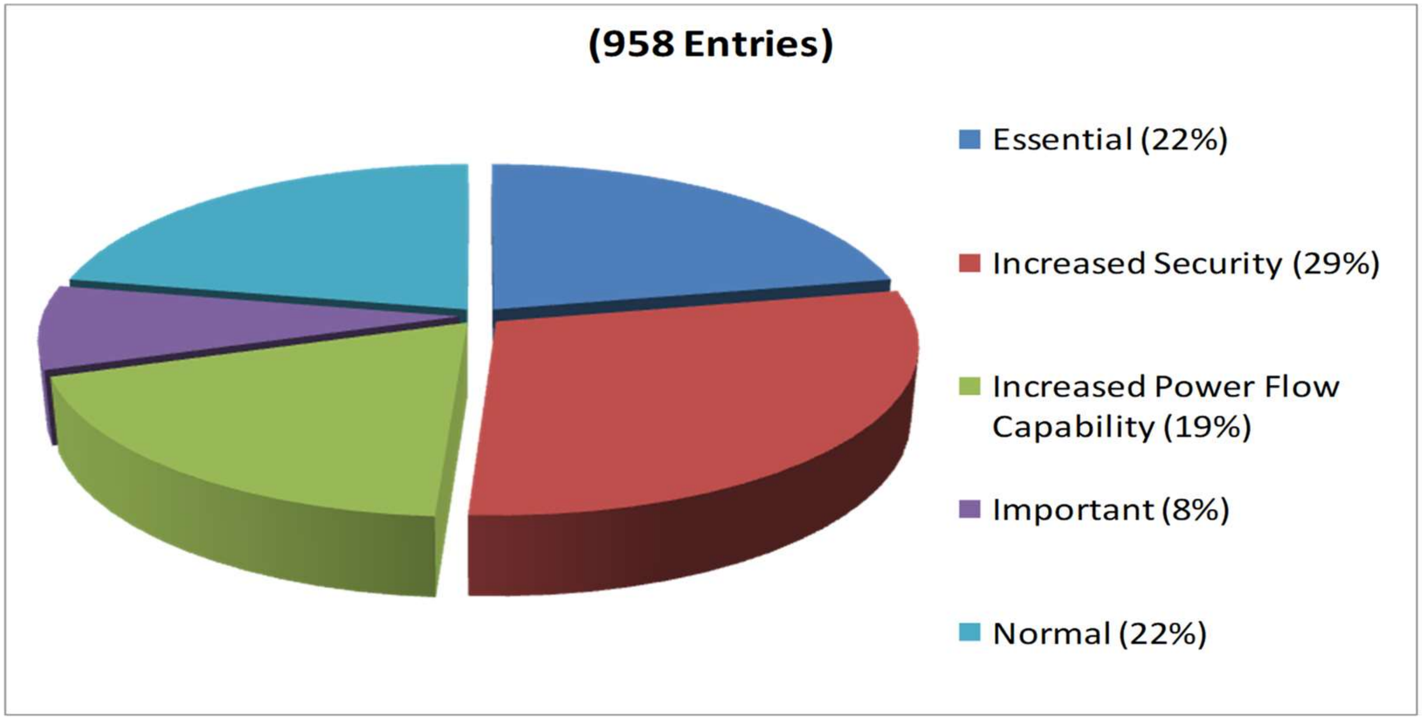


SIPS Reported by continent

V. Madani, D. Novosel, S. Horowtiz, J. Amantegui, M. Adamiak, Guy Colpron, et. al, IEEE PSRC Report on Global Industry Experiences with System Integrity Protection Schemes (SIPS), IEEE Transactions on Power Delivery, Vol. 25, No. 4, October 2010

J.-M. Gagnon (CA), V. Madani, (US) G. Pauloet (BR). al. Defense Plan against extreme contingencies, CIGRE Electra 316, SC 2, April 2007, WG C2.02.24

SIPS Classification



Normal or Normal system improvements (49%) - Three components:
19% Increased Power Flow, 8% Important, 22% Normal

System Security (51%) – Two components:
22% Essential, 29% for Increased Security - At one time was the primary intent of SIPS

Source: IEEE PSRC Global Industry Experiences with SIPS, 2010

Power Oscillations

Inter-area Oscillations

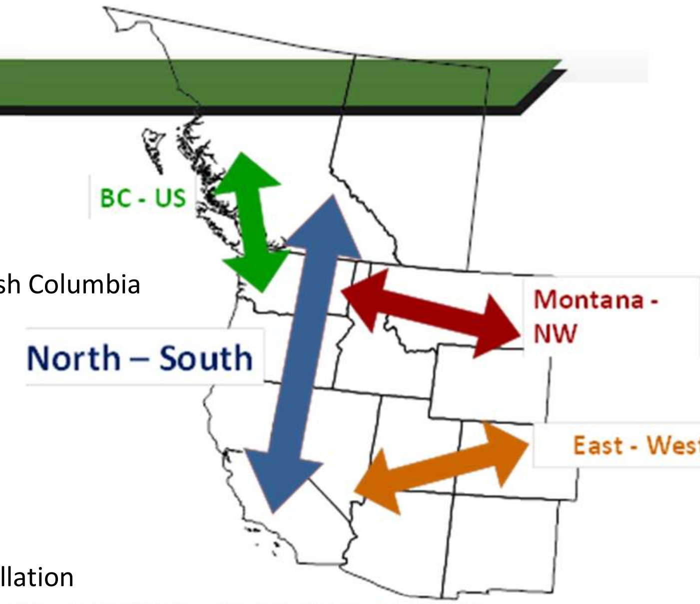
Groups of inertias; e.g. between large systems (areas) long distances away from each other

Disturbances cause angular change across transmission paths

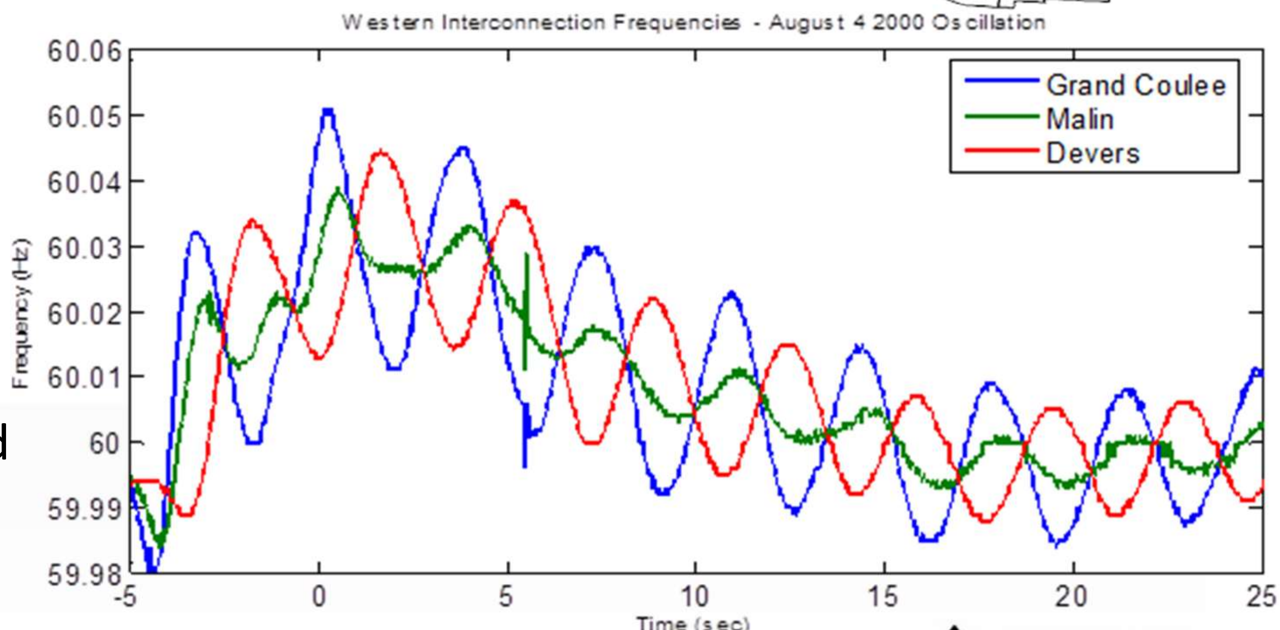
Oscillatory response as inertias swing against each other

If too severe, system separation may be required to maintain stability

BC – British Columbia



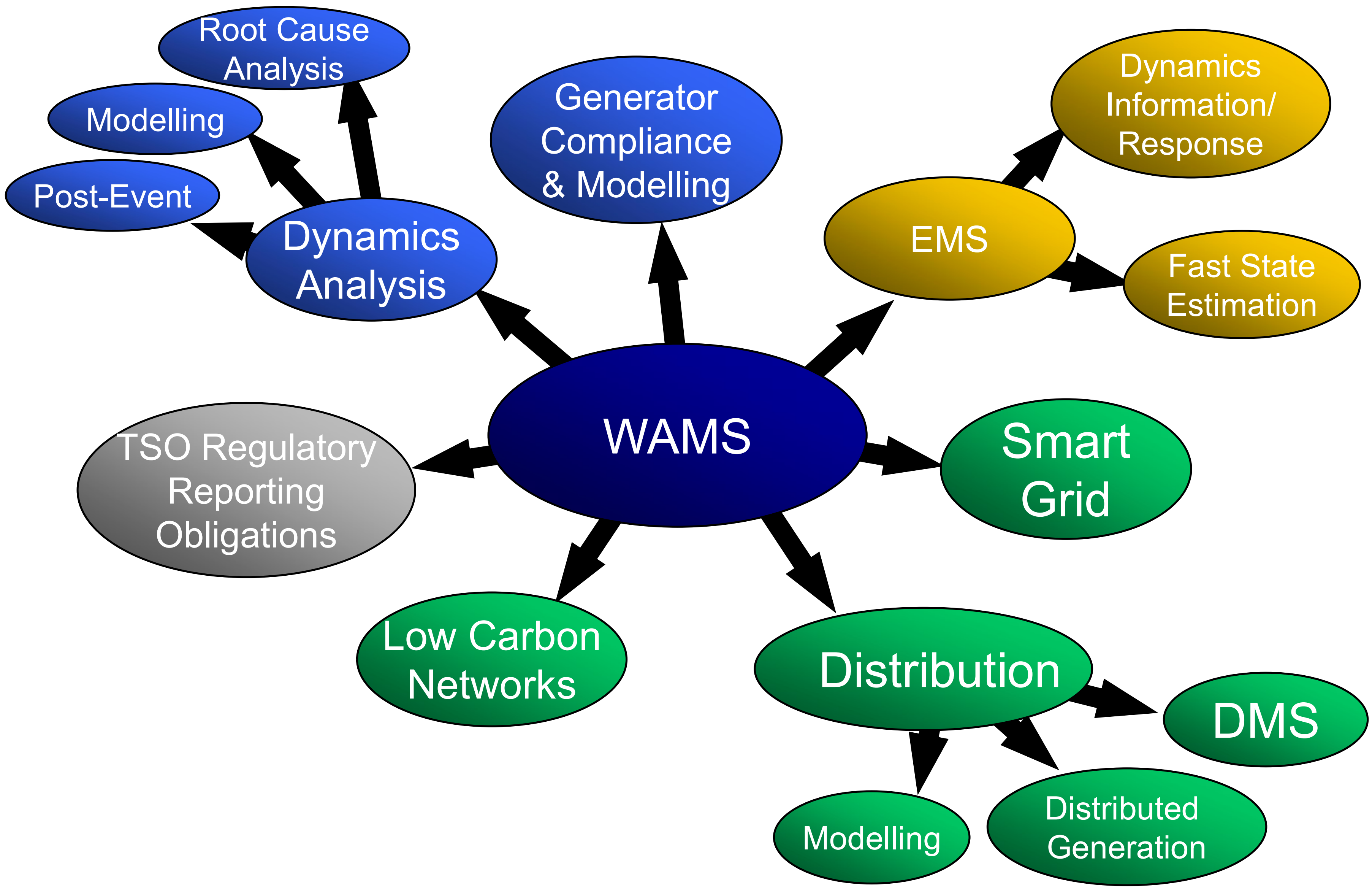
North-South Oscillation



Oscillations at High Penetration of Inverter-Based Generation (IBG)

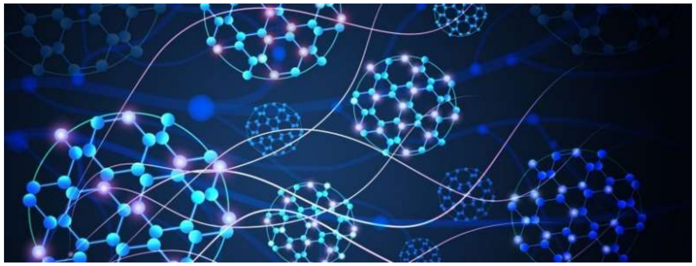
- High penetration of IBG, below 50%, will not principally change the structure of oscillations in bulk systems but create new phenomena
- What to expect at higher penetrations?
  - Existing structure of oscillations and related issues continue to exist for some time
  - Reduced number of local and inter-area modes and change in modes' parameters
  - New phenomenon, Possibility of relatively localized high-frequency oscillations, 10…1000 Hz
    - ✓ These oscillations (caused by control systems in the inverters, most likely localized by one system of inverters) require PMUs monitoring at high frame rates (120 and above per seconds)
    - ✓ Alternative, "point on waive" measurement, limited need in data exchange
  - High-frequency oscillations are likely to be localized without creating system-wide effect. These oscillations will be largely depended on IBG controls
  - Likely emergence of new sources of forced oscillations (in traditional electromechanical frequency range) such as IBGs, microgrids

Wide Area Monitoring System Components



What is Synchrophasor Technology?

- Latest precision time stamped measurement technology
  - (voltages, currents, frequency, frequency rate-of-change, etc.)
- Far higher resolution scans
  - e.g. 30-240 samples/second, for 60Hz Power system
  - 25-100 samples or higher for 50Hz system
  - Compared to one every 4-8 seconds and no time tag
  - Improved visibility into dynamic grid conditions.
  - Early warning detection alerts
- Started with Transmission
  - Proliferating into distribution systems
- Precise GPS time stamping
  - Wide-area Situational Awareness
  - Faster Post-Event Analysis



Synchrophasors show the DNA of power system in real-time

Why PMU?

Improve Security

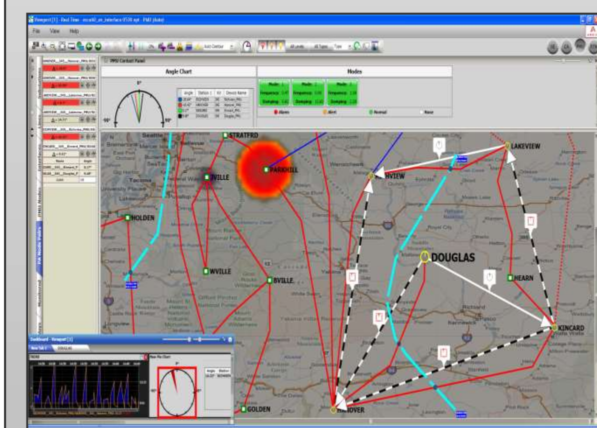
- EARLY WARNING OF INSTABILITY
- OSCILLATION

1) Sub & Super synchronous oscillations (SSO), 2) Intra-area power oscillations

- SITUATIONAL AWARENESS
- ISLANDING RECOVERY
- BLACKSTART

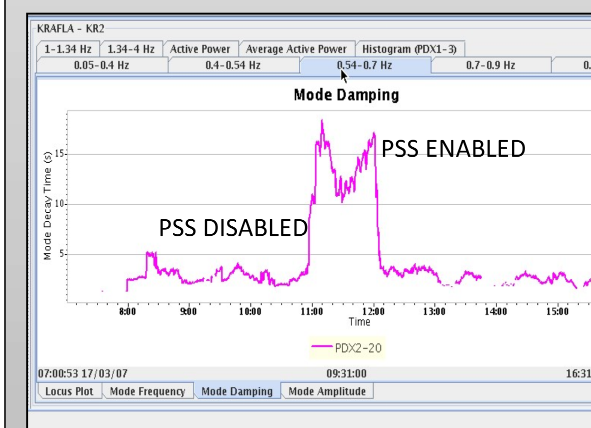
Increase Transfer

- RELIEVE DAMPING CONSTRAINTS
- STATE ESTIMATION & CONTINGENCY ANALYSIS
- IDENTIFY LINE PARAMETERS

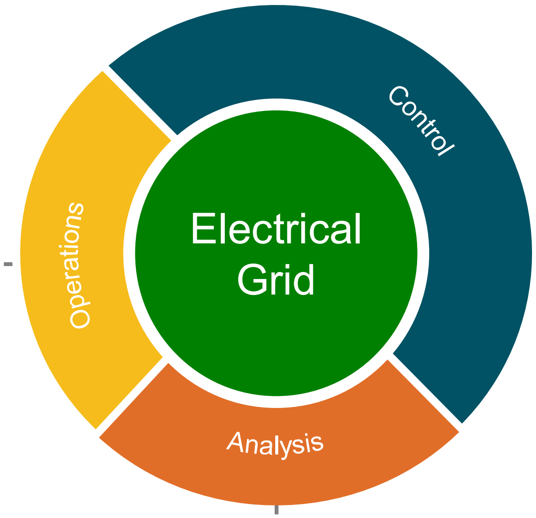


System Analysis

- PSS TUNING
- PLANT COMMISSIONING
- POST-EVENT ANALYSIS
- IMPACT OF RENEWABLES
- IDENTIFY DYNAMICS ISSUES
- RESONANCE AC/DC



"Model, Measure, Monitor, Mitigate!"



Control Room Operations
Wide-Area situational awareness and coordination across seams.

Create and manage robust real-time variable stability limits.

Add Operational Response Guidance to Situational Awareness for Critical Conditions

Engineering Analysis
Big Data Analytics

Risk assessment, data mining, baselining for grid vulnerability.

Analysis tools for condition monitoring, model validation, control tuning, post-event analysis, compliance monitoring.

Wide Area Control
(TO Engagement Required)

Coordinated control hierarchy, centralized (via EMS/DMS), or decentralized as appropriate.

- Model based
- Contingency Analysis
- Measurement based

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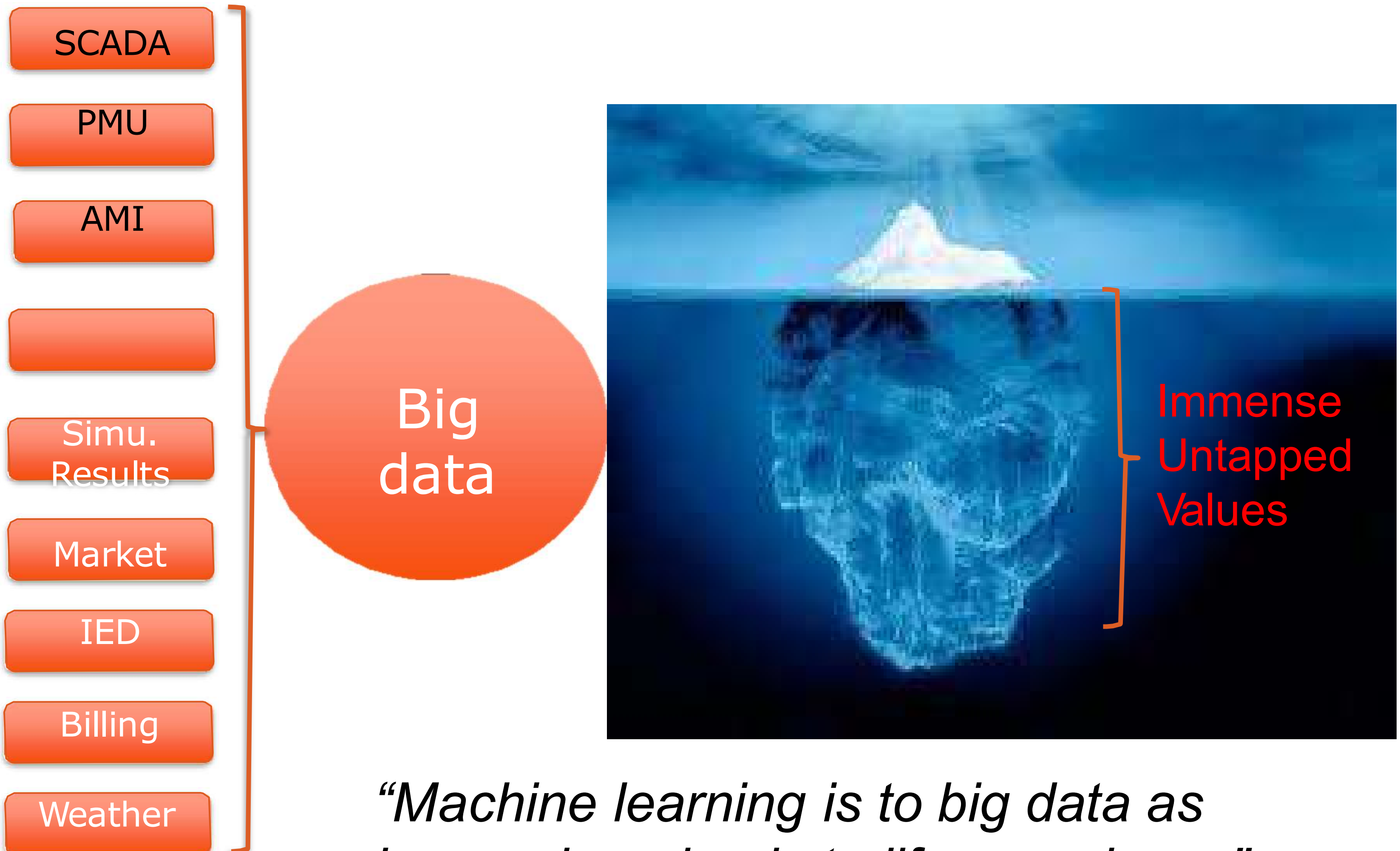
Early Stages in Tapping to "big data"

Requires Precision Timing and Security



"Machine learning is to big data as human learning is to life experience"

PMU – Phasor Measurement Unit – Measurements Synchronized to microsecond resolution or better

Energy and Technology Transformation

Today - Crucial economic and social function depend on **resilient**, **secure**, **and reliable** operation of the power and energy infrastructure.

Energy related low carbon initiatives and Grid modernization are in full gear worldwide

Source and load control at the distribution level are quickly becoming key requirements in this evolving system

A changing environment requires a transformed grid

Immense investments in power system upgrades and deployment of advanced technology-based sensors and measurement devices

Digital Substation business case is becoming more evident / relevant, and human machine interface for managing power system assets is gaining attention

Machine Learning and Robotic Inspection for substation equipment is now in experimental testing in parts of the world.

Cognitive computing, and ability to interact with humans is within reach, due to the advancements in technologies like natural language processing and facial recognition

Machine Governance, Machine ethics, social robotics, technical challenges of engineering ethical machines, along regulatory rules

CIMON: New Space Cadet
Crew Interactive Mobile Companion

Robotic Substation Yard Inspector 24/7
Outdoor Equipment Maintenance Inspector
(Year 2 in service operation)

The road ahead

- Energy Conservation and resource transformation are making positive environmental impact
- Consumers have become early adopters and trend continues
- DER penetration will continue to grow, downward costs
- Managing the system impact from DER remains foremost worry for utilities and ISOs
- Need for a deeper understanding of building blocks of Energy Wonderland and stumbling blocks
- Improved system observability and smarter automation key enablers to facilitating DERs. Takeoff may be due to confluence of things from cost of components to efficient energy management requirements
  - Synchrophasor Implementation into the Control Rooms and Integration into Modern EMS
  - Linear State Estimators improve EMS data quality and security significantly
  - Battery size, overall cost, reliability over life cycle, and recycling related issues
  - IoT (Internet of Things) driven products are accelerating Energy Harvesting initiatives
- Data Mining, Man-Machine interaction will grow exponentially
- Sustainability roadmap and lifecycle strategy are key in a rapidly evolving grid
- More work to do in standards, regulatory policy and markets
- Operational lessons from the Current Pandemic (COVID-19) will offer new thinking in investment, resilience, and in managing the grid

Module 2 Summary – Energy Landscape Transformation, Characteristics Change, Control Shift, Operational Challenges, Hybrid Power Plants (Grid Forming vs. Grid Following), Need for inertia and properly balancing generation mix, System Integrity and Wide-area Systems

Thank You!

Vahid Madani, DLP, FIEEE
vmadani@gridtology.com
vmadani@ieee.org