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Economic Analysis of Wind Generation and Energy Storage for Electric Utility Systems

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ECONOMIC ANALYSIS OF WIND GENERATION AND ENERGY STORAGE FOR ELECTRIC UTILITY SYSTEMS

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Abstract

If wind generators are being evaluated as part of a larger electric utility generation system, the economic analysis should consider all of their effects upon the make-up and operation of the rest of the system. The introduction of wind generators changes the characteristics of the effective load seen by the rest of the system and consequently shifts the optimal mix of base, swinging, and peaking capacity and their operation. Storage systems used in conjunction with wind generators must also be evaluated. The storage can also be evaluated by determining its effect upon load characteristics. It is shown that the storage evaluation and wind generation evaluation can be separated in most cases.

1. INTRODUCTION

The evaluation of a wind generation system which is designed to be part of a larger generation system for an electric utility requires not only an assessment of the performance of the wind generation system but also an assessment of its interaction with other generation facilities and its impact upon their operation. When this approach is applied to wind generators which do not utilize storage but dump their output directly into the electric utility grid, unexpected impacts on capacity mix and fuel use are found. The total return for the wind generators is also found to be greater than with traditional evaluation methods.

Energy storage is often proposed to be used in conjunction with wind generators in order to provide the ability to schedule wind generator output in the same manner as other power plants. The consideration of a storage device adds to the complexity of the economic evaluation of the wind generation plant. However, it is shown that the evaluation of the energy storage can be separated from the evaluation for the wind generators in most cases. This allows traditional methods for evaluating energy storage not associated with wind generation to be used to evaluate storage for wind generation systems.

2. WIND GENERATOR EVALUATION WITHOUT STORAGE

When no energy storage is included as a part of a wind generation system, the output is dumped directly into the utility's grid. This output is random and does not necessarily follow the load. Because of the random nature, the economics of wind generators without storage are usually based on the incremental cost of the generation which would otherwise be used to fill that portion of the load. This approach tends to underestimate the return for such a wind generation system and may incorrectly assess its overall impact.

The cost to build and operate an electric generation system is significantly affected by the characteristics of the load it must serve. The character of the load can be summarized in a conventional load duration curve as shown in Figure 1. By directly dumping the output of the wind generators into the grid, the effective load which must be served by the rest of the generation system is reduced whenever the wind is blowing. The cost of serving this new load as compared to the cost of serving the load without the wind generators is then the basis of evaluating the economics of the wind generation system.

Hourly load and wind data for an Oklahoma utility were used to assess the impact of a wind generation system on the load. The wind generators were assumed to have a maximum output equal to 10% of the peak electric utility system demand, with this output being attained in winds of 20 mph and above. In winds below 7 mph, they were assumed to be inoperative. Between these points the output was proportional to the cube of the wind velocity.

Load duration curves were calculated from the hourly data both with and without the wind generators. The results are shown in Figure 2. The contribution of the wind generators is seen to uniformly lower the curve except in the region of the peak load where the reduction is fairly small.

In order to determine the effect of this change in the load on electric utility costs, the cost parameters of the conventional generation system must be known. The investment and fuel cost shown in Table I for nuclear, coal, and oil fired gas turbine capacity were used for the purpose of this example. Using these fixed and variable costs, a simple optimum capacity mix can be calculated. The total cost of electricity generated by a given capacity is determined by:

$$TC = VC + FC/U$$

where:

TC is the total cost per kwh

VC is the variable cost of operation,

FC is the yearly fixed cost, and

U is the number of hours per year for which the capacity is utilized.

The curves described by this equation are compared for each of the three capacity types in Figure 3. The loads of a given duration are then best filled with the type of capacity with the lowest total cost for that amount of utilization. In this example, loads lasting less than 3460 hours/year are best filled with the oil fired gas turbines; loads lasting between 3460 and 7490 hours/year are best filled with the coal capacity, and loads lasting more than 7490 hours/year are best filled with the nuclear capacity.

These results were then applied to the load duration curves with and without the wind generators to determine the optimum capacity mix. The cost to build and operate the generation facilities in each case was then calculated, The results are summarized in Tables 2 & 3. The wind generators were also evaluated in the traditional way using the incremental cost of the energy replaced. This information is shown in Table 4 for comparison.

The traditional approach is seen to significantly underestimate the return for the wind generators. In addition, the impact upon fuel use and capacity mix is considerably different. The wind generators are seen to cause a relative shift from base loaded capacity to peaking capacity. The result is little savings in variable operation cost but a fairly large savings in fixed costs. This result is the opposite of what is usually considered to be the case.

3. EVALUATION WITH STORAGE

As seen in the previous example, the cost of wind generators without storage must be relatively low in order for them to compete with conventional capacity. An energy storage unit is often proposed to allow the random generation to be used in a scheduled manner and thus improve the economics of the wind generation system.

Before attempting to evaluate such a system, its operation should be looked at. The addition of a storage unit will have no effect upon the operation of the wind generators. Even if the energy storage was full and the load on the utility low, it would still be economical to operate the wind generators as their incremental cost of operation is essentially zero and thus much lower than even base loaded capacity.

This is a very important factor in addressing energy storage economics for a wind system. If the storage does not affect wind generator operation, the only way it can improve the wind generation system economics is to allow the output of the wind generators to be used in a manner so as to further decrease the costs for the rest of the generation system. This can be done by storing the output during periods of low incremental generation cost and generating from storage during periods of high incremental cost. It can also be done by generating from storage during periods of peak demand so as to reduce overall capacity requirements. These two objectives generally coincide as incremental cost is high when the peak loads are being supplied.

Just as it would be economical to use wind generator output even when the storage is full, it is also economical to fill the storage unit during periods of low incremental generation cost even if the wind is not blowing, as this energy put into storage can be taken back out when incremental cost is higher. Thus, it is seen that the storage unit would be charged whenever incremented cost was low and it would be discharged whenever incremental cost was high whether or not the wind was blowing.* Similarly, the wind generators operate whenever the wind is blowing regardless of the amount of energy in storage.

Although there appears to be no interaction between the storage and the wind generators, this is not exactly the case. The contribution of the wind generators may change the nature of some of the load fluctuations and, thus, change the performance of the storage. What this lack of direct interaction between the storage and wind generators does do is allow the storage to

*For this to be true the wind generator and the storage device must be physically separated. A typical example of where this would be true is pumped hydro storage. The pumps are run by electric motors and not directly by the windmills. This requirement is met in most storage schemes be evaluated in exactly the same manner when wind generators are involved as when they are not. The only difference is that the load used for the evaluation is that which is left after the output of the wind generators is subtracted. Thus, a valid method for evaluating storage devices not associated with wind generators is also valid for storage which is associated with wind generators.

The selection of a storage system involves complex trade-offs between fill rate, output rate, total energy storage capacity, and possibly other parameters. It is outside the scope of this paper to investigate these trade-offs. However, a sample evaluation of a single storage system is made to demonstrate the methodology and to estimate the economic the economic gain from storage associated with wind generation.

T he storage system for this example is assumed to have a maximum output equal to 10% of the peak utility system load. It can store sufficient energy to generate at this rate for six hours. It also can be filled in six hours. The filling and generating rates are independent of the energy in storage. The overall efficiency is 70%.

The next step in the evaluation is to define operating criteria for the storage. This in itself is a complex problem and will not be addressed at length here. Even if optimum criteria were determined, they could not be used in actual utility operation as they would require perfect foreknowledge of what actual loads would be. Any realistic operating criteria used to evaluate storage must include the effect of imperfect foreknowledge of loads.

For this sample calculation, the following criteria are used:

(1) The storage is always filled between the hours of 12:00 midnight and 6:00 a. m. If the storage is not empty at the beginning of the fill period, the fill rate is reduced from the maximum such that the fill is completed during this period with a constant fill rate.

(2) Generation from storage does not take place unless the utility system load is greater than the minimum load of the previous night (including the load from filling the storage).

(3) It is assumed daily peaks can be predicted accurately enough that generation from storage can be used to minimize the daily peak.

Using this system and these criteria, the effect of the storage on the load duration curve was calculated using the same hourly data as before, both with and without the wind generators. The results are shown in Figure 4. These load duration curves were then used to evaluate the cost of operating the rest of the generation system just as in the evaluation of the wind generators. The results are summarized in Tables 2 & 3.

4. DISCUSSION AND CONCLUSIONS

The results presented in Tables 2 and 3 and in Figure 4 indicate both wind generators and storage devices can significantly affect load characteristics. The wind generators tend to lower the load duration curve but make it more "peaky" while the storage tends to flatten it out and significantly reduce the total capacity required.

Most of the savings with the wind generators comes from the reduction in the amount of nuclear capacity required. It has little effect on the coal and oil capacity. Significant savings are obtained from the reduction in both oil and coal capacity required with the storage. These are offset somewhat by an increase in nuclear capacity requirements.

When the storage and wind generation are combined, the total savings is somewhat less than the sum of the savings when each are considered independently. This should not be totally unexpected. The wind generators add a highly unpredictable random component to the load which makes it much more difficult to design a good operating criterion for the storage. The result is the storage is used less effectively. This does not mean that storage should not be used with wind generation, as there is a very significant increase in the savings when the storage is added. It does indicate that wind generators and storage combined are not likely to be economical unless each one is economical by itself in the first place.

Table 1. Cost Parameters Used for Sample Calculation

Item	Oil Fired Capacity - Peaking Turbine	Coal Fired Capacity - Steam Turbine	Nuclear Capacity
Investment Cost ($/KW Installed)	250	550	800
Yearly Fixed Cost ($/YR/KW)*	37	84	122
Fuel Cost (¢/10^6 BTU)	175	80	25
Heat Rate (BUT/KWH)	12,000	9,800	11,000
Variable Cost from Fuel (¢/KWH)	2.10	0.785	0.275
Other Variable Costs (¢/KWH)	0.15	0.10	0.10
Total Variable Cost (¢/ KWH)	2.25	0.885	0.375

*Assumes all fixed costs arise from initial investment, a 15% interest rate, and a 30-year life span.

Table 2. Capacity Requirements and Energy Generated With Wind Generation and Storage

	Without Wind Generation Without Storage	With Wind Generation Without Storage	Without Wind Generation With Storage	With Wind Generation With Storage
Oil Fired Capacity (MW)	1076.40	1097.10	879.75	900.45
Coal Fired Capacity (MW)	289.80	289.80	196.65	227.7
Nuclear Capacity (MW)	703.80	662.40	786.60	724.5
Energy Generated with Oil (MWH)	0.8325×10^6	0.8185×10^6	0.7886×10^6	0.7477×10^6
Energy Generated with Coal (MWH)	1.6610×10^6	1.6052×10^6	1.1390×10^6	1.2927×10^6
Energy Generated with Nuclear (MWH)	6.0917×10^6	5.7039×10^6	6.8017×10^6	6.2333×10^6

Table 3. System Savings With Wind Generation and Storage

	With Wind Generation Without Storage	With Storage Without Wind Generation	With Storage With Wind Generation
Oil Fired Capacity Fixed Cost ($)	-0.766×10^6	7.276×10^6	6.510×10^6
Coal Fired Capacity Fixed Cost ($)	0	7.825×10^6	5.216×10^6
Nuclear Capacity Fixed Cost ($)	5.051×10^6	-10.102×10^6	-2.525×10^6
Oil Fired Capacity Variable Costs ($)	0.315×10^6	0.988×10^6	1.909×10^6
Coal Fired Capacity Variable Cost ($)	0.494×10^6	4.620×10^6	3.257×10^6
Nuclear Capacity Variable Cost ($)	1.453×10^6	-2.663×10^6	-0.533×10^6
Total Savings ($)	6.547×10^6	7.944×10^6	13.834×10^6
Maximum Economic Cost of Wind Generation and/or Storage ($/KW)*	207.7	252.0	438.8

*Assumes all costs arise from initial investment, a 30 year lifespan, and a 15% interest rate.

Table 4. Wind Generation Evaluation By Incremental Cost and Load Duration Calculations.

	Without Wind Generation	With Wind Generation By Load Duration Calculations	With Wind Generation By Incremental Cost Calculations
Oil Fired Capacity (MW)	1076.40	1097.10	1976.40
Coal Fired Capacity (MW)	289.80	289.80	289.80
Nuclear Capacity (MW)	703.80	662.40	703.80
Energy Generated with Oil (MWH)	0.8325×10^6	0.8185×10^6	0.6891×10^6
Energy Generated with Coal (MWH)	1.6610×10^6	1.6052×10^6	1.4369×10^6
Energy Generated with Nuclear (MWH)	6.0917×10^6	5.7039×10^6	6.0016×10^6
Total Savings ($)	---	6.547×10^6	5.548×10^6
Maximum Economic Cost of Wind Generation ($/KW)*	---	207.7	176.0

*See footnote on Table 3.

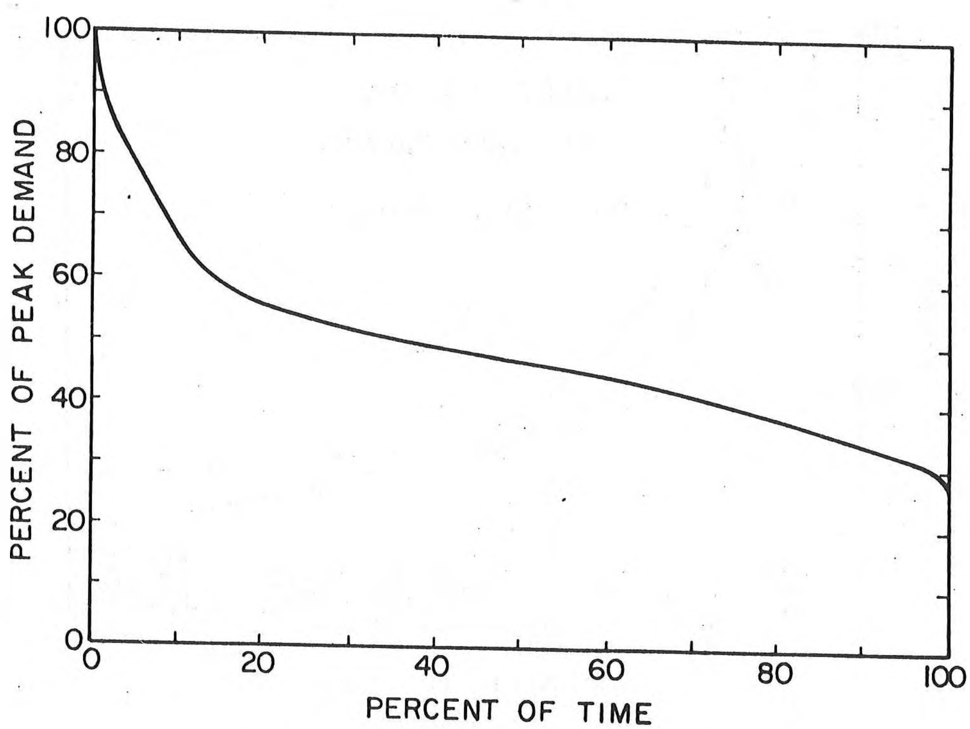

Figure 1. A Typical Load Duration Curve

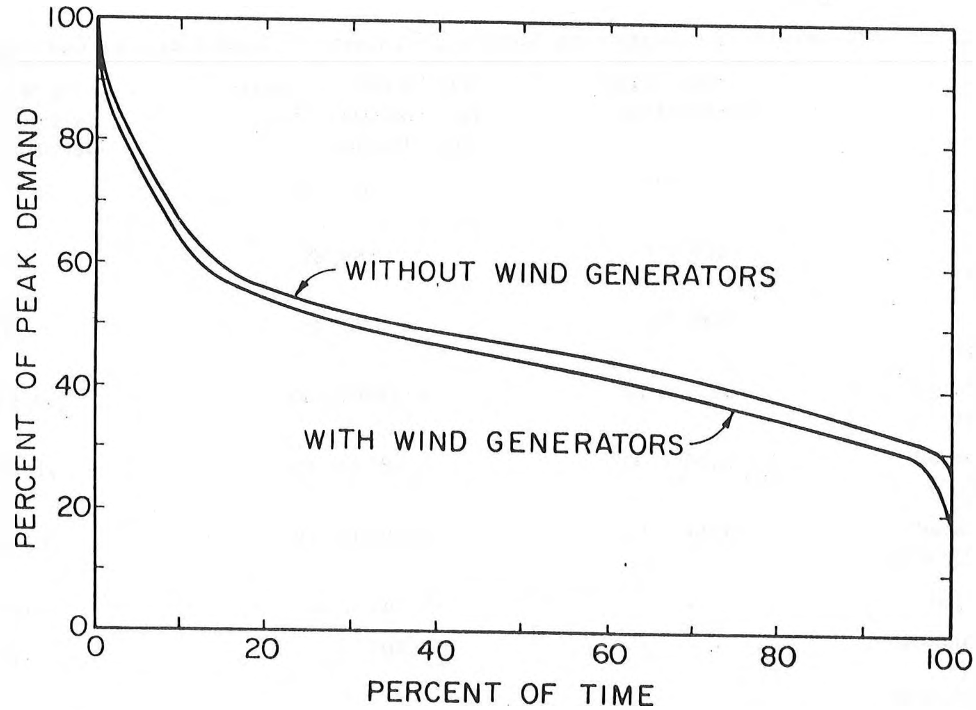

Figure 2. Effective Load Duration Curves With and Without Wind Generators Installed

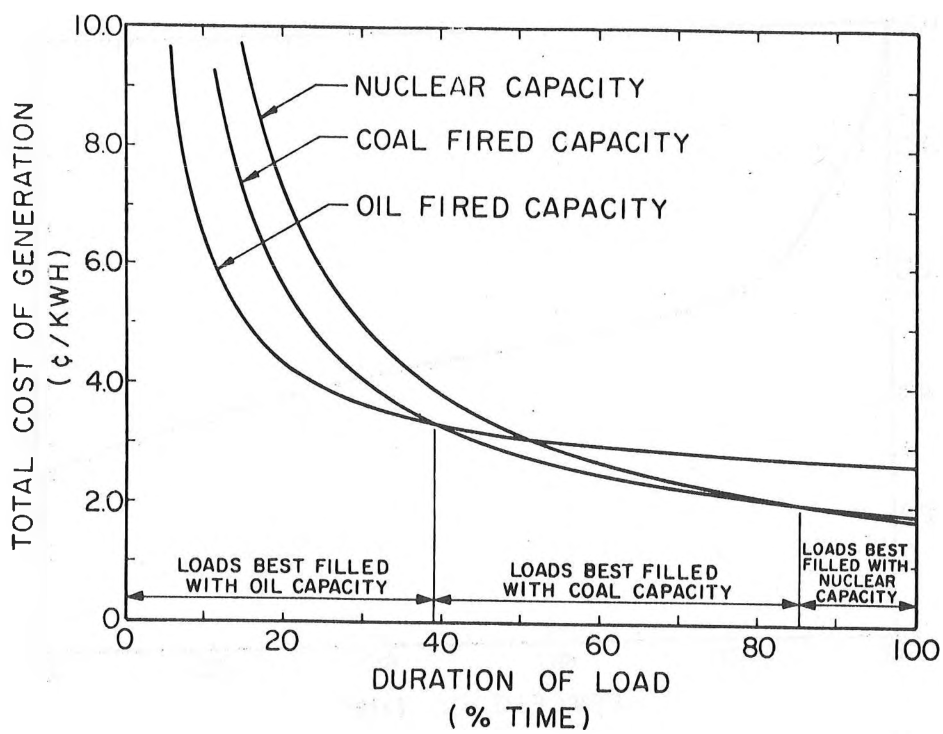

Figure 3. Determination of the Optimum Combination of Generation Capacity.

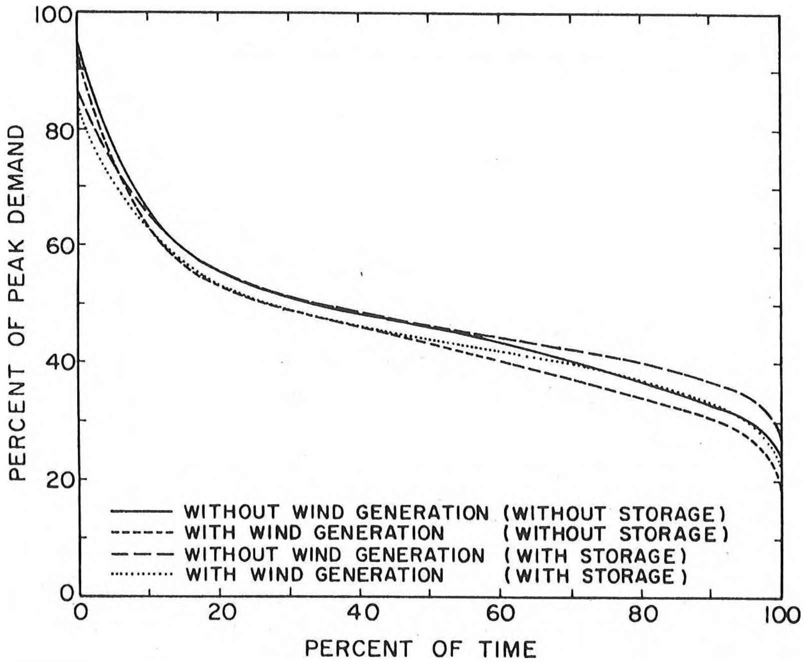

Figure 4. Effect of Wind Generation and Storage on Load Characteristics

5. BIOGRAPHIES

Byron W. Jones received his B.S. in Mechanical Engineering from Kansas State University and his M.S. and Ph.D. in Mechanical Engineering from Oklahoma State University. He has been an Instructor and Teaching Associate at the School of Mechanical and Aerospace Engineering, Oklahoma State University. He is currently on a National Science Foundation Energy Related Postdoctoral Fellowship and is doing energy systems modeling at the School of Mechanical Aerospace Engineering, Oklahoma State University and at the Montana Energy and MHD Research and Development Institute in Butte, Montana.

Peter M. Moretti received his education at the California Institute of Technology in Pasadena; on a Fulbright Scholarship to the Technische Hochschule Darmstadt in Germany; and at Stanford University. He has worked as a project engineer at INTERATOM in Germany, and as a senior engineer for the Westinghouse Advanced Reactor Division. He is currently a Professor of Mechanical Engineering at Oklahoma State University in Stillwater. His research includes computer modeling of the energy system and utility company operations; flow-induced vibrations in large heat-transfer equipment; and experimental modeling of thermally stratified lakes and ponds. He has spent several summers with the Experimental Investigations Branch at NASA/Ames Research Center.