Underground Energy Storage for Electrical Power Generation

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ABSTRACT

Soaring demands for electrical power coupled with environmental restrictions, construction delays and an acute shortage of premium fuels has created a dilemma for the industry such as it have never known. The numerous smaller problems of the past have grown into giants compounding one another in a negative synergism.

Base-load power production faces serious problems such as construction delays and high capital cost but is the most secure portion of electrical power production. Peak and semi-peak power production are in the most serious difficulty because they depend largely on premium fuels which are critically short in supply and ever increasingly more expensive.

Energy storage of excess production from base-load plants during off-peak hours offers the most readily available source to provide for the ever increasing peak power demands. Pumped hydros during the last decade have done much to fulfill this role. Several dozen sites which are now operating or nearing completion will provide over 16,000 Mw of capacity for peak power production from stored base-load energy. The shortage of available sites, environmental restrictions and cost increases have for all practical purposes eliminated this alternative.

The most recent trend which is receiving world-wide attention but most particularly in Europe is to store off-peak base-load energy by means of compressing air and storing it at high pressure in underground reservoirs then using it as a source for power production by means of gas turbines. For this application enormous amounts of compressed air must be stored at low cost in relatively leak proof reservoirs. Salt cavity storage is currently receiving the greatest attention and several are under advanced stages of design or development in Europe. Mined rock cavities and porous rock storage also appear practical and are also under active investigation.

The technology developed for underground natural gas storage during the past two decades will be of great benefit in establishing this further innovation for storing energy in another form.

INTRODUCTION

Electrical energy production and distribution has always been forced to contend with great fluctuations in daily demand. Requirements for electricity during daily peaks frequently run two and a half times greater than nighttime base-load requirements. In past years this variation in demand was met by an "overkill" where excess production capacity and excessive use of fuels could be afforded and were expended. This nation, however, having tasted the sweet taste of low-cost electrical energy has hungered after ever decreasing costs, yet at the same time demanding greater daily load variation. These two requirements work against one another and have put a heavy strain on the electrical power industry. When added to this dilemma are fuel shortages, construction delays, environmental restrictions, regulatory impositions and capital shortages, clearly a crisis situation has arrived. Anyone who can help must help as we have all become addicted to low cost and readily available electricity.

The lowest cost, most efficient and least polluting electricity is produced from the giant nuclear or coal-fired base-load plants. These plants, particularly the nuclear, have a very high capital cost but very low fuel cost. This means low cost electricity can be produced only if the plant operates at a high capacity factor, thus spreading the high capital cost over a larger number of units of electricity. As the capital cost of the base-load plants increases so must the capacity factor if electricity costs are to be kept low.

In order to produce electricity at what we have been thinking of as a reasonable cost, a nuclear plant must operate at a plant capacity factor of above 80%. Introducing such plants into systems which have a load factor of often around 60% requires compensating adjustments. If the large plant is to operate at nearly a constant level, then complimentary power systems must provide for the peaks in the daily load curves or an energy-storage system is required.

During the last ten years the trend has been to use gas turbines to provide peak load to supplement the base-load plants or pumped hydros for energy storage wherever possible. A few dozen pumped-hydro sites have been built and provide a national generating capacity of around 16,000 Mw. By 1980 there is expected to be 24,000 Mw (Korsmeyer, 1972, p. 3). Gas turbine sales have increased sharply until currently they account for over 11% of the total capacity for the 100 top utilities (Owens, 1971, p. 54). As a general rule by present industrial standards, about 15 to 20% of a total system capacity should be peaking capacity, either from gas turbine or pumped hydro. The difficulty is that neither can continue to supply the need.

Acceptable sites for pumped-hydros storage are becoming exceedingly scarce or prohibitively expensive near the populated areas of the country where peaking power is most needed.

Conventional gas turbines on the other hand are rapidly becoming unacceptable since they require premium fuels which are becoming unavailable or extremely expensive. Conventional gas turbines, as used intermittantly for peak power generation have an exceedingly poor heat rate, consuming 16,000 Btu/kwh of which 12,587 Btu/kwh is lost as waste heat (Wright, 1970, p. 21). With the prioritizing of uses and probable rationing of the premium fuels, this use with a thermal efficiency of 22% will certainly come far after residential space heating with a thermal efficiency of 75% or greater.

AIR STORAGE POWER GENERATION

General description

The high heat rate of gas turbines results from the fact that they must yield about 2/3 of the gross power output to drive the compressors for the required air flow. If compressed air could be provided from another source and supplied to the turbine, the net power output per unit would be nearly tripled and the heat rate would be reduced to about 5,000 Btu/kwh. With suitable storage facilities, air could be compressed with excess nighttime power from a base-load coal or nuclear power plant, then supplied to the gas turbine at the daily peak-demand period. Two-thirds of the work for peaking would then be done with excess energy produced from the least expensive fuels consumed at the lowest heat rate in the most efficient plants.

Historical background

The idea of using underground storage of compressed air for peaking power dates back around 24 years. At that time the technology and economics for underground compressed gas storage were not well established. Commercially available gas turbines were also small and expensive in terms of capital costs per kw of capacity. Since then, gas turbines have become available in sizes 5 to 10 times larger and with correspondingly lower capital cost per kw of output. Efficiencies have also improved. During the same time period underground gas storage practices and technology have become widely established and economically justified. The author has been granted patents by the United States and numerous foreign governments applying constant pressure storage of gases to energy storage and power generation (Lang, 1970). These concepts are also described in other technical literature (Kalapasev, 1970).

European projects

In Europe there are currently specific underground air storage power generating plants under study and design in Sweden, Finland, Great Britain, W. Germany, France, Denmark, Poland, and Yugoslavia. Advanced equipment designs, operating parameters, cost and performance evaluation for these projects have been made by ASEA of Sweden (Ollson, 1969), Kraftwerke Union of West Germany (Kraftwerke Union, 1972), and Brown Boveri Sultzer of Switzerland (Bebié, 1973). The project sizes range from 200 to 360 Mw with estimated costs from $60 to $86 per kw of capacity. Projected heat rates are as low as 4770 but average around 5000 Btu/kwh. Total power generation costs generally are expected to be below all but the large base-load plants operating at high capacity factors. The components used in air storage power plants are essentially the same as are used in the standard gas turbines of these manufacturers.

The air storage reservoirs for the European projects include solution mined salt cavities, abandoned mines and aquifers. Some are to be constant pressure storages from aquifer water drives or hydraulic compensations of open cavities, and others are to be variable-pressure dry storages. The latter are less efficient in terms of utilization of cavity space, requiring considerably more space per kwh of peaking capacity and are also thermodynamically less efficient.

Domestic activities

In spite of the considerable activity related to air storage power plants in Europe, surprisingly little interest has developed in the United States. This is largely due to the fact that domestic power generation equipment manufacturers have traditionally been relied upon for the backbone of the industry technological developments. The domestic producers of gas turbine power peaking units currently produce models which are not readily adaptable to air storage systems.

Domestic gas turbine producers have been reluctant about making the necessary design modifications in their gas turbines, at least partly because of a desire in recent years to avoid becoming involved with turnkey projects, or projects requiring custom adaptation of equipment. This is especially true when "outside of house" technology such as "underground reservoir engineering" is required. This trend, also prevalent in the case of pumped hydros, has resulted in the fact that almost all of the generating equipment used is foreign manufactured. Certainly the manufacturer desires to sell his products with the least inconvenience and will as long as it remains a seller's market. The diminishing supply of the premium fuels and rising prices have brought the day in which 16,000 Btu/kwh gas turbines can no longer be sustained. Indeed this extravagance has contributed substantially to the present fuel crisis.

In the midst of the energy crisis lies an opportunity for those who own or are skilled in technology for the utilization of underground storage reservoirs. Underground cavities or porous rock reservoirs adapted to low cost energy storage by means of compressed air can go a long way to improve the situation in that they will:

1. Conserve fuel (especially premium fuels).
2. Reduce air pollution by displacing older inefficient fossil fuel plants.
3. Increase reliability and provide a quick means to add to reserve capacity at a low capital cost.
4. Increase the capacity factor of a nuclear plant thereby reducing the total electrical costs.
5. Greatly reduce the total cost of peak power production.
6. Provide large quantities of energy storage for emergency and startup power after power failures.

EVALUATION OF UNDERGROUND SPACE FOR AIR STORAGE

In order to lend assistance to the electrical power industry along these lines it becomes necessary to learn of their practices and problems. Then perhaps the means and benefits of using underground resources can be established. Last year Dr. McKelvey, Director of the U.S. Geological Survey, presented a paper before the Washington AIME entitled "Underground Space—An Unappraised Resource" (McKelvey, 1972). He called for new thinking and the re-evaluation of the role underground storage and its effect on our economy. Such resources can be appraised but with so many possible uses, the task becomes one of determining the highest and best use.

Herein presented are some economic considerations for evaluating the use of underground storage space for air

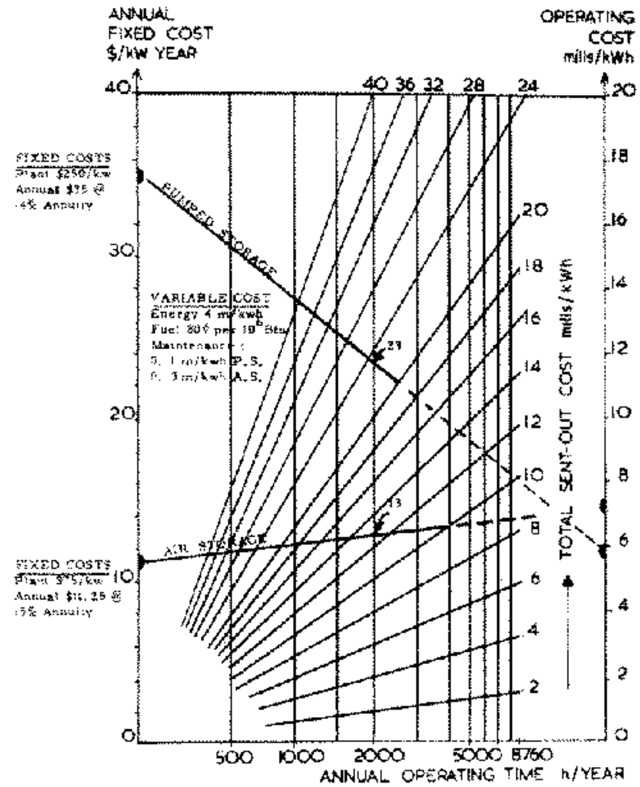

Figure 1. Do-it-yourself Nomogram for Total Send-out Cost.

storage plants. A number of assumptions are made which are not represented as being average but certainly can be demonstrated to be realistic for a substantial portion of the electrical industry.

Pumped storage projects in advanced stages of planning or early stages of development on the Eastern seaboard are currently costing between $250/kw and $300/kw. The need and value of an energy storage system differs from one power system to another but generally are greatest in conjunction with nuclear power plants. An example is described (Calvert and Heilman, 1971) evaluating the combining of a 750 Mw pumped hydro with a 2250 Mw nuclear power plant. In this case where the nuclear plant is expected to cost $300/kw it is concluded that a cost of $250/kw is justified for the energy storage system. Nuclear plants currently under development on the Eastern seaboard are expected to cost on the order of $500/kw by the time of completion. This increasing capital cost of nuclear power plants will inevitably increase the need and value of energy storage systems.

Air storage plants offer numerous advantages over pumped hydros, among which are greater flexibility, greater site availability, less environmental disturbance and even an overall lower total fuel consumption (Korsmeyer, 1972) (Djordjevic, 1971). Let us assume that air-energy storage plants are worth $250/kw of capacity if they can deliver 10 hours of energy on daily storage cycles.

Three major turbine manufacturers are estimating total air storage plant surface equipment costs in the order of \$60 per kw. We may then estimate that the developed underground air storage reservoir can be worth \$190 per kw. For example, a 200 Mw air storage plant would require an air flow of 370 M^2 scf at 40 atm. over a 10 hour period and by comparison would be worth \$38 million. This could be provided by a 10 M^2 cubic foot hydraulically-compensated solution-mined salt cavity at 1400 feet for a cost of \$10 million. A hydraulically—compensated solution-mined salt cavity of this capacity could be developed for as low as \$3.5 million whereas a high permeability aquifer storage is estimated to cost around \$2 million.

Another way to estimate the value of an air storage power system is to calculate the total send-out cost for electricity produced by air storage power and compare it to an alternate system. Using a "Do-it-yourself" nomogram of Stal Laval (Harboe, 1971, p. 10) and applying the assumptions given concerning relative fixed and variable costs, it can be seen that substantial total savings can result by use of air storage power plants. At 2000 hours of annual operating time a 10 mill/kwh saving would result over a pumped storage system. For a 200 Mw air storage power plant costing \$15 million the annual total savings would be \$4 million.

Since the overriding concern of the day is the shortage of premium fuels, let us consider air storage power plants in perspective to fuel consumption. Gas turbines are widely used for peak power production throughout the United States. Several of the larger utilities operate between 1000 and 2000 Mw of gas turbine generators for between 1000 and 2000 hours per year. About two-thirds of these are operated with natural gas and one-third with distillate fuel (Owens, 1971, p. 55). As mentioned earlier in the paper, air storage power plants use similar turbines but save 11,000 Btu of premium fuel per kwh. Let us consider the example from a fuel perspective. The electrical utility again operates 200 Mw of gas turbines for 2000 hours per year. At the energy production of 400 million kwh per year, about 4.4 trillion Btu savings in premium fuel would result. This is about 4.4 billion cu. ft. of natural gas which is worth \$2,800,000 plus pipeline demand charge of \$460,000 or a total of \$3,260,000 annual savings. If distillate fuel at 85¢ per 10^6 Btu were used the total annual premium fuel savings would be \$3,740,000. Since several of the larger utilities have gas turbine peaking capacity of between 1000 and up to 2000 Mw the example given can be multiplied 5 or 10 times within individual power systems. Substituted for this premium fuel has been excess nighttime nuclear fuel or coal with moderate losses from energy conversion. This trade of 65¢ to 85¢ per million Btu fuel for 17¢ nuclear fuel or 30¢ coal is economically attractive.

Another way to look at the highest and best use of the underground part of the system could be demonstrated in an aquifer with a 2 billion standard cubic foot capacity and pressure of 40 atm. If used for a 200 Mw air storage power plant, it would save 4.4 M^3 scf of natural gas annually if operated 2000 hours and allowing a 5 to 1 cushion-to-operating ratio for the reservoir. The same reservoir if operated for annual storage of natural gas at a 2 to 1 cushion-to-operating ratio could only hold 1 M^3 scf for more favorable marketing periods. The former example conserves premium fuel, the latter does not. In the case of a similar example using open cavity storage, 10 million cu. ft. of storage space at 40 atm. would be required for 400 M^2 scf of daily air storage capacity and would likewise save 4.4 billion cu. ft. of natural gas annually.

The savings in peaking fuel costs alone in the case of air storage are staggering and will increase as fuel becomes more scarce and expensive. Still the total savings exceed the fuel savings alone because the capital cost of the plants is projected to be substantially below any other method of power production. Further the introduction of the air storage plants into a larger system improves the thermal efficiency of the base load plants by allowing them to operate at a higher load factor.

CONCLUSIONS

The development of low cost and efficient energy storage should be a target of high national priority because nearly all projected future power systems whether fusion, MHD, solar, tidal, wind, etc. will require efficient energy storage systems to allow production of low cost and readily available energy. In addition, it should be an exceedingly high priority to divert as much power generation from premium fuels to coal and nuclear as soon as possible.

The blending together of the two completely different technologies of power engineering and reservoir engineering will certainly present a new challenge of technical cooperation. The anticipated savings in fuel and capital, however, appear great enough to reward all such efforts many times over.

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