Energy Storage

A Nontechnical Guide

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Acronyms and Abbreviations

AC	Alternating current
ATC	Available transfer capability
Btu	British thermal unit
CAES	Compressed air energy storage
CAO	Control area operator
C&I	Commercial and industrial
DC	Direct current
DG	Distributed generation
DOD	Depth-of-discharge
DOE	Department of Energy
DR	Demand response
DSM	Demand side management
EEI	Edison Electric Institute
EIA	Energy Information Agency
EPA	Environmental Protection Agency
EPAct	Energy Policy Act
EPC	Engineering, procurement, and construction
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
ESA	Energy Storage Association
ESC	Energy Storage Council
ESS	Energy Storage Systems
FACTS	Flexible AC current transmission system
FERC	Federal Energy Regulatory Commission
GW	Gigawatt
GWh	Gigawatt hour
HTS	High-temperature superconductivity
HVDC	High voltage direct current
IEA	International Energy Agency
ISO	Independent system operator
kVA	Kilo-volt-ampere
kW	Kilowatt
kWh	Kilowatt-hour

LDC	Local distribution company
LTS	Low-temperature superconductivity
MISO	Midwest independent system operator
MJ	Mega joule (1MJ=0.28 kWh)
MRO	Maintenance, repair, and operation
MVA	Mega-volt-ampere
MVAR	Megavars
MW	Megawatt
MWh	Megawatt hour
NAS	Sodium sulfur
NEP	National Energy Policy
NERC	North American Electric Reliability Council
NETL	National Energy Technology Laboratory
NGA	Natural Gas Act
NiCd	Nickel cadmium
NREL	National Renewable Energy Laboratory
NOx	Nitrous oxides
NYMEX	New York Mercantile Exchange
O&M	Operation and maintenance
OMB	Office of Management and Budget
ORNL	Oak Ridge National Laboratory
PCS	Power conversion system
PF	Power factor
PHS	Pumped-hydro (electric) storage
PJM	Pennsylvania–New Jersey–Maryland Interconnection
PUC	Public Utility Commission
PURPA	Public Utility Regulatory Policy Act
R&D	Research & development
RTO	Regional Transmission Organization
SMES	Superconducting magnetic energy storage
SNL	Sandia National Laboratory
SO_2	Sulfur dioxide
T&D	Transmission & distribution
Tcf	Trillion cubic feet
TES	Thermal energy storage
UPS	Uninterruptible power supply
US	United States
VAR	Volt-ampere reactive
VRLA	Valve-regulated lead acid
WTG	Wind turbine generator

Foreword

Electricity is the most useful and flexible of all energy sources. To provide this capability, the power industry in modern industrialized societies developed power stations of various sizes and capabilities to provide a continuous, reliable, and affordable supply of electricity as the demand varied on daily, weekly, and seasonal cycles. Lately however, this centrally organized and controlled market design has become unstable. This has caused investment for new large power stations to become riskier as repaying their development costs can no longer be guaranteed through assured power sales in a highly regulated market.

Solutions to this challenge follow one of two competing strategies. The first is simply to continue extending the power transmission grid in order to open up additional markets for these new generation facilities. The second is to focus on a distributed supply strategy reliant upon smaller and distributed power generation and energy storage resources to provide a more stable and secure electricity supply. Each of these strategies implies a different direction for the future of the power industry. The first strategy represents a continued centralization of power production to offset increasing transmission infrastructure costs, whereas the second strategy represents a focus on local production and management of electricity to avoid excessive infrastructure build-out and grid management costs. This second option is the most promising one as it enables significant progression toward improvements of energy efficiency, leads to enhanced energy security, and—above all—promotes wind and solar power for the electricity supply.

Richard Baxter shows in his book how diverse the possibilities of electricity storage really are. These technologies have been widely overlooked by the power industry for many years as the industry's focus has been fixated on large-scale supply strategies. Through this fundamental book for the energy industry of tomorrow, Richard Baxter has broadened the industry's horizon by showing how it will be revolutionized by energy storage technologies—enabling greater use of renewable energy, and promoting a more flexible, efficient, and stable self-correcting energy infrastructure.

Dr. Hermann Scheer
General Chairman World Council for Renewable Energy
President EURSOLAR
Recipient of the Alternative Nobel Prize
Member of the German Bundestag

1 STORAGE AND THE ELECTRIC POWER INDUSTRY

The electric power industry has some immense challenges before it—that, we can all agree, is glaringly obvious; the good news is that energy storage technologies offer real solutions to some of the most pressing of these issues. Many of the worst problems stem from issues built into the system through the market structure. One of most vexing is that the current power system is built around a central tenet: Electricity must be produced when it is needed and used once it is produced. This rule necessitates rigid procedures for operating the system—raising inefficiency, lowering reliability, and reducing security. Although radical solutions from pundits abound, most industry veterans understand the sheer scale and interconnectivity of the system mean that change here comes most readily through evolutionary and not revolutionary means. Because energy storage technologies are usually enabling technologies and not disruptive ones, their expanded use will enhance the value of existing assets by providing more flexibility and options—supporting the inherent infrastructure-centric nature of the market.

energy usage, the firm's demand charges will decline, and total costs will be far more predictable—reducing significant amounts of uncertainty in their potential earnings.

Energy storage technologies can be—and already are—used to lower companies' power bills. Obviously, firms with high-priced tariffs stand to benefit from storing low-cost power at night and using it during peak demand the next day. However, many others (even those where energy costs make up a small portion of costs) can also reduce their cost of electricity if one part of their load is highly variable—for instance the previously mentioned cooling load. Here, thermal energy storage is already used by many commercial firms to essentially create large blocks of ice at night, which are then used to assist with the daily air-cooling load for air conditioning. According to some vendors, these units can many times reduce cooling peak power demand by upwards of 50%, producing a 30% overall reduction in the cost for cooling. If integrated into the design of a new building, these systems can even result in a reduction of the cooling infrastructure equipment size requirement, sometimes by 40% to 60%—providing additional benefits for the firm. Because of these results, typical payback periods for these installations (new and retrofit) can be realized in one to three years.[13] Newer storage technologies are enabling a wide variety of other useful applications as well. For instance, flywheels are capable of capturing wasted energy in repetitive motion situations. This role of acting as a dynamic sink and source for power fits well with transportation sector applications, where repetitive starts and stops produce very inefficient use of energy. Although container port lifting cranes and light-rail/subway systems all exhibit these usage patterns, they are currently under served because previous battery technologies could not support these applications, leaving these firms with no solution to their problems. If an energy storage solution is used to lower the operator's costs, even the local utility stands to save because the load swings on the power lines feeding these installations are reduced.

and in the distribution markets, storage facilities provide much-needed physical balancing services. This enables pipeline companies to optimize pipeline pressure and overall performance by maintaining as constant and high a flow rate (pipeline utilization) as possible—allowing pipeline firms to maintain service with lower capital investments.

Marketing diverse facility types is also tied to their varied capital and operating costs. Because the majority of natural gas storage is used for seasonal heating demands, depleted natural gas reservoirs and aquifers make up the largest component of underground natural gas storage, comprising 95% of the total working gas. In 2000, it cost on average $0.48/MMBtu per season to store natural gas in a depleted field.[7] These facilities cycle once per year, injecting natural gas from May to October (214 days) and withdrawing it from November to April (151 days). Because it takes approximately 180 days to fill and approximately 120 days to withdraw, the operators and customers of these facilities are generally price insensitive as they have very little operational flexibility. With the capability of only one cycle per season, the profitability of the facility becomes more of an issue of seasonal price changes than operational activity. Because of the low deliverability of these primary storage facilities, the amount of working gas in storage has become a leading indicator of short-term natural gas prices, especially during the later half of a heating season when stock levels—and thus deliverability—make the market more susceptible to volatility in a cold snap.

Unfortunately, the increasing demand from natural gas–fired power facilities (mostly during the summer) is putting stress on this historical pattern and affecting the seasonal demand injection/withdrawal schedule. As more natural gas–fired plants are brought online to supply power for cooling loads, these plants compete for natural gas supplies in the middle of the injection season. The need for more flexibility—higher deliverability—has, therefore, put a premium on salt-dome storage facilities. These facilities only require approximately 20 days to fill and approximately 10 days to fully withdraw the natural gas in storage (depending on size). Although they represented only increase from 1990, when only 74 GW of installed generating capacity existed. The current 20 GW of capacity in the United States (up from 15 GW in 1990) represent 2.5% of the nation's summertime generating capability. Other developed countries have also invested heavily in these facilities, with Japan maintaining roughly 10% of its total generating capacity in PHS storage facilities, and European Union (EU) countries maintaining more than 32 GW of PHS storage capacity.

Example—Rocky Mountain, GA.[1] The Rocky Mountain facility—developed in 1991—is a three-unit, 848-MW pumped storage hydroelectric plant located in Floyd County near Rome, Georgia. Oglethorpe Power's Rocky Mountain pumped-storage facility was originally intended to run in a peaking mode, but in its first calendar year of service ran every day except one to take advantage of strategic power marketing deals. The facility won the 1998 Powerplant Award from *Power Magazine* for demonstrating the value of large-scale energy storage to a regional power market.

Example—Dinorwig, Wales, UK.[2] The Dinorwig plant in Wales, UK, is one of the most well-known pumped storage plants in the world. It was constructed between 1976 and 1982 in Europe's largest man-made cavern under the hills of North Wales. Each of the station's six generating units acts as both pump and turbine, delivering 317 MW of power, sustaining 1,800 MW for a total of five hours. Working volume for the facility is 6 million cubic meters, with a head of approximately 600 m. If held as spinning reserve, the entire plant can reach maximum output in less than 16 seconds.

Example—Okinawa, Japan.[3] The world's first seawater PHS plant was built in Kunigami Village, Okinawa Prefecture, Japan, in 1999 with a rated capacity of 31.4 MW. Taking advantage of Japan's abundance of coastline, these facilities can be located in rural areas near power facilities to lower power transmission losses. This PHS storage facility was built by the Electric Power Development Company for the Agency for Natural Resources and Energy of the Ministry of International Trade as a pilot facility. The facility's upper reservoir is located 500 m from the ocean

Vanadium redox. Energy in vanadium redox flow batteries is stored chemically in two ionic species of vanadium suspended in an aqueous sulfuric acid solution with approximately the same acidity level as that of a lead-acid car battery. During operation (discharge), the two electrolytes flow from the separate holding tanks to the cell stack for the reaction, with ions transferred between the two electrolytes across the proton exchange membrane. The concentration of each ionic form of the vanadium electrolyte changes when the flow battery is discharged, when the potential chemical energy is converted to electrical energy. After the reaction, the spent electrolytes are returned to the holding tanks, but because of the changed chemical nature of the electrolytes, self-separation occurs. During recharging, this process is reversed. Vanadium redox flow batteries operate at normal temperatures, and there is no discharge of the electrolyte solutions from the facility during operation. The electrolytes also have an indefinite life, so they can be used in follow-on installations after removal of the facility.

Zinc bromine. Energy in a zinc bromine flow battery is stored chemically in an aqueous solution of zinc and bromine ions that only differ in their concentration of elemental bromine. During operation (discharge), the electrolytes flow from the separate holding tanks to the cell stack for the reaction. The metallic zinc dissolves into the electrolyte, and zinc ions and bromine ions are allowed to migrate across the microporous polyolefin membrane to the opposite electrolyte, equalizing the charge and converting potential chemical energy to electrical energy. Unlike other flow batteries, the electrodes of the zinc bromine battery cell serve as substrates for the actual chemical reactions. This requires that circulation be maintained to free up surface area for further reaction, and that the battery be fully and regularly discharged to prevent degradation of performance (stripping). During recharging, this process is reversed; zinc is deposited on the negative electrode, and bromine is formed at the positive electrode and remixes with the electrolyte. After the reaction, the spent electrolytes are returned to the holding tanks, but because of the changed chemical