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Distribution Storage Networks

June 2017

JD Taft
R Huang

U.S. DEPARTMENT OF ENERGY

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Executive Summary

Distribution storage networks are interconnected distribution-level bulk energy storage devices that function as core infrastructure elements to provide both grid resilience and defense against IoT-based cyber grid security threats. The recognition that these are core grid functions changes how storage of this type valued, financed, and operated as compared to storage for ancillary grid services. Distribution storage networks make use of fast bilateral storage to buffer the grid from edge device-based volatilities; this is the essence of both its resilience capability and its cyber defense capability. These storage networks must be core grid components because resilience is an intrinsic grid characteristic and both it and cyber defense of the distribution grid are the responsibility of the distribution utility.

As core infrastructure, distribution networks can be treated via least cost/best fit rather than through benefit/cost analysis. Operation of such systems is consonant with standard utility operating and safety practices, control systems, and financial models, thus presenting very little in the way of barriers to adoption, unlike the third party ownership models. In addition, storage deployed in this manner is not just firm-dispatchable, it is also *firm-designable*, meaning that the utility can place the amount of storage it needs in the locations where it is needed for grid operational purposes at the time that it is needed.

Contents

Figures

Tables

1.0 Background

Many forms of energy storage are proposed for use in the electric power grid. Each of these forms has a useful function and value but deployment and integration of storage is to some extent hampered by two factors:

- the focus on multi-service operating modes, benefit/cost analyses, power market-based monetization of storage components, and attempts at value-stacking
- integration and coordination issues for storage owned by non-utility entities

The root issue is the treatment of storage as an ancillary device, with the resultant delegation of storage ownership and operation to third parties. Some uses of storage do not decouple well from grid operations however, and so it is worthwhile identifying those uses and the proper roles and relationships that go with them.[1] Recognition that some uses of storage are not ancillary in nature leads to the definition of certain storage classes as core grid elements, without in any way detracting from the other uses of storage and their associated owner models and value streams.

In what follows, we recognize that the responsibilities of the Distribution Operator include grid operations, distribution reliability, and distribution grid physical and cyber security. Under some forward-looking models, this may expand to include the coordination and management of DERs in the distribution service area and interface to a system operator.

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[1] GMLC Grid Services Master List

2.0 Storage as a Core Grid Component

The combination of fast bilateral storage, flexible interface, and advanced controls forms a general purpose grid component, as fundamental as a power transformer or a circuit breaker.[1] The fast bilateral property refers to storage that accepts electricity from the grid, stores it and then can return it to the grid in the form of electricity and do so in a manner that is not just fast but equally fast in either direction. This implies that storage power flow direction can be reversed very quickly (sub-second or even sub-cycle time frame). A second key reason for use of a flexible interface is the usefulness of managing power flow in a continuous manner.

> The technology triple of fast bilateral storage, power electronics interface, and advanced controls forms a basic grid component, as fundamental as a power transformer or circuit breaker.

A defining capability of such a component is the decoupling of power system volatilities; this can be source/load volatility or bulk system/distribution volatility. This capability allows distribution storage networks to increase grid resilience, perform stabilization, and secure the grid against DER manipulation. An essential characteristic is the speed with which the storage device can operate.

[1] JD Taft and A Becker-Dippmann, "Grid Architecture," Section 5.3.2.3, available online: http://gridarchitecture.pnnl.gov/media/white-papers/Grid Architecture - DOE QER.pdf

3.0 Key Grid Functions

Fast bilateral storage of the type described above could provide the grid functions listed in the table below.

Table 1. Distribution Storage Grid Functions

Function	Description	Comments
Generation/load decoupling	Bulk storage at the distribution substation or primary feeder level can buffer the grid from fast net load and feeder level voltage fluctuations caused by edge-connected DER such as rooftop solar PV.	The use of storage in this manner can eliminate the need for DSTATCOM for voltage stabilization.
Leveling demand curves	Substation level storage can be used to level or flatten demand curves over the course of a day without impinging on consumer activities.	Size of the storage and how storage is shared across substation service areas determines how much flattening can be achieved.
Volatility export suppression	System operators find the increasing export of volatility from the distribution level to the bulk energy system level to be problematic; under some DSO models, it is the responsibility of the Distribution Operator to manage volatility export.[1]	Distribution storage networks can act as the buffer to smooth out power variations due to solar PV or distribution connected wind generation.
Resilience augmentation	This follows directly from the volatility decoupling/buffer property of storage; locating the storage at the distribution level provides decoupling from source volatility in both directions.[2]	Storage networks can enable the utility to perform "line packing" in advance of severe weather, planned outages, etc. to provide ride through.
Cyber security	This follows directly from the recognition that some IoT-based vulnerabilities are based on creation of (possibly synchronized) volatility of sources and loads at the distribution grid edge.[3]	Distribution storage networks can act as the buffer to cushion the shock of cyber-induced edge-based fluctuations.

[1] P De Martini and L Kristov, "Distribution Systems in High Distributed Energy Resources Future," available online: https://emp.lbl.gov/sites/default/files/lbnl-1003797.pdf
[2] J D Taft, "Electric Grid Resilience and Reliability for Grid Architecture," GMLC white paper.
[3] J D Taft, "Defending the Electric Grid from IoT," GMLC white paper.

4.0 Distribution Storage Networks

The simplest way to implement distribution level storage would be to place a storage unit in each distribution substation. This would also be the most expensive approach. Another way would be to put storage units in some distribution substations and interconnect them via feeders to form *storage networks*. Sharing across substation service areas would require partial feeder meshing, but this is done to enable load rollover and FLISR[1] anyway.

Distribution storage networks have six basic elements:

1. Fast reflexive storage devices (energy goes in and out as electricity)
2. Fast low latency bilateral interfaces (energy flow in either direction, switching direction with low latency)
3. Interconnection feeder circuits (to enable sharing across substation service areas)
4. Power flow controllers
5. Advanced controls (both internal and system level)
6. Communications capability (to support operation as a coordinated network)

Feeder interconnections may take any of several topological forms. Four such forms are shown in the figures below. For the sake of clarity, the control and communications networks are not shown.

The topologies feature various types and amounts of redundancy and vary in terms of number of feeders committed per storage substation, as well as the number of power flow controllers needed per substation. Figure 3 and Figure 4 provide symmetrical structure, whereas Figure 1 and Figure 2 are asymmetric in that they have hub substations that differ in form and function from the spoke stations. Hub stations host the storage units, making them unique; this is embedded in the feeder connection structure. In Figure 3 and Figure 4, any of the substations can host a storage unit. Storage networks do not have to cover the entire utility service areas in one network. Substations make be grouped and partitioned into multiple distribution storage networks at the discretion of the system designer.

Note: the diagrams indicate the use of power flow controllers. These could be solid state devices, but could also use other technologies such as variable frequency transformers.

[1] Fault Location, Isolation, and Service Restoration

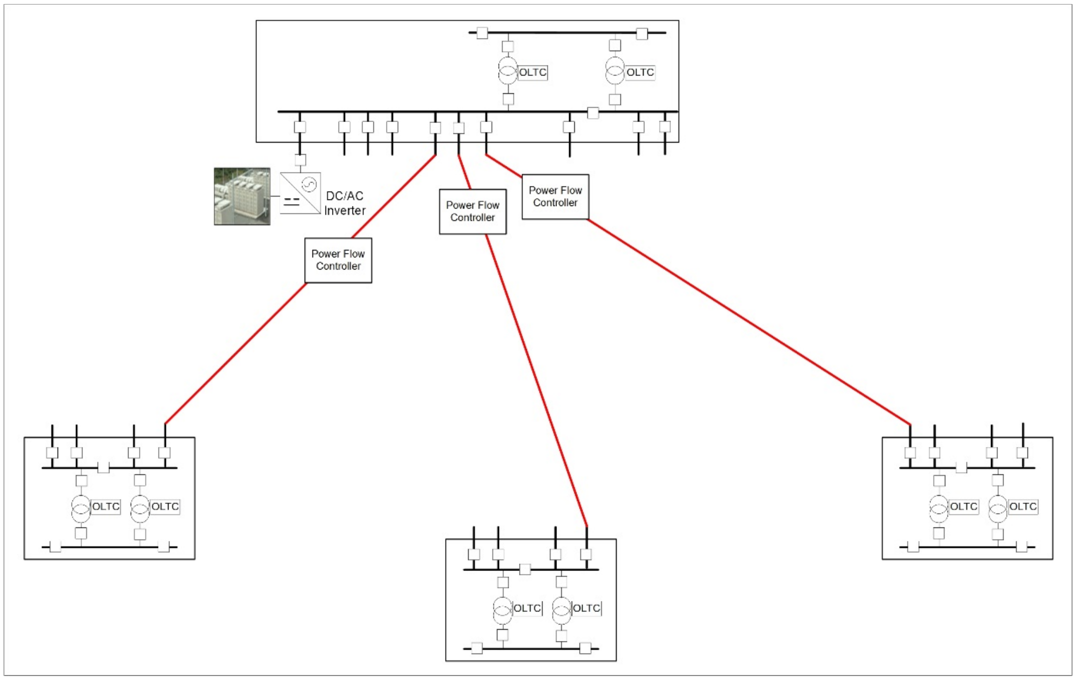

Figure 1. Hub and Spoke Distribution Storage Network

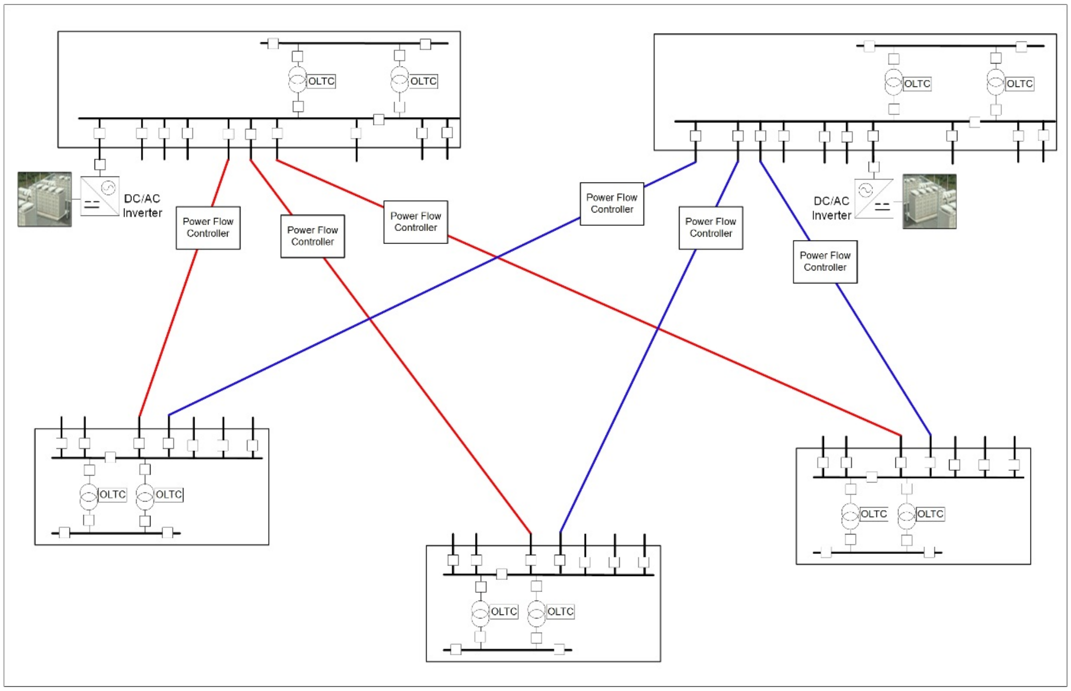

Figure 2. Dual Hub and Spoke Distribution Storage Network

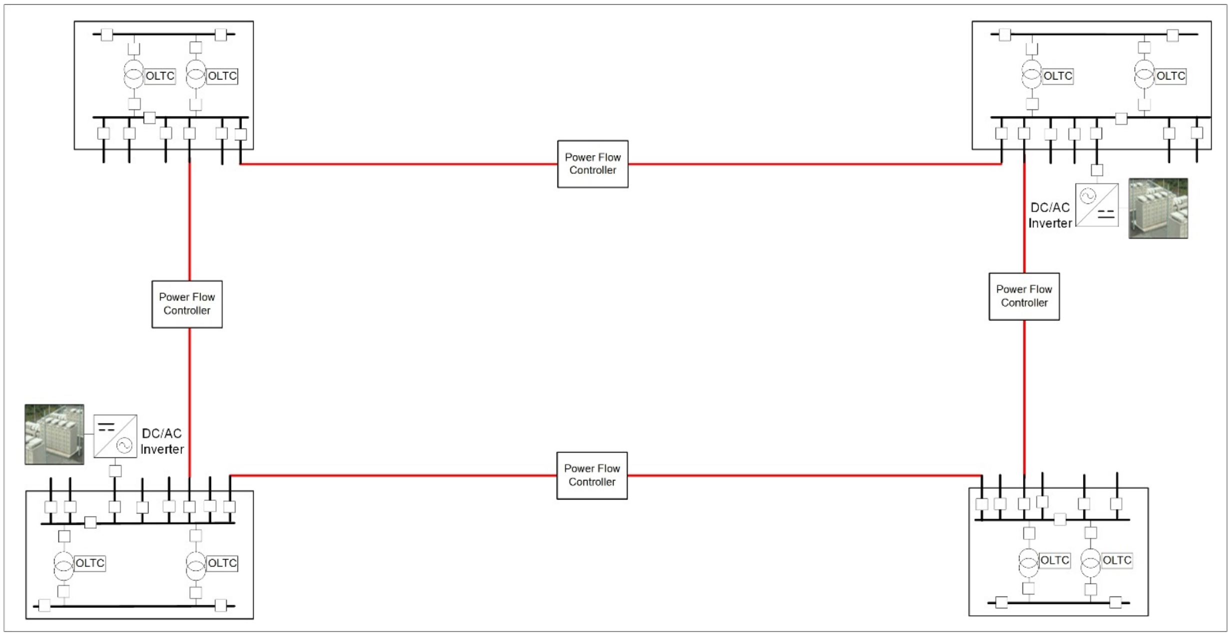

Figure 3. Loop Distribution Storage Network

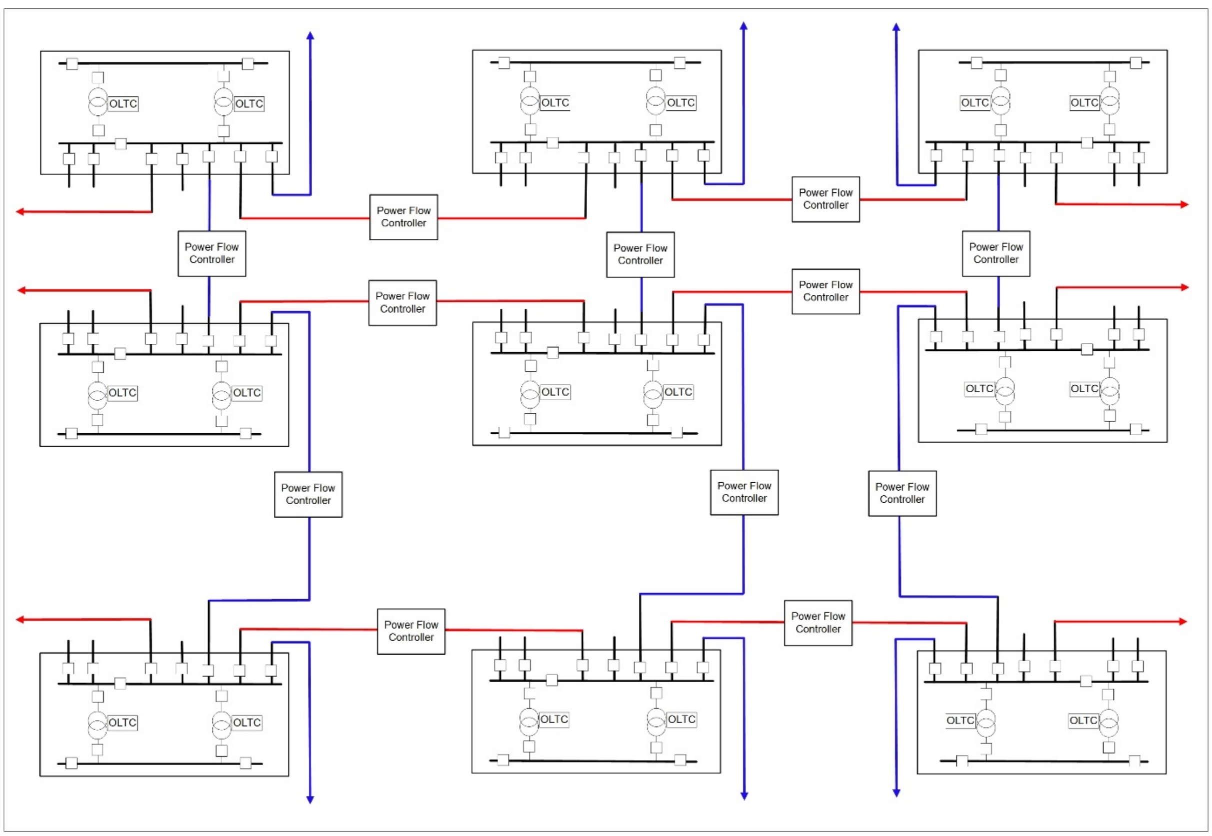

Figure 4. Full Mesh Distribution Storage Network

The interconnection topologies impact system design and performance. As an example, three of the topologies (hub, dual hub, and loop) were simulated using substation loading data and local proportional control for the storage devices to determine the effect of interconnection topology on the size of storage needed to flatten demand curves. Figure 5–Figure 7 below show the results of the simulations. Note that the bandwidth shown in Figure 5 is defined as the upper and lower thresholds of the substation load for the discharging and charging of the battery, and various bandwidths represent different flattening levels for the substation loads. Or in other words, if the substation load is within the bandwidth, the storage will not discharge or charge power from the grid side.

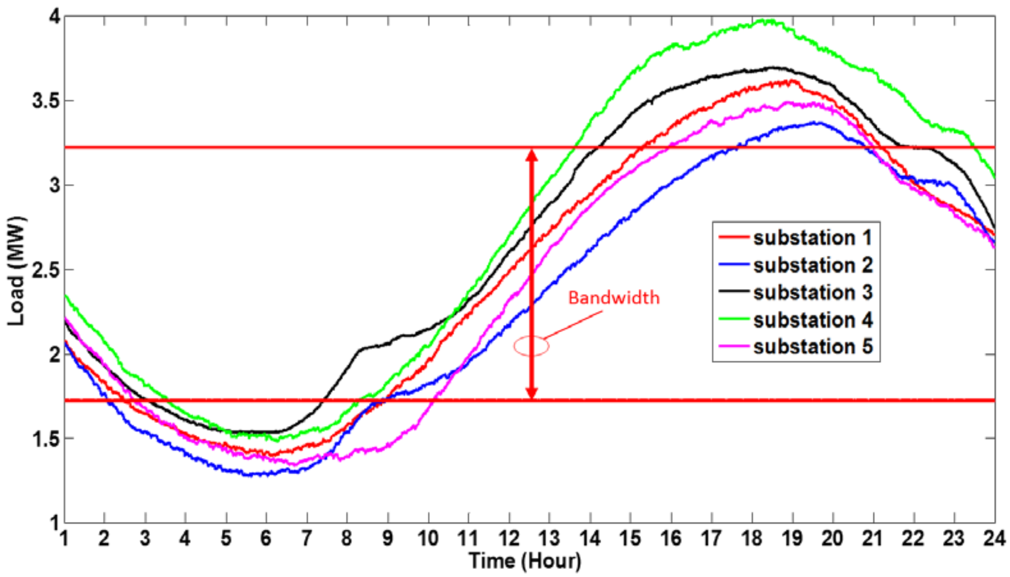

Figure 5. Substation Loading Curves and Battery Charge/Discharge Thresholds

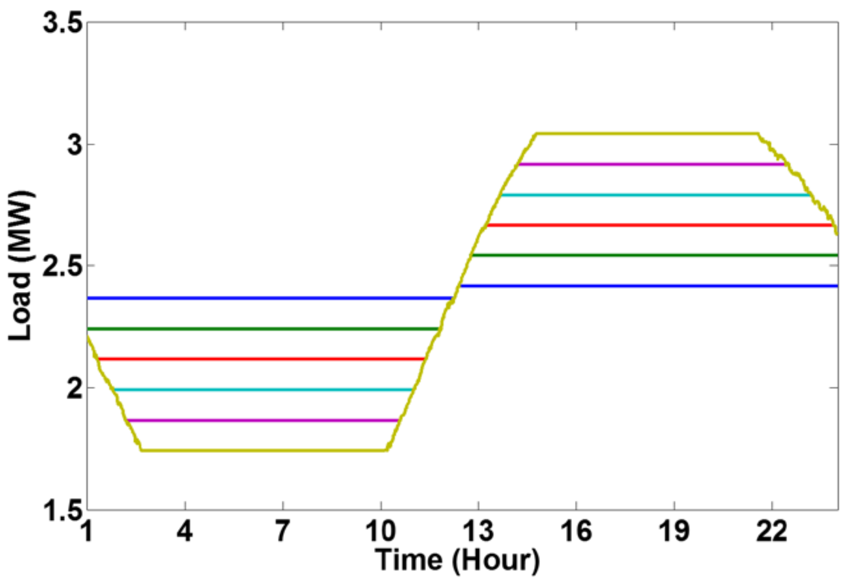

Figure 6. Load Shapes with Battery Flattening For Various Bandwidths

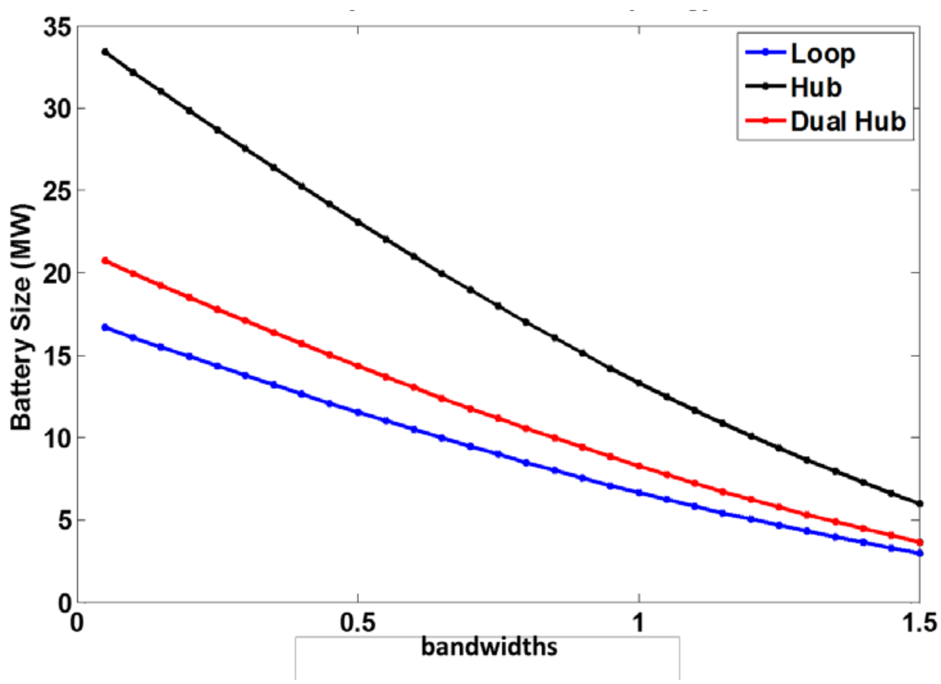

Figure 7. Effect of Bandwidth on Battery Size for Differing Topologies

The simulation study shows that shared batteries can be used to flatten load shapes across multiple substations and that the topology of the interconnections for battery sharing have an impact on battery size needed to achieve a given level of flattening. The effect becomes more pronounced as the bandwidth narrows (as the net load curves are made flatter).

Battery interconnection topology is therefore a consideration in the design of distribution storage networks. More work remains to be done to determine the effect of battery interconnection topology on the other functions of Table 1 and under different load profiles.

5.0 Valuation

There are several methods by which grid investments may be evaluated. These include traditional utility cost-customer benefit, “opt-in” self-supporting costs, integrated power system and societal benefit-cost, and least cost, best-fit methods. The DSPx Project Modern Grid Decision Guide Volume III recommends use of least cost, best-fit for core platform elements.[1]

To appreciate the approach to valuation of distribution storage networks, it is helpful to understand the concept of platform as it applies to electric power systems. In general a platform is a stable base of components and capabilities, upon which various modular application capabilities are built in such a way that they share the underlying stable component set[2]. For power grids, the physical infrastructure, such as wires, transformers, circuit breakers, etc., comprise part of the platform, but other components, such as sensing and operational communications, should also be considered as core in a modern grid.[3]

Realizing the distribution storage networks fit the description of platform elements and thus qualify as core infrastructure components, and so should be treated accorded to the “least cost/best fit” approach to valuations and consequent financing.

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[1] P De Martini, et. al., “Modern Distribution Grid Decision Guide, Volume III,” DSPx Project, available online: https://doe-dspx.org/ . See Table 1.

[2] P De Martini, et. al., “Modern Distribution Grid Decision Guide, Volume III,” DSPx Project, available online: https://doe-dspx.org/ , Section 2.3.2.

[3] J Taft and P De Martini, “Sensing and Measurement Architecture for Grid Modernization,” available online: http://gridarchitecture.pnnl.gov/media/advanced/Sensor%20Networks%20for%20Electric%20Power%20Systems.pdf

6.0 Final Comments

Distribution storage networks can provide key capabilities to distribution grids, namely increased resilience and consequent buffering of power volatilities caused by either distribution grid edge devices or by variable generation or other issues at the bulk system level. A byproduct of this is buffering from IoT-based cyber threats involving manipulation of distribution-connected smart devices.

Storage devices can be shared over multiple substation service areas, so it is not necessary to put bulk storage in every substation. The type of storage that must be used for these purposes is fast-operating, and provides energy back to the grid in the same form as it was received from the grid. Practically speaking, this means that some forms of storage, as valuable as they are, should remain in the category of grid services, while the functions of distribution storage networks should be treated as core platform elements. Since the utility can determine when and where to place storage, and size it as needed, Distribution Storage networks are firm-designable, as opposed to DER, whose penetration the utility has very little influence over. Distribution Storage Networks can be installed proportionally to need and there is no operational equitability constraint as there would be with DER.

The implication of the classification of distribution storage networks as core platform is that they be treated via least cost, best-fit valuation and financing approaches rather than benefit/cost analysis. Since the operating model for such infrastructure does not require the development of a new ecosystem, new third party compensation schemes, or a new coordination mechanism, the barriers to deployment of this class of storage systems are lower than for more general grid services-oriented models of storage application.

Appendix A

Comparison of Distribution Storage Networks and DER

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Comparison of Distribution Storage Networks and DER

The table below compares selected key characteristics of Distribution Storage Networks and DER.

Table A.1. Comparison of DSN and DER

Characteristic	DSN	DER
Firm dispatchable	Y	N
Firm designable	Y	N
Can be core infrastructure	Y	N
Needs 2nd, 3rd, and 4th parties? (storage owner, aggregator, market operator)	N	2nd, Y 3rd, Probably 4th, Maybe
Can participate in a market?	Probably not, but not necessary or even desirable to do so	Y
Dependent on IoT?	N	Y
Utility can manage its cyber security?	Y	N
Utility can manage its safety?	Y	N
Fits existing utility business and operational models	Y	N
Impacts utility interconnection process?	N	Y
Requires some form of equitable operation?	N	Most likely

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