IJEEP
INTERNATIONAL JOURNAL OF ENERGY ECONOMICS AND POLICY
EJ EconJournals
ISSN: 2146-4553

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2016, 6(1), 128-133.

EJ EconJournals

Reconstructing Renewable Energy: Making Wind and Solar Power Dispatchable, Reliable and Efficient

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ABSTRACT

This paper is important because it explains how to create a grid-scale energy storage system (ESS) that makes, for the first time, wind and solar renewable energy—dispatchable, reliable and efficient. Existing and recent discoveries in battery technology are analyzed, with the most appropriate recommended for use in the new ESS. Additionally, an innovative time-shifting ESS design approach is presented that decouples electricity production from use, considerably improving total wind and solar power peak average capacity contribution values. This minimizes the need for expensive standby natural-gas combustion turbine peaker plants—thereby decreasing costs by 75%. Furthermore, this advanced ESS improves performance by making the interconnection grid more reliable and better able to handle changing customer demands, relieves transmission congestion, and decreases unscheduled power outages—and also provides ancillary services; thereby improving system-wide benefits by 30-to-40%, further reducing effective ESS costs, perhaps to zero.

Keywords: Renewable Energy, Efficiency, Dispatchable, Grid-Scale Energy Storage System
JEL Classifications: G31, G38, H44, K23

1. INTRODUCTION

The U.S. Energy Information Administration's (EIA) Annual Energy Outlook 2015 (2015) projects that total renewable energy generation will increase 72%, from 525 billion kilowatt-hours (kWh) in 2013, to 900 billion kWh in 2040. Wind and solar renewable energy will account for nearly two-thirds of the growth. U.S. Department of Energy: Office of Scientific and Technical Information, (2015), Wind Vision predicts that by 2050, wind power will provide 35% of total U.S. electricity generating capacity.

In 2014, the U.S. installed 61.9 megawatts (MW) of energy storage, an increase of 40% from 2013, comprising 180 individual installations, averaging 344 kilowatts (kW) per energy storage facility. Energy storage installations have a total market size of $128 million dollars and are expected to grow to 220 MW in 2015, reaching 850 MW by 2019, a continued growth of 40% per year, resulting in cumulative energy storage installations of 2.5 GW. Ninety percent of energy storage systems (ESSs) are grid-scale, installed in front of the meter.

Because the electricity produced by wind and solar renewable energy depends on unstable weather conditions, which change unexpectedly, wind and solar power generation is intermittent and variable. Using the current battery technology and the existing ESS design approach, requires a substantial number of standby, natural-gas combustion turbine (NGCT) peaker plants to be kept in reserve, ready to produce electricity when required. NGCT peaker plants are expensive and costs will continue to rise—as wind and solar power interconnection grid capacity percentages increase—if the existing electric ESS design approach and battery technology continue to be used (Prentis, 2015a).

About 97% of the battery storage market on the interconnection grid currently uses rechargeable Lithium-ion (Lit-ion) batteries (GTM Research and the Energy Storage Association, 2015). In addition, rechargeable Li-ion batteries are presently the dominant battery chemistry technology, used worldwide, in billions of cell phones, laptop computers and electric vehicles. However, what is appropriate to power mobile consumer electronics is not the best choice for a stationary, grid-scale ESSs.

Li-ion batteries have a relatively high cost for raw materials and a low 1,000 charge-discharge cycle durability. Consequently, Li-ion batteries, when being deeply discharged, daily, need replacement about every 3 years, and therefore, cannot last the 30 years necessary to be cost effective in a grid-scale ESS.

Li-ion batteries have fully recharging/discharging cycle times of about 2 hours (h). Consequently, "long duration" ESSs are only capable of delivering energy for 2-4 h. This makes Li-ion batteries impractical for a grid-scale ESS, which should have about 6 h of energy storage to supply energy during both morning and evening peak demand periods.

Additionally, rechargeable Li-ion batteries pose a safety hazard, resulting from using a flammable electrolyte that is kept under pressure. In response to safety concerns, the Boeing Company recently warned passenger airlines on the dangers of transporting bulk shipments of Li-ion batteries that can explode, in a chain reaction, because of "thermal runaway," possibly destroying the airplane during flight. In addition, the Federal Aviation Administration conducted tests and warned that fire-retardant chemicals, on airplanes, may be incapable of extinguishing fires that result from Li-ion battery "thermal runaway." Consequently, Li-ion batteries can be dangerous, overheat and catch fire—similar to what can happen to extremely corrosive sodium-sulfur (Na-S) batteries that have 300-350°C operating temperatures.

Fire safety hazards, high raw material costs, low durability and slow recharging/discharging cycle times make Li-ion batteries technically unsuited for a cost-effective, 6 h grid-scale ESS. Research into advanced battery technologies is ongoing; the most promising are discussed next.

2. LITERATURE REVIEW

Prospective advantages of lithium-air (Li-O_2) and lithium-sulfur (Li-S) warrant continued research (Bruce, et al., 2012). New Li-O_2 research, still in the development stage, has theoretical energy density per kilogram comparable to gasoline, has shown improved recharging efficiency and increased ability to be charged and discharged (MIT Technology Review, 2015). Li-S batteries are demonstrated to be practical, have an energy density three-to-four times that of Li-ion batteries, use less expensive raw materials, but need to increase the 1,500 charge-discharge cycle durability, to be cost-effective for grid-scale energy storage applications.

Lithium-titanate (Li-ti) batteries are modified Li-ion batteries that charge in about 10 minutes. Voltage (V) is 2.4 V versus 3.7 V for Li-ion. Energy density is 90 Wh/kg versus 200 Wh/kg for Li-ion, with durability cycles of 9,000, resulting in an expected life of 20+ years. Li-ti batteries have proven their practicality in the electric-transport industry—used by Honda and Mitsubishi for electric vehicles. Li-ti batteries may be competitive with Li-ion batteries for an ESS application, but also use expensive materials in their manufacture, including lithium and hard to get cobalt, which is mined mainly in African conflict zone countries—making Li-ion and Li-ti impractical, when compared to competing battery choices.

Magnesium-ion (Mg-ion) batteries, in comparison with Li-ion, are made from materials less costly to acquire, significantly increase energy density and offers improvements in safety. Most encouraging, Toyota is investing in Mg-ion battery technology. However, Mg-ion battery chemistry is not yet perfected. Magnesium reacts with other materials, interfering with ion movements through the electrolyte. In addition, accelerated dendritic growths significantly reduce the Mg-ion's charge-discharge cycle durability (Wan and Prendergast, 2014).

Nickel-hydrogen (Ni-H_2) battery technology is proven, with many space-age satellite applications, most notably the orbiting Hubble Space Telescope. Ni-H_2 batteries have advantages—high-reliability, light weight, safety, are maintenance free, have high durability with frequent charge-discharge cycles of 50,000 (Liu et al., 2005). Ni-H_2 batteries, unfortunately, have many disadvantages, including: Low energy density of about 60 Wh/kg, low voltage at 1.5 V, a high self-discharge rate, and require high pressure storage. In addition, Ni-H_2 batteries are made from exotic materials, making them very expensive. Consequently, high cost prohibits Ni-H_2 battery use in an efficient grid-scale ESS.

Economic analysis of the advanced grid-scale ESS, presented in this paper, supports incorporating a new battery technology. The innovative time-shifting ESS design approach that decouples electricity production from use, is offered that explains how best to use the new battery technology to make, for the first time, intermittent and variable renewable solar and wind energy—dispatchable, reliable, efficient, standardized, modular, flexible, transportable, easily-sited and grid-integrated.

3. DATA AND METHODOLOGY

3.1. New Al-ion Battery Technology

A new discovery on aluminium-ion (Al-ion) batteries (Lin, et al. 2015) offers clear advantages for an ESS. Independent research on basic Al-ion material-science advances, presented in the literature, is extensive, beginning in 2011 (Jayaprakash, et al. 2011), (Xiong, et al. 2011), (Wang, et al., 2013), (Mon, 2013).

When compared to Lithium-ion batteries, Al-ion batteries are low cost—using aluminium, graphite and chloride versus lithium, cobalt and ethylene carbonate materials for Li-ion, and are safe, environmentally friendly and easy to decommission—in comparison to Li-ion batteries that require treatment like hazardous waste.

Al-ion batteries demonstrate long lasting durability, up to tens-of-thousands of cycle times versus 1,000 cycles for Li-ion. Al-ion batteries have ultrafast charging times of one minute, producing a 60/h charging and discharging rate—the "C" rate of current—when compared to Li-ion batteries, which may take 2 h to charge—resulting in a very low "1/2C" rating for Li-ion—which then requires costly buffering with capacitors. Al-ion batteries, with a lower cost and a high "60C" rating, require less buffering, allowing for better solutions when designing the Al-ion ESS.

Al-ion batteries can be bent and folded into many shapes in their flexible polymer-coated pouch, and have a long life, lasting

30 years in an ESS, with daily charge-discharge cycles. The energy density is reported by a co-author to have already doubled in the lab, to 80 Wh/kg, and generates two volts of electricity, which should increase by improving the graphite cathode material. At 80 Wh/kg, 4 kWh is 50 kg, operating at 60 C charge/discharge rate, produces 240 kW of power. Three thousand kW (3 MW) of power requires 625 kg of Al-ion batteries. Making the Al-ion ESS dispatchable for 6 h may require six times 625 kg, equaling 3,750 kg of Al-ion batteries, for each 3 MW of power from renewable energy.

The Al-ion ESS is categorized by both power capacity and energy capacity, and would be rated at a 3 MW power capacity, with 6-h storage capacity, equivalent to an energy capacity of 18 MWh, with an expected 90% round-trip efficiency.

Currently, on the Texas Interconnection grid, ESSs are used only to smooth and stabilize intermittent and variable renewable energy, in real time. The existing ESS design approach is a restrictive application, and would not derive the best use of the Al-ion battery technology.

The Al-ion battery technology will be used in the new ESS time-shifting design approach that decouples electricity production from use, which is described next.

3.2. New ESS Time-Shifting Design Approach

The innovative time-shifting Al-ion ESS design approach decouples electricity production from use, by first producing renewable energy electricity—then delivering the electricity to the Al-ion ESS—and only then supplying electricity from the Al-ion ESS to the interconnection grid, 24 h later. Electricity is never delivered, in real time, directly from the renewable energy source to the interconnection grid, as is the current ESS smoothing and stabilizing practice for renewable energy intermittent and variable real-time supply.

The unique Al-ion ESS design approach presented permits the decoupling of wind and solar electricity generation—from when and where the renewable resource power is produced, to when and where the power is needed—which are major new advantages.

Consequently, the improvement in how the new Al-ion battery technology is used, results in a cost-effective change in application procedure—where electricity is available for transmission, daily, independent of the prevailing wind's speed or the sun's intensity.

The innovative ESS is a major change from using energy storage only to smooth and stabilize renewable energy power, in real time. Over a 24-h period, wind and solar power generation is used only to recharge Al-ion batteries in the ESS—never supplying electricity directly to the interconnection grid, until the next day.

Time shifting wind electricity supply—from low demand at night to peak-loads during the day—is arbitraging the high and low cost of daily electricity generation (Lamont, 2013). Stored electricity is reliably available, used when wanted, without the need for conventional reserve capacity (Prentis, 2014a).

This paper's new Al-ion renewable ESS is best implemented using a turnkey operation, which is presented next.

3.3. Al-ion ESS Turnkey Operation

The new Al-ion ESS is assembled at the manufacturing plant, filling a 53-foot long shipping container, housing 3,750 kg of Al-ion batteries, HVAC, and a computer operating system to control grid congestion and energy market interface connection requirements. Then, the prepackaged Al-ion ESS shipping container is trucked to the renewable energy site, as a complete assembly—able to be used on arrival at its destination location—by placing it on a prewired and preinstalled concrete pad, ready for turnkey operation.

Modular construction of the Al-ion batteries allows for plug-in replacement if individual battery packs fail. Maintenance for the Al-ion ESS is minimal.

The Al-ion ESS is flexible and easily scalable. If more than 3 MW of power capacity and 18 MWh of energy capacity are generated each day; additional outfitted shipping containers are installed at the site.

This Al-ion ESS concept approach moves away from the expensive custom design, fixed site transformation process—used by Blattner Energy, an engineering, procurement and construction company, on the 20 MW Lee/DeKalb Li-ion ESS in northern Illinois, completed in February 2015 (Energy Storage Association, 2015)—to a much less expensive standardized flow design, transportable transformation process (Prentis, 1987).

Going from a proprietary design method to a standardization modular design requires open data communication and common software specifications for different parts suppliers, thereby having available interoperable components to speed products to market. As a result, recurring engineering system integration will no longer be needed—reducing unit costs, improving reliability and power output, and allowing data to be easily shared—so the Al-ion ESS works in concert with the existing interconnection grid system. This important advancement ends the need for reinventing a renewable energy system integration protocol.

The Electric Reliability Council of Texas (ERCOT) is the independent system operator (ISO) administering the Texas Interconnection grid, and supplies the capacity, demand and reserves report data for this research (Electric Reliability Council of Texas (ERCOT), 2015). The U.S. Energy Information Administration (EIA) (2013) reports on the capital costs for electricity plants used in this research (Prentis, 2015b). The results of the Al-ion ESS economic analysis are presented next, starting with an analysis of the existing ESS design approach.

4. EMPIRICAL RESULTS

4.1. Existing ESS Design Approach

ERCOT assesses the effective load carrying capacity (ELCC) of non-coastal wind at 12% and ELCC for coastal wind at 56% of total rated wind capacity, which can be relied upon at the time of peak demand. The ELCC for solar power is estimated at 80%.

The total installed wind capacity in the Texas Interconnection grid is 11,379 MW for non-coastal wind and 1,680 MW for coastal wind installations. The peak average capacity contribution (PACC) values for wind power is 12% times 11,379 MW for non-coastal wind and 56% times 1,680 MW for coastal wind. Consequently, only 2,306 MW of wind power can be currently relied upon to meet resource adequacy requirements, at peak demand. For solar power, the PACC is 80% times 303 MW, equaling 242 MW.

The PACC total value for wind and solar is 2,548 MW. Typically, because wind and solar power ELCCs are low, expensive NGCT peaker plants are required to be available as reserve capacity to supply power at peak demand. Adding to this problem, wind and solar power ELCCs decline as wind and solar percentages of total system capacity increase.

4.2. Innovative Time-Shifting, Al-ion ESS Design Approach

For the new Al-ion ESS design approach, wind turbine capacity factors are reported to be at least 50%, which should be the minimum ELCC attainable, because renewable energy resources are operated over a 24-h period—capturing peak wind production periods, with energy storage in the Al-ion ESS cumulative—and then dispatched to meet system reliability needs the next day. Consequently, the ELCC for non-coastal wind is set at 50%. To be conservative, the ELCCs for coastal wind and solar are set only 5% higher, at 61% and 85%, respectively.

ERCOT's PACC for wind and solar power, using an Al-ion ESS, is 50% times 11,379 MW, plus 61% times 1,680 MW, plus 85% times 303 MW, equaling 6,972 MW. Consequently, 4,424 MW of expensive NGCT peaker plants would no longer be needed for reserve capacity.

NGCT peaker plants' overnight capital and fixed operation and maintenance (OM) costs are $980,340/MW times 4,424 MW, totaling $4.34 billion dollars. EIA reports, from 2002 to 2015, average natural gas (NG) prices are $4.25 dollars per thousand cubic feet (Mcf), making an efficient NGCT peaker plant fuel costs $42.15/MWh. Variable non-fuel OM costs are $15.45/MWh. NG fuel and variable non-fuel OM costs total $57.60/MWh—however, at the high end, older inefficient NGCT peaker plants' fuel and variable non-fuel OM costs may be twice this amount—multiplied times 4,424 MW times 6 h/day times 365 days/year times 30 years, equals $16.74 billion dollars.

NGCT peaker plant costs total $21.08 billion dollars, over a useful life of 30 years. The Al-ion ESS has no fuel or variable OM costs, meaning if overnight capital and fixed OM costs are less than $8,273,155/MW, the Al-ion ESSs is economical.

The weighted average system price for grid-scale ESS currently in use in 2014 is $2,064,000/MW. A savings of $21.08 billion dollars divided by $2,064,000/MW equals 10,213 MW, which would then be the power available at peak times, up from 2548 MW presently, an increase of 401%. An extra 7,665 MW is available for PACC when using the advanced Al-ion ESS design approach, at only 25% of the cost of expensive NGCT peaker plants.

NGCT peaker plants and Al-ion batteries have useful lives that are about equal, 30 years, making depreciation of capital costs comparable. One can think of the Al-ion batteries being the consumable fuel, and the depreciation charge, over its 30 year useful life, the fuel cost.

EIA reports that capital costs for NGCT peaker plants, in US dollars per kW, are about half that of onshore wind, a sixth that of offshore wind, and quarter that of solar photovoltaic. However, capital costs for renewable energy are dropping quickly. For example, in report entitled, "Financing the Future of Energy," authored by the University of Cambridge and PwC, commissioned by the National Bank of Abu Dhabi (Parkinson, 2015), predicts that future investments in electric power will be almost entirely in renewable energy. Coal, NG, oil and nuclear fuels will find it difficult to compete.

ACWA Power—which is a $23 billion Saudi energy firm—bid to supply electricity from a new 200 MW solar facility, at a very competitive US$0.0584 dollars per kWh, without subsidies. Combining this inexpensive solar renewable energy source, with a cost-effective Al-ion ESS, would further reduce costs, making the new electric solar power system and Al-ion ESS a clear winner versus existing renewable energy generation and existing ESS design, using lithium-ion battery technology.

Additionally, the Brattle Group (2014) says 30-40% of the system-wide benefits from interconnection grid-scale ESSs are attributed to system reliability, and transmission and distribution functions. For example, the easily-sited Al-ion ESS may be located at congested nodes on the grid to reduce locational marginal prices (Liu, et al. 2014). This further reduces effective Al-ion ESS costs, perhaps to zero.

In addition, the smallest NGCT peaker plants are about 50 MW, and therefore, are less flexible than an Al-ion ESS, which is more adaptable, able to be deployed in 3 MW increments and then scaled-up over time.

From an operations and environmental standpoint, NGCT peaker plants take minutes to dispatch, have significant standby costs, produce considerable CO_2 emissions and are single purpose. In comparison, Al-ion batteries take only seconds to dispatch, and therefore can respond much faster to interconnection grid changes, have low standby costs, produce zero direct CO_2 emissions and are applicable to ancillary services; thereby adding another important capability to the constant need to balance electrical supply with demand. All of these reasons, plus much lower costs for the Al-ion ESS, will insure that expensive NGCT peaker plants are replaced by the new Al-ion ESS, for interconnection grid capacity services.

Additionally, the Al-ion ESS compares favorably with competing, alternative technology ESSs. For example, the Al-ion ESS is easily sited, safe, environmentally friendly and has a small space requirement—in comparison with pumped-storage hydroelectricity, which requires considerable land space availability and water resources—and when compared to compressed air energy storage, which needs an existing large underground geological storage facility, such as a salt mine.

When the Al-ion ESS design approach becomes policy, and is fully implemented; it will materially transform and modernize the electric power industry.

5. DISCUSSION

Economic analysis of a new, grid-scale, renewable ESS design concept, using Al-ion battery technology and a time-shifting ESS design approach is presented in this paper. The new grid-scale ESS design approach explains how best to use the Al-ion battery technology to make—for the first time—intermittent and variable solar and wind renewable energy—dispatchable, reliable, efficient, standardized, modular, flexible, transportable, easily-sited and grid-integrated.

The innovative, time-shifting Al-ion ESS decouples electricity production from use, first producing renewable energy electricity—then delivering the electricity to the Al-ion ESS—and only then supplying electricity from the Al-ion ESS to the interconnection grid, 24 h later. ERCOT and EIA data are used to make an economic justification for Al-ion battery use in time-shifting, grid-scale ESSs.

Energy density is less crucial in a stationary ESS than in portable electronics and electric vehicles that use rechargeable lithium-ion (Lit-ion) batteries. The advanced Al-ion ESS makes use of inexpensive materials, high cycle durability for long life and low capital costs, an ultrafast charging and discharging time, safety—to be easily sited and decommissioned—and flexibility, to fit a shipping container and be placed at the site for operation. In addition, the Al-ion ESS is portable, for ease of construction and transport, and is modular, for high reliability and ease of maintenance. The Al-ion ESS will use grid-integrating optimizing software, making the Al-ion ESS dispatchable. Al-ion batteries fit all of these innovative ESS time-shifting design approach requirements.

Because of time-shifting, stored electricity is now dispatchable daily, from the Al-ion ESS, when needed, not when produced by intermittent and variable wind and solar renewable energy. The ISO grid scheduler knows in advance the amount of Al-ion ESS stored power available to supply the interconnection grid, the next day, and can easily plan for conventional power plant reserve capacity—in the unlikely event it is deemed necessary. Thus, there is no longer the need to closely match intermittent and variable renewable energy electrical supply with variable electricity demand—resulting in a more reliable electric power system (Prentis, 2014b).

The Al-ion ESS is calculated to cost only 25% of expensive NGCT peaker plants currently in use on the interconnection grid, over its 30 years expected life. Total savings come from time-shifting wind and solar power, thereby using the power more efficiently. In addition, Al-ion batteries are expected to be much less costly than Li-ion batteries, now being used on interconnection grid-scale ESSs. Therefore, Al-ion ESS costs should further decline, over time.

Total wind and solar PACC values are considerably improved, significantly reducing the need for expensive standby NGCT peaker plants—thereby reducing costs by 75% and making the Al-ion ESS dispatchable and efficient. In addition, this advanced Al-ion ESS improves performance by making the interconnection grid more reliable and better able to handle changing customer demands, relieves transmission congestion and decreases unscheduled power outages—and also provides ancillary services, thereby increasing system-wide benefits by 30-to-40%—further reducing effective Al-ion ESS costs, perhaps to zero.

6. CONCLUSION AND POLICY IMPLICATIONS

A creative, cost-effective, time-shifting, grid-scale Al-ion ESS for wind and solar renewable energy electricity generation is explained in this paper. The innovative time-shifting Al-ion ESS design approach decouples electricity production from use, by first producing renewable energy electricity—then delivering this electricity to the Al-ion ESS—and only then supplying electricity from the Al-ion ESS, to the interconnection grid, 24 h later. Electricity is never delivered directly from the renewable energy sources, to the interconnection grid, in real time, as is the current ESS smoothing and stabilizing practice.

The innovative Al-ion ESS time-shifting design concept permits the decoupling of wind and solar electricity generation, from when and where the renewable resource power is produced, to when and where the power is needed, which are major new advantages over the existing ESS approach.

The interconnection grid-scale, low maintenance Al-ion time-shifting ESS is valuable, not only to deal with the unpredictable changes in weather, but as importantly, to deal with the continual changes in electrical demand.

The advanced Al-ion time-shifting ESS improves performance by making the interconnection grid more reliable and better able to handle varying customer demands, relieves transmission congestion and decreases unscheduled power outages. In addition, the time-shifting, Al-ion ESS provides ancillary services; thereby improving system-wide benefits by 30-to-40%, further reducing effective ESS costs, perhaps to zero.

Having abundant, dispatchable, reliable, efficiently produced electricity, available from renewable energy, is the goal fulfilled in this paper. The new, grid-scale Al-ion time-shifting ESS presented is economically efficient and universally advantageous—for power generation suppliers, consumers and the environment. When the Al-ion ESS design approach becomes policy, and is fully implemented; it will materially transform and modernize the electric power industry.

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