IEEE

IEEE PES
Power & Energy Society®

ENERGY STORAGE PRIMER

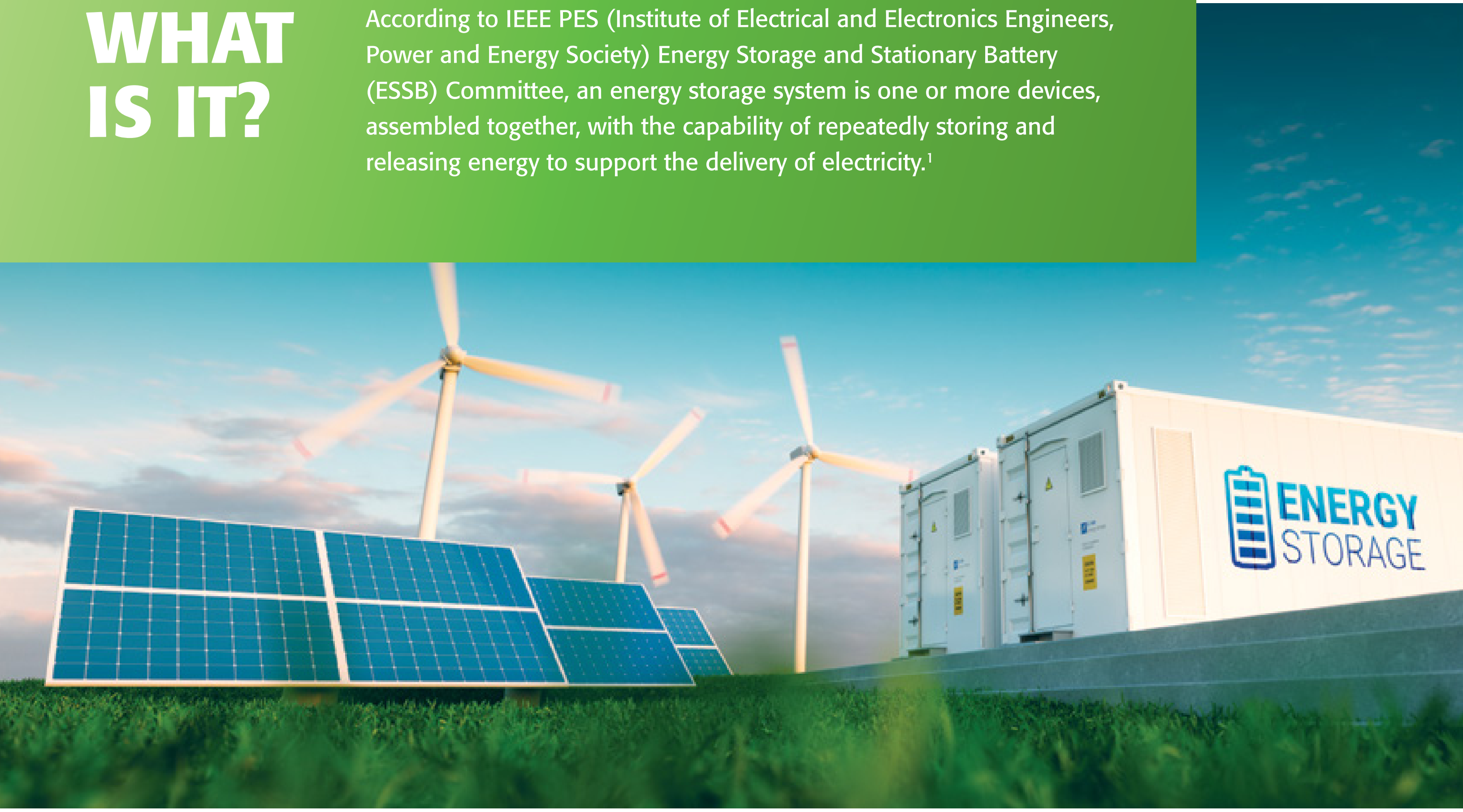
WHY ENERGY STORAGE?

The broad-based interest in energy storage has been largely driven by the growth in renewable energy sources of electricity.

As the penetration of renewable generation increased, it had become obvious that the variability of these sources and the fact that renewables are not always available when the power is needed, were becoming a problem. As a consequence, fossil-based operating reserves are required to augment renewable generation to ensure reliability. Energy storage can provide a superior solution to the variability problem when compared to fossil-based generation, while also improving the availability of renewables to provide electricity upon demand. Energy storage is a flexible resource for grid operators that can deliver a range of grid services quickly and efficiently. The rapid growth of policy mandates and incentives for renewable generation and, more recently, for energy storage, the need for modernization of the grid infrastructure, and the desire to decarbonize the economy, are the principal drivers behind the renewed interest in energy storage.

WHAT IS IT?

According to IEEE PES (Institute of Electrical and Electronics Engineers, Power and Energy Society) Energy Storage and Stationary Battery (ESSB) Committee, an energy storage system is one or more devices, assembled together, with the capability of repeatedly storing and releasing energy to support the delivery of electricity.[1]



---

[1] New definition to be incorporated in IEEE Std 1881, IEEE Standard Glossary of Stationary Battery Terminology

INTRODUCTION

The traditional grid design assumes that electricity must be produced and consumed at nearly the same time. Energy storage changes this equation and allows production and consumption to be decoupled.

Energy storage may have a role at virtually any point in the electricity system. The specific needs required of energy storage depend on the processes it serves at a given point in the system. As a result, there is no single energy storage technology that is best suited for all possible applications. There is a need for many different types of storage with a broad range of characteristics. This in turn, may create public confusion as to what is meant by the term "energy storage."

Energy storage can reside on a bulk power system, at the generation and transmission level, in distribution systems, or at consumers' premises (behind the meter). Storage on the consumer side includes water heating, space heating or cooling, refrigeration, or batteries. A fast-growing application of storage, in the form of batteries, is electric vehicles.

In principle, storage is an excellent means to increase utilization of electric grid assets. Storage also enables society to use more variable and uncertain renewable generation, such as wind and photovoltaics. By storing the renewable supply that exceeds the demand, rather than curtailing it, the renewable electricity output can be shifted to times when it is more valuable. This also can buffer against disruption in production or delivery of electricity. Unfortunately, the cost of many of these applications still exceeds their value, compared to conventional solutions. As energy storage technology becomes cheaper, a wider range of applications will become accessible.

The purpose of this primer is to provide a fundamental understanding of the roles of energy storage in the electric grid[2] and explain why it is more complex than simply inserting a battery into a phone, requiring careful engineering design expertise. As with other elements of grid modernization, it must be recognized that there will be costs associated with pursuing the path of increased usage of energy storage technologies.

There is No Single Energy Storage Technology that is Best Suited for All Possible Applications

---

[2] We define the grid as the entire electricity infrastructure, from generation to customer premises.

STORAGE SYSTEMS

A storage system is characterized in terms of both energy capacity (kWh, MWh, GWh) and rated power (kW, MW, GW).

This is reflected in the costs of storage – it has both a power and an energy component.

ENERGY CAPACITY COST ($/KWH)

+

RATED POWER COSTS ($/KW)

÷

DURATION OF STORAGE (HOURS)

STORAGE COST

There may be other system elements that increase the total capital cost of the storage system. This is a frequent source of confusion. For example, a quote of storage cost in $/kWh either includes an underlying assumption about the duration of the storage or neglects the power component.

ELECTRIC GRID APPLICATIONS

As a general rule, a storage system is charged with inexpensive or surplus electricity and storage is discharged when electricity commands a premium price or is essential for the functioning of the application.

Energy storage on the electricity grid may be used for:

- **Reliability services**[3] – for example balance rapid changes in demand and supply, especially where higher-mass rotating generators (e.g., steam turbines) have been retired.
- **"Firm" up or smooth variable sources**[4] – reduce the effects of fluctuations in wind or solar generation so that renewable resources become comparable to conventional generation options that have a fixed electricity supply rating and can provide more reliable operation.
- **Arbitrage** – reduce costs by storing lower price electricity for use in higher price periods.
- **Demand response** – provide options to almost instantaneously reduce demand by relying on customer-side storage.
- **Defer (delay) infrastructure additions and increase infrastructure utilization** – in the generation, transmission, or distribution networks. In fact, storage can reduce infrastructure requirements even in consumer premises.

Energy Storage is a Flexible Resource that Can Deliver a Range of Grid Services

Clearly, the value of adding storage varies among the various applications. Even for the same type of application there may be significant variations in benefits depending on location. Proper sizing, siting, and selection of storage systems requires careful engineering design and costing; it cannot be done on an ad-hoc or simplistic rule-based process.

One critical near-term need is to alleviate the rapid changes of supply that may be caused by variable renewable resources. Fast-ramping storage technologies may serve these short-duration requirements in an economically attractive manner.

Somewhat longer-duration storage may be required to shave peaks or shift loads[5] and thus defer infrastructure additions on the grid, particularly for distribution systems. Storage is often used in buildings to defer usage to less expensive times of the day.

---

[3] Reliability services, also called ancillary services, are those functions that support the continuous flow of electricity from generators to consumers

[4] The location of the storage for firming renewable sources is not fixed. The storage may be collocated with the renewable generation, where the facility operator is paid more for power that can be dispatched when needed; or it may be closer to the consumer to avoid congested transmission lines. Storage may be in the form of a single large system, or may consist of several smaller systems, such as residential batteries.

[5] Peak shavings refers to measures taken to reduce the maximum electricity requirement. Load shifting refers to moving electricity requirements from one time period to another.

CLASSIFICATION/ DIMENSIONS OF STORAGE/ ATTRIBUTES

Time Scales

There are several timescales relevant to energy storage utilization:

- **Discharge duration capability per unit of power rating.** This is typically in minutes and hours but can also be in days to weeks.
- **Duty cycle.** The frequency with which the storage is charged and discharged. Typically, duty cycles are sub-hourly, daily or less frequent.
- **Response time or ramp rate**. The time required to go from charge to discharge or standby to full charge or discharge.

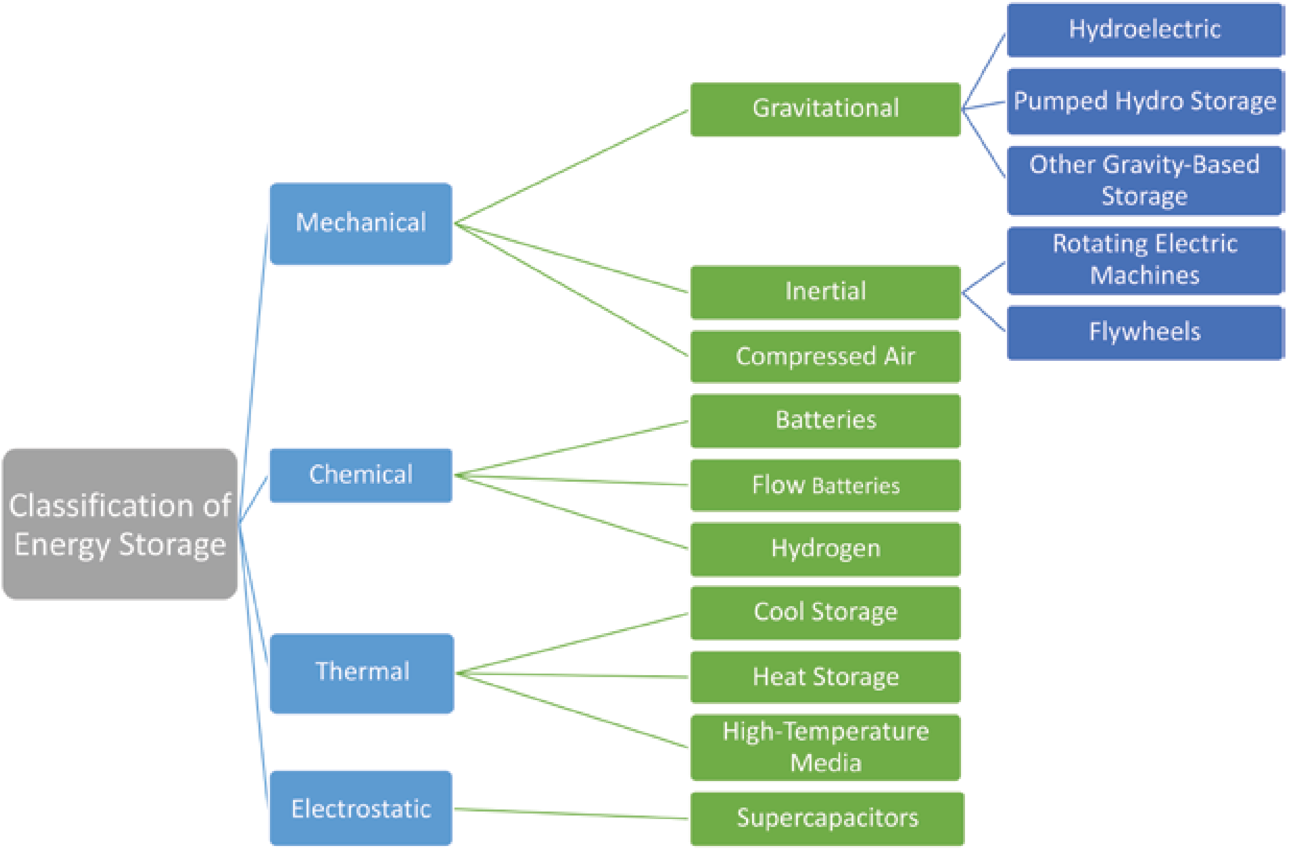
Storage Medium or Energy Form

It is challenging to store electricity itself, so virtually all commercial storage technologies convert electrical energy to some other form of energy. Energy can be stored in a variety of forms (electrochemical, thermal, etc.) and there are numerous technologies spanning the range of storage media. The different technologies, classified by energy form, are summarized in Figure 1 (see page 6).

In most cases energy storage is charged by electricity from the grid and discharge electricity back to the grid. The exception to the electricity-in-electricity-out rule is thermal energy storage, where electricity is used to heat or cool a storage medium for later use, substituting for electricity that would have been used to provide heating or cooling directly. For example, cool storage systems may chill water or make ice during off-peak hours in order to lower air-conditioning loads during peak hours.

In general, rapid duty cycling, short discharge times (<1 hour) and fast response times are needed to provide reliability services. Storage with longer discharge duration (>1 hour), longer duty cycles, and slower response times can provide bulk energy in competition with generation. As shown in Figure 2 (see page 9), this can also be expressed in terms of Power vs Energy applications and corresponding energy storage systems.

Figure 1: Energy Storage Technology Types



This primer does not cover additional energy storage technology options and system concepts, which are still in the R&D pipeline. The goals are to improve performance characteristics and reduce the cost of energy storage applications.

Performance Characteristics

Energy storage technologies are normally compared based on their physical attributes and electrical performance. These characteristics include:

Size and Weight

Metrics such as energy density, specific energy, power density and specific power together determine the footprint, overall volume, and weight for the required system.

Power and Energy Ratings

The power rating of an energy storage system (ESS), typically in kilowatts or megawatts, is the rate at which electricity can be discharged from the system; the energy capacity, typically in kilowatt-hours or megawatt-hours, indicates the length of time the storage system can provide energy at the rated power.

Ramp Rate

The time required to go from charge to discharge or standby to full charge or discharge. This can be very fast for batteries and flywheels, which can switch from full charge to full discharge within milliseconds; or it could take tens of minutes or longer, as is the case for pumped hydro storage.

Performance Characteristics (Continued...)

Scalability

Some technologies can be scaled from systems rated at a few kilowatt-hours, such as residential ESS, to much larger systems rated at tens or even hundreds of megawatt-hours. Others, such as pumped hydro, are mainly suitable for large-scale installations with gigawatt-hours of energy.

Cycling Capability

Technologies differ in their ability to be repeatedly charged and discharged including time to charge and how much of the energy can be used during a discharge.

Roundtrip Efficiency

The percentage of (useful) energy that can be extracted from storage compared to the amount of energy that was charged into storage. Roundtrip efficiency is about 70-80% for pumped hydro storage and around 85% for Li-ion batteries.

Storage Losses

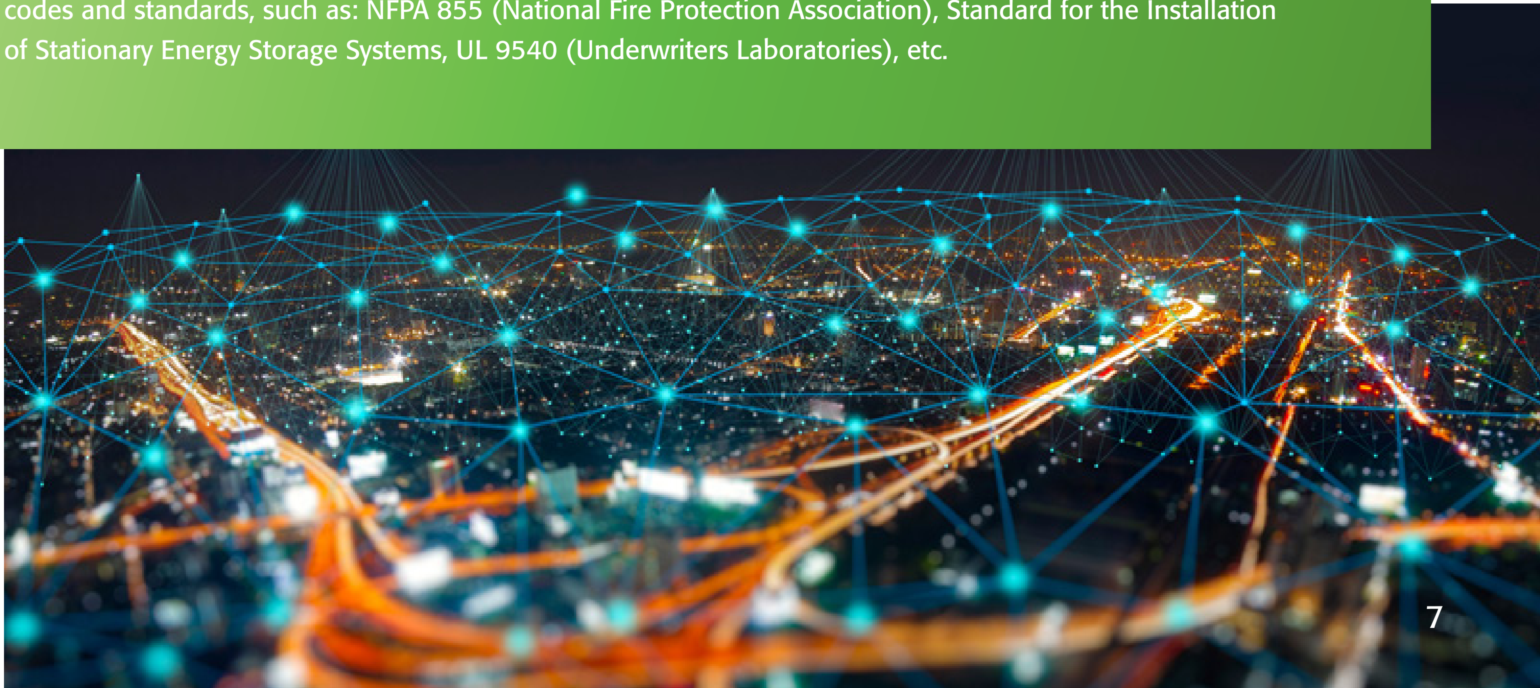
All storage systems are net consumers of energy. Storage losses include roundtrip efficiency losses, self-discharge, and consumption in auxiliary systems, both during normal operation and on standby.

Capacity Loss Over Time

Many energy storage technologies, particularly batteries, exhibit a reduction in energy capacity (energy rating) as the system ages.

Grid performance requirements and standards impact the design, deployment, and operation of energy storage systems. An example is IEEE Standard 1547-2018, which establishes interconnection and interoperability requirements for energy storage systems connected to distribution circuits. This is a rapidly evolving industry area, with efforts underway to address significant gaps in technical standards for energy storage.

In addition, due to safety concerns, energy storage systems will be required to comply with relevant safety codes and standards, such as: NFPA 855 (National Fire Protection Association), Standard for the Installation of Stationary Energy Storage Systems, UL 9540 (Underwriters Laboratories), etc.



MATCHING OF STORAGE TYPES TO APPLICATIONS

Incorporating storage into routine transmission & distribution (T&D) planning

With the continuing reductions in the cost and increasing availability of battery storage, there is growing interest in many states in the use of storage systems to defer investments in the T&D system, improve performance and utilization of the T&D system, and improve customer reliability.

Energy Storage Continues to Emerge as One of “Non-Conventional Alternatives”

These applications are generally not market-based and have to be justified in an engineering and economic sense as compared with traditional T&D solutions. Examples include:

- Deferring investments in grid resources as load grows, where the time value of the deferred investment is compared to the cost of deploying energy storage for that period; and
- Improving the ability of the grid to accommodate photovoltaics (PV) by using storage to smooth PV production and to mitigate high voltages caused by high PV penetration at peak.

A “hybrid” application is one that can significantly increase the value of an energy storage system by designing it to serve multiple applications. An example that bridges T&D investment deferral with market applications is congestion[6] relief where the storage can be controlled rapidly to mitigate overloads.

There are also examples of pilot projects where storage is used to mitigate short-term events that limit transmission capacity below the maximum possible. These events can be triggered by the grid’s response to sudden disturbances (lighting strikes and faults) in the generation and transmission system.

All these applications require detailed engineering analysis in order to size the storage power and energy capacity correctly, and today only a modest fraction of possible uses are practical when compared with conventional solutions due to the costs of storage.

---

[6] Congestion is a description of limitations on the transmission system to deliver less expensive generation to some customers (often urban areas) requiring the use of more expensive generation. Storage can help alleviate this.

Selecting a Storage System

Figure 2 provides a simplified summary of the characteristics of energy storage applications and the storage technologies that are commonly applied to address them.

Figure 2: Power and Energy Dimensions of Energy Storage Applications

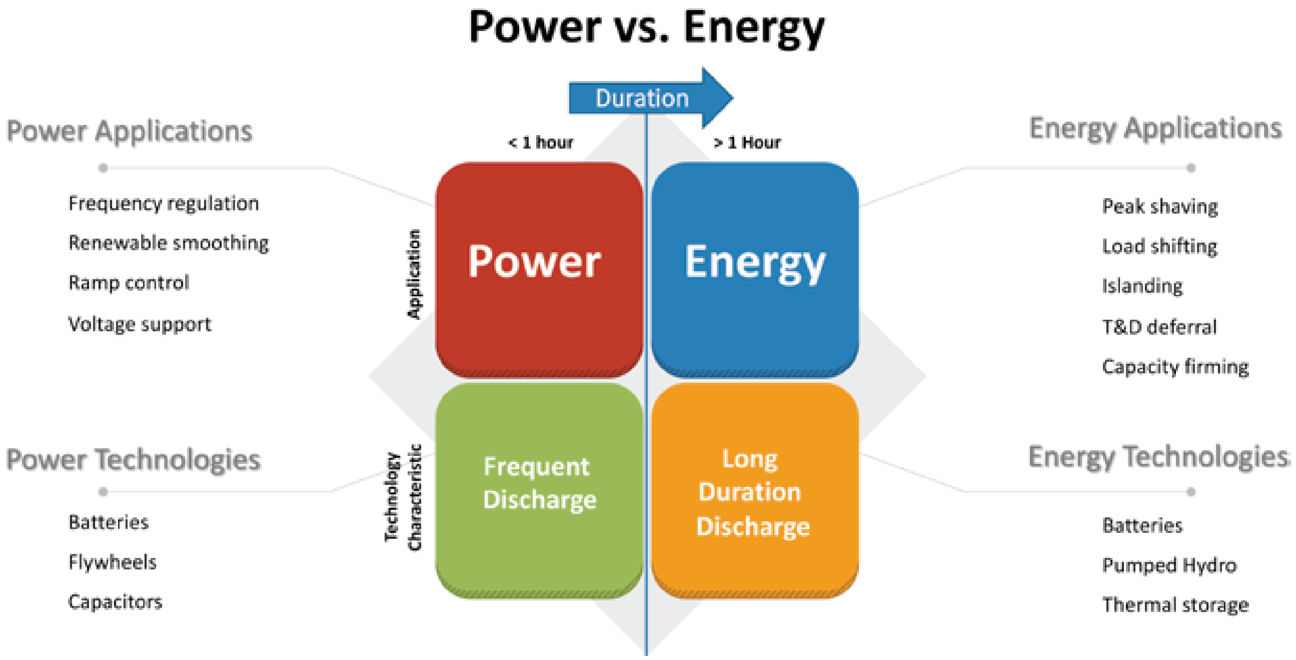
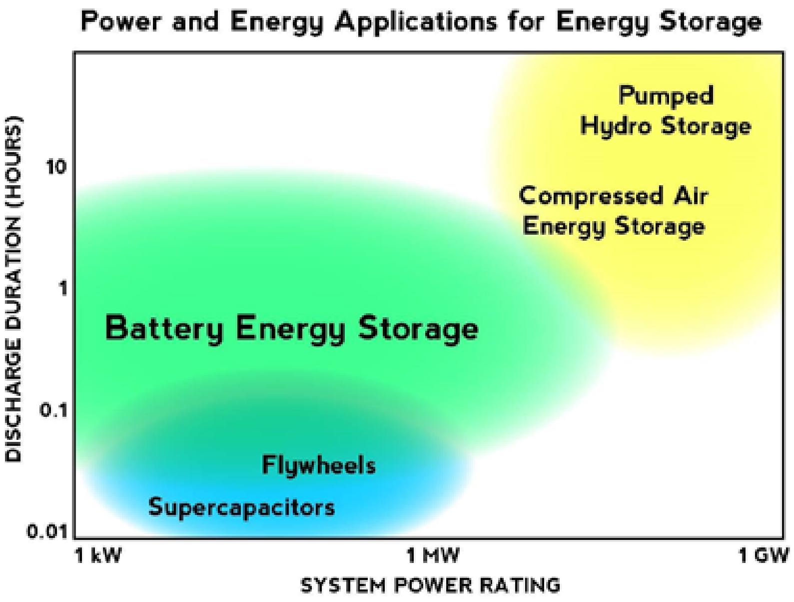


Figure 3: Traditional Grid Application Requirements and Corresponding Storage Systems



Most of the installed energy storage capacity is pumped hydro. However, most of the recent installations are battery based, primarily lithium ion. The reason is that batteries have a broad range of applications. This is seen in Figure 3, which summarizes the traditional (not including consumers' options) grid-related applications and the storage systems capable of serving these applications.

Energy storage systems in the lower part of Figure 3 are principally used for power applications; they can provide a rapid response (fractions of a second) with a relatively short discharge duration, which is needed for grid operational support. Systems in the upper part are preferred for energy applications. These are capable of shifting larger quantities of energy from one time interval to another.

IN CONCLUSION

Storage offers great potential benefits throughout the electric grid, but it is still too expensive for many potential applications.

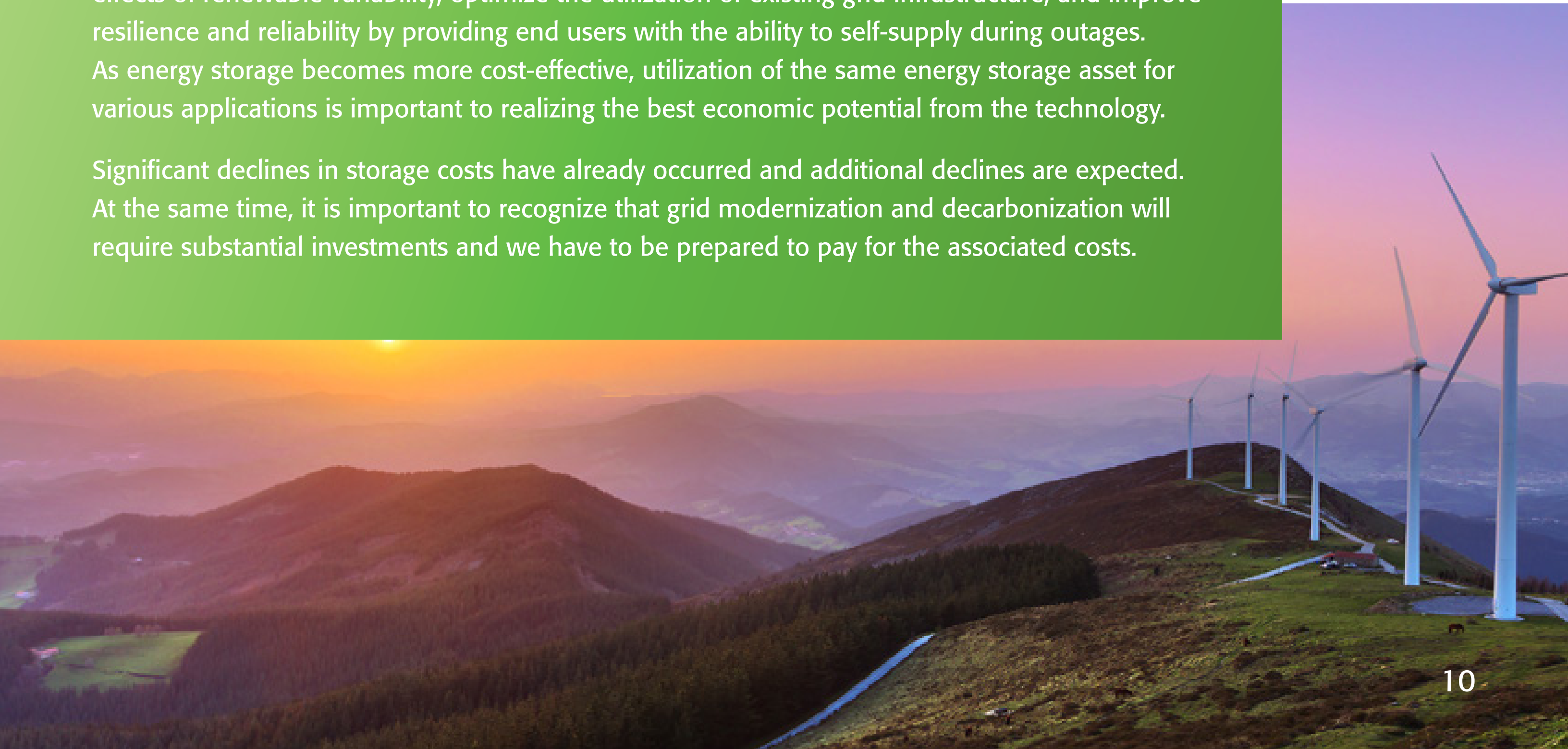
However, energy storage already has a growing place at the technology table where electricity prices are high (for at least parts of the day or season), in areas with very high concentrations of variable renewables, or in 'islanded' grids (including real islands) and off-grid electric services.

Energy can be stored in a variety of forms (electrochemical, thermal, etc.) and there are numerous technologies spanning the range of storage media. There is no single technology that meets the needs of all applications. In fact, there is a need for different types of storage with a range of energy and power performance characteristics. The use cases for storage mostly fall into discharge-time 'buckets' of less than one hour and longer than one hour. This primer does not cover other energy storage options and system concepts, which are still in the R&D pipeline. We expect improved performance and cost reductions when these become commercial.

Storage enables society to use more variable and uncertain renewable generation, such as wind and photovoltaics. By storing the renewable supply that exceeds the demand, rather than curtailing it, the renewable energy can be shifted to times when it is needed. However, under some circumstances, curtailment of excess renewable generation may be more economical - less expensive - than adding energy storage to the system.

Energy storage continues to emerge as one of "non-conventional alternatives" to mitigate the effects of renewable variability, optimize the utilization of existing grid infrastructure, and improve resilience and reliability by providing end users with the ability to self-supply during outages. As energy storage becomes more cost-effective, utilization of the same energy storage asset for various applications is important to realizing the best economic potential from the technology.

Significant declines in storage costs have already occurred and additional declines are expected. At the same time, it is important to recognize that grid modernization and decarbonization will require substantial investments and we have to be prepared to pay for the associated costs.



FOR FURTHER READING

As mentioned, the growing interest in storage is to a large extent driven by regulatory policy. U.S. DOE maintains up-to-date information on energy storage policies.

- DOE OE Global Energy Storage Database, Federal and state Energy Storage Policies; https://www.sandia.gov/ess-ssl/global-energy-storage-database-home/

Electric power industry is ready to implement energy storage. IEEE has developed a number of standards designed to assure proper deployment of the technology.

- IEEE Std 1679-2020 IEEE Recommended Practice for the Characterization and Evaluation of Energy Storage Technologies in Stationary Applications; https://standards.ieee.org/standard/1679-2010.html
- IEEE Std 2030.2-2015 IEEE Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure; https://standards.ieee.org/standard/2030_2-2015.html
- IEEE Std 1547-2018, IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, https://standards.ieee.org/standard/1547-2018.html
- Draft IEEE Std P1547.9 Guide to Using IEEE Standard 1547 for Interconnection of Energy Storage Distributed Energy Resources with Electric Power Systems; https://standards.ieee.org/project/1547_9.html

GLOSSARY

Terms and Acronyms Used in This Document

Ancillary services

Specialty services and functions that facilitate and support the continuous flow of electricity so that supply will match the demand for electricity.

Curtailment

Reduction in electric generator output from its maximum electricity supply rating for operational or economic reasons. The term has come into use as a result of requirements that, due to local or system constraints renewable generation sources reduce their output, compared to what they could produce if not constrained.

Discharge

The process of extracting stored energy from the energy storage system

Electrical load

Amount of electricity being consumed

ESS

Energy Storage System(s)

kW, MW, GW (power rating)

kilowatt, Megawatt (1000 kW), Gigawatt (one million kW)

kWh, MWh, GWh (energy capacity)

kilowatt-hour, Megawatt-hour, Gigawatt-hour

T&D

Transmission and Distribution

AUTHORS

Lead Author

Veronika Rabl

Member, IEEE Power and Energy Society Industry Technical Support Leadership Committee; Past Chair, IEEE-USA Energy Policy Committee

Members

Curtis Ashton

Training Director, East Penn; Chair, IEEE PES Energy Storage and Stationary Battery Committee (ESSB)

Babu Chalamala

Manager, Energy Storage Technology, Sandia National Laboratories; Vice Chair, IEEE PES Energy Storage and Stationary Battery Committee (ESSB)

Ralph Masiello

Industry Advisor, Quanta Technology; Life Fellow IEEE

Jim McDowall

Senior Technical Advisor, Saft America Inc.; Standards Coordinator/Past Chair, IEEE PES Energy Storage and Stationary Battery Committee

Damir Novosel

Chair, IEEE Power and Energy Society Industry Technical Support Leadership Committee; President, Quanta Technology

Michael Ropp

Principal Member of Technical Staff, Sandia National Laboratories; Working Group Co-Chair, IEEE 1547.9; member, SCC21

Mark Siira

Director of Utility Compliance and Solutions – ComRent; Chair of IEEE 2030.2-2015; Chair of IEEE Standards Coordinating Committee 21

Charlie Vartanian

Sr. Technical Advisor, ES Integration, Pacific Northwest National Laboratory; Secretary IEEE P1547.9

Chan Wong

Manager of AMI Lab of Entergy; DOE Liaison of IEEE PES Industry Technical Support (ITS)

Shana Pepin

The authors appreciate the assistance of Shana Pepin, Project Manager, IEEE Power and Energy Society

This document was created under the auspices of the Memorandum of Understanding between IEEE and the U.S. Department of Energy. It reflects inputs received from the broader IEEE community as well as comments received from Kerry Cheung, Program Manager and Strategist, and Eric Hsieh, Director, Grid Systems and Components, both at the Office of Electricity, U.S. Department of Energy.