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978-1-009-01403-8 — Energy Storage Applications in Transmission and Distribution Grids
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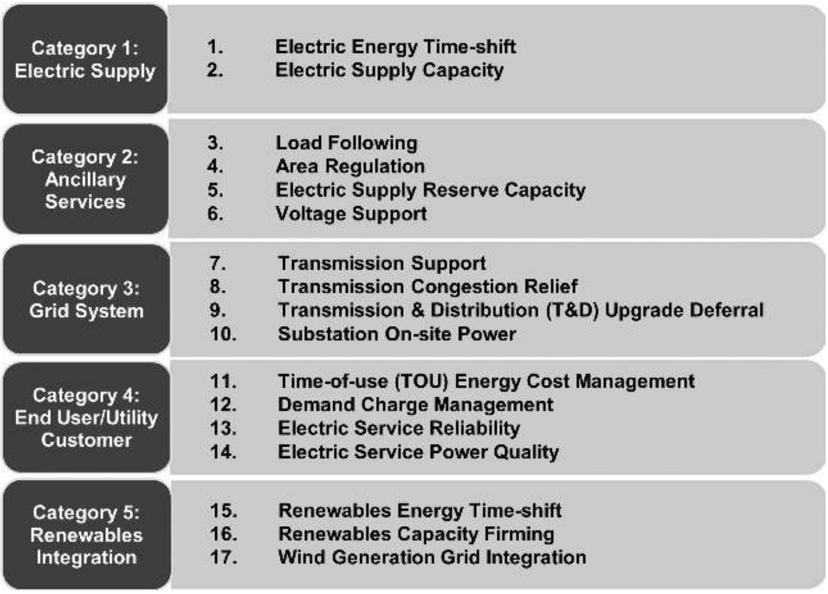
1 Introduction

Energy storage is increasingly attracting the interest of policy makers, regulators, project developers, and electric utilities. These modular assets can rapidly inject and absorb not only reactive power but also real power, making them of universal utility along the electricity value chain from generation plants to consumers. U.S. Department of Energy and Sandia National Labs [1] [2] published a comprehensive list of 17 applications that serve multiple stakeholders: behind-the-meter (BTM), distribution, transmission, generation, and wholesale markets, as shown in Figure 1-1. With the decreasing chemistry prices and deepening of the supply chain, energy storage applications are increasingly economical as compared to conventional solutions. The focus of this section is on Transmission and Distribution (T&D) applications.

Electricity flows on T&D lines according to Kirchhoff's laws, based on the levels and locations of power injections and withdrawals, the impedances of the lines, and the topology of the network. To maintain reliability, power injections and withdrawals are constrained to avoid violating one or more of the system operating criteria in the form of line current overloads, voltage violations, dynamic or transient instabilities, flicker, harmonic distortions, or subsynchronous resonances during normal system operating conditions or after the onset of a preselected set of planning contingencies. An obvious example is the case of limiting the combined flow on two parallel transmission lines to the lower emergency rating of either line to avoid overloads should one of the lines experience a sudden outage. This operating philosophy indeed causes the average loading of transmission lines as a percentage of their rating, in most systems, to be less than 50% at any time. These limitations on power injections and withdrawals, although prudent and necessary, have enormous economic consequences. Quite often, they are triggered by loading patterns that are infrequent and may last only a few hours in a day or in a season.

Energy storage can inject and withdraw electric power within its design and operating limits, and thus, when located appropriately, can help expand the flow capability of the grid by absorbing the excess power or supplying the deficit power during those constrained hours, either continuously or after the onset of a contingency. One should be aware that if the level or persistence of overloads is high, energy storage will not be a viable technical or economical solution when compared to other traditional solutions.

The rapid dynamic response of a storage system while injecting and absorbing active power and, when equipped with a four-quadrant inverter, reactive power, and its readily available reservoir of energy, albeit limited, can help system planners to increase the transfer limits on congested interfaces that are



Category 1: Electric Supply	1. Electric Energy Time-shift 2. Electric Supply Capacity
Category 2: Ancillary Services	3. Load Following 4. Area Regulation 5. Electric Supply Reserve Capacity 6. Voltage Support
Category 3: Grid System	7. Transmission Support 8. Transmission Congestion Relief 9. Transmission & Distribution (T&D) Upgrade Deferral 10. Substation On-site Power
Category 4: End User/Utility Customer	11. Time-of-use (TOU) Energy Cost Management 12. Demand Charge Management 13. Electric Service Reliability 14. Electric Service Power Quality
Category 5: Renewables Integration	15. Renewables Energy Time-shift 16. Renewables Capacity Firming 17. Wind Generation Grid Integration

Figure 1.1 Energy storage can provide up to 17 services

constrained post contingencies either by thermal limits, stability limits, or voltage limits. It can also counteract the effects of solar intermittency in distribution networks and thus increase the hosting capacity of distributed energy resources (DERs) and provide differentiated delivery reliability or resilience wherever required. A properly sized and sited storage system can provide several grid-reliability and efficiency services while facilitating public policy initiatives, as summarized in Figure 1–2.

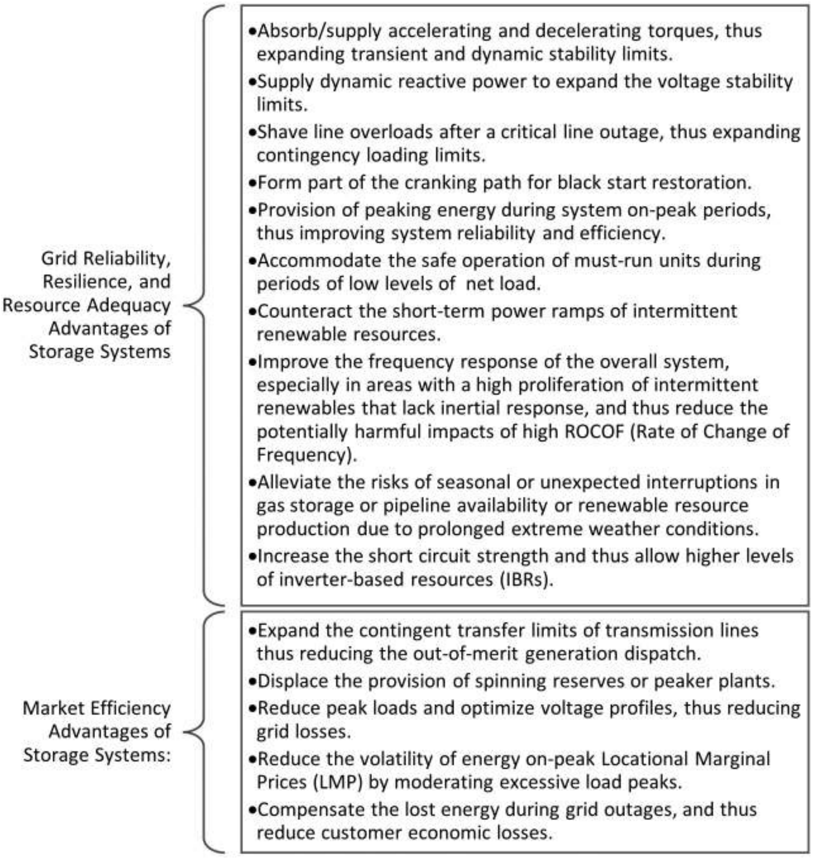
The objective of this Element is to present methods of analysis to help transmission and distribution planners to properly examine the technical and economical efficacy of energy storage as a non-wire solution (NWS) to address not only grid reliability but also grid performance. Key emphasis will be on siting, sizing, revenue stacking, and techno-economic lifetime analysis. The scope of this Element excludes other important planning aspects such as control system design including selection of measurement signals and controller parameter tuning, and protection system design and relay settings.

1.1 Strategic Value of Energy Storage as a T&D Resource

Electric power systems are inherently complex to manage. The instantaneous production, transport, and delivery of energy requires multiple layers of autonomous protection and control systems, primarily at the generation plants, T&D

grid, load, and supervisory control centers, to ensure the quality of delivery in this massive just-in-time power system. Energy storage can be right-sized and managed to add strategic value to existing systems as follows:

- Improve the utilization of existing T&D lines by time shifting power injections and withdrawals to reduce system overloads and in so doing increase the flow limits.
- Provide substantial flexibility to help position the grid gradually on a modernization path to economically accommodate new forms of intermittent energy sources and consumption patterns.
- Leverage the modularity of energy storage to de-risk grid investments especially in the face of growing planning uncertainties and lengthy permitting processes.



Grid Reliability, Resilience, and Resource Adequacy Advantages of Storage Systems

- Absorb/supply accelerating and decelerating torques, thus expanding transient and dynamic stability limits.
- Supply dynamic reactive power to expand the voltage stability limits.
- Shave line overloads after a critical line outage, thus expanding contingency loading limits.
- Form part of the cranking path for black start restoration.
- Provision of peaking energy during system on-peak periods, thus improving system reliability and efficiency.
- Accommodate the safe operation of must-run units during periods of low levels of net load.
- Counteract the short-term power ramps of intermittent renewable resources.
- Improve the frequency response of the overall system, especially in areas with a high proliferation of intermittent renewables that lack inertial response, and thus reduce the potentially harmful impacts of high ROCOF (Rate of Change of Frequency).
- Alleviate the risks of seasonal or unexpected interruptions in gas storage or pipeline availability or renewable resource production due to prolonged extreme weather conditions.
- Increase the short circuit strength and thus allow higher levels of inverter-based resources (IBRs).

Market Efficiency Advantages of Storage Systems:

- Expand the contingent transfer limits of transmission lines thus reducing the out-of-merit generation dispatch.
- Displace the provision of spinning reserves or peaker plants.
- Reduce peak loads and optimize voltage profiles, thus reducing grid losses.
- Reduce the volatility of energy on-peak Locational Marginal Prices (LMP) by moderating excessive load peaks.
- Compensate the lost energy during grid outages, and thus reduce customer economic losses.

Figure 1.2 Advantages of storage systems for grid reliability and market efficiency

1.2 Role of Energy Storage in T&D Planning

Transmission and distribution (T&D) grids are operated under strict reliability standards that do not allow lines and transformers to overload beyond their thermal ratings and do not allow bus voltages to wander outside acceptable bounds. The reliability standards address operating criteria not only under normal or intact (i.e., N-0) conditions but also under potential contingencies (N-1, N-1–1) that take one or multiple grid elements out of service. The reliability standards ensure robustness and security of the extra-high voltage grid to avoid the risk of cascading outages and widespread loss of load. They also assure customers served from the distribution grid of an agreed-upon level of service quality.

Within a typical planning horizon that spans 5–20 years, system planners update the demand forecast and consider the impact of the planned retirements of generation assets, the interconnection queue of resources, and the health of existing T&D assets on grid reliability and the need for T&D upgrades and reinforcements. The menu of conventional upgrades includes enhancements to existing assets and building new ones such as substations, lines, transformers, reclosers, shunt reactive compensation, and dynamic technologies such as Flexible AC (FACTS) and smart wires. Utilities are increasingly evaluating energy storage as a non-wire alternative (NWA) to address grid capacity, reliability, resilience, market efficiency, and renewable integration needs.

1.3 How Does Energy Storage Affect System Reliability?

Energy storage rapidly injects and absorbs electric power at its point of interconnection (POI) and in so doing alters the power flow on T&D lines. The flow can increase on some line segments and decrease on other line segments. Similarly, when equipped with four-quadrant inverters, energy storage is capable of injecting and absorbing reactive power, and consequently can increase or decrease bus/node voltages. If the storage systems are located within the grid where they can reduce the flow on overloaded lines and/or bring bus/node voltages within acceptable operating bands, then they can provide grid reliability services and be utilized as grid assets either to replace or to complement conventional assets. However, an important distinction should be made between the reactive power provided by inverter-based sources as compared to those provided by conventional rotating equipment during low voltage or short circuit situations being significantly lower due to the limited overcurrent ratings of inverters. In addition, for systems with high levels of renewable generation assets that displace conventional generation assets, the same storage systems can additionally provide other essential reliability services including:

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- Inertial frequency response to limit the rate of change of frequency (RoCoF) within mandated limits,
- Primary frequency response to control the frequency excursions without triggering load-shedding schemes,
- Stiffening the grid's short-circuit strength to enable proper operation of renewable inverters, and
- Mitigating potential flicker concerns by renewable inverters.

1.4 Should the Storage System Charge or Discharge to Affect Grid Reliability?

Excessive load growth or generation penetration (e.g., renewable resources) can instigate grid thermal and voltage violations. For grid violations that are predominantly driven by excess load, operating energy storage in a discharge mode is helpful, while for grid violations driven predominantly by excess generation, a charging mode is helpful. In a general setting with multiple grid thermal and voltage violations, one or multiple coordinated storage systems, some operating in discharge mode and others in charge mode, might be required to effectively address these grid reliability violations.

1.5 How Much Energy Capacity Is Required?

The obvious initial driver for the required level of energy storage capacity is the hourly profile of the line overloads. The higher the overloads, the higher the power that should be charged or discharged; while the longer the duration of the overloads, the deeper the energy reservoir need to be sized.

However, there is also a not-so-obvious driver. Energy storage, by its nature, is an asset with limited energy and, therefore, should have the opportunity to recharge if it has been called upon to discharge to address a grid need (or to discharge if it already charged to address a grid need). Recharging a storage system increases the loading of the grid and might trigger a grid violation if not performed when the grid can accommodate it. These reliability restrictions on the timing to recharge the storage system, in some cases, drive the energy capacity requirements higher. For example, if, during a consecutive five-day period, the hourly load forecast is high, requiring the storage system to discharge six hours each day to shave the load, but during the remaining hours of each day, the storage can only be recharged by half the energy amount that was discharged, then the storage capacity will have to be upsized to 3.0x the daily energy discharge needs. On the first peak day, the storage will enter the peak load period with 3.0x capacity and will enter the second day with 2.5x, the third day with 2.0x, the fourth with 1.5x, and the fifth with 1.0x. Energy storage should be designed to have enough energy capacity to either ride through the overload duration or to provide ample time until grid operators switch loads or redispatch generation.

1.6 Can Storage System Increase the Grid Transfer or Hosting Capacity?

Unlike conventional T&D lines, energy storage does not create new grid capacity. Instead, it exploits the hourly profile of load and renewables to maximize the utilization of existing grid capacity. Transmission systems are typically half-loaded in anticipation of outages to avoid the risk of overloading transmission circuits before the generation can be redispatched. This is due to the inherent limited availability of automatic controls in the transmission grid such as line switching. Energy storage provides the requisite controls to increase the grid loading or transfer limits up to but not exceeding the thermal limits. Similarly, in distribution networks, energy storage can shave peak load, mitigate the effects of reverse flows and intermittency, and thus increase the hosting capacity.

1.7 When Can a Storage System Provide Other Services?

Grid violations can occur during normal or intact (N-0) grid operation, but more prevalently they occur under grid contingencies (e.g., N-1 or N-1–1). These grid violations are frequently seasonal (e.g., summer-peak or spring off-peak), and thus, the need for storage assets to provide grid services is typically infrequent and seasonal. For example, a winter-peaking utility might project a few hours or days during the winter season when the utility's reliability standards will be violated. The MW and MWh storage-capacity requirements to mitigate grid violations will vary hourly, depending on the degree of these violations. The operation of the storage asset can be optimized to provide market services such as capacity or ancillary services and/or to provide services to the local host such as backup power whenever the full storage capacity is not required for grid reliability. This value-stacking capability is an important feature of storage systems that can help to offset its cost. However, in terms of priority, reliability is the primary function and takes precedence, while revenue stacking is a secondary function that can be exploited when the reliability needs permit.

1.8 Analysis Techniques When Planning Energy Storage

The increasing variability and unpredictability of power flows in the T&D grids, instigated by the proliferation of distributed energy resources (DERs) and variable renewable resources (VERs), increases the complexity of grid planning and necessitates the development of more advanced analysis tools and processes. The traditional capacity planning that assumed dispatchable centralized resources and unidirectional flows on distribution grids is giving way to performance planning that seeks to assure successful integration of DERs and VERs while adhering to reliability standards. The traditional practice of examining grid performance at a limited number of operating snapshots (e.g., summer-peak or spring off-peak) is no longer adequate, and in many cases, a more complex hourly (e.g., 8760) series power flow and contingency analysis is required. The variability of renewable profiles and load profiles and their uncertain alignment may require probabilistic analysis such as Monte Carlo simulations wrapped around the 8760 time-series analyses. Furthermore, the dynamic interactions between inverter-based resources (IBR) on the transmission and distribution grids following a system event on either side are increasingly driving the need for integrated T&D analysis.

On one hand, unlike traditional T&D lines, which work passively without time limits and without active controls to increase transfer capacity, energy storage provides a similar core functionality, but for a limited time window, and requires active monitoring and control to coordinate and manage its real and reactive outputs and state of charge. On the other hand, the footprint, modularity, and potential movability of energy storage is a significant advantage, especially when deployed in the vicinity of load centers and for edge-of-grid applications. The proper analysis of energy storage as an alternative or a complement to traditional wire solutions should explore not only the core functionality but also the flexibilities and vulnerabilities inherent in each technology and supporting systems and their ability to de-risk capital investments in the face of increasing levels of uncertainty.

Six key aspects are critical to the successful planning of energy storage as grid assets:

1. Siting
2. Sizing
3. Revenue stacking
4. Techno-economic lifetime comparative analysis
5. Control system signals and relay tuning
6. Protection system design and settings

A methodology is proposed in this Element for each of the first four aspects along with applications and case studies. Siting and sizing analyses methods and formulas are presented in Sections 2.1 and 2.2 respectively for transmission grid applications. This is followed in Sections 3.1–3.4 by representative examples of the use of siting and sizing methods in market efficiency, grid reliability, renewable integration, and sub-transmission interruptions and load backup applications. Section 4 presents methods and an example of siting and sizing storage for distribution grid applications. A techno-economic comparative analysis methodology is presented in Section 5, while Section 6 presents techniques of valuing the optionality of energy storage. Modeling of energy storage in power system analysis tools is provided in Section 7 for steady-state, stability, and transient analysis applications. Additionally, three case studies are provided in Section 8 that illustrate the applications of energy storage as NWA; The first case study is focused on a transmission reliability application; the second on a distribution reliability application; and the third on the integration of wind assets into a transmission grid. A detailed presentation of revenue stacking is presented through the second case study in Section 8.2.

1.9 Transmission Reliability Criteria

Transmission grid planning is mandated to comply with minimum performance standards, such as NERC TPL-001–4 in North America. The performance requirements ensure that within the planning horizon, the Bulk Electric System (BES) will operate reliably over a broad spectrum of system conditions and following a wide range of probable contingencies as summarized in Table 1.1. Contingency classification per the NERC TPL-001–4 standard can be summarized as follows: P0 is intact system (N-0); P1 is a single-element failure (circuit, generator, transformer, shunt device); P2 is also a single-element failure

Table 1.1 NERC TPL-001–4: P1–P7 categories

	Type	Initial Loss	Contingency
P0	N-0	-	-
P1	N-1	-	Gen, T Ckt, Trafo, Shunt
P2	N-1	-	Line Section, Bus, Breaker
P3	N-1–1	Generator	Gen, T Ckt, Trafo, Shunt
P4	N-x	-	Stuck breaker (Gen, T Ckt, Trafo, Shunt, Bus Section)
P5	N-x	-	Delayed fault clearing due to relay failure (Gen, T Ckt, Trafo, Shunt, Bus Section)
P6	N-1–1	T Ckt, Trafo, Shunt	T Ckt, Trafo, Shunt
P7	N-x	-	Common Structure (2 Ckts)

NOTES:
N-0 = Normal system state
N-1 = Single contingency
N-x = Multiple contingencies
Ckt = Circuit

(line section, bus, breaker); P3 is a loss of a second element after a period of losing a generator (N-1–1), P4 is a multiple-element loss (stuck breaker), P5 is also a multiple-element loss (delayed fault clearing due to relay failure); P6 is a loss of a single element (line, transformer, shunt) followed by a loss of another single element (N-1–1), and P7 is a loss of multiple elements (common structure).

2 Siting and Sizing Methods for Transmission Applications

Transmission grids are operated well below their thermal capacities to ensure the security of supply deliverability even under a wide range of potential equipment outages and supply interruptions. Unlocking the latent underutilized capacity of the grid while ensuring system security has a great economic value [3].

Transmission systems are designed to interconnect generation and load areas and transfer energy efficiently while meeting a stringent set of reliability criteria [4]. Over decades, transmission networks have expanded mainly by utilizing passive conventional systems known as “wires solutions” (i.e., transmission lines, transformers, switchgear), which require an operational philosophy of keeping networks almost half-loaded in a preventive posture in anticipation of potential contingencies that push systems toward their thermal, voltage, or stability limits. Networks are restricted 100% of the time from reaching their full capability in transferring power from low-cost production regions to high-cost load centers due to the risk of events that typically last less than 2% of the time. These prudent operational restrictions, dictated by the capability of the conventional systems that make up transmission networks, lead to congestion costs that can have significant economic impacts on many stakeholders [3] [5] or hinder public policy goals of integrating renewable clean energy resources.

Energy storage offers many potential benefits to transmission and distribution (T&D) systems due to the ability of modern power electronics, and some electro-chemistries, to rapidly change from full discharge to full charge modes, or vice versa [2]. These characteristics have led to increasing interest in utilizing energy storage to economically unlock the inherent transmission or distribution grid capacity. Strategic siting and sizing of storage resources will allow the operators to load the grid above its contingent capacity and closer to its intact or normal system capability (Figure 2.1), and to utilize the storage resources to absorb or inject power post contingencies up until a system re-dispatch is invoked.

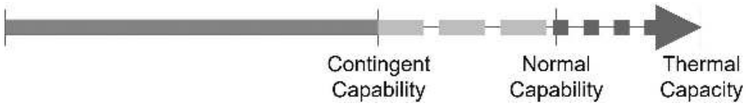

Figure 2.1 Indicative operating limits in a transmission grid

This section provides a theoretical basis for optimizing the sites and sizes of energy storage that can increase the reliable transfer capacity across a transmission interface, flow gate, or boundary. These methods and formulas are original work of the author and have been utilized extensively in the conduct of many NWA projects. Several publications on siting and sizing energy storage have focused on optimizing the economics of renewable variable energy resources [6]–[9] or system frequency response [10], while others [11]–[16] have focused on generalized optimization methods for alleviating grid constraints or spatial-temporal energy arbitrage. In contrast, the approach presented in this section provides many advantages:

- Highly scalable to large power systems.
- Focuses on transmission or networked distribution grid security under all planning contingencies (P1–P7) [4].
- Takes as input the familiar representation of the system in terms of a power flow model and the set of contingencies and monitored facilities without the need to precalculate transfer capacity limits.
- Can be performed by transmission planners by manipulating existing power flow and security analysis tools.
- Provides valuable locational insights that enable an iterative planning process using storage-only or hybrid solutions encompassing combinations of conventional wire solutions and storage solutions.

2.1 Siting Analysis

The power flow on a line or through a transformer is influenced by the power injections at all buses through Power Transfer Distribution Factors (PTDF), and also by outages of other lines through Outage Transfer Distribution Factors (OTDF). Discharging an energy storage at a particular bus will influence the flows on all lines either in a decreasing manner or an increasing manner depending on its location and the prevailing direction of power flows.

The optimal site for an energy storage is one that reduces the flows on all congested lines under all contingency scenarios. In practice, several sites might be able, or required to mitigate a group of grid congestions, and thus a ranking of candidate sites is necessary in terms of their effectiveness to relieve congestion. The analysis is influenced by the grid structure (topology and equipment ratings), loading profile, renewable energy profile, and the contingency list. A robust algorithm is presented next to identify the optimal sites and rank them. The resulting siting index can be plotted geographically in a heat map format to guide the site selection process.