Pacific Northwest NATIONAL LABORATORY

PNNL-29414

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

October 2019

R O'Neil
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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Executive Summary

In recent years, bulk energy storage has been applied to electric power systems as an auxiliary device for the support of grid reliability via grid services. This approach is useful but only extracts value from storage on a marginal basis because grid services involve only a tiny fraction of the power flowing in a grid. While storage is flexible enough to perform many services, assessing its value on a stacked-services basis obscures its real value: storage is a buffer for electric energy flows. All of its capabilities stem from this one fundamental property. Limiting storage to use as an ancillary services device leaves this primary value untapped.

The real value of storage is as a means to provide a key characteristic missing from power grids: the ability to absorb stresses with little or no loss of performance – the essence of resilience. Storage applied systematically throughout the grid can provide the missing "shock absorber" springiness that the grid is missing. To provide this value, storage must be incorporated into the grid as core infrastructure and must be deeply integrated into grid operations. Doing so will provide far-reaching benefits to users of electricity at all levels, including vastly increased system resilience, expanded system operational flexibility, support for critical lifeline functions during critical events, and even improved cyber security.

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1.0 Background

U.S. electric power systems were developed in the 20th Century largely with two goals in mind: reliability and safety. Limitations in technology led to the development of a grid that tightly couples generation to demand (load) and in fact operates in a manner referred to as "load following," meaning that generation is continually adjusted to match load. These goals remain paramount but electric power systems in the U.S. have undergone and continue to undergo significant changes due to evolution in user expectations, emergence of new technologies, and intense strategic focus on resilience,[1] cyber security, and interdependency issues. Some of the key trends and systemic issues include:

- Splitting of generation into traditional transmission-connected bulk generation and distribution-connected generation
- Increasing integration 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[2]
- Increasing volatility (unpredictable variability) of both generation and load due to penetration of Variable Energy Resources (VER - mainly wind and solar photovoltaic generation), resulting in operational challenges at both the bulk power system and distribution levels
- Threats to system operation from extreme weather and cyber-related events

These trends and issues have resulted in both structural and operational changes to the US grid and have worsened electric power system vulnerabilities and exposed new ones.

In virtually all other kinds of complex systems, volatility of flow occurs and is handled using buffers. Buffers are mechanisms for decoupling flow variations, especially random or unpredictable variations. The presence of a buffer provides a system with "springiness" or "sponginess" that makes the system able to tolerate a variety of perturbations. Communication systems have "jitter buffers" to even out the flow of data bits in communication network data transmission. Logistics systems have buffers – they are called warehouses. Water and gas systems have buffers – they are called storage tanks.[3] In each case, the buffer is some form of controlled storage that evens out irregular flows, thus reducing or eliminating the impact of volatility (fluctuation or interruption) in source or use. Buffers are like shock absorbers – they provide the springiness that makes systems internally resilient to external disturbances. Electric power grids are unique among complex systems in that they have traditionally had essentially no capacity for internal buffering for energy flows. In fact, lack of such springiness is a systemic vulnerability: it leaves the system brittle and anti-resilient.

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

Until recently, electric power grids were mainly limited to a form of energy storage called "pumped hydro storage" – to charge, water is pumped from a lower reservoir to an elevated

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[1] See Appendix A for a short discussion on terms relating to grid characteristics.

[2] Note that the Grid of Things involves two kinds of connectivity: electrical (to the grid) and communications (often to the internet).

[3] Gas systems also use "line packing" which is increasing line pressure to pack extra gas into the pipes for short term storage.

one, then the water is released back down through a hydro generator to generate power. Pumped storage has historically been used for daily arbitrage, generating when electricity demand is high and charging at times of low demand to take advantage of lower cost off-peak electricity, operating in tandem with large thermal plants. This method of electric energy storage is of limited usefulness in a resilience context due to its inherent lack of operational flexibility.

More recently, many newer bulk energy storage technologies have arisen for grid use. However, bulk energy storage for the grid has generally been viewed only as a means to bolster reliability of the grid in three ways:

- 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)

Some forms of grid energy storage are functionally very flexible and so in recent years it has been the practice to treat grid storage as an attached (as opposed to embedded) ancillary device capable of supplying many different services to the grid. The types of services that grid storage could provide are listed in Appendix B. This has led to the paradigm of “stacking” services, meaning supplying multiple services with the same storage device, perhaps even to different service consumers.

These uses of storage to date have improved grid reliability at the margins but have not changed the essential resilience characteristics 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**.

All of the valuable functions of grid energy storage flow from this 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.

2.0 Some Basic Storage Concepts

2.1 Storage Types

Grid energy storage receives energy in the form of electricity from the power grid and then later either returns it to the grid as electricity (“reflexive”) or converts it to some other use (“transitive”) as Figure 1 illustrates.

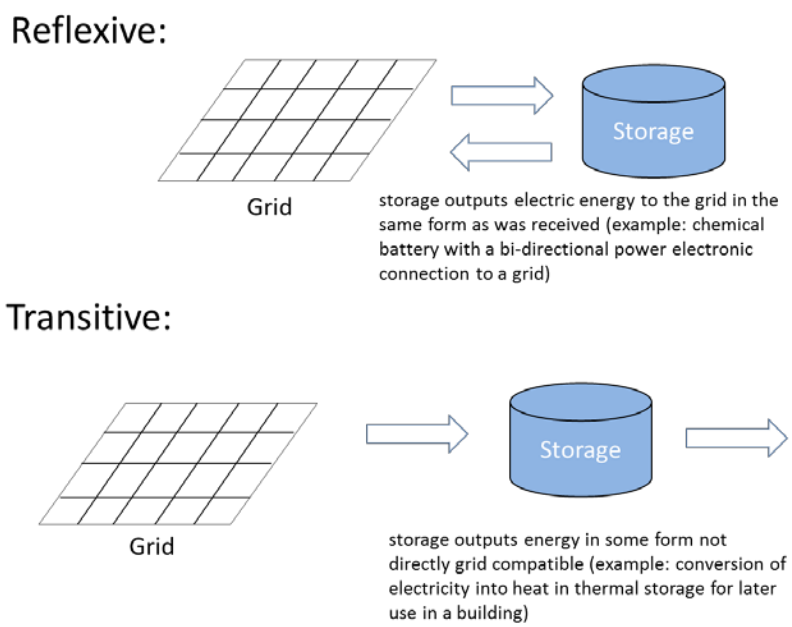
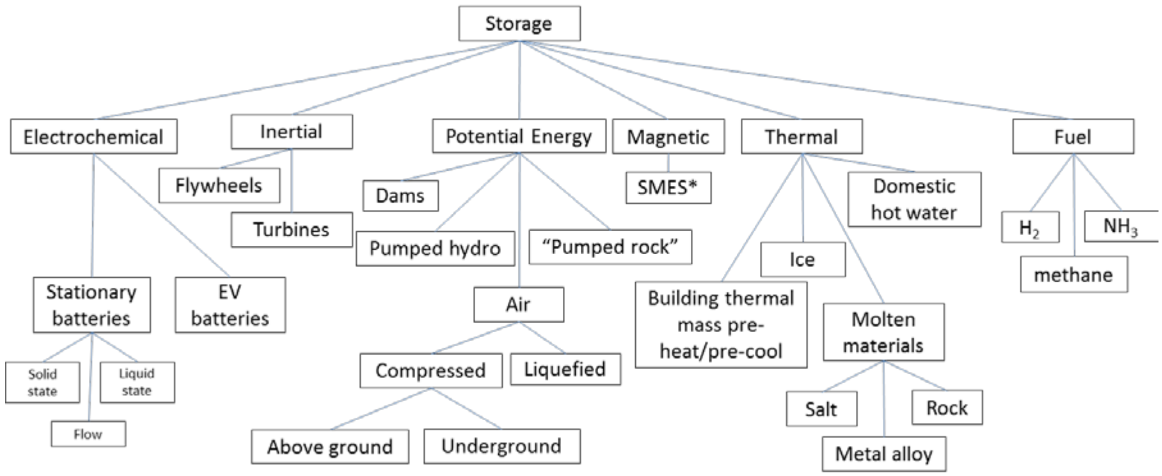


Figure 1. Reflexive and Transitive Grid Storage

There are a great many technologies that can provide grid energy storage – Figure 2 below categorizes a number of them. They differ in performance and cost, and while grid energy storage is generally a functionally flexible tool, not all types of storage are equally suitable for all uses.



* Superconducting Magnetic Energy Storage

Figure 2. Grid Energy Storage Technologies

It is not necessary to delve deeply into engineering details in order to understand storage issues at the architecture, investment planning, or regulatory levels. Instead, for strategic and public policy purposes, we may concentrate on externally visible characteristics, and thereby not have to be concerned with the details that come into play when developing implementations.

2.2 Key Storage Characteristics

For strategic purposes, bulk energy storage for the electric grid can be thought about in terms of a small set of inherent characteristics as seen from "outside of the box," regardless of the technology inside the storage device. These characteristics are listed in Table 1.

Table 1. Key Storage 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)

Other technical factors come into play when considering actual installations, such as charge/discharge mode switching times, stored energy dissipation (leakage) rate, operating conditions, physical footprint, safety measures, "state of health," performance degradation, etc. These are important engineering considerations but are not crucial at the strategic planning and grid architecture stages.

3.0 Storage as Core Grid Infrastructure

Reflexive storage can operate with considerable functional flexibility to support grid resilience. We refer to storage in this context as (internal) core grid infrastructure, distinct from (external) edge-attached ancillary devices supplying reliability services.[4]

Think of grid energy storage as a general purpose energy system component, as shown in Figure 3. This component has three major elements: the energy storage device, advanced controls,[5] and a flexible grid interface. Note that while it would not be unusual to consider electrochemical batteries for the storage elements, implementations based on other technologies are possible and no assumption about the internals of the storage device are necessary for architecture or strategic planning purposes. The reason for the power electronics element is that while the electric power grid uses alternating current (AC) most storage elements operate with direct current (DC). Power electronics provide the means to connect the two together and also offer much flexibility in terms of actual control functions. Real storage devices also have storage management systems[6], communications interfaces, and other apparatus, but the three elements shown in the diagram are the basis for grid energy storage systems that can be used as general purpose energy system components.

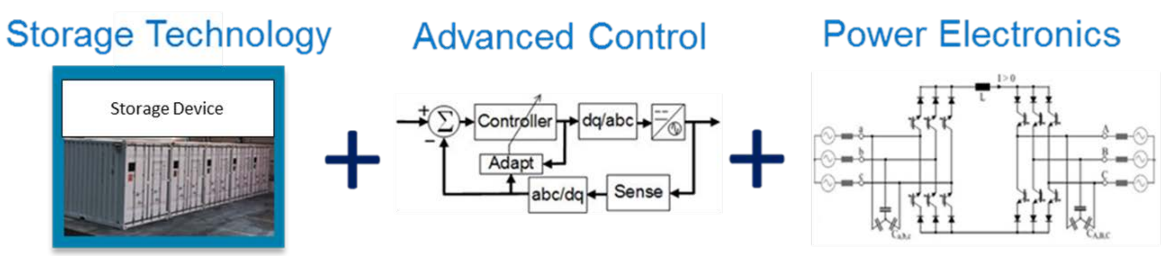


Figure 3. Key Elements of a General Purpose Grid Storage System

> The combination of storage, power electronics, and advanced control should become a new energy system component, as fundamental as a transformer or circuit breaker and used throughout the grid.

3.1 Embedded Storage for Grid Operations

To make use of bulk energy storage as a grid shock absorber, it must be embedded in the grid as core infrastructure and integrated with grid control, not used as an ancillary services device. In this model, embedded storage is used for operational issues such as those listed in Table 2.

Table 2. Embedded Grid Energy Storage Functions

Item No.	Function

[4] Such grid services and reliability-enhancing uses of storage can and likely will co-exist with embedded core storage, following already established models for operation and justification.
[5] Advanced storage control is multi-modal, so that the storage device can be used in a number of ways and the operating mode can be changed very quickly and automatically to meet changing grid conditions.
[6] Systems local to the device that manage charging, monitor device health, etc.

1	Flatten demand curves – use of storage in a cyclic manner to shift apparent demand so as to make the aggregated demand seen by the bulk power system as flat (over daily time cycles) as possible
2	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
3	Manage apparent load volatility (handle variations in net load due to Behind the Meter activity); manage edge generation volatility (such as from solar PV)
4	Reduce exchange of volatilities between bulk system and distribution systems
5	Mitigate system ramping constraints
6	Facilitate source/load matching and source/load decoupling; loosen balance and area frequency control constraints
7	Defend against edge-based volatility attacks (IoT attacks)
8	Support Electric Vehicle charging (zero outage operation)
9	Facilitate microgrid adoption
10	Maximize VER energy extraction to avoid curtailment (generation peak shifting)
11	Support Distributed Energy Resources integration by managing edge-based volatility
12	Enable energy banking/warehousing to facilitate energy networking and congestion management
13	Support generation black start – provide initial station power to selected generators and also act as interim load while generation is stabilizing
14	Manage volatility exchange between bulk natural gas and electric generation systems – to even out the mismatch between desired constant gas flow and peaking gas turbine generator operation

Improving grid infrastructure with embedded storage will improve transmission-level and distribution-level resilience, will support critical lifeline capabilities for emergencies such a critical load outage ride-through and generator black start, and improve joint operating characteristics of natural gas-electric generation systems.

3.2 Embedded Grid Storage Operating Requirements

To be useful for the purposes described above, grid storage should be:

- 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-assured – 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 and ownership of embedded grid storage assets. It is also conceivable that a third party may own the storage, but the utility must still control it.[7] Note that the utility would not bid storage-based services into wholesale electricity markets, or engage in energy arbitrage. Embedded storage would be used for delimited purposes related to grid operations only, for regulatory reasons.

[7] This is the model being used at HECO; a third party may be the owner, but the utility pays a tariff and controls the storage directly as it sees fit. There is no concept of value stacking or differentiated services.

4.0 Embedded Storage Architectural and Operational Issues

The purpose of embedding storage into core grid infrastructure is to provide essential buffering for both transmission and distribution systems, each level having its own buffering/shock absorber issues. In addition, the presence of Variable Energy Resources at either level causes problematic export of volatility from one to the other. The dynamics of this volatility exchange are increasingly a challenge for grid operations.[8]

4.1 Large Central vs. Smaller Distributed Storage Structure

Building massive storage units can present significant upfront cost and engineering issues, but another approach is available. Instead of creating a few giant centralized storage units, it is possible to create a distributed set of storage units where each unit is of a manageable size, and then control the set of storage units as a group, operated so as to provide system wide benefits as well as local benefits. In this arrangement, the storage capacity can be built up incrementally, but the operational impacts can be realized as the installed base grows. In fact, storage units can be shared across substations and therefore across service areas.[9,10] In addition, storage units can be placed for specific purposes such as in proximity to wind farms, community solar "gardens" or clusters of electric vehicle chargers. While each storage unit may be of modest (for grid scale purposes) size, the aggregate storage can grow to be substantial and the investment can be spread over considerable grid infrastructure. By integrating the units into a coordination and control network, storage-based grid resilience can grow incrementally over time, rather than requiring a complete giant deployment before any benefits occur.

4.2 Locating Embedded Storage Network Components

Three allocation strategies for determining storage device location have been studied via power system simulations:

1. Locate storage at generator buses
2. Locate storage only on transmission buses (substations and switching stations) but not Transmission/Distribution (T/D) interface substations
3. Locate the storage devices at load connection points (transmission/distribution substations)

Engineering considerations may result in hybrid variations of these three approaches and even location outside of substations some cases, but as a matter of strategic planning and grid architecture, 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

[8] The so-called duck curve and increasing difficulty in assessing the need for generation reserves are two examples.
[9] GMLC Grid Architecture Team, GMLC 1.2.1 Advanced Bulk Power System Reference Architecture, WIP.
[10] PNNL Staff, Distribution Storage Networks, PNNL-26598, June 2017, available online: https://gridarchitecture.pnnl.gov/media/advanced/Distribution_Storage_Networks_v0.3_PNNL.pdf

- Effective placement for managing T/D volatility exchanges
- Effective placement for managing distribution edge-based volatility attacks

Location of storage at generation buses suffers from technical issues related to close-in electrical faults and is not as effective as the other strategies in dealing with edge-based volatility attacks.[11]

4.3 Embedded Storage 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 to greater effect than if they operate independently.

When operating as a Coordinated Storage Network, two control and coordination structures are possible. One is conventional centralized control, as, shown in Figure 4.

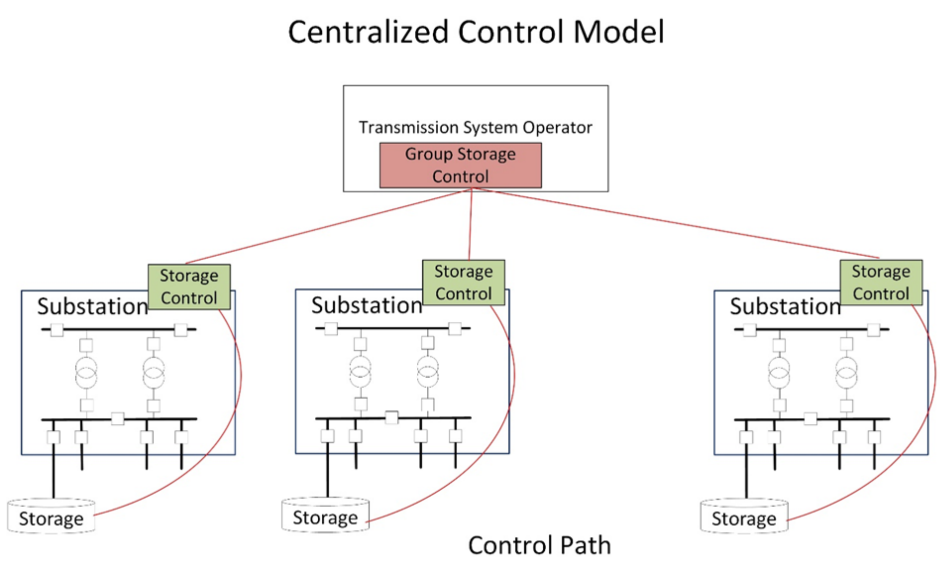


Figure 4. Centralized Control of Storage Networks

The structure of Figure 4 raises the issue of how to operate storage for purposes related to Distribution operations. An emerging systemic issue for grid operations is the lack of operational coordination between transmission system operators and distribution systems.[12] Existing coordination structures suffer from tier-bypassing and gapping problems[13] that lead to conflicts in managing energy resources that are distribution-connected but have significant impact or potential for operational support at the transmission level while simultaneously impacting

[11] PNNL simulation studies (work in progress).
[12] Operational Coordination across Bulk Power, Distribution and Customer Systems, prepared for the Electricity Advisory Board, U.S. Department of Energy, February, 2019.
[13] See Appendix C for a short discussion of coordination tier-bypassing and gapping.

distribution reliability and use of the resources for distribution resilience and operational flexibility purposes.

This is exactly the same issue that has arisen with the coordination of Distributed Energy Resources (DER) in general (limiting the availability of DER as a resource for Bulk Power System resilience support) and has led to the present industry discussions about Distribution System Operators (DSOs) and layered decomposition of coordination.[14,15,16] Figure 5 illustrates a DSO/layered decomposition model that provides the structural framework to resolve the transmission/distribution coordination issue for storage networks in particular and DER in general.

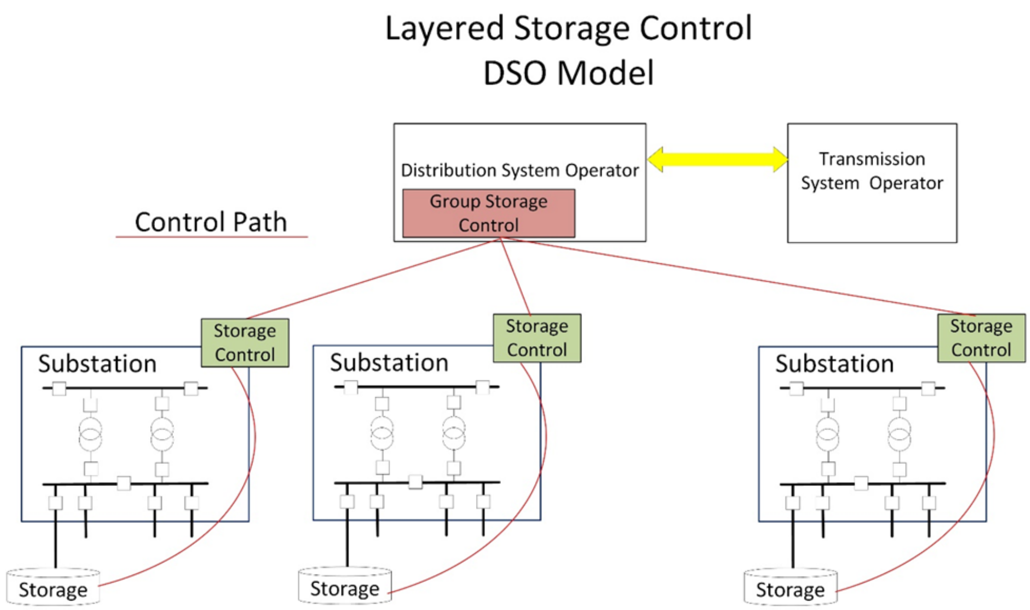


Figure 5. Layered Coordination of Storage Networks via Distribution System Operators

In this approach, the Transmission System Operator (TSO) coordinates with the DSO that actually directly controls the storage assets. This eliminates the tier-bypassing and coordination gapping problems in an efficient manner. The control and coordination model of Figure 5 is preferable from a grid architecture standpoint, but the industry structure to support this is not yet in place.[17] Using embedded storage as the key scenario, the evolution of grid coordination from the model of Figure 4 to Figure 5 can lead the way for full systemic integration of DER in general.

[14] P De Martini and L Kristov, Distribution Systems In A High Distributed Energy Resources Future, FUER Report No. 2, October 2015, available online: https://gridarchitecture.pnnl.gov/media/advanced/FEUR_2%20distribution%20systems%2020151022.pdf
[15] L Kristov and P De Martini, 21st Century Electric Distribution System Operations. May 2014, available online: https://gridarchitecture.pnnl.gov/media/white-papers/21st%20C%20Electric%20System%20Operations%20%20050714.pdf
[16] GMLC Grid Architecture Team, High Resilience reference Grid Architecture Package, Feb. 2019, available online: https://gridarchitecture.pnnl.gov/media/zip/High_Resilience_Ref_Arch_March_2019.zip
[17] Meaning DSOs do not yet exist, although they are being widely contemplated.

Embedded storage must also have a fallback local control mode so that devices can operate even when there are wide area outages of communications and control. In this fallback mode, each storage device relies upon local control and local sensing and measurement, as shown in Figure 6.

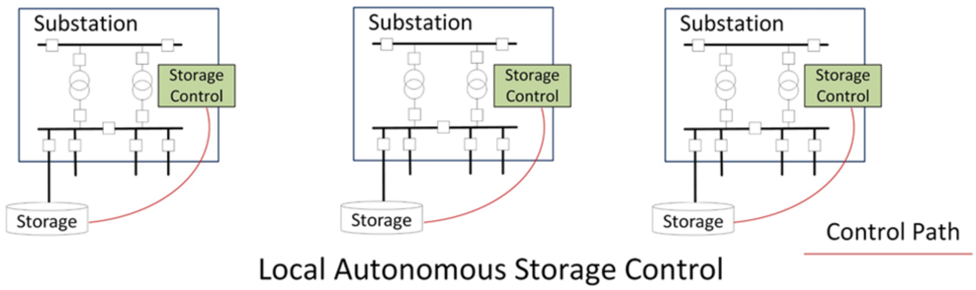


Figure 6. Fallback Local Storage Unit Control

5.0 Summary Comments, Recommendations, and Next Steps

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, and this has implications at all levels of the grid and for all forms of threats to the grid. Until recently there has not been a solution to this problem and therefore grids operate in a somewhat brittle, tightly-coupled load-following mode that is increasingly unsustainable.

The solution to this issue is to embed bulk energy storage into the grid as core infrastructure, thus giving the grid the springiness or sponginess that it needs to be able to handle shocks to the system that may come from a variety of sources. Such storage will act as the shock absorber that has been missing from both transmission and distribution. Key requirements to enable the shock absorber are that the storage be embedded as core infrastructure (not treated as edge-attached third party services devices) and that it be controlled by electric utilities.

Applying storage in this manner to the grid will address existing weaknesses (lack of buffering), add new capabilities to support lifeline functions for critical events, enable improved overall grid operational flexibility and efficiency, add new protections against cyber-attack, and enable integration of renewable energy sources to the grid.

5.1 Recommendations for Implementation

If a utility, transmission system, or regional grid is to undertake the deployment of storage as core infrastructure, then:

- 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

Engineering and supporting analytical work will determine specific storage types, sizes, and other design and implementation specifications for any specific installation, within the general architectural guidelines set forth above.

Incorporation of storage as an essential, embedded feature of the grid has implications for ownership, control, and regulation of the asset, as well as valuation and locational planning.

5.2 Next Steps

By addressing the systemic issue of improving core grid infrastructure through the use of embedded storage to provide the buffering that is lacking now, it will be possible to:

1. Resolve Federal and State level positions on the use of storage for purposes besides grid services (namely resilience and operational flexibility)

2. Clarify the modification of industry structure to accommodate coordination of shared or coupled operating resources in the context of the DSO model for T/D coordination
3. Complete and validate valuation approaches for emerging assets and resources such as storage and DER in general

In addition to improving grid resilience and operational flexibility through buffering, this will help greatly to secure the grid, to enable critical lifeline capabilities, and to resolve large scale issues of grid modernization related to coordination structure, implementation, valuation, and regulation.

Appendix A – Grid Characteristics

A number of terms are used to characterize power grids but unfortunately these terms are often vaguely defined or are overloaded with multiple definitions. The definitions in Table A.1 derive from the work on Grid Architecture and have proven useful for clarifying the underlying concepts when considering fundamental issues of grid structure and their effects on grid behavior and performance.

Table A.1. Grid Characteristics Definitions Used in Grid Architecture

Term	Definition
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.
Robustness	The ability to tolerate perturbations and uncertainty in grid operations.
Resilience	The ability of the grid to avoid or withstand stress events without suffering operational compromise or to adapt to and compensate for the strain so as to minimize compromise via graceful degradation.
Flexibility	The ability to adjust to or compensate for variations in operating conditions from within a fixed set of functions, capabilities, and structures.
Agility	The ability to make adjustments quickly. The key issue here is not the nature of the adjustments, but the speed with which they can be applied.
Electric reliability	The degree to which electric service that meets applicable usability standards is available over any given time period in a given service area. Consists of availability and usability
Electric availability	The percentage of time a voltage is uninterrupted. This is primarily about outage and restoration, outage being a failure event and restoration being a utility function.
Electric usability	The degree to which electricity can be employed for a specified purpose.
Extensibility	The ability to add, subtract, and scale system functions and capabilities with only incremental changes in structure and with no impact to other functions or capabilities.
Optionality	The availability of multiple means (options) to solve a given problem.
Adjustability	The ability to make parametric or small structural changes to accommodate changing conditions.

Note that these characteristics are not merely standalone concepts. They are actually related and an understanding of how they are related provides a powerful means for reasoning about the grid and changes to it. Figure A.1 illustrates the structural relationships among these characteristics. More explanation of these concepts can be found on the Grid Architecture website.[1,2]

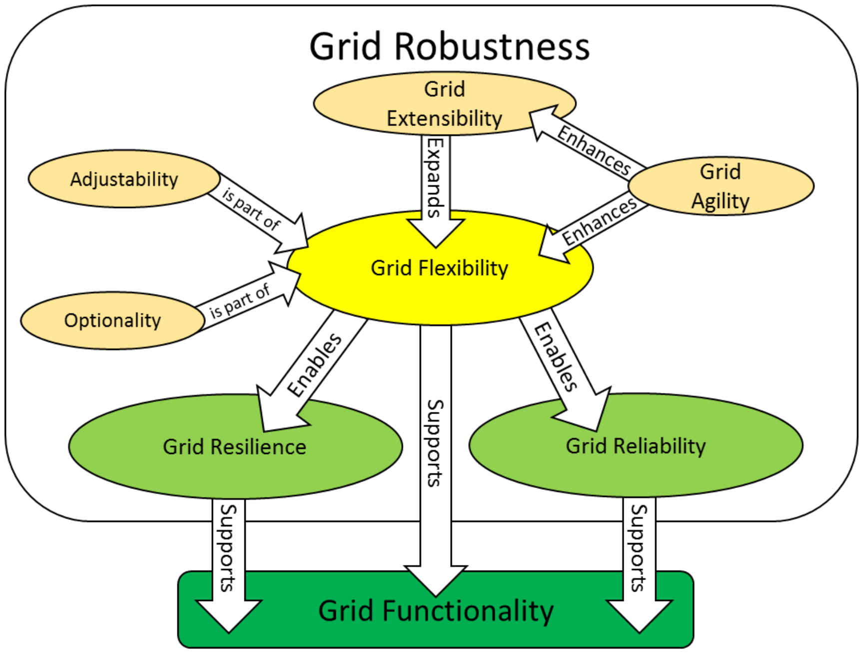


Figure A.1. Relationships of Key Grid Characteristics

[1] JD Taft, Electric Grid Resilience and Reliability for Grid Architecture, PNNL-26623, March 2018. Available online: https://gridarchitecture.pnnl.gov/media/advanced/Electric_Grid_Resilience_and_Reliability_v4.pdf

[2] JD Taft, et al., Grid Characteristics: Using Definitions and Definition Structure for Decision-Making, PNNL-SA-141678, Feb 2019. Available online: https://gridarchitecture.pnnl.gov/media/methods/Grid_Characteristics_Definitions_and_Structure.pdf

Appendix B – Typical Storage-Based Grid Services

Table B.1 created by Sandia National Laboratories catalogues storage-based grid services. The functional flexibility of storage makes it a candidate for supplying a wide array of grid services and there has been some consideration of using storage to supply services not just to the bulk energy system but also to distribution systems (see the footnote for a comprehensive listing of grid services[1]).

Table B.1. Storage-Based Grid Services

		Discharge Duration*		
#	Type	Low	High	Note
1	Electric Energy Time-shift	2	8	Depends on energy price differential, storage efficiency, and storage variable operating cost.
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 for 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

[1] GMLC project, Grid Services Master List (spreadsheet). Available online: https://gridarchitecture.pnnl.gov/media/advanced/GMLC_Grid_Services_Master_List.xlsx

Appendix C – Tier Bypassing, Coordination Gaps, and Hidden Coupling

Grid coordination and control evolved from the 20th Century grid, which did not contemplate significant levels of active distribution-level resources. Consequently, as penetration of such resources has proceeded, coordination has proven to have limitations whose consequences are unfavorable to future grid operations. These issues are structural and can be addressed via Grid Architecture.

C.1 Hidden Coupling

Hidden coupling occurs when two or more grid elements end up being unintentionally connected (usually indirectly), thus causing operational issues including unpredicted behavior and reliability problems. Hidden coupling in distribution grids can occur several ways. Figure C.1 below shows three ways that occur on different scales.

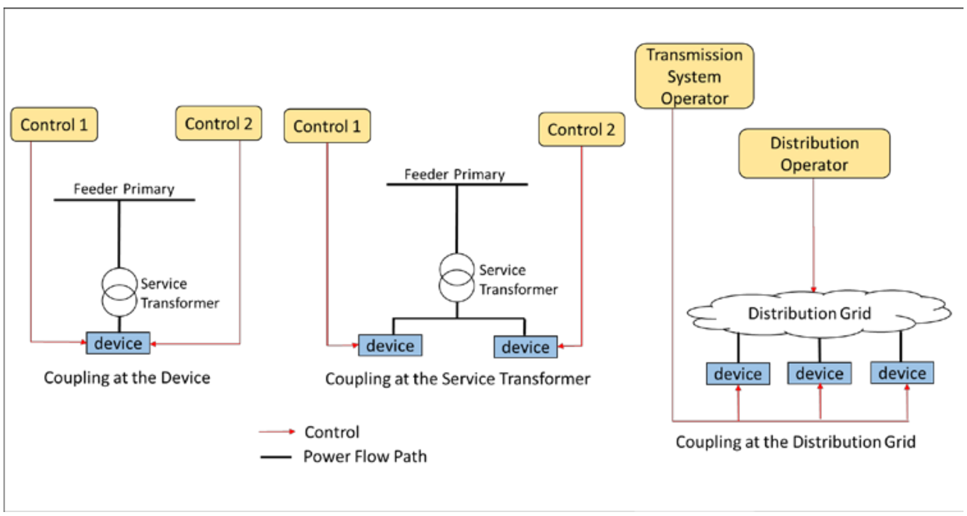


Figure C.1. Forms of Hidden Grid Coupling

Each of the examples shows coupling of the controls at various levels - at the device if two or more controls attempt to use the same device; at the service transformer if two devices are controlled separately but are electrically connected on the same secondary; and at the distribution grid if one control manages DERs while the other manages grid operations devices, all of which are electrically connected to the same distribution system. More subtle forms of coupling are possible and any of these may arise without being obvious, hence the term hidden coupling. The third case also illustrates a roles and responsibilities conflict, as discussed above.

The problem that hidden coupling creates is the potential for conflicting commands that the individual controls may issue due to being unaware of each other and of their coupling. Such controllers can end up competing or even attempting to override each other. There are two primary means of avoiding the problems of hidden coupling: structure the controls so that none of the situations above or any others can exist in the first place, or arrange for the separate controls to coordinate with each other so as to resolve any conflicts before they arise. The first solution is preferable to the second because moving the coupling elsewhere (into the control systems) creates other problems related to system brittleness and anti-resilience.

C.2 Tier Bypassing

Tier bypassing is a problem that arises when organizational roles and responsibilities and consequent industry structure allow control from a higher level to "reach past" an intermediate level to control devices that impact the responsibilities of the intermediate level organization. Figure C.2 below shows an example coordination bypass and gapping situation. The black arrows represent control paths. Note that the tier bypassing leads to the third hidden coupling problem of Figure C.1 above. At scale, it results in the creation of distribution reliability issues as well as grid stability issues when the penetration of DER is high.

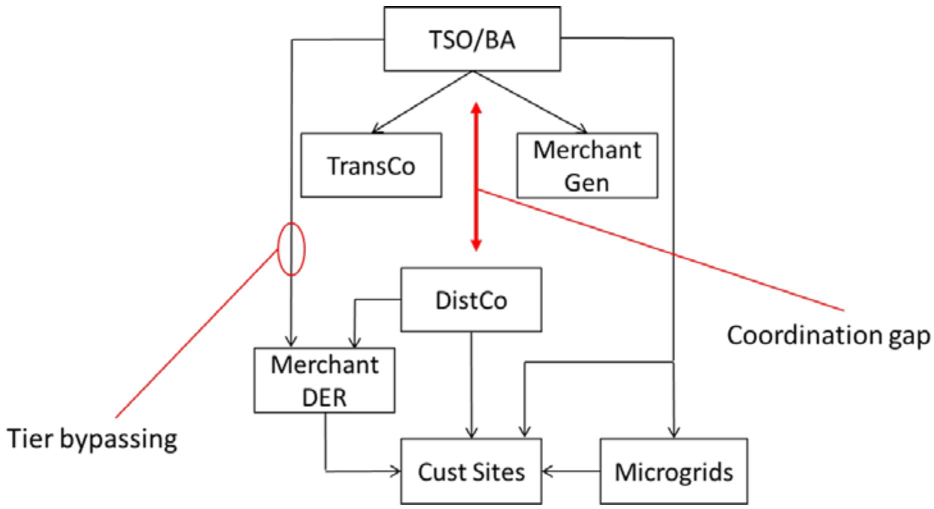


Figure C.2. Tier Bypassing and Coordination Gapping

Figure C.3 illustrates how layered decomposition can restructure coordination to resolve the bypass and gapping problems.

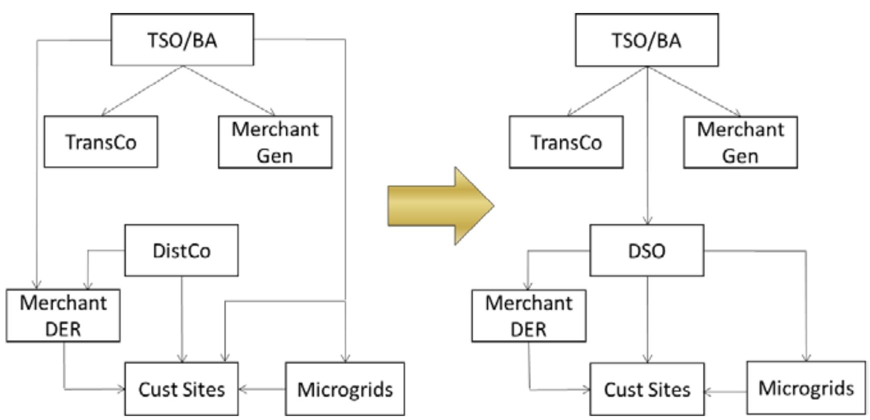


Figure C.3. Re-structuring Coordination to Correct Bypassing and Gapping

This tier bypassing issue and its resolution are at the root of much of the discussion about Distribution System Operator models. This type of structural resolution involves industry structure and the roles and responsibilities of the various relevant organizations and becomes more complicated with the introduction of third parties like aggregators and merchant DER operators. Layered decomposition can resolve these issues structurally.

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