

Quick Facts

- Electric energy storage (EES) uses forms of energy such as chemical, kinetic, or potential energy to store energy that will later be converted to electricity. Such storage can provide three basic services: supplying peak electricity demand by using electricity stored during periods of lower demand, balancing electricity supply and demand fluctuations over a period of seconds and minutes, and deferring expansions of electric grid capacity.
- Global EES capacity is 90 gigawatts (GW), which is only 3 percent of electric power production capacity due to the high capital cost of EES compared to natural gas power plants which can provide similar services, and regulatory barriers to entry in the electricity market. Of that global capacity, 22 GW of EES is in the United States (2.5 percent of U.S. power capacity).
- EES can potentially smooth the variability in power flow from renewable generation and store renewable energy so that renewable generation can be scheduled to provide specific amounts of power, which can decrease the cost of integrating renewable power with the electricity grid, increase market penetration of renewable energy, and lead to greenhouse gas emission (GHG) reductions.

Background

Electric energy storage (EES) technology has the potential to facilitate the large-scale deployment of variable renewable electricity generation, such as wind and solar power, which is an important option for reducing GHG emissions from the electric power sector. Wind and solar power emit no carbon dioxide (CO₂) during electricity generation but are also variable or intermittent electricity sources. Wind power only produces electricity when the wind is blowing and solar power only when the sun is shining, thus the output of these sources varies with wind speeds and sunshine intensity. Since operators of the electricity grid must constantly match electricity supply and demand, this makes variable renewable resources more challenging to incorporate into the electricity grid than traditional baseload (e.g. coal and nuclear) and dispatchable (e.g. natural gas) generation technologies, which can be scheduled to produce power in specific amounts at specific times. Electric grid operators have several options for managing the variability of electricity supply introduced by large amounts of renewable generation, one of which is EES.¹

EES promises other benefits unrelated to renewable energy, such as improved grid reliability and stability, deferral of new generation and transmission investments, and other grid benefits.²

Description

EES technologies vary by method of storage, the amount of energy they can store, and how quickly and for how long they can release stored energy. Some EES technologies are more appropriate for providing short bursts of electricity for power quality³ applications, such as smoothing the output of variable renewable technologies from hour to hour (and to a lesser extent within a time scale of seconds and minutes); however, EES is not currently used specifically to smooth out renewable generation.⁴ Other EES technologies are useful for storing and releasing large amounts of electricity over longer time periods (this is referred to as peak-shaving, load-leveling, or energy arbitrage).⁵ These EES technologies could be used to store variable renewable electricity output during periods of low demand and release this stored power during periods of higher demand. For example, wind farms often generate more power at night when winds speeds are high but demand for electricity is low; EES could be used to shift this output to periods of high demand.

The major technology options for EES include the following:

- **Pumped Hydro**

Pumped hydro storage uses low-cost electricity generated during periods of low demand to pump water from a lower-level reservoir (e.g., a lake) to a higher-elevation reservoir. During periods of high electricity demand (and higher prices), the water is released to flow back down to the lower reservoir while turning turbines to generate electricity, similar to conventional hydropower plants. Pumped hydro storage is appropriate for load-leveling because it can be constructed at large capacities of 100-1000s of megawatts (MW) and discharged over long periods of time (4 to 10 hours).⁶

- **Compressed Air**

Compressed air energy storage (CAES) is a hybrid generation/storage technology in which electricity is used to inject air at high pressure into underground geologic formations. When demand for electricity is high, the high pressure air is released from underground and used to help power natural gas-fired turbines. The pressurized air allows the turbines to generate electricity using significantly less natural gas. CAES is also appropriate for load-leveling because it can be constructed in capacities of a few hundred MW and can be discharged over long (4-24 hours) periods of time.⁷

- **Rechargeable Batteries**

Several different types of large-scale rechargeable batteries can be used for EES including sodium sulfur (NaS), lithium ion, and flow batteries. Batteries could be used for both power quality and load-leveling applications. In addition, if plug-in hybrid electric vehicles (PHEVs) become widespread, their onboard batteries could be used for EES, by providing some of the supporting or “ancillary” services⁸ in the electricity market such as providing capacity, spinning reserve⁹, or regulation¹⁰ services, or in some cases, by providing load-leveling or energy arbitrage services by recharging when demand is low to provide electricity during peak demand.

- **Thermal Energy Storage**

There are two very different types of thermal energy storage (TES): TES applicable to solar thermal power plants and end-use TES. TES for solar thermal power plants consists of a synthetic oil or molten salt that stores solar energy in the form of heat collected by solar thermal power plants to enable smooth power output during daytime cloudy periods and to extend power production for 1-10 hours past sunset.¹¹ End-use TES stores electricity from off-peak periods through the use of hot or cold storage in underground aquifers, water or ice tanks, or other storage materials and uses this stored energy to reduce the electricity consumption of building heating or air conditioning systems during times of peak demand.¹²

- **Hydrogen**

Hydrogen storage could be used for load-leveling or power quality applications.¹³ Hydrogen storage involves using electricity to split water into hydrogen and oxygen through a process called electrolysis. When electricity is needed the hydrogen can be used to generate electricity via a hydrogen-powered combustion engine or a fuel cell.

- **Flywheels**

Flywheels can be used for power quality applications since they can charge and discharge quickly and frequently. In a flywheel, energy is stored by using electricity to accelerate a rotating disc. To retrieve stored energy from the flywheel, the process is reversed with the motor acting as a generator powered by the braking of the rotating disc.

- **Ultracapacitors**

Ultracapacitors are electrical devices that consist of two oppositely charged metal plates separated by an insulator. The ultracapacitor stores energy by increasing the electric charge accumulation on the metal plates and discharges energy when the electric charges are released by the metal plates. Ultracapacitors could be used to improve power quality because they can rapidly provide short bursts of energy (in under a second) and store energy for a few minutes.¹⁴

- **Superconducting Magnetic Energy Storage (SMES)**

Superconducting magnetic energy storage (SMES) consists of a coil with many windings of superconducting wire that stores and releases energy with increases or decreases in the current flowing through the wire. Although the SMES device itself is highly efficient and has no moving parts, it must be refrigerated to maintain the superconducting properties of the wire materials, and thus incurs energy and maintenance costs.¹⁵ SMES are used to improve power quality because they provide short bursts of energy (in less than a second).

Environmental Benefit / Emission Reduction Potential

While EES is not needed with current levels of renewable generation nor with renewable generation levels projected in the near term, greater use of EES can potentially enable very large penetration of variable renewable generation in the longer term by lowering the cost of connecting these resources with the transmission grid and of managing the increased variability of generation.¹⁶ For example, a recent modeling analysis conducted by the National Renewable Energy Laboratory (NREL) examined the effect of EES on wind power.¹⁷ In a “business-as-usual” case, NREL’s model projected that building about 30 GW of EES could allow for the installation of an additional 50 GW of wind generation capacity by 2050 (a 17 percent increase compared to a scenario with no EES). NREL also modeled a scenario that required 20 percent of electricity to come from wind power by 2030. In this case, NREL found that investments in EES (in the form of CAES) became economic once wind penetration reached 15 percent of generation and that EES would lower the cost of electricity in the case of high wind penetration by 3 percent (about \$3/MWh) in 2050.¹⁸

EES enables GHG emission reductions by two main mechanisms:

- EES can be used instead of natural gas generators to smooth out the variable output of renewable resources such as wind or solar power from hour to hour, and allow these resources to be scheduled according to daily fluctuations of electric demand. For example, the use of CAES to smooth wind power generation would result in a 56 percent reduction in CO₂ emissions per kilowatt-hour of electricity, compared to smoothing variable wind power with generation from a gas turbine, and would enable a greater penetration of wind power.¹⁹
- EES charged with electricity from low-carbon sources can be used to displace fossil fuel generation to provide regulation services by smoothing out the fluctuations between supply and demand over a period of less than 15 minutes. This use of EES could reduce the amount of fossil fuels burned by generators, leading to GHG and conventional emission reductions.

However, EES can also increase GHG emissions if recharged with cheap electricity from high-carbon baseload coal power plants to displace more expensive peaking power from lower-carbon natural gas generators. The GHG emission reduction potential from EES depends on its use with renewable or low-carbon (i.e. nuclear or coal with carbon capture and storage (CCS)) resources.

Cost

The up-front capital costs of EES vary by technology. Total capital costs per unit of power capacity for most EES technologies are high compared to a \$800-1100/kW natural gas power plant,²⁰ varying from \$300-\$450/kW for SMES and ultracapacitors, \$600-\$1800/kW for CAES, \$1500-\$3000/kW for batteries, \$2000/kW or more for hydrogen and fuel cells,²¹ \$2500-\$4000/kW for pumped hydro, and \$3700-\$4300/kW for flywheels.²² These costs are highly uncertain and complicated by the fact that the cheaper technologies, such as SMES, ultracapacitors, and some batteries, are only available with small (a few kilowatt to MW) power capacities. Integrating many small units of these cheaper storage technologies into a 100+ MW-scale utility application would lead to additional cost and complexity.

The cost premium for stored electricity,²³ which depends on the lifetime of the EES technology and its useable energy storage capacity, are not well understood for most EES technologies. One study calculated a cost premium of \$0.05-0.12/kWh for pumped hydro storage, \$0.07-0.86/kWh for batteries, and \$0.07-0.64/kWh for flywheels.²⁴ EES technologies at the low cost ranges seem promising in a few applications when competing against average U.S. peak electricity prices of \$0.18/kWh.²⁵

TES for solar thermal power plant and end-use applications are also commercially promising. A solar thermal power plant with TES is projected to have a lower levelized cost of electricity²⁶ compared to a solar thermal power plant without storage.^{27,28} The Electric Power Research Institute (EPRI) has also found that the use of end-use TES systems can save between 2-7 percent of annual heating/cooling energy costs, if well-designed.²⁹

Current Status of Electric Energy Storage

The current use of EES technologies is limited compared to the rates of storage in other energy markets such as the natural gas or petroleum markets. EES capacity, most of which is pumped hydro, is only 2.5 percent of U.S. electric power capacity.³⁰ However, demonstration projects of various EES technologies are underway in the U.S. and internationally.

- **Pumped Hydro**

The majority of EES in operation today consists of pumped hydro facilities. The U.S. has 38 pumped hydro facilities in operation that provide up to 22 GW of power, including 9 large-scale facilities.^{31,32,33} Japan has 12 large-scale pumped hydro facilities in use.³⁴ The potential use of this technology is limited by the availability of suitable geographic locations for pumped hydro facilities near demand centers or generation.

- **Compressed Air Energy Storage (CAES)**

Two CAES facilities are in operation today: a 290 MW facility in Huntorf, Germany, which is used to level variable power from wind turbines, and a 110 MW facility in McIntosh, Alabama, which is used to provide a variety of power quality functions.³⁵ Some studies forecast that CAES will provide the bulk of EES services by 2050 because of its lower capital and operating costs.³⁶

- **Batteries**

Thus far, sodium sulfide (NaS) batteries have been used by utilities worldwide in 196 large-scale demonstration projects with a total capacity of 270 MW, of which 70 MW are in Japan.^{37,38} Lithium ion and flow batteries are relatively early-stage technologies which require research to lower capital costs, improve cycle life, and improve environmental and safety protocols.³⁹

- **Thermal Energy Storage (TES)**

The only commercial demonstration of TES integrated with a solar thermal power plant currently in operation is AndaSol One in Spain, which uses synthetic oil as the storage medium. Research is underway to develop molten salts as a potentially more efficient medium for TES. End-use TES is most cost-effective in regions with mild temperatures and relatively low humidity.⁴⁰ Demonstrations of end-use TES technologies have occurred in the United States, United Kingdom, Germany, and Scandinavia. For example, about 8 percent of residential water heaters in the United Kingdom use a specific TES material that is heated at night in order to heat water throughout the day and reduce peak electricity consumption.⁴¹

- **Hydrogen**

There are some demonstrations of EES using hydrogen and fuel cells for utility applications. However, hydrogen storage requires significant cost reductions prior to large-scale deployment since electrolysis is about 70-85 percent efficient while fuel cells are about 60 percent efficient, resulting in at most 42-51 percent efficiency to provide electricity to the grid, which is much lower than the 70-95 percent efficiencies of other EES technologies.^{42,43}

- **Flywheels**

Several installations of flywheels to provide power quality services have taken place across the United States. Flywheels are favored because of their high cycle life⁴⁴ of 100,000 to 2,000,000 cycles⁴⁵ and fast charging and discharging times of a few seconds to 15 minutes.⁴⁶ More research needs to be conducted to improve the energy densities⁴⁷ of this storage technology.

- **Ultracapacitors**

In 2003, the EPRI Power Electronics Application Center conducted a successful demonstration of a large 100 kW uninterruptible power supply (UPS) using ultracapacitors. However, experts argue that before further tests of this technology occur, more fundamental breakthroughs to lower costs and improve energy densities are required.^{48,49}

- **Superconducting Magnetic Energy Storage (SMES)**

Several MW-capacity SMES demonstration projects are in operation around the United States and the world to provide power quality services, especially at manufacturing plants requiring ultra-reliable electricity such as microchip fabrication facilities.⁵⁰ SMES requires further research to lower capital costs and improve energy densities.

Obstacles to Further Development or Deployment to Electric Energy Storage

- **High Capital Costs**

The capital costs of current EES technologies are high compared to natural gas generators that provide similar services.

- **Need for Large-Scale Demonstration Projects**

EES technologies such as CAES require a few large-scale demonstration projects before utility managers will have the confidence to invest in these technologies. Although there is one operating CAES facility in the United States, subsequent projects have faced delays and cancellations.⁵¹

- **Transmission Planning Processes**

Transmission planning only takes into account the location of demand centers and generation facilities. As a result, geographically remote EES facilities such as pumped hydro or CAES have limited access to the transmission grid.⁵²

- **Regulatory Barriers**

Federal and state regulations treat EES as a type of electric generation technology rather than as an investment in transmission capacity. Thus transmission and distribution companies are barred from owning EES.⁵³ In addition, most renewable portfolio standards or government investment or production incentives are written for renewable generation only and exclude EES, despite the fact that EES can enable higher penetration of renewable energy.^{54, 55}

- **Conservative Industry Culture With Respect to Technology Risks**

Regulated utilities are risk averse and reluctant to invest in new technologies, such as EES, due to the capital-intensive nature of electric generation and the lack of competition in the market. Deregulation of the electricity industry in parts of the U.S. created a competitive market for generation, but generator owners are unsure whether they will be able to recover their capital costs and are also reluctant to invest in new technologies. In general, the energy industry invests a tiny fraction of profits in research and development compared to other industries, which limits the pace of improvements in technologies such as EES.⁵⁶

- **Incomplete Electricity Markets**

Most regions of the U.S. have not yet fully developed markets and transparent prices for all the types of ancillary services that EES (and generation) technologies provide besides providing electricity, such as regulation, spinning reserve, load-following,⁵⁷ and other services.

Policy Options to Help Promote Electric Energy Storage

- **Carbon Price**

A price on carbon, such as that which would exist under a greenhouse gas cap-and-trade program (see [Climate Change 101: Cap and Trade](#)), would raise the cost of electricity produced from fossil fuels relative to the cost of electricity from variable renewable sources, such as wind and solar power, and from low carbon sources, such as nuclear and coal power with CCS. This would, in turn, increase the value of the services provided by EES in situations where EES could store relatively inexpensive low-carbon electricity to displace carbon-intensive power.

- **Real-Time Electricity Pricing**

The cost of producing and delivering electricity to consumers varies throughout the day, since cheaper baseload coal or nuclear power plants generate more of the electricity at night when demand is low, and more expensive peaking power plants must be activated during the day when demand is high. However, most residential consumers are charged a flat price for electricity, and commercial and industrial consumers face demand charges for high power consumption and higher peak electricity rates that are not set according to the daily hour-by-hour variations of electricity production costs. If consumers were charged a real-time price for electricity, the high cost of peak electricity would be transparent and investments in EES to reduce peak load would have greater value.

- **Markets for Ancillary Electric Services**
EES technologies would benefit from receiving prices set by competitive markets for ancillary electric services such as regulation, spinning reserve, and load-following, which would increase the overall value of EES.
- **Relaxation of Ownership Restrictions**
EES can serve both generation and transmission functions, but existing deregulated electricity markets place limits on who can own such facilities. Removing restrictions on the ownership of EES facilities by end-use customers, transmission owners, or distribution companies could enable greater market penetration of EES.⁵⁸
- **Integration of EES in Transmission Planning**
Decisions regarding new transmission lines could factor in the location of large-scale EES sites, as well as demand centers and generation facilities. Investments in EES are often less costly than building new transmission lines. The Federal Energy Regulatory Commission could modify rules so that EES is subject to transmission pricing incentives and a part of the transmission planning process.⁵⁹
- **Loan Guarantees for Large-Scale EES Demonstration Projects**
The Energy Policy Act of 2005 authorized loan guarantees for “innovative technologies” that reduce GHG emissions; however EES technologies do not qualify. Federal loan guarantees for initial large-scale EES projects could accelerate commercialization.⁶⁰
- **Basic and Applied Research and Development**
Low charge/discharge efficiencies, low cycle lives, and high capital costs make most EES technologies less economically competitive for smoothing out renewable energy or providing power quality services compared to power plants that provide similar services. Federal or state investments and incentives for private investment in basic and applied research and development would help to improve the performance of existing technologies and support the discovery of fundamental breakthroughs for the next generation of EES technologies.

Related Business Environmental Leadership Council (BELC) Company Activities

- [AEP](#)
- [BASF](#)
- [Dow Chemical Company](#)
- [DTE Energy](#)
- [DuPont](#)
- [Entergy](#)
- [General Electric](#)
- [Johnson Controls](#)
- [Lockheed Martin](#)
- [PG&E](#)

- [PNM Resources](#)
- [Royal Dutch/Shell](#)

Related Pew Center Resources

Climate Change 101: Technology. See http://www.pewclimate.org/global-warming-basics/climate_change_101.

Komor, Paul. 2009. *Wind and Solar Electricity: Challenges and Opportunities*. Forthcoming.

Morgan, Granger, Jay Apt, and Lester Lave. 2005. *The U.S. Electric Power Sector and Climate Change Mitigation*. See http://pewclimate.com/global-warming-in-depth/all_reports/electricity.

Further Reading / Additional Resources

American Physical Society (APS). 2007. *Challenges of Electricity Storage Technologies*. See http://www.aps.org/policy/reports/popa-reports/upload/Energy-2007-Report-Electricity_StorageReport.pdf.

California Independent System Operator (CAISO). 2007. *Integration of Renewable Resources: Transmission and Operating Issues and Recommendations for Integrating Renewable Resources on the California ISO-Controlled Grid*. See Chapter 7, "Storage Technology," available at <http://www.uwig.org/CAISOIntRenewablesNov2007.pdf>.

Denholm, Paul. 2008. *The Role of Energy Storage in the Modern Low-Carbon Grid*. National Renewable Energy Laboratory. See <http://tinyurl.com/d4t4pu>.

Electric Power Research Institute/Department of Energy. *Handbook of Energy Storage for Transmission and Distribution Applications*. Palo Alto, CA: 2003. 1001834. See <http://my.epri.com/portal/server.pt?>

Electricity Advisory Committee. 2008. *Bottling Electricity: Storage as a Strategic Tool for Managing Variability and Capacity Concerns in the Modern Grid*. See <http://tinyurl.com/c7v698>.

International Energy Agency (IEA). 2008. *Empowering Variable Renewables: Options for Flexible Electricity Systems*. See http://www.iea.org/g8/2008/Empowering_Variable_Renewables.pdf.

Jewell, Ward et al. 2004. *Evaluation of Distributed Electric Energy Storage and Generation*. Power Systems Engineering Research Center. See http://www.pserc.org/cgi-pserc/getbig/publicatio/reports/2004report/jewell_der_final_report_2004.pdf.

Lee, Bernard and David Gushee. 2008. *Massive Electricity Storage*. American Institute of Chemical Engineers. See <http://tinyurl.com/3z94h2>.

National Renewable Energy Laboratory (NREL). "Energy Storage Basics." See http://www.nrel.gov/learning/eds_energy_storage.html.

National Renewable Energy Laboratory (NREL). "Energy Storage and Wind Power." See http://www.nrel.gov/wind/systemsintegration/energy_storage.html.

Peters, Roger and Lynda O'Malley. 2008. *Storing Renewable Power*. Pembina Institute. See <http://pubs.pembina.org/reports/StoringRenewablePower-jun17.pdf>.

Rastler, Dan. 2008. "Demand for New Energy Storage." *Electricity Perspectives*. Sept/Oct. See <http://www.eei.org/magazine/EEI%20Electric%20Perspectives%20Article%20Listing/2008-09-01-EnergyStorage.pdf>

Walawalkar, Rahul, and Jay Apt. 2008. *Market Analysis of Emerging Electric Energy Storage Systems*. National Energy Technology Laboratory. See <http://204.154.137.14/energy-analyses/pubs/Final%20Report-Market%20Analysis%20of%20Emerging%20Electric%20Energy%20Storage.pdf>.

Yan, Chi-Jen and Eric Williams. 2009. *Energy Storage for Low-Carbon Electricity*. Duke University Climate Change Policy Partnership. See http://www.nicholas.duke.edu/ccpp/ccpp_pdfs/energy_storage.pdfhttp://www.nicholas.duke.edu/ccpp/ccpp_pdfs/energy_storage.pdf.

¹ Other approaches for managing the variability of renewable generation include increasing the interconnectedness of electric grids, developing more flexible generation technologies capable of increasing or decreasing output at faster rates (called ramping rates), demand response programs which create flexibility in demand, and market mechanisms, such as different pricing structures for variable renewable resources. For more information, see the resources under Further Reading, especially the Pew Center's report on wind and solar power and the reports from IEA and CallSO.

² Jewell, Ward et al. 2004. *Evaluation of Distributed Electric Energy Storage and Generation*. Power Systems Engineering Research Center. See <http://tinyurl.com/d7c3uk>.

³ Power quality is defined as the provision of power with specified voltage and frequency characteristics to the customer. Small imbalances in the sub-minute time frame between electric supply and demand, and the physical properties of electric generators, electricity-consuming devices, and the transmission grid itself lead to small deviations (1 to 5 percent) between the expected and actual voltage and frequency of power delivered, which can cause highly sensitive equipment such as computers to fail. When electric supply and demand are in balance, these deviations in voltage and frequency are eliminated.

⁴ California Independent System Operator (CAISO). 2007. *Integration of Renewable Resources: Transmission and Operating Issues and Recommendations for Integrating Renewable Resources on the California ISO-Controlled Grid*. See Chapter 7, "Storage Technology," available at <http://www.uwig.org/CAISOIntRenewablesNov2007.pdf>.

⁵ Load leveling or peak shaving refers to the use of electricity stored during times of low demand to supply peak electricity demand, which reduces the need for electric generation from peaking power plants. The use of EES for load-leveling is also known as "energy arbitrage" since it may be possible to earn a profit by charging EES with cheap electricity when demand is low and selling discharged electricity at a higher price when demand is high. Load leveling can also be achieved through demand-side measures such as using higher peak prices to induce a reduction in peak demand through demand charges, real-time pricing, or other market measures.

⁶ Rastler, Dan. 2008. "New Demand for Energy Storage." *Electricity Perspectives*. Sept/Oct. See <http://www.eei.org/magazine/EEI%20Electric%20Perspectives%20Article%20Listing/2008-09-01-EnergyStorage.pdf>

⁷ Ibid..

⁸ Generators (and potentially EES) provide energy and ancillary services to electricity markets. Energy services are defined as providing electric generation to meet demand, usually scheduled on a day-ahead basis. The term, "ancillary services" includes a variety of services related to power quality. For example, in some electricity markets, generators (and potentially EES) are paid for the capacity of power they can produce, whether or not they are actually generating, in order to ensure that the market has sufficient capacity to meet peak demand.

⁹ Spinning reserve is an ancillary service in the electricity market defined as the ability of (usually a generator) to remain on and ready to start generating given notice over a short period of time (15 minutes to an hour).

¹⁰ Regulation refers to an ancillary electric service (usually provided by electric generators) to maintain power quality by following unpredictable minute-by-minute fluctuations in electric demand.

¹¹ Price, H., et al. (2002). "Advances in Parabolic Trough Power Technology." *Journal of Solar Energy Engineering* 124: 109-125.

- ¹² End-use thermal energy storage could also be considered a type of demand response as it reduces the electricity use of heating or air conditioning systems during times of peak demand. By pre-cooling or heating the building during off-peak times and using a few hours of hot or cold storage in the form of aquifers, water/ice tanks, or heat storage materials, the heating, air-conditioning, and refrigeration loads of the building can be shifted to off-peak hours. For more information, see International Energy Agency. Energy Conservation through Energy Storage website. <http://www.iea.org/eces>; Kintner-Meyer, M, and Emery, A. F. 1995. "Optimal control of an HVAC system using cold storage and building thermal capacitance." *Energy and Buildings*. Vol. 23, p.19-31.
- ¹³ Schoenung, S. M. Hydrogen Energy Storage Comparison. Department of Energy. See <http://www.osti.gov/bridge/servlets/purl/763084-JtAYM6/webviewable/763084.pdf>
- ¹⁴ American Physical Society (APS). 2007. *Challenges of Electricity Storage Technologies*. See <http://www.aps.org/policy/reports/popa-reports/upload/Energy-2007-Report-ElectricityStorageReport.pdf>.
- ¹⁵ Ibid.
- ¹⁶ Denholm, Paul. 2008. *The Role of Energy Storage in the Modern Low-Carbon Grid*. National Renewable Energy Laboratory. See <http://tinyurl.com/d4t4pu>.
- ¹⁷ Sullivan, P., Short, W., and Blair, N. 2008. "Modeling the Benefits of Storage Technologies to Wind Power." American Wind Energy Association (AWEA) WindPower 2008 Conference. Conference Paper NREL/CP-670-43510.
- ¹⁸ Ibid.
- ¹⁹ Greenblatt, J. B., Succar, A., Denkenberger, D. C., Williams, R. H., and Socolow, R. H. 2007. "Baseload wind energy: modeling the competition between gas turbines and compressed air energy storage for supplemental generation." *Energy Policy*. 35: 1474–1492.
- ²⁰ California Public Utility Commission. Greenhouse Gas Modeling. "New Combined Cycle Gas Turbine (CCGT) Generation Resource, Cost, and Performance Assumptions." www.ethree.com/GHG/21%20Gas%20CCGT%20Assumptions%20v4.doc. Development and construction capital costs from 2002 escalated by 3% per year to 2009 from Northwest Council. "Natural Gas Simple-Cycle Gas Turbine Power Plants." <http://www.nwcouncil.org/energy/powerplan/grac/052202/gassimple.htm>.
- ²¹ Schoenung, 1999. Hydrogen storage cost/storage hour figures are escalated by 3% from 1999-2009.
- ²² Rastler, 2008.
- ²³ The cost premium is the difference between the cost of electricity discharged from an EES facility and the cost of the electricity used to charge the EES facility.
- ²⁴ Poonpun, P., and Jewell, W. T. 2008. "Analysis of the Cost per Kilowatt Hour to Store Electricity." *IEEE Transactions on Energy Conversion*. Vol 23. No 2. June.
- ²⁵ Ibid.
- ²⁶ Levelized cost of electricity (LCOE) is defined as the ratio of the sum of the plant operation and maintenance costs and amortized capital costs to the annual plant generation.
- ²⁷ Price, H., et al., 2002
- ²⁸ While TES increases the capital costs of a solar thermal power plant, it also increases the total electricity output from the power plant by using a larger solar collector to heat the molten salt-based TES material and allowing the plant to operate during sundown. The increase in power output is greater than the increase in capital costs for the TES material and additional solar collector area.
- ²⁹ Electric Power Research Institute. "Thermal Energy Storage Systems Operation and Control Strategies Under Real-Time Pricing." Palo Alto, CA: 2004. 1007401.
- ³⁰ APS, 2007.
- ³¹ Rastler, 2008, claims there are 150 pumped hydro storage facilities providing up to 22 GW of electric storage.
- ³² APS, 2007, claims there are 38 pumped hydro plants providing 19 GW of electric storage in U.S.
- ³³ Sullivan, et. al., 2008.
- ³⁴ Business Insights. 2009. "The Future of Electrical Energy Storage: The Economics and Potential of New Technologies." Executive Summary. <http://www.reportlinker.com/p0105458/The-Future-of-Electrical-Energy-Storage-The-economics-and-potential-of-new-technologies.html>.
- ³⁵ Rastler, 2008.
- ³⁶ Sullivan, et. al., 2008.
- ³⁷ Rastler, 2008.

³⁸ Gyuk, I., Kulkarni, P., Sayer, J. H., Boyes, J. D., Corey, G. P. and Peek, G. H. 2005. "The United States of Storage." *IEEE Power & Energy Magazine*. March/April.

³⁹ APS 2007

⁴⁰ Kintner-Meyer, M, and Emery, A. F. 1995

⁴¹ Baker, J. 2008. "New Technology and Possible Advances in Energy Storage." *Energy Policy*. Vol. 36, p 4368–4373.

⁴² APS, 2007

⁴³ Schoenung, 1999.

⁴⁴ Cycle life is defined as the number of times an EES technology can be charged and discharged up to its maximum charging capacity during its lifetime.

⁴⁵ Walawalkar, Rahul, and Jay Apt. 2008. *Market Analysis of Emerging Electric Energy Storage Systems*. National Energy Technology Laboratory. See <http://204.154.137.14/energy-analyses/pubs/Final%20Report-Market%20Analysis%20of%20Emerging%20Electric%20Energy%20Sto.pdf>.

⁴⁶ Rastler, 2008.

⁴⁷ Energy density is defined as the ratio of the energy storage capacity in kWh to the physical footprint required for the technology, often in expressed in units of square meters. Energy density is most important for vehicular applications.

⁴⁸ APS, 2007.

⁴⁹ Walawalkar and Apt, 2008.

⁵⁰ APS, 2007.

⁵¹ Electric Power Research Institute/Department of Energy. *Handbook of Energy Storage for Transmission and Distribution Applications*. Palo Alto, CA: 2003. 1001834. Chapter 15, p15-2. See www.epri.org/research

⁵² Yan, Chi-Jen and Eric Williams (Nicholas Institute). 2009. *Energy Storage for Low-carbon Electricity*. Duke University Climate Change Policy Partnership. See http://www.nicholas.duke.edu/ccpp/ccpp_pdfs/energy.storage.pdf.

⁵³ Ibid.

⁵⁴ Ibid.

⁵⁵ The Energy Independence and Security Act of 2007 (EISA 2007) is an exception, as it provides \$50 million in basic research funding, \$80 million in applied research funding for automotive and utility energy storage, and defines "deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal-storage air conditioning" as a "Smart Grid" characteristic" and eligible for matching grants and other incentives for Smart Grid technologies found in the law. Source: Peters, Roger and Lynda O'Malley. 2008. *Storing Renewable Power*. Pembina Institute. See <http://pubs.pembina.org/reports/StoringRenewablePower-jun17.pdf>.

⁵⁶ Margolis, R. M., and Kammen, D. M. 1999. "Underinvestment: The Energy Technology and R&D Policy Challenge." *Science*. Vol. 285. no. 5428, pp. 690 – 692.

⁵⁷ Load-following is an ancillary service in the electricity market defined as the ability of (usually a generator) to increase or decrease electricity output over a short period of time (15 minutes to an hour) according to the predicted change in electric demand throughout a day.

⁵⁸ Nicholas Institute, 2009.

⁵⁹ Ibid.

⁶⁰ Ibid.