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ENERGY STORAGE TECHNOLOGIES FOR UTILITY SCALE INTERMITTENT RENEWABLE ENERGY SYSTEMS

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ABSTRACT In current conventional utility systems, fossil fuel or nuclear power plants must back up intermittent renewable electricity generators if the utility grid is to have acceptable reliability. For low levels of intermittent power, this can be achieved without difficulty or added expense. For high levels this reliance on other generators becomes explicit and increasingly expensive, and transmission capacity also becomes an issue. An attractive alternative to the conventional approach is one that relies on bulk or utility scale storage of intermittent electricity to provide system reliability. A comparison of the currently available storage technologies shows that the most cost effective and environmentally acceptable is a compressed air energy storage (CAES) system and especially its more advanced derivatives (CASH, CAES with Humidification and CAESSI, CAES with Steam Injection). For wind energy systems, both short term and seasonal storage are technically and economically feasible.

Background

It is increasingly obvious that anthropogenic global climate change must be taken seriously, and that carbon emissions must be reduced drastically if serious harm to the Earth's biosphere is to be avoided. This certainly will involve dramatically reducing or eliminating the use of carbon based fuels to generate electricity and utilizing nuclear or solar energy systems instead. While nuclear power can technically be used to replace fossil fuels, it has important disadvantages, most significantly the irreducible finite possibility of a catastrophic accident. It would thus be desirable to limit its use to a minimum and satisfy most or all of our electricity needs using solar power. However, if solar generated electricity is to be a credible alternative it must have technical characteristics equal to those of fossil or nuclear power; that is, it must be easily utilized in modern industrial state, and its cost must be reasonable. Since renewable resources are generally diffuse, remote from major demand centers, and intermittent, the issues of transmission and storage must be addressed; fortunately, it is easy to demonstrate that an affordable technical solution to the challenge of electricity storage already exists.

The need for utility scale storage is illustrated by the current status of wind energy, which now supplies about 15 percent of Denmark's electricity. Wind turbines are by far the lowest cost and most successful source of renewable electrical energy available today. This is due both to the superb quality of the turbines developed over the past decade, as well as to far-sighted and effective public policy that mandates a justifiably high price for wind electricity. These same policies do have some negative effects, however, which up to now have not impeded the rapid increase of wind electricity onto the grid. Utilities, in most cases, are forced to absorb the costs of transmission line and substation reinforcement and of insuring overall system reliability. Given low wind turbine capacity factor (25-30 percent), transmission has already become an issue in some areas, while system reliability is increasingly a problem as wind penetration grows above 10 percent of average electricity demand, as it has in Denmark. In addition, a new system of balancing charges designed to insure that supply balances demand in deregulated markets threatens to penalize wind quite strongly [1].

One way to resolve these issues to the advantage of wind and other intermittent energy is to include storage on the system in a way that recognizes the wind/storage plant as a unified entity: that is, the output of the total system should be classified as renewable energy. This will resolve immediate transmission and reliability issues as well as allowing wind in the not too distant future to supply up to about 80 percent of total electricity demand [2].

Comparison Of Storage Technologies

Pumped storage, batteries, superconducting magnet energy storage, flywheel energy storage, regenerative fuel cell storage and compressed air energy storage could be considered for bulk power storage; a cost comparison [3,4] of these is listed in Table 1. The critical parameters for these systems are the cost for power output (plant capital cost, \$/kW) and the cost of energy storage capacity, given as the cost per hour of operation at full output power (storage capital cost, \$/kWh$_{op}$). The systems are compared with a 50 hour reservoir size which would allow intermittent wind energy to be transformed to baseload power for a wind regime with a wind speed autocorrelation time of about 8 hours. Based on a wind plant/CAES system simulation that included the wind speed autocorrelation time [5], this reservoir size is reasonably adequate for short term baseload operation but far below what is necessary for seasonal storage, so that the comparison understates the advantages of CAES.

To put this problem in perspective, it is useful to compare the energy density of a typical fossil fuel to alternative storage media. Fuel oil has an energy density of about 38 GJ m^{-3}; for comparison, a 25 kG magnetic field has an energy density of 10 MJ m^{-3}, a cubic meter of water at a height of 100 m, 1 MJ m^{-3}, a rechargeable gell cell battery, about 240 MJ m^{-3}, compressed air (80 Bar), 8 MJ m^{-3} and a rechargeable fuel cell (Innogy PLC), 120 MJ m^{-3}. Fossil fuels have an immense advantage on this basis alone. If one also considers their very low cost and ease of transportation and utilization, the advantages of fossil fuels would appear to be overwhelming. Yet intermittent renewable energy, with a properly chosen storage system, can in fact be competitive, both technically and economically as defined below, with fossil and nuclear systems.

Technical competitiveness means that intermittent renewable energy systems with storage must have the same forced outage and scheduled outage rates, as well as all other measures of power quality, as the best fossil fuel or nuclear systems. Economic competitiveness means that the electricity market must be designed so that cost of electricity delivered is affordable for consumers and profitable for producers and equipment manufacturers. Given the advantages of fossil fuel systems (low installed capital costs, relatively low fuel costs, lack of any cost assigned to the damage done by mining, transportation or burning fuels), it is not realistic to assume that renewable energy can compete as the markets presently function. However, with the excellent renewable energy technologies now available and the increased understanding and awareness of the dangers of the alternatives, it is clear that the rules by which markets currently operate must be adjusted to allow renewable energy to supply a much larger fraction of the demand.

Pumped Storage. Pumped storage (Table 1), with an overall efficiency of about 75 percent, is widely used around the world. However, it is only economical in large installations (1000 MW), and the aboveground reservoir has a significant environmental impact due to its size and dynamic behavior. In addition, many regions do not have any suitable sites for storage reservoirs or have sites only in areas where there is strong opposition to such a facility. Finally, the installed capital cost of aboveground pumped storage is much higher than for a CAES system; seasonal storage, which requires two to three hundred hours of storage capacity, is not economical. And while the environmental impact of an underground pumped storage reservoir is minimal, the cost is high.

Battery Storage. Battery storage, with an overall efficiency of 75 percent, is also a possible candidate (Table 1). While the plant capital cost (\$/kW) is low, the storage capital cost is quite high, and the total installed capital cost, even for advanced batteries, is extravagant. In addition, the volume of materials needed for a utility scale facility raises environmental issues that are difficult to overcome. Certainly the use of lead acid batteries, even in advanced systems, would be out of the question. Furthermore, the battery system cost does not include the replacement cost. Clearly, the use of batteries in a utility scale storage system is not realistic.

Superconducting Magnets. Large scale superconducting magnet energy storage systems (90 percent efficiency) are still under development (Table 1), while small scale systems used for short term dropout protection on critical equipment like computers are already deployed. Again, the very high storage capital cost for these systems (\$300/kWh$_{op}$) makes these systems economically impractical for utility scale systems. Also, the environmental impact of large solenoids and their associated unconfined magnetic fields might be a problem.

Flywheels. Flywheels (70 percent efficiency) have long been used to store energy in rotating machinery, and larger flywheels using advanced materials are under development. Once again, their very high storage capital cost (\$300/kWh$_{op}$) indicates that while such systems may be useful in special applications like automobiles, bulk electricity storage using flywheels is highly impractical (Table 1).

Regenerative Fuel Cells. The newest storage technology is based on the recently developed regenerative fuel cell [4]. To charge the system, electrical energy is converted into chemical energy in two electrolytic solutions in the fuel cell and pumped into storage tanks; during discharge the process is reversed. Fuel cell electrodes function as a cation selective membrane; these are made of carbon fiber, a low cost and high strength material. The electrolytes are concentrated solutions of sodium bromide and sodium polysulphide, which are readily available commercially. System lifetime is estimated to be greater than 15 years; overall system efficiency is about 65 percent.

The technology has many advantages. The system is modular so that it can be easily expanded and easily repaired; tens or hundreds of modules are linked in series and parallel. Storage capacity is separately adjustable from power output. The response time of the system is less than 3 seconds, so that applications such as spinning reserve, load leveling, and distributed generation (peak shaving) are feasible.

Costs listed in Table 1 are based on the first large-scale system to be built, a 15 MW, 120 MWh facility to be constructed in Wales (UK), and are expected to drop as more experience is gained; it already appears to be competitive with battery storage systems. This appears to be a promising technology for certain applications, but one that is likely to remain significantly (factor of 2-3) more expensive than CAES, even with large reductions in the Cell plant and storage capital costs and with high fossil fuel costs for the CAES system. This is a consequence of the relatively low capacity factor at which storage systems operate and the much higher plant and storage capital costs of the Regenerative Cell system compared to the CAES system.

Compressed Air. Compressed air energy storage (CAES) was invented in Germany in 1949, and a 290 MW CAES facility has been operating reliably at Huntorf since 1978. In the USA a more modern plant has been in operation since 1991 at the Alabama Electric Cooperative in Macintosh, Alabama USA [6,7].

CAES is based on gas turbine (or jet engine) technology that has advanced enormously over the past decade. A turbine is in principle a simple machine consisting of a compressor, a combustor and an expander. A turbine extracts energy from a fuel in a simple thermodynamic Joule cycle of isentropic compression of the input gas, isobaric heating of the compressed gas in the combustor, and isentropic expansion and isobaric rejection of heat in the expander. Modern single cycle combustion turbines have an efficiency of between 30 and 40 percent, so that about 60 to 70 percent of the output of the expander is used to drive the compressor [8]; it is this energy (less any losses) that is available for storage in a CAES system, as explained below.

CAES can be understood as interrupting this thermodynamic cycle; instead of injecting the compressed gas directly into the combustor, it is stored in an underground reservoir. When power is needed, high-pressure gas is withdrawn from the reservoir and the remainder of cycle completed.

A CAES system in its simplest form consists of a compressor, a turboexpander (a combustor and expander), a generator and an underground storage volume such as a solution mined cavern in a salt deposit, a capped porous rock formation such as a depleted gas reservoir, or a hardrock cavern or abandoned mine. To charge the reservoir, power is supplied to a compressor which pumps air at a pressure of about 80 bar into the underground storage reservoir. When power is needed the high pressure air is withdrawn from the cavern and supplied with fuel to the turboexpander to generate electricity.

This system has many important advantages. Power generation is based on gas turbines, which are simple, reliable, and inexpensive. The storage medium is air, which is readily available and free. The turboexpander, which does not drive the compressor, has a very high ramp rate, so that the system can be brought on line and respond to system changes very quickly; in addition, the heat rate is constant over a wide range of output power. The compressor charging system is completely independent from the generator and can be sized to match the wind resource and wind turbine array. In the US, geological surveys have indicated that suitable underground conditions for CAES systems are found over about 80 percent of the country, including those areas with good wind resources. Finally, the environmental impact of the underground storage volume is minimal.

Two parameters characterize CAES system efficiency, a heat rate (HR, Btu/kWh) and an energy ratio (ER), or the ratio of the input energy to the output energy. Since CAES uses fuel itself, the energy output is greater than the energy input, and ER is less than 1. For example, the AEC CAES plant the HR is 4100 Btu/kWh and the ER is 0.82.

There are several ways to enhance the efficiency of the simple CAES system. The most direct is to preheat the compressed air in a recuperator before it enters the turboexpander to extract additional energy from the exhaust gas. This lowers the heat rate and reduces operating costs; it has been implemented in the Alabama Electric Cooperative CAES plant.

One possible improvement [9] in the basic system is to generate steam, then inject it with the compressed air from the storage volume into the turboexpander where it is heated and expanded. This type of plant (CAESSI, CAES with steam injection) has a higher heat rate but a lower energy ratio, as well a significantly lower installed capital cost.

Another possibility is to heat and humidify air from the storage volume in an air saturator, then pass it through a recuperator before injection into the turboexpander. This plant (CASH, or CAES with Humidification) has a lower installed capital cost and a lower heat rate than CAESSI, and appears to be the most economical version of the CAES concept. Compared to the basic CAES system, storage volume is reduced by a factor of 1.67 using CASH, resulting in a significant reduction in the total system installed capital cost. A CASH plant might have an HR of 5000 Btu/kWh and an ER of 0.5.

The wind resource can vary significantly during the course of the year, in many cases being much better in the winter or spring than in the summer, so that a system with a seasonal energy storage capacity would be a great advantage. Costs of seasonal storage using a CAES or CASH system are compared in Table 2 with a 250 hour storage reservoir [10] CASH systems have an installed capital cost that is about 20 percent lower than CAES systems for both solution mined caverns or porous rock reservoirs. Both systems are technically and economically feasible possibilities for bulk electrical seasonal energy storage.

Recommendations

In order to insure that CAES systems can easily be adapted to wind industry needs, several issues must be addressed. These are CAES siting potential, demonstration plants, and possible new regulations.

CAES Siting Potential. The first issue is CAES siting potential. Geological surveys have been done in the USA that have identified regions where storage reservoir based on solution mined salt caverns, porous rock or hardrock caverns could be located. Favorable underground conditions for one or more of these types of reservoirs have been identified over more that 85% of the continental US, indicating that CAES systems are indeed a reasonable bulk electricity storage option there. Similar results might be expected in Europe, India or China, for example, but this needs to be documented.

Demonstration Plant. A demonstration plant that combines a CAES system with the appropriate number of wind turbines should be built. One possible configuration would be a 200 MW wind/CAES baseload facility; this would require about 575 MW of installed wind turbine capacity coupled to a CAES system with a 225 MW compressor charge rate and a 150 MW discharge rate. Since the required amount of nameplate wind turbine capacity already exists in several locations, only the CAES plant and any required transmission upgrade needs to be financed at an estimated cost of $75 million ($500/kW).

While CAES plants are already operational in Germany and the USA, they typically are coupled to a baseload rather than to an intermittent power plant. A demonstration plant would serve to resolve the details of the control system that coupled intermittent wind energy to the high power compressors. Most importantly, such a project would overcome the reluctance of a utility or company to be the first to build a new type of installation by underwriting the risk inevitably associated with a unique type of effort.

Renewable Energy/Fossil Fuel Combination Plants. It is critical that the total integrated system consisting of the renewable energy source and storage system, including those storage technologies that use fossil fuels directly, be considered a renewable energy supplier. For example, following the guidelines in PURPA (Public Utilities Regulatory Policies Act) in the USA, a power plant may be considered to be a renewable energy facility (a qualifying facility) provided that the fossil fuel energy input is limited to 25 percent of the total annual energy input.

An illustration of this approach is given by the Luz solar thermal power plants[11] in California. These use natural gas or fuel oil to generate steam in parallel with sun-tracking parabolic trough solar concentrators. In this fashion, the plant could generate power reliably at times of maximum demand and thus capture a premium price for its output. The Luz Company was forced into bankruptcy by low natural gas prices in 1991; however, their plants were the largest and most economical solar electric technology developed to date.

Using PURPA as a model, legislation allowing fossil fuel/renewable energy hybrid plants to be considered as renewable energy facilities should be enacted elsewhere.

Conclusion

The basic CAES system can be considered a reliable and demonstrated technology and is ideally suited for use with current wind turbine arrays; more advanced CAES concepts appear to have even greater promise for use with large high penetration intermittent wind energy systems. A comparison with alternative storage technologies indicates that CAES systems are to be preferred by a large margin both on environmental and on economic grounds. With the appropriate governmental actions with regard to site surveys, demonstration plants and legislation, CAES systems should be an important part of the effort to reduce and finally eliminate our dependence on fossil fuels.

Table 1. Storage Plant Installed Capital Cost*

(from R. Schainker, EPRI, 1996 Power Gen. Conf., Orlando, FL, USA and

Innogy (Regenerative Fuel Cell))

Storage Technology	Plant Capital Cost $/kW	Storage Capital Cost $/kWh$_{op}$	Hours (b) (full power)	Installed Capital Cost (ICC) $/kW	COE (e) ($/kWh)
CAES (a) >110 MW (Large)	390	1	50	440	0.0613
50MW (Small)	530	2	50	630	0.0675
Pumped Hydro Conventional (1000 MW)	1100	10	50	1600	0.119
Underground (2000 MW)	1200	50	50	3700	0.187
Battery (Target) (c) Lead Acid	120	170	50	8620	0.347
Advanced	120	100	50	5120	0.233
Superconducting Magnet 1000 MW (Target)	120	300	50	15120	0.5484
Flywheel (Target) 100 MW	150	300	50	15150	0.565
Regenerative Fuel Cell (15 MW) (d)	1500	150	50	9000	0.370

*Costs for the Fuel Cell are in 2000 Dollars, and all others in 1994 Dollars. According to the US Department of Commerce, there has been a negligible change in Producer Prices from 1994 through 2000. Thus, the quoted 1994 Dollar figures have not been adjusted.

(a) This capital cost is for the reservoir capacity per hour of full power plant operation, and is based on a solution mined salt cavern storage reservoir and basic CAES cycle. CASH and CAESSI systems and porous rock storage reservoirs have significant technical and economic advantages for wind energy applications.

(b) Based on a wind speed autocorrelation time of 8 hours and baseload operation.

(c) Battery cost does not include battery replacement.

(d) Proprietary System; information from Innogy Technology Ventures, Ltd; costs are approximate based on a 15 MW, 120 MWh system, and an exchange rate of 1.5 USD/UK Pound.

(e) COE (Cost of Electricity) comparisons are computed as follows:

For CAES Systems: COE ($/kwh) = ICC*CCR/(8766*CF) + EC*ER + HR*FC, where the heat rate (HR) is 4500 Btu/kWh, the Fuel Charge is $5/mmBtu, the Energy Ratio (ER) is 0.49, the cost of electricity used to charge the reservoir (EC) is $0.05, the capacity factor (CF) is 0.35 and the capital charge rate is 0.1;

For Other Systems: COE = ICC*CCR/(8766*CF) + EC/Efficiency

Table 2. Comparison of CAES and CASH for Seasonal Storage

Storage Technology	Plant Capital Cost \$/kW	Storage Capital Cost $\$/\mathrm{kWh}_{op}$	Hours* (full power)	Installed Capital Cost (ICC) \$/kW
CAES Solution Mined Cavern	390	1	250	640
CAES Porous Rock	390	0.5	250	515
CASH Solution Mined Cavern	350	1	250	511
CASH Porous Rock	350	0.5	250	431

*Based on wind class 3 (350 W/m^2) summer and wind class 5 (550 W/m^2) spring wind regime.

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