GRID ARCHITECTURE

The Use of Embedded Energy Storage for Electric Grid Resilience, Operational Flexibility, and Cyber-Security

Jeffrey D. Taft, PhD
Chief Architect for Electric Grid Transformation
Pacific Northwest National Laboratory

21 January 2020

Pacific Northwest NATIONAL LABORATORY

Thinking About the Whole Grid:

Grid Architecture as Complexity Management

System Complexity and Electric Grids




Low Complexity | Medium Complexity | High Complexity | Power systems are off the chart…

Complexity is the hidden bear in the room when dealing with grid modernization.

System Architecture

Architecture

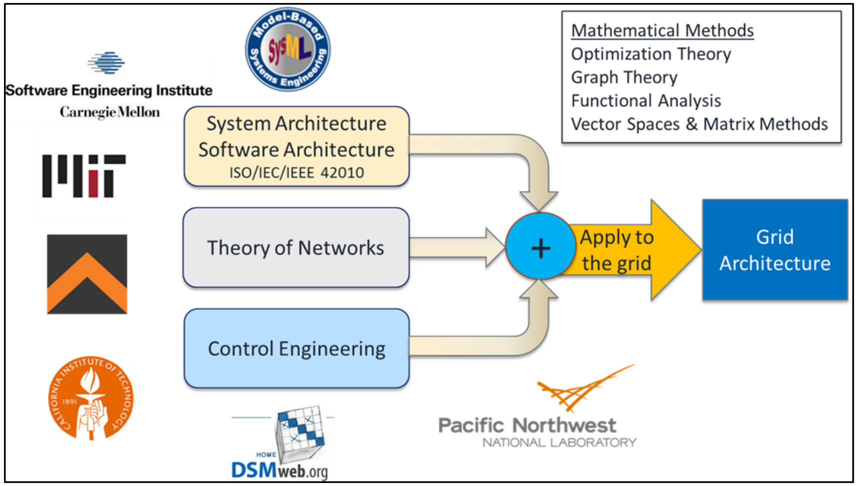
- An abstract depiction of a system, consisting of black box components, structure, and externally visible properties

Purposes:

- Identify legacy constraints
- Remove barriers and refine essential limits
- Help manage complexity (and therefore risk)
- Support early stage modernization processes
- Identify gaps in structure, technology
- Assist communication among stakeholders
- Define platforms
- Inform interfaces and interoperability

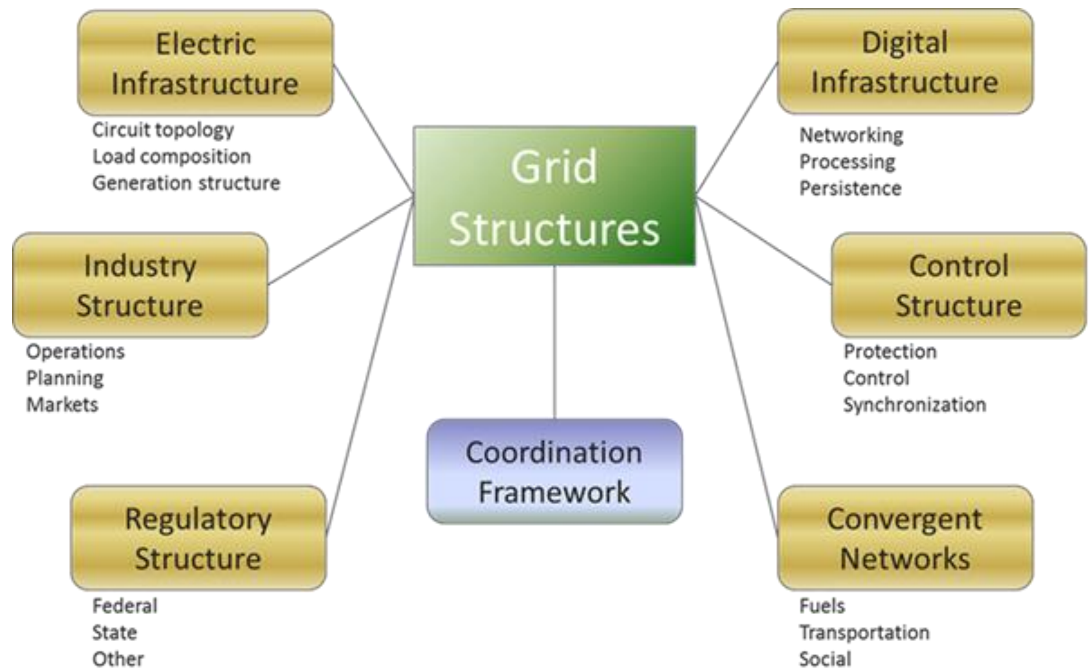
Grid Architecture is the application of system architecture, network theory, and control theory to the electric power grid.

A grid architecture is the highest level description of the complete grid, and is a key tool to help understand and define the many complex interactions that exist in present and future grids.



Grid Architecture Focuses on Structure

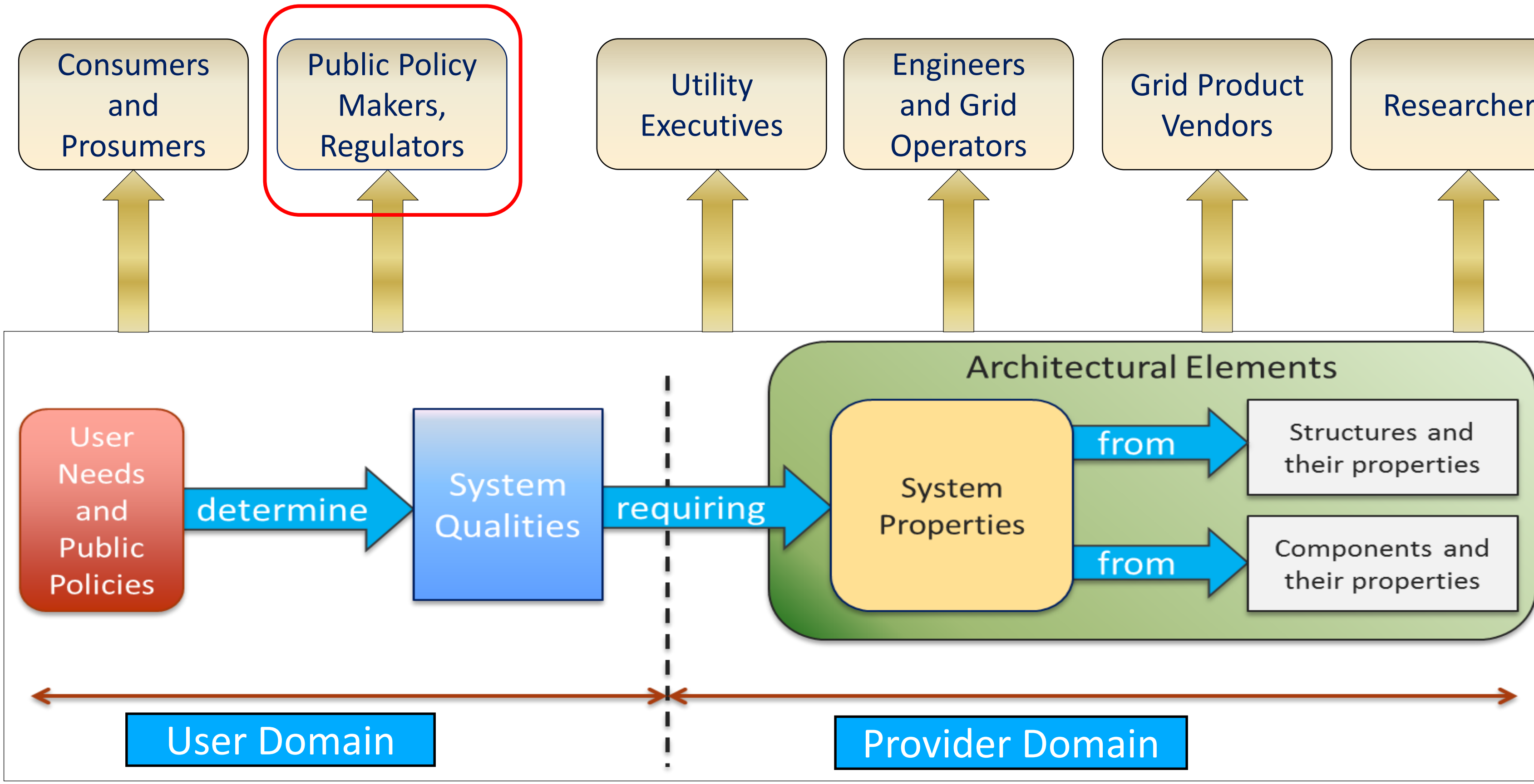
- The grid is composed of many inter-linked structures
- Because we have inherited much legacy grid structure, new capabilities and improved characteristics can require understanding of existing grid structure and potential changes to grid structure
- Determining minimal changes to relieve structural constraints is a key grid architecture problem



- Get the structure right and all the pieces fit into place neatly, all the downstream decisions are simplified, and investments are future-proofed
- Get the structure wrong and integration is costly and inefficient, investments are stranded, and benefits realization is limited

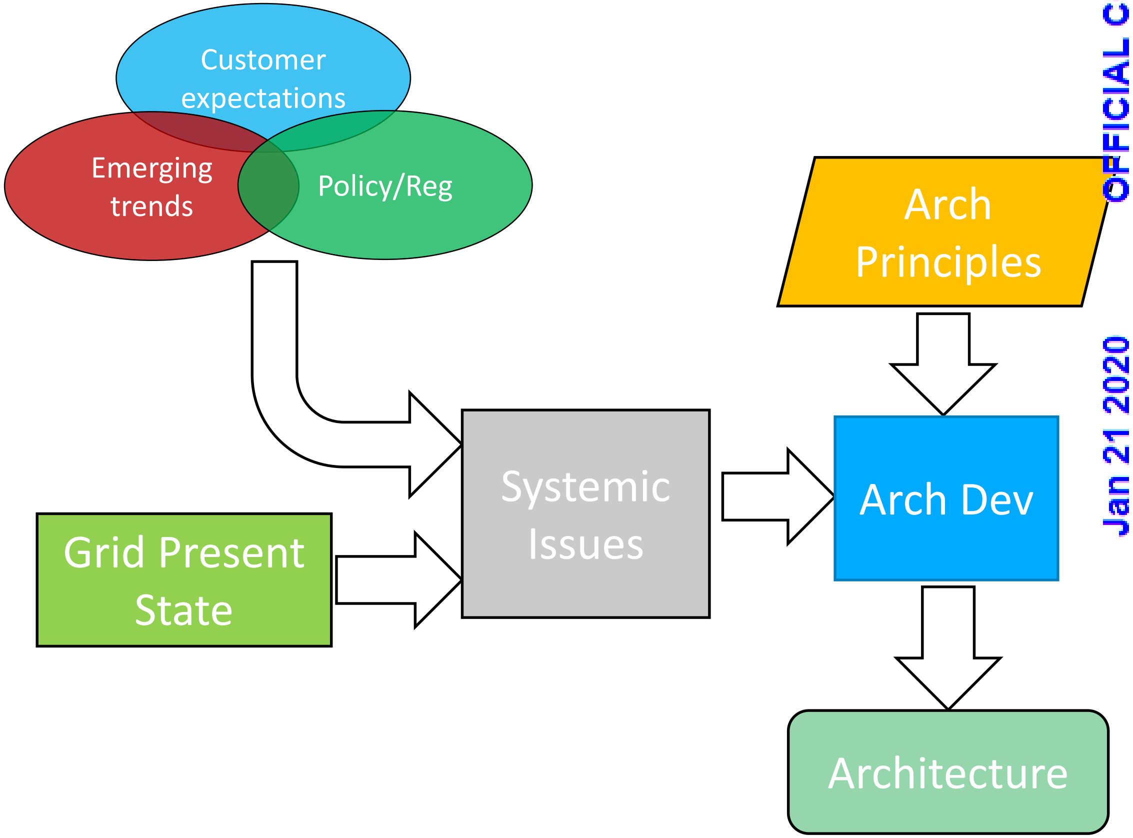
You Do Not Have to be an Architect to Use the Results of Grid Architecture

Grid Architecture supports a wide range of stakeholders, including:



Grid Architecture Methods

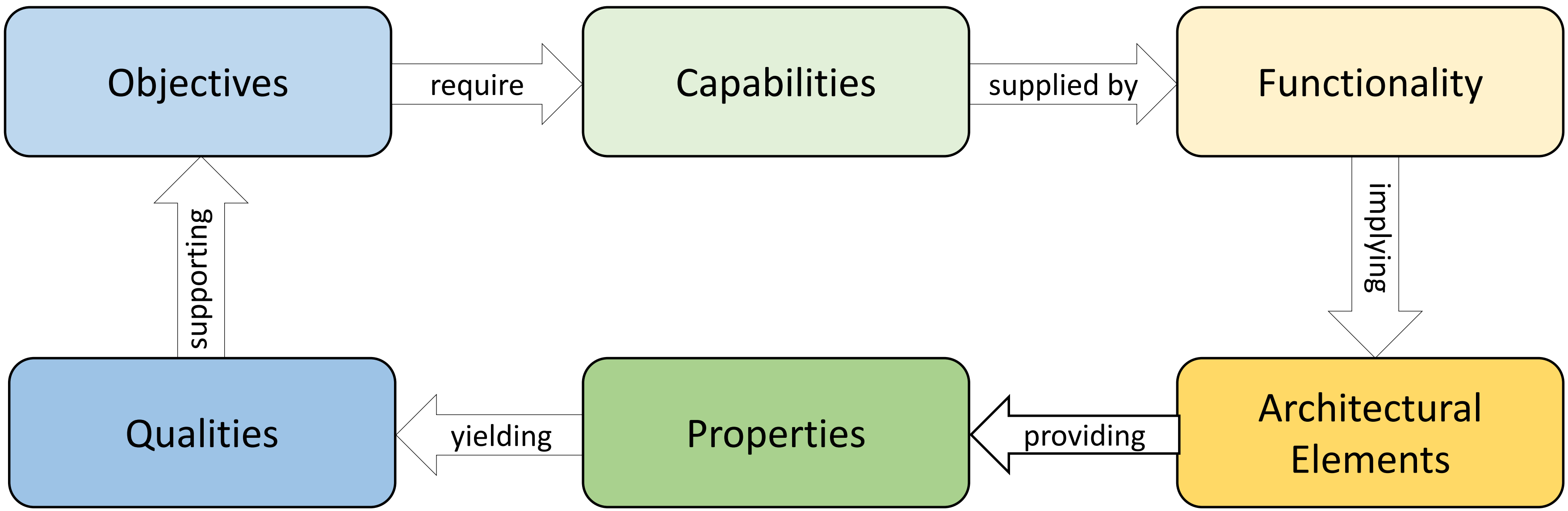
- Clarity of definitions
- Focus on structure
- Uses foundational principles
- Driven by:
  - User requirements
  - Emerging trends
  - Public policy/regulation
- Agnostic to:
  - Products and services
  - Business models
  - Hype cycles
- Reference architectures are instructive, not prescriptive



Manage Complexity

Produce Insight

The Architectural Virtuous Circle

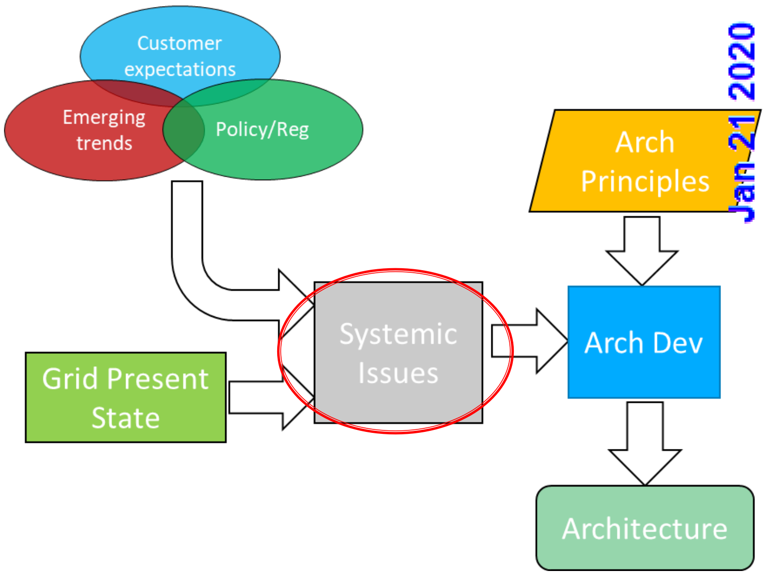


Being clear on objectives will help greatly to untangle what you want to do about storage.

Embedding Energy Storage Into Core Grid Infrastructure

Some Systemic Issues for Grid Storage

- Splitting of generation into traditional transmission-connected bulk generation and distribution-connected generation
- Increasing volatility (unpredictable variability) of both generation and load due to penetration of Variable Energy Resources, resulting in stresses on the load-following control system model
- Increasing integration/interdependency of electric grids and natural gas systems
- Development of ubiquitous communication connectivity, leading to the Internet of Things (IoT) and its electric system corollary, the Grid of Things



These issues all relate to two characteristics: grid resilience and operational flexibility.

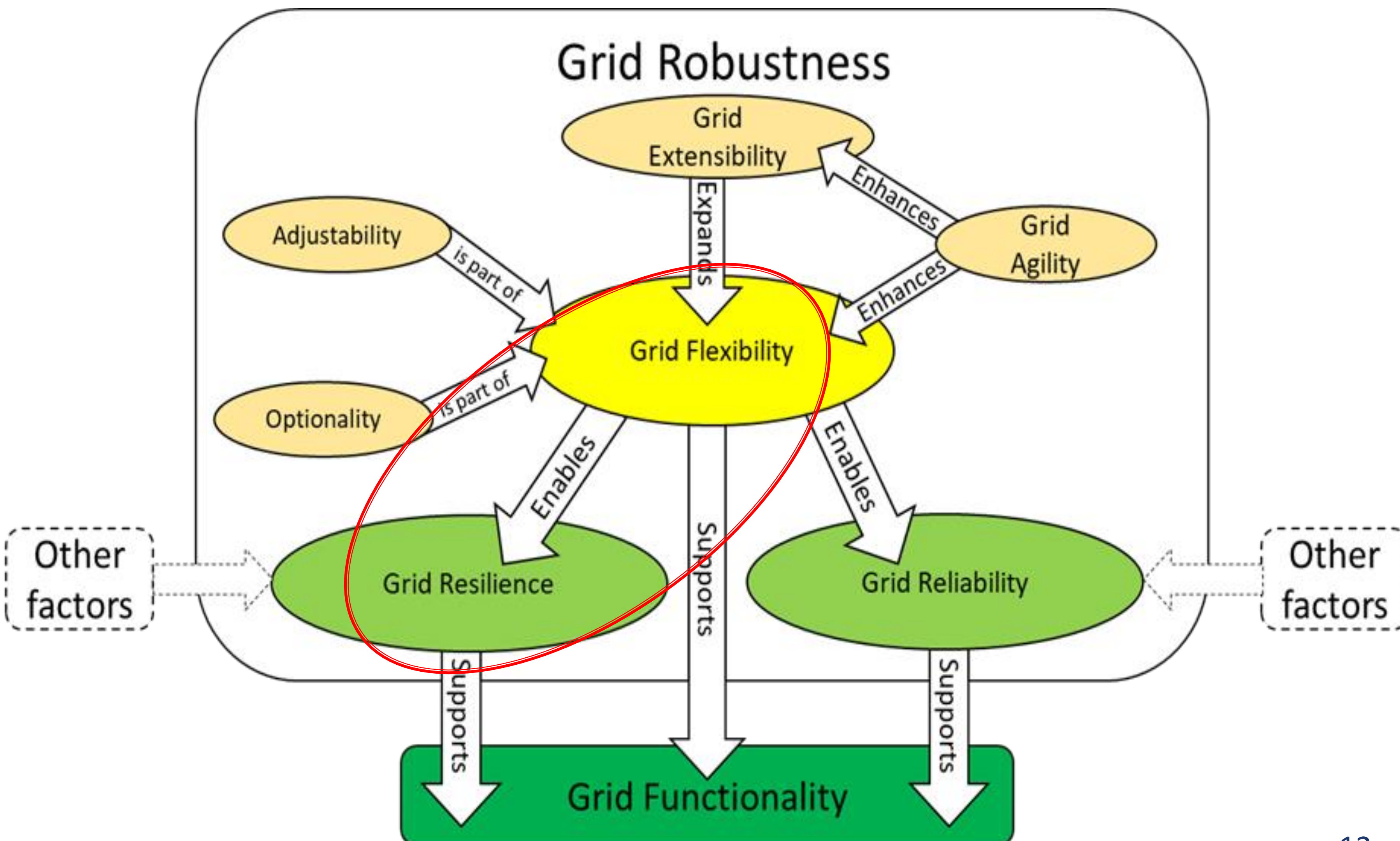
The Infamous "ilities" List

- Doyle's "ilities" list

Accessibility, accountability, accurate, adaptability, affordability, auditability, autonomy, availability, credibility, process capability, compatibility, composability, configurability, correctness provability, customizable, debugability, degradability, determinability, demonstrability, dependability, deployability, discoverability, distributability, durability, effectiveness, efficiency, evolvability, extensibility, failure transparency, fault tolerance, fidelity, flexibility, inspectability, installability, integrity, interchangeability, interoperability, learnability, maintainability, manageability, mobility, modifiability, modular, nomadicity, operability, orthogonality, portability, precision, predictability, producibility, provability, recoverability, relevancy, reliability, repeatability, reproducibility, resiliency, responsiveness, reusability, robustness, safety, scalability, seamlessness, self-sustainability, serviceability, supportability, securability, simplicity, stability, standards compliancy, survivability, sustainability, tailorability, testability, timeliness, traceability, ubiquitousness, understandability, upgradability, usability

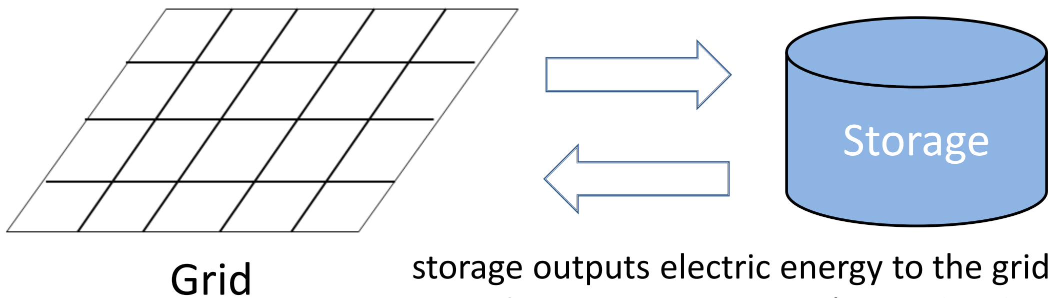
Being bombarded with all this just leads to chaos.

Definition Structure & Embedded Grid Storage



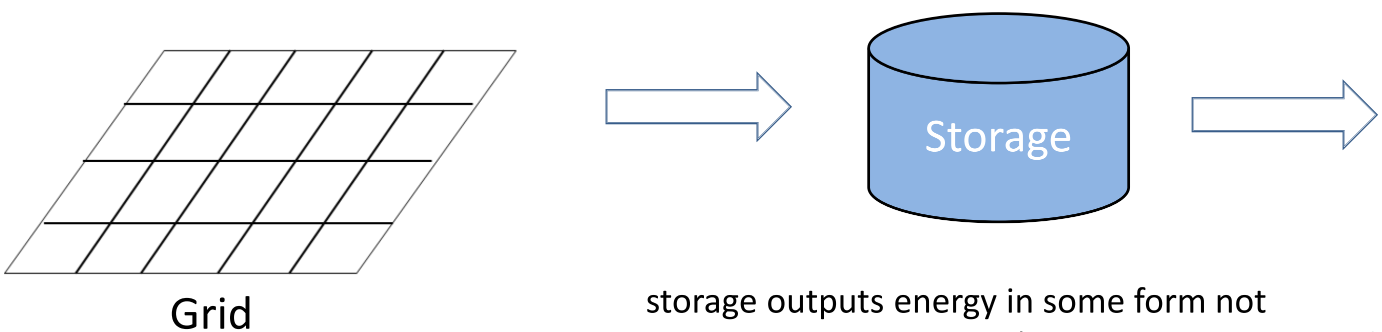
The Two General Storage Models

Reflexive:



storage outputs electric energy to the grid in the same form as was received (example: chemical battery with a bi-directional power electronic connection to a grid)

Transitive:



storage outputs energy in some form not directly grid compatible (example: conversion of electricity into heat in thermal storage for later use in a building)

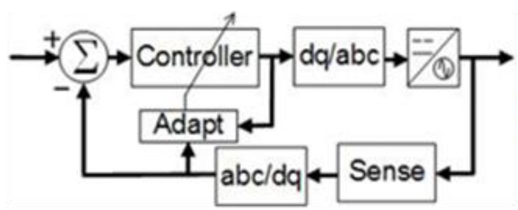
Reflexive Storage

- Energy in from grid and back out to grid
- Three parts:
  - Storage element (several possible technologies)
  - Advanced controls (fast mode-switching, multi-function)
  - Fast, flexible interface to grid (inverter)

Storage Technology

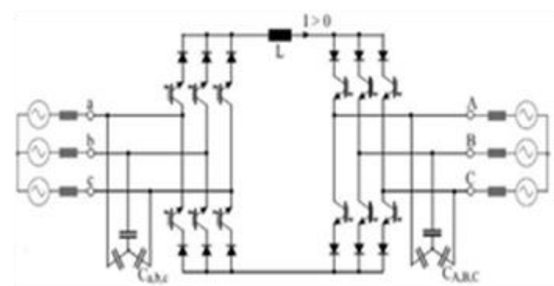
+

Advanced Control



+

Power Electronics



Six Key Characteristics

Item	Storage Characteristic
1	Maximum energy storage capacity – largest amount of energy that the storage unit can contain (how "big" it is - typically measured in Megawatt-hours)
2	Maximum charge rate – fastest rate at which energy can flow into the storage unit from the grid (how "big" the inlet port is - typically measured in Megawatts since flow or time rate of change of energy is power)
3	Maximum discharge rate – greatest rate at which energy can flow out of the storage unit to the grid; may not be the same as maximum charge rate (how "big" the outlet port is - typically measured in Megawatts)
4	Round trip efficiency – energy lost as energy cycles through the storage device
5	Maximum number of charge/discharge cycles (places an effective limit on useful lifetime)
6	Cost (typically $ per MegaWatt-hour for capacity or $ per MegaWatt for power rating)

Traditional Uses and Models

- Much like other DER, storage has been thought of as supplying grid services
- This has led to a view of storage as an ancillary device
- More recently , the view of what constitutes "services" has greatly expanded

FERC defines grid services as "Those services necessary to support the transmission of electric power from seller to purchaser, given the obligations of control areas and transmitting utilities within those control areas, to maintain reliable operations of the interconnected transmission system. Ancillary services supplied with generation include load following, reactive power-voltage regulation, system protective services, loss compensation service, system control, load dispatch services, and energy imbalance services."

- Catalog of over 40 services, some of which are real and some of which are aspirational, can be found here: https://gridarchitecture.pnnl.gov/media/advanced/GMLC_Grid_Services_Master_List.xlsx

Storage for Ancillary Services

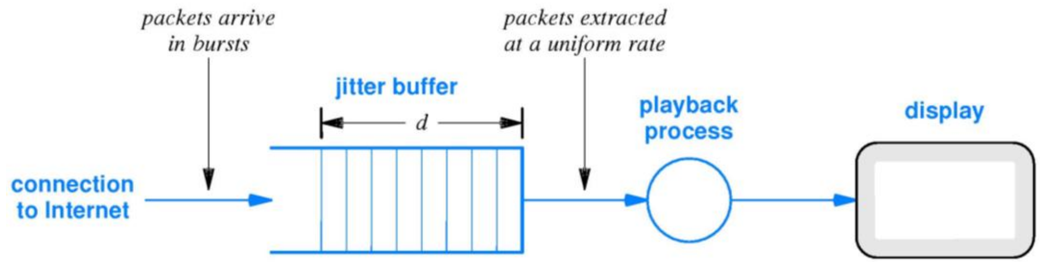
- To date, storage has been used:
  - As an auxiliary device supplying a variety of ancillary services
  - As a special case reliability improvement in place of other measures such as increased transmission capacity
  - As a tool for postponing infrastructure investment (Non-wires alternatives)

- These uses of storage to date have improved grid reliability at the margins but have not changed the system-wide resilience of the grid

- This is because they do not fully capitalize on the essential core value of storage: its use as **the shock absorber for the grid**

The Role of Buffering in Complex Systems

- Most complex systems have buffers
  - communications (jitter buffers)
  - logistics (warehouses)
  - water and gas (tanks)



- Buffers decouple flow volatility (unpredictable variability)
- This gives a system "springiness" that counters the brittleness a system has otherwise
  - Lack of "springiness" (buffering) is a vulnerability (anti-resilience)
- Storage buffers are "shock absorbers"

Power grids lack shock absorbers and so are inherently lacking in resilience.

Some Storage Buffer Functions

- Avoid/mitigate outages – local supply during outages, including ”line packing” in advance of resilience events such as severe storms; outage ride-through support for critical facilities and services
- Manage apparent load volatility (handle variations in net load due to Behind the Meter activity)
- Reduce exchange of volatilities between bulk system and distribution systems
- Facilitate source/load matching and source/load decoupling; loosen balance and area frequency control constraints
- Defend against edge-based volatility attacks (IoT attacks)
- Fuel flow variability compensation
- Facilitate microgrid adoption
- Support generation black start – provide initial station power to selected generators and also act as interim load while generation is stabilizing

All of these functions of grid energy storage flow from one essential characteristic: it buffers variable energy flows. Recognition of that basic concept leads to an understanding of why storage should be embedded in the core infrastructure of the grid.

Embedded Storage Operating Requirements

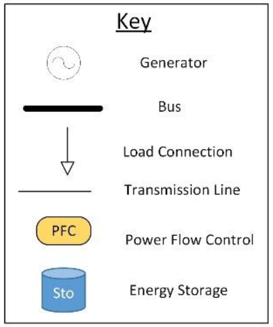
- Firm designable – it must be possible for the utility to specify where the storage units are placed and how much capacity/capability to put there

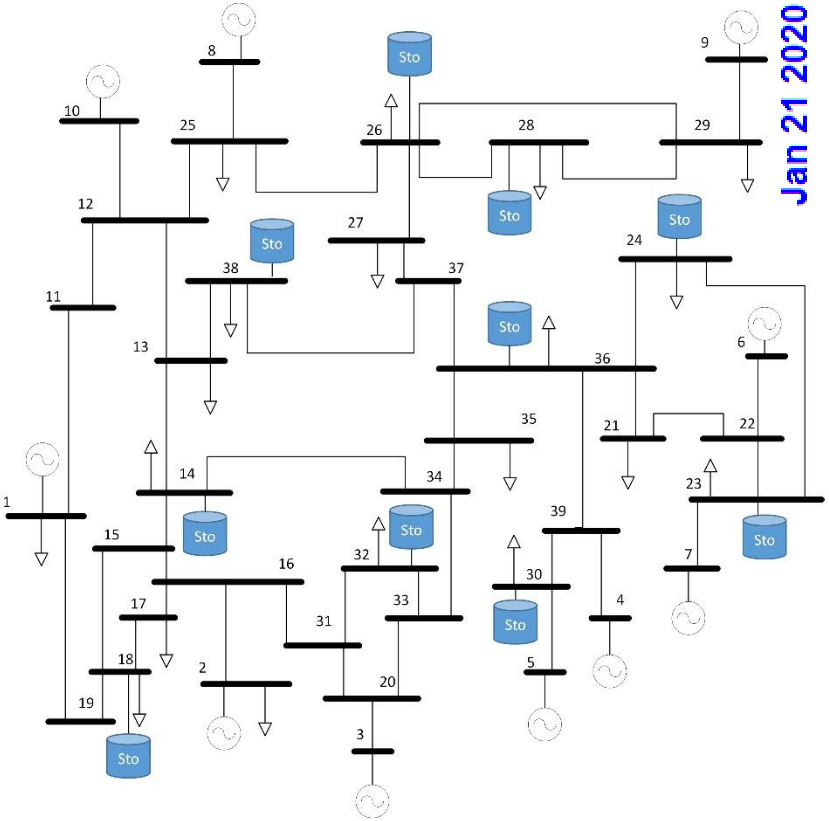
- Firm dispatchable – the utility must have direct control of the storage units so as to be able instantly to select operating modes and meet dynamic operating objectives as well as special objectives during resilience events
- Securable – storage operational and control must meet utility standards for cyber and physical security
- Service-assurable – presence of the storage must not be optional. Its availability must be assured in the same manner as other utility assets and cannot become unavailable if third party ownership changes hands or a third party exits a business or an owner wants to opt out.

These factors point to utility control of embedded grid storage assets.

Architectural Issues: Size and Location

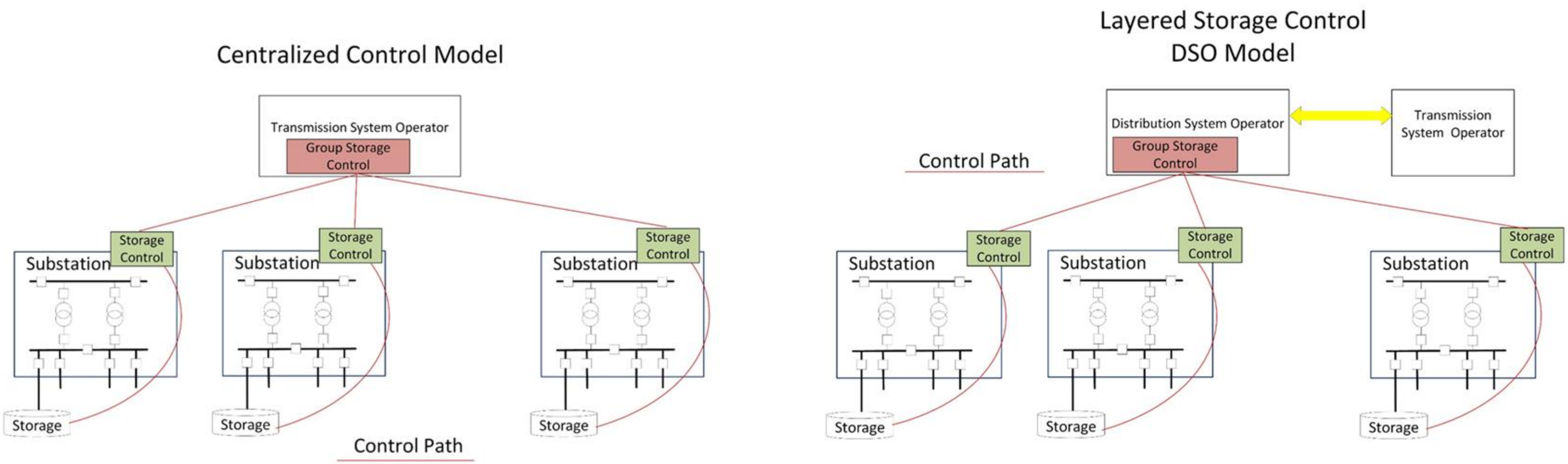
- Use multiple modest-sized units rather than a very few giant storage devices
- Location at T/D interface substations on the low side bus provides a number of advantages:
  - Maximum potential usefulness for both transmission and distribution
  - Lower interface cost than placement on high voltage transmission buses
  - Effective placement for managing T/D volatility exchanges
  - Effective placement for managing distribution edge-based volatility attacks



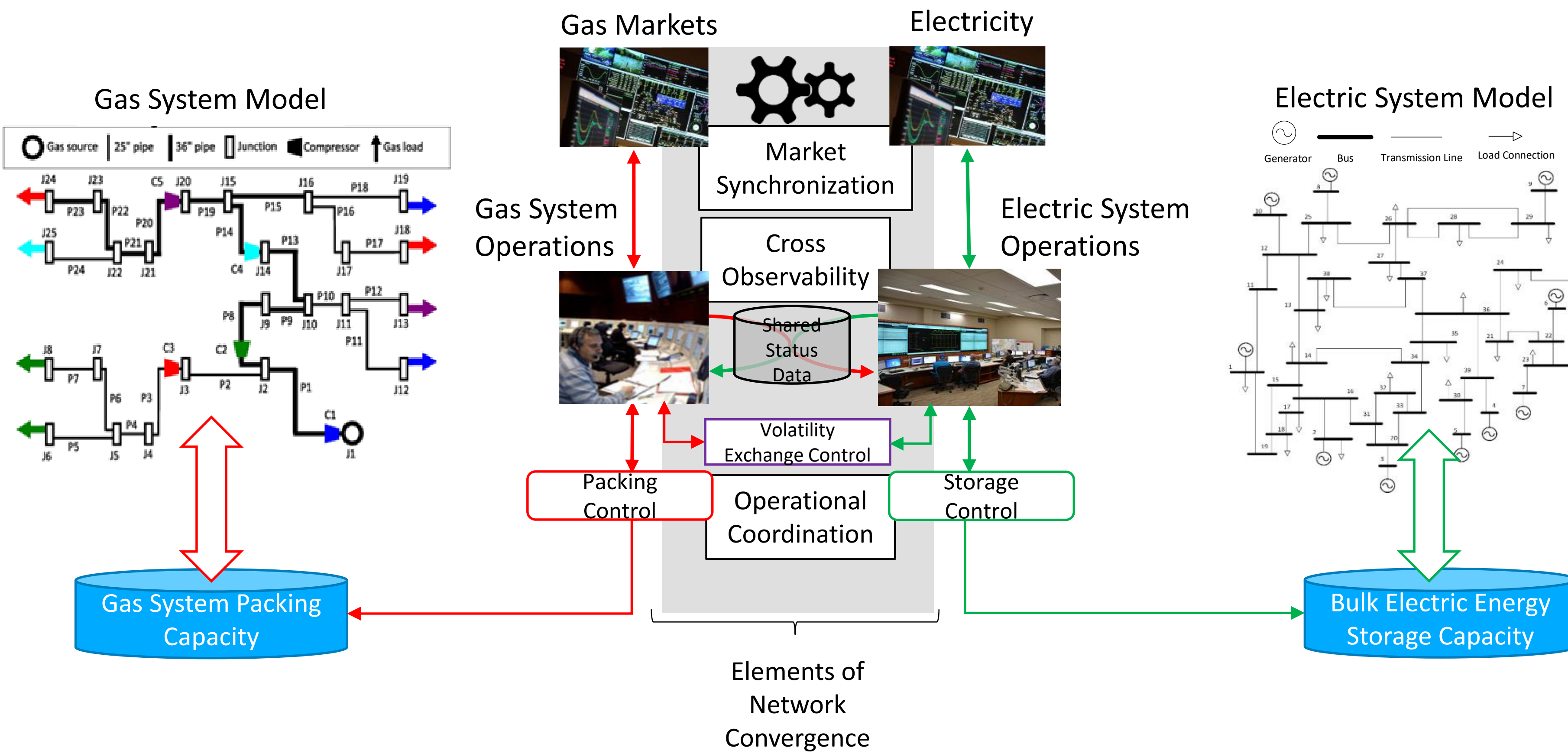


Architectural Issues: Operation

- Rather than treat storage as a set of discrete components operating independently, embedded storage can be treated as a coordinated group of storage devices – a Coordinated Storage Network
- These components can be managed and controlled collectively for grid operational purposes by the operators of the grids to which the storage is attached for greater effect than if they operate independently



Gas/Electric Convergence and Joint Storage



These two connected systems have different flow rate requirements. Storage (on both sides) can resolve the mismatch.

Summary and Recommendations

- Electric power grids lack a capability common to other types of complex systems: internal buffering
- The lack of internal buffering means that power grids are missing a key aspect of resilience.
- The solution to this issue is to embed bulk energy storage into the grid as core infrastructure.
- Key requirements to enable the shock absorber are that the storage be embedded as core infrastructure and that it be controlled by electric utilities.

Recommendations

- Deploy grid energy storage as a systemic upgrade, not as edge-attached services devices
- Deploy storage as a large number of smaller distributed units rather than as a few giant central devices
- Locate storage units at T/D interface substations
- Control groups of storage units as Coordinated Storage Networks
- Let control of the storage units reside in the electric utilities

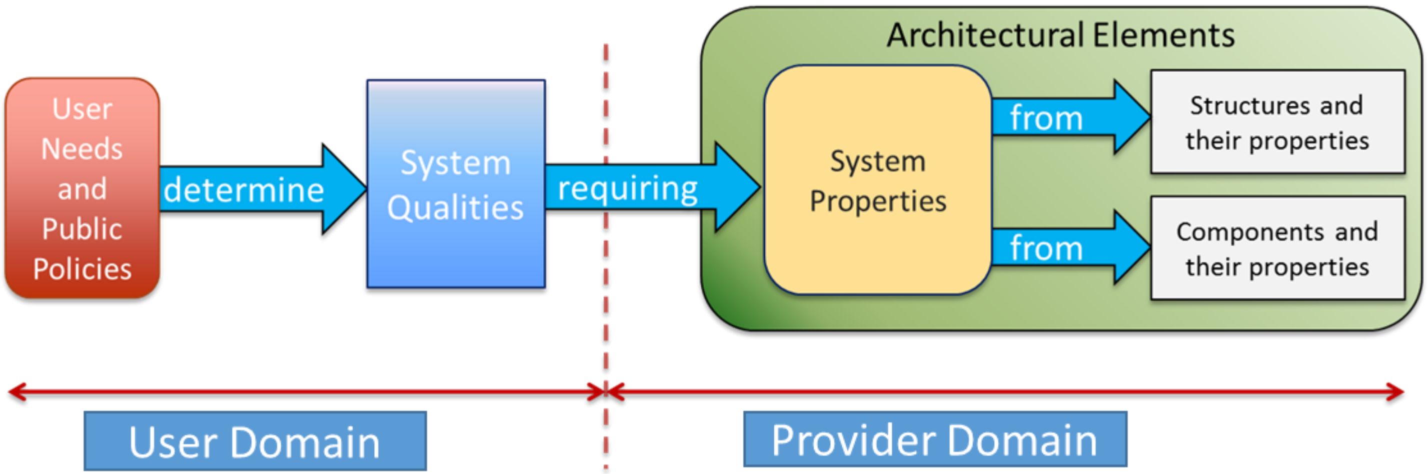
Questions & Discussion

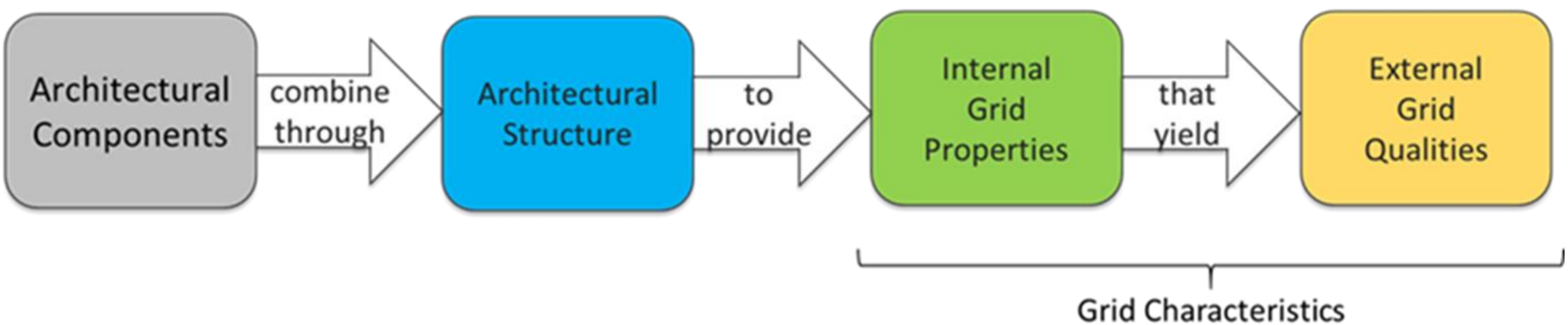
See the core infrastructure storage paper on the Advanced Concepts page of the Grid Architecture website : https://gridarchitecture.pnnl.gov/

Resource slides

Qualities and Properties

- System Qualities represent the consumer viewpoint (users of the system)
- System Properties represent the provider viewpoint (developers and operators of the system)





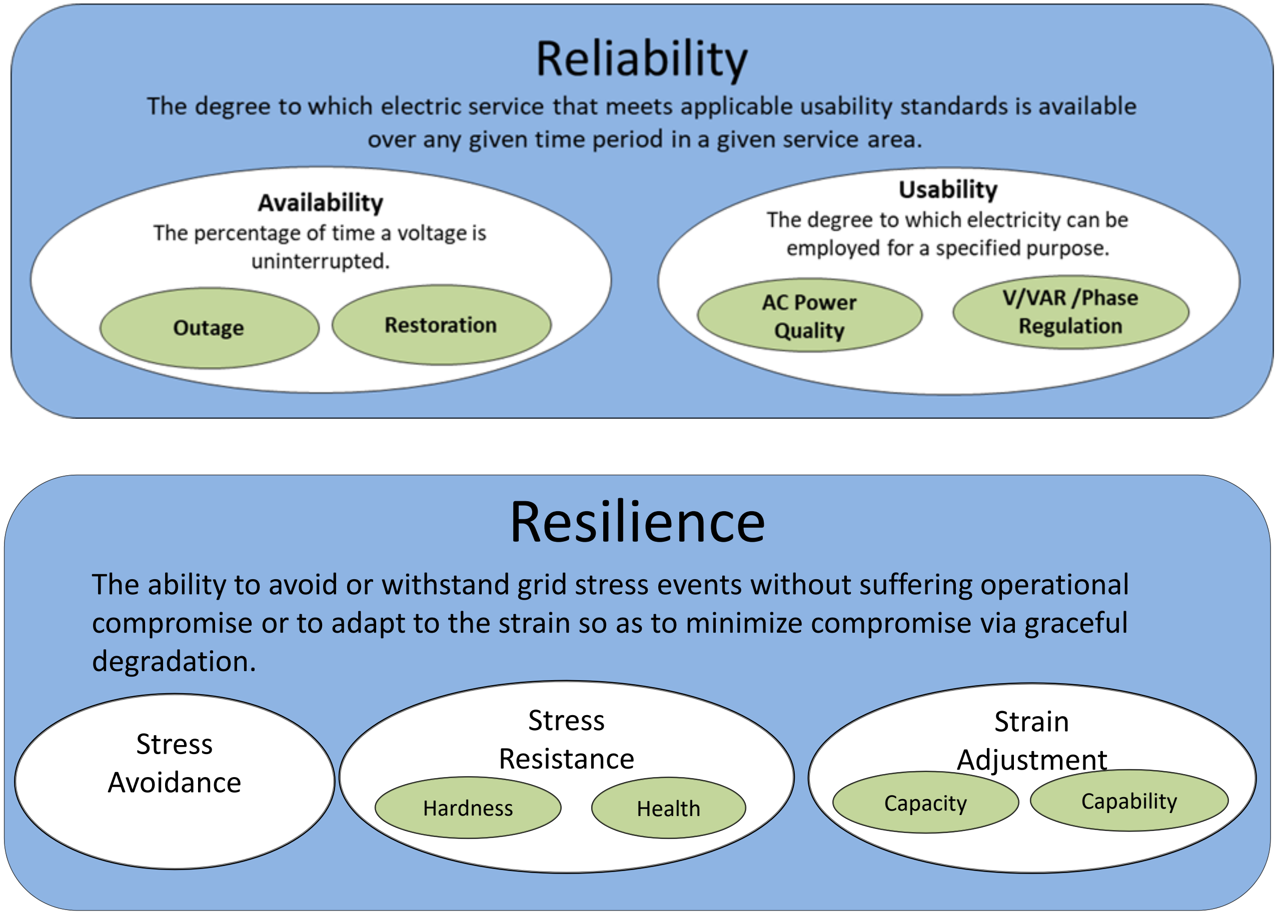
Defining Grid Characteristics

- Capability - the ability to perform certain actions or achieve specific outcomes
- Functionality - the set of tasks, operations, or services that a grid can supply or carry out. Functions provide the means to implement capabilities
- Optionality – the availability of multiple means (options) to solve a given problem. Use of DER can increase the optionality associated with keeping the grid in balance.
- Adjustability – ability to make parametric or small structural changes to accommodate changing conditions.

Grid Flexibility, Extensibility, and Agility

- Flexibility is the ability to deal with variations in operating conditions with a given set of grid assets and capabilities
  - Adjustability is the capability to alter parameters and processes within a fixed overall framework to deal with changing operating conditions
  - Optionality is the availability of alternative means of dealing with a given issue
- Extensibility is the capability to modify the set of assets and capabilities to meet new operating requirement outside the bounds of what can be met with the flexibility of the existing grid
- Agility is ability to make changes (in either class) quickly
  - refers to the *speed* with which adjustments can be made and so is a time dimension property

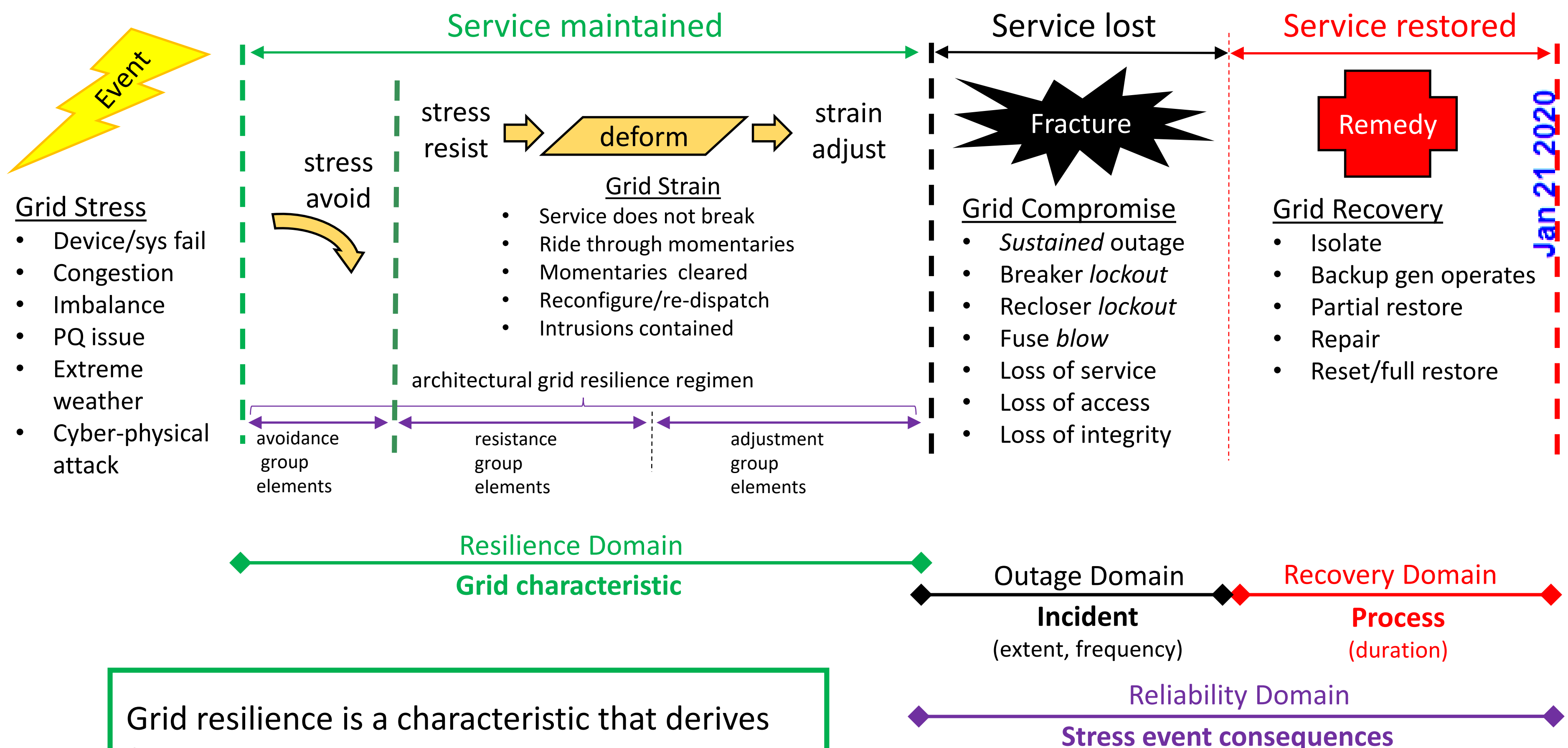
Reliability and Resilience



Grid resilience is a characteristic that derives from both grid *components* and *grid structure*.

Resilience, Reliability, and Recovery

Grid resilience is the ability to avoid or withstand grid stress events without suffering operational compromise or to adapt to the strain so as to minimize compromise via graceful degradation.



Grid resilience is a characteristic that derives from both grid *components* and *grid structure*.

Services List (SCE Model)

Category		Description
Customer		Maintain power quality
Customer		Optimize energy bill
Customer		Provide uninterruptible power supply
Customer		Carbon/operational optimization
Customer		Commodity price risk mitigation
Customer		Integrate intermittent distributed generation
Distribution Operations		Integrate intermittent distributed generation
Distribution Operations		Defer system upgrades
Distribution Operations		Mitigate outages
Distribution Operations		Improve power quality
Balancing Authority/Market Operations		Provide frequency regulation service
Balancing Authority/Market Operations		Provide spin/non-spin reserves
Balancing Authority/Market Operations		Provide capacity
Balancing Authority/Market Operations		Provide ramping
Balancing Authority/Market Operations		Shift energy usage
Balancing Authority/Market Operations		"Firm" renewable output
Balancing Authority/Market Operations		avoid energy dumping and/or min load issues
Balancing Authority/Market Operations		Provide black start
Balancing Authority/Market Operations		Market price mitigation
Balancing Authority/Market Operations		Provide in-basin generation
Balancing Authority/Market Operations		Smooth intermittent resource output
Transmission Operations		Smooth intermittent resource output
Transmission Operations		Improve short duration performance
Transmission Operations		Provide system inertia
Transmission Operations		Local constraint mitigation
Transmission Operations		Avoid congestion fees
Transmission Operations		Defer system upgrades
Transmission Operations		Improve system reliability
Energy Services		Performance contract risk mitigation
Energy Services		3rd party customer operational services support
Energy Services		Procurement risk mitigation

Source: P De Martini

Value Stacking and Market Monetization

- FERC Order 841 regarding storage
- Fragmentation of market products
- Bulk energy system vs. distribution system benefits accrual issues
- Note that times scales can be significant

#	Type	Discharge Duration*		
		Low	High	Note
1	Electric Energy Time-shift	2	8	Depends on energy price differential, storage efficiency, and storage variable operating co
2	Electric Supply Capacity	4	6	Peak demand hours
3	Load Following	2	4	Assume: 1 hour of discharge duration provides approximately 2 hours of load following.
4	Area Regulation	15 min.	30 min.	Based on demonstration of Beacon Flywheel.
5	Electric Supply Reserve Capacity	1	2	Allow time for generation-based reserves to come on-line.
6	Voltage Support	15 min.	1	Time needed for a) system stabilization or b) orderly load shedding.
7	Transmission Support	2 sec.	5 sec.	Per EPRI-DOE Handbook of Energy Storage fo Transmission and Distribution Applications.[17]
8	Transmission Congestion Relief	3	6	Peak demand hours. Low value is for "peaky" loads, high value is for "flatter" load profiles.
9.1	T&D Upgrade Deferral 50th percentile	3	6	Same as Above
9.2	T&D Upgrade Deferral 90th percentile	3	6	Same as Above
10	Substation On-site Power	8	16	Per EPRI/DOE Substation Battery Survey.
11	Time-of-use Energy Cost Management	4	6	Peak demand hours.
12	Demand Charge Management	5	11	Maximum daily demand charge hours, per utility tariff.
13	Electric Service Reliability	5 min.	1	Time needed for a) shorter duration outages or b) orderly load shutdown.
14	Electric Service Power Quality	10 sec.	1 min.	Time needed for events ridethrough depends on the type of PQ challenges addressed.
15	Renewables Energy Time-shift	3	5	Depends on energy cost/price differential and storage efficiency and variable operating cost.
16	Renewables Capacity Firming	2	4	Low & high values for Renewable Gen./Peak Load correlation (>6 hours) of 85% & 50%.
17.1	Wind Generation Grid Integration, Short Duration	10 sec.	15 min.	For a) Power Quality (depends on type of challenge addressed) and b) Wind Intermittency.
17.2	Wind Generation Grid Integration, Long Duration	1	6	Backup, Time Shift, Congestion Relief.

*Hours unless indicated otherwise. Min. = minutes. Sec. = Seconds.

Sandia National Laboratories

Expenditure Treatment Options

No.	Expenditure Purpose	Methodology
1	Grid expenditures to replace aging infrastructure, new customer service connections, relocation of infrastructures for roadwork or the like, and storm damage repairs.	Least-cost, best-fit or other traditional method recognizing the opportunity to avoid replacing like-for-like and instead incorporate new technology
2	Grid expenditures required to maintain reliable operations in a grid with much higher levels of distributed resources connected behind and in front of the customer meter that may be socialized across all customers.	Least-cost, best-fit for core platform, or Traditional Utility Cost-Customer Benefit based on improvement derived from technology.
3	Grid expenditures proposed to enable public policy and/or incremental system and societal benefits to be paid by all customers.	Integrated Power System & Societal Benefit-Cost (e.g., EPRI and NY REV BCA)
4	Grid expenditures that will be paid for directly by customers participating in DER programs via a self-supporting margin neutral opt-in DER tariff, or as part of project specific incremental interconnection costs, for example.	These are "opt-in" or self-supporting costs, or costs that only benefit a customer's project and do not require regulatory benefit-cost justification.

Source: Modern Distribution Grid Volume III Decision Guide (DSPx Project)