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# Discussion

## Energy Storage Technologies for Utility Scale Intermittent Renewable Energy Systems

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### Background

If solar-generated electricity is to be a credible alternative to fossil or nuclear power it must have technical characteristics equal to those sources of energy; that is, it must be easily utilized in a 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. Indeed, access to and cost of transmission and system reliability penalties are already having an impact on the integration of wind energy onto utility grids.

Wind turbines are by far the lowest cost and most successful new source of renewable electrical energy available today. This is due both to the superb quality of the turbines developed over the past decade, and 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 generated electricity. 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 factors (20–30%), transmission has already become an issue in some areas, while system integration is increasingly a problem as wind penetration grows above 15% of average electricity demand, as it has in Denmark. In the UK a new system of balancing charges [1] designed to insure that supply balances demand in deregulated markets threatens to penalize wind quite strongly. A recent detailed study [2] of one British wind turbine array showed that it would have actually lost money selling power under its original contract, but with the new charges factored in. In the US Pacific Northwest, the Bonneville Power Administration [3] has proposed similar regulations that are projected to add about $0.025/kWh to the cost of wind energy.

One way to resolve these issues to the advantage of wind and other intermittent renewable 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 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 [4].

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### Comparison of Storage Technologies

Pumped storage, batteries, superconducting magnet energy storage, flywheel energy storage, regenerative fuel cell storage, and compressed air energy storage (CAES) could be considered for bulk power storage; a comparison [5],[6] 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, or constantly available, 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 [7], 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 38,000 MJ $m^{-3}$; 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 fully 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.

The advantages and disadvantages of potential utility scale storage technologies are described below.

**Pumped Storage.** Pumped storage is widely used around the world. However, it is generally economical only in large installations (1000 MW), and the aboveground reservoir has a significant environmental impact due to its size and dynamic behavior. In

**Table 1 Storage Plant Installed Capital Cost* (from R. Schainker, EPRI, *1996 Power Gen. Conf.*, Orlando, FL, and Innogy (Regenerative Fuel Cell))**

| Storage Technology | Efficiency | 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 | NA | 390 | 1 | 50 | 440 | 0.0613 |
| 50 MW (Small) | | 530 | 2 | 50 | 630 | 0.0675 |
| Pumped Hydro | | | | | | |
| Conventional (1000 MW) | 0.75 | 1100 | 10 | 50 50 | 1600 | 0.119 |
| Underground (2000 MW) | | 1200 | 50 | | 3700 | 0.187 |
| Battery-Target (c) | | | | | | |
| Lead Acid | 0.75 | 120 | 170 | 50 | 8620 | 0.347 |
| Advanced | | 120 | 100 | 50 | 5120 | 0.233 |
| Superconducting Magnet 1000 MW (Target) | 0.9 | 120 | 300 | 50 | 15120 | 0.5484 |
| Flywheel (Target) 100 MW | 0.70 | 150 | 300 | 50 | 15150 | 0.565 |
| Regenerative Fuel Cell (15 MW) (d) | 0.65 | 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

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. And while the environmental impact of an underground pumped storage reservoir is minimal, the cost is high. Finally, the installed capital cost of aboveground pumped storage is much higher than for a CAES system; seasonal storage, which requires 200–300 hours of storage capacity, is not economical.

**Battery Storage.** Battery storage is also a possible candidate. 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 magnets for energy storage are still under development, 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 ($300/kWh$_{op}$) makes these economically impractical for utility scale systems. In addition, the environmental impact of large solenoids and their associated unconfined magnetic fields might be a problem.

**Flywheels.** Flywheels 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.

**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. System lifetime is estimated to be greater than 15 years; overall system efficiency is about 65%.

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 the 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, Germany since 1978. In the U.S.A., a more modern 110 MW plant with a storage capacity of about 2700 MWh has been in operation since 1991 at the Alabama Electric Cooperative in Macintosh AL [8],[9].

CAES is based on gas turbine (or jet engine) technology that has advanced enormously over the past decade; modern single cycle combustion turbines now have an efficiency of between 30 and 40%.

A turbine is, in principle, a simple machine consisting of a compressor, a combustor, and an expander; it extracts energy from a fuel in a simple thermodynamic Joule cycle [10]. Air is first compressed at constant entropy (isentropic compression) in the compressor, then heated at constant pressure (isobaric heating) in the combustor. Energy is extracted at constant entropy and heat rejected at constant pressure in the expander; the extracted energy is used both to drive a generator to produce electricity and to run the compressor. 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 used to charge the storage reservoir is completely independent of the generator and can be sized to match the wind resource and wind turbine array. In the U.S., geological surveys have indicated that suitable underground conditions for CAES systems are found over about 80% of the country, including those areas with good wind resources. Finally, the environmental impact of the underground storage volume is minimal.

There are several ways to improve upon the simple CAES system concept and decrease the energy ratio, the underground storage volume and the total installed capital cost [11]. These could reduce the cost of energy from the enhanced CAES system by 15–20%.

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. Seasonal storage using a CAES system with a 250-hour storage reservoir for an average annual wind class four resource has been analyzed [12]. This evaluation demonstrates that electrical seasonal energy storage is both technically and economically feasible.

## 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.** Geological surveys have been done in the U.S.A. that have identified regions where storage reservoirs based on solution mined salt caverns, porous rock or hardrock caverns could be located. 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 about $75 million ($500/kW).

While CAES plants are already operational in Germany and the U.S., 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 couples 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 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 U.S., 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% of the total annual energy input.

An illustration of this approach is given by the Luz solar thermal power plants [13] 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 globally.

## Summary

Intermittent renewable energy is widely perceived as not being competitive with conventional sources of power in utility scale systems. This false impression is due mainly to the lack of understanding that a reliable, cost-effective utility scale storage technology does actually exist. A small, well-focused program incorporating the above elements of site surveys, legislation and demonstration plants would be a key factor in overcoming this misperception and allowing renewable intermittent energy to supply a very large fraction of total electricity demand.

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