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APPLYING TECHNOLOGY: USING COMPUTER SOFTWARE TO ANALYZE CLIMATOLOGICAL DATA FOR AN INTERDISCIPLINARY METEOROLOGICAL STUDY

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1. INTRODUCTION

The purpose of this study is to illustrate how the current generation of computers, software, and data availability can help expand the horizons of the modernized National Weather Service (NWS) to meet the needs of a changing world. As pollution concentrations rise to harmful levels over large metropolitan areas, and nuclear energy sources continue to meet resistance from the public, other non-polluting energy solutions are actively being sought (Schaeffer et al. 1994). Solar power has been noted as a pollution-free and renewable energy resource for decades, but thus far has not had wide spread use across the United States. The best locations for installing solar power energy systems lie within the "sunbelt" that encompasses the southern tier of states (Schaeffer et al. 1994). However, a question arises as to whether the northern areas of the United States, where long winters and cool summers are predominate, are out of the realm of possibility for solar power applications. By using the National Climatic Data Center's (NCDC) Solar and Meteorological Surface Observation Network (SAMSON) data available on CD-ROM, Quattro Pro software (Campbell 1993), and the Statistical COrrelation and REgression (SCORE) program (Wooldridge and Burrus 1995), an analysis of the climate of Binghamton, NY, and a numerical simulation of a hypothetical solar power energy system was conducted to assess the potential for solar energy applications in the Binghamton area. Although this study focuses specifically on Binghamton, NY, the approach employed is not site-specific and can be utilized for any location where solar applications are being considered.

2. BACKGROUND

South central New York state has a reputation for being cloudy and snowy for much of the year. Common sense would indicate that the use of solar power in this area would prove to be futile. However, when one considers solar energy in a more complete sense, the notion begins to gain credibility. Solar power applications that are most familiar to people involve solar radiation incident on a surface that is either converted to heat (direct gain) or induces a photovoltaic (PV) reaction. However, another less apparent application uses solar radiation that manifests itself as kinetic energy in the form of air currents moving around the globe. As such, the wind is a result of solar radiation and therefore makes wind power generation a legitimate form of solar energy (McVeigh 1983).

An energy generation system that makes use of several different power producing methods is called a hybrid system. Binghamton, NY, appears to be in a favorable location for a hybrid solar power system that uses both incident solar radiation and wind power. Located at latitude 42° north, Binghamton has a maximum possible day length of 917 minutes on the summer solstice. With only a moderate mean summer cloud cover, the percent of possible sunshine in Binghamton reaches its climatic maximum of 60 to 65% during the summer months. These two factors make Binghamton an appropriate candidate for direct gain and/or PV solar power applications during the summer. However, at the time of the winter solstice, Binghamton is limited to a maximum possible day length of only 545 minutes. Due to extensive cloud cover, the percent of possible sunshine is at its minimum of approximately 30%. These factors indicate that solar power applications relying on incident solar radiation will function poorly, if at all, during the winter months. Thus, incident solar radiation would be most useful for power generation during the summer season.

What makes Binghamton a favorable candidate for a hybrid solar power system is the wind climatology of the area. During the summer months when insolation is at a maximum, the average wind speed is at a minimum of roughly 3.5 m/s. However, during the winter months when insolation is at a minimum, the average wind speed is at a maximum of approximately 5 m/s. Thus, use of wind power generation would be most beneficial during the cold season and would be complimentary to devices using incident solar radiation.

With this type of climate in mind, a hypothetical hybrid solar power system was devised that would take advantage of Binghamton's seasonal weather changes, and thus function in a useful capacity year round. To this end, it was necessary to consider the implications of incident solar radiation in both its direct and diffuse components. When the sky is predominantly cloudy, most of the solar radiation travelling though the atmosphere becomes scattered and reaches the surface of the earth in a diffuse form. Direct gain systems, such as those found in hot water systems, depend on direct incident radiation to function. Since the winters at Binghamton are predominantly cloudy, direct gain apparatus would not function well year round. This fact eliminated direct gain components from the hybrid system.

On the other hand, PV cells function on total incident solar radiation, which is a sum of the direct and diffuse components. While direct incident radiation produces the best results, a PV device could still make a contribution to a system by utilizing diffuse incident radiation. This feature makes a PV cell more practical for use during the winter months, since it will still be productive under cloudy winter skies. Therefore, the hypothetical solar power system used in this study consisted of a PV device and one wind turbine.

2.1 Photovoltaic System

The PV device was determined to be a PV cell of crystalline construction with an effective surface area of 1 m^2. Crystalline construction allows the cell to convert 13% of the solar radiation incident on its effective area to electricity. This 13% efficiency is an average figure for PV cells of crystalline construction and is subject to other variables such as cell temperature (Schaeffer et al. 1994). To keep the model as simple as possible, such external variables were not included during the numerical simulation and the 13% efficiency figure was used in all PV cell calculations.

2.2 Wind Turbine System

Much effort went into defining the specific characteristics of the wind turbine to be used in this power generation model. Generating power from a moving airstream involves converting the kinetic energy (E_K) of moving air into electrical energy (E_E). The kinetic energy of the moving air per unit mass (m) is given by the basic equation: $\frac{1}{2}mV^2$, where V is the wind speed. The mass flow rate through a given cross-sectional area A, is given by ρAV, where ρ is the density of the air. Thus, the equation for the kinetic energy of a moving airstream is:

$$E_K=\frac{1}{2}\rho AV^3. \qquad (1)$$

The maximum amount of energy that can be extracted from a moving airstream is 59.259% of the total energy (McVeigh 1983). Since the remaining energy of the airstream is inaccessible, the 59.259% figure is taken to be 100% of the energy available to the wind turbine. A well designed rotor can have an aerodynamic conversion efficiency of 75% of the available energy (McVeigh 1983). The wind turbine used in this model is assumed to have an aerodynamic conversion efficiency of 75%. This figure should not be mistaken for an overall efficiency of the wind turbine, since it does not take into account losses of energy associated with other mechanical and electrical aspects of the system.

Since the rotor of a wind turbine of diameter D sweeps out a circular cross-sectional area, the right hand side of equation (1) becomes $(\pi\rho D^2V^3)/8$. The equation can be simplified as:

$$E_K=K_rD^2V^3, \qquad (2)$$

where K_r is a constant that includes the wind dynamics and the aerodynamic efficiency of a rotor power system. Using the conversion efficiencies mentioned above, the value of K_r can be calculated to be 2.096 x 10^{-4} kg/m^3mb, assuming an air density of 1.201 kg/m^3 and a pressure of 1000 mb.

Converting equation (2) into a form that yields electrical output gives:

$$E_E=K_rD^2V^3K_sH, \qquad (3)$$

where H is time in hours and K_s is a semi-empirical factor associated with the statistical nature of wind energy recovery. McVeigh (1983) gives a value for K_s of 2.06. This value of K_s was used for all wind power calculations in this study. Using a time step of 1 hour, and giving the hypothetical wind turbine a rotor diameter of 2.5 m (a representative diameter for a small wind turbine), substitution of all known quantities into equation (3) yields:

$$E_E=2.699\times10^{-3}V^3. \qquad (4)$$

This equation calculates the maximum wind power (in kWh) that is available to a wind turbine for an airstream moving with a velocity, V (m/s).

The siting of the hypothetical wind turbine is an important factor in determining how much power is actually available to the system. For simplicity, the hypothetical wind turbine was assumed to be located at the same location and height as the anemometer at the Binghamton Regional Airport. The anemometer is located at the center of the runway complex at a height of 22 ft AGL. It should be noted that this is not an ideal height for siting a wind turbine, since the wind environment becomes more favorable (e.g., higher speeds due to reduced friction) at higher altitudes. Commercially available systems usually recommend tower heights of 50 to 100 ft AGL. However, since the climate data were collected at 22 ft AGL, an attempt to position the hypothetical wind turbine higher would have necessitated a high degree of extrapolation and interpolation, greatly increasing the inaccuracy of the computations.

After siting the turbine, it was necessary to determine an overall efficiency for the wind turbine system in converting available wind power into electrical energy. To do this, the power curves of 5 wind turbines, which were considered to be a representative sample of current commercially available systems, were compared to amounts of maximum available wind power computed from equation (4) for wind speeds between 3 and 17.9 m/s. These wind speeds were chosen to represent common turbine start-up and maximum generation speeds, respectively. For wind speeds above 17.9 m/s, a turbine rotor will maintain a constant rate of rotation. This feature, common on most wind turbines, allows constant power production at higher wind speeds without damaging the generator or power storage system. The overall efficiency of the 5 wind turbines were calculated by taking the observed power generation and dividing it by the computed maximum available wind power (Fig. 1). The efficiencies of all 5 turbines were then averaged together to produce an average overall wind turbine efficiency (curve denoted by dark boxes on Figure 1).

Perhaps the largest single source of error in this model involved compiling the overall wind turbine efficiencies for the 5 commercially available units. The only power data available for these units consisted of power generation vs. wind speed graphs, or power curves. The data used in calculating the overall wind turbine efficiencies were extracted manually from various points along the power curves. Although care was used during the manual interpolation, some of the graphs were difficult to read. This likely accounts for the high degree of scatter illustrated in Figure 1. However, the data points do converge along the average turbine efficiency curve, which provides a fair degree of confidence that using these data will produce satisfactory results.

After inspecting the curves, it was apparent that the overall wind turbine efficiency/wind speed relationship was not linear. Therefore, an equation had to be derived from the average overall wind turbine efficiency curve that would be valid at any wind speed. Turbines are much more efficient at lower wind speeds but produce more power at higher wind speeds due to the cubic increase of available wind power with increasing wind speed (Eq. 4). The following equation was generated by inputing the overall average wind turbine efficiency curve data into the SCORE program (Wooldridge and Burrus, 1995):

$$E_{ff}=.051+2.219X^2-.4283X^3 +.0277X^4-.000604x^5. \quad (5)$$

Please note, although we expected the relationship to be adequately represented by a cubic polynomial, this equation appeared to be reasonable and fit the data well. Equation 5 was used to calculate an average overall wind turbine efficiency for any wind speed (Fig. 2).

For the hypothetical wind turbine used in this study at Binghamton, hourly wind speeds for the period 1961-1990 were used to compute the maximum available wind power in the airstream Equation 4. A corresponding average overall wind turbine efficiency was calculated from Equation 5. The maximum available wind power and average overall wind turbine efficiency were then multiplied together to obtain a hypothetical wind turbine power generation.

3. RESULTS

The hypothetical hybrid solar power system was used to conduct a numerical simulation of energy generation based on past meteorological conditions. Hourly data for the 30-year period from 1961-1990 were taken from the NCDC SAMSON CD-ROM and imported into the Quattro Pro spreadsheet software package for analysis. The NCDC data consisted of wind speeds (m/s) and total solar radiation (Wm^{-2}). Note, in the absence of higher resolution data, the calculations performed during the simulation assume that the wind speed on the CD-ROM is valid as an average wind speed for the entire hour preceding the time of the observation.

The monthly and yearly power generation normals that were calculated based on the numerical simulation are presented in Table 1. The results are very similar to the seasonal solar and wind climate profiles that are common in Binghamton. Wind power production peaks in the winter months, but reaches a minimum during the summer, which corresponds to the periods of highest and lowest average wind speed, respectively. PV cell power production peaks in the summer months but reaches a minimum during the winter. This corresponds to the seasonal variation in insolation at Binghamton, as well as to the months of greatest and lowest percent sunshine, respectively. Note that the monthly power generation totals for February are artificially lower due to the short length of the month.

Initial inspection of the data may lead to the conclusion that the wind turbine is vastly superior to PV cells for power generation. However, it is important to consider the fact that the PV cell data is based on an effective area of only 1 m^2. This area was chosen to approximate the effective area of a single PV cell. However, the electrical output from a single PV cell is not enough to meet the power needs of even a small household, let alone any type of commercial business. To overcome this problem, many hybrid system designs utilize an array of several PV cells to generate power. When the numerical simulation was modified to represent a hybrid system containing 5 PV cells, the results illustrated in Table 2 were obtained. The modified hybrid system is better suited for the summer climate in Binghamton, with the PV cells actually generating more power than the wind turbine from May through September.

By examining the modified monthly power totals for 5 PV cells and a wind turbine, it is clear that these are not trivial amounts of generated power. These totals show that a substantial portion of the energy budget, for a highly efficient household or business, can be met with a hybrid solar power system of this type. Most importantly, the monthly power generation totals indicate that this portion of the energy budget can be met consistently year round.

4. DISCUSSION AND SUMMARY

This study was not intended to arrive at a definitive answer to the question of whether Binghamton, NY, is a suitable location for solar power applications, nor was it designed to undertake a cost analysis of the economic factors surrounding solar power systems. Rather, this study was designed to demonstrate how incorporating climatic data into a hypothetical solar power system could act as a baseline for individuals, corporations, and utilities, which might be contemplating alternative (i.e. solar) energy sources. By monitoring current energy consumption, it would be possible to use the results of this study to design a solar energy system that could supplement or replace current methods of acquiring electrical power. For an energy efficient household that utilizes a little power, the monthly normals of power generation summarized in Table 2, may prove to be sufficient. For other more energy intensive applications, the monthly normals may be well below operative requirements.

As demonstrated in this study, by increasing the number of PV cells in the model, system design and configuration play an important role in generating specific amounts of power. If the power generation normals arrived at in this study are inadequate due to current power consumption, adding more PV cells, or perhaps another wind turbine may increase the normals to an acceptable level. The deciding factors for or against solar power differ significantly from case to case. By utilizing the results of a study such as this, individuals can make an educated decision regarding alternative energy sources.

This study was made possible by the computing technology and data now available to modernized NWS offices. This capability gives NWS employees the ability to expand their projects to include subjects that not only involve operational meteorology, but related disciplines as well. This is important because there are many disciplines that are related to meteorology which could benefit from the expertise of NWS employees. Such interdisciplinary activities will likely become a major part of the modernized NWS.

The availability of 30 years worth of hourly climatic data on CD-ROM was an invaluable dataset to work with. Some of the parameters on the CD (such as the solar radiation data used in this study) are derived fields that were calculated by NCDC using computer models and other meteorological data. By having these derived parameters already calculated and integrated into the standard hourly dataset, this study was facilitated considerably.

Both of the software packages used in this study, Quattro Pro (Campbell 1993) and the SCORE statistical analysis program (Wooldridge and Burrus 1995), provided examples of how personal computers can support NWS field research. Quattro Pro proved to be a powerful tool for manipulating data and has excellent graphics capabilities. SCORE is a useful tool for performing statistical calculations including linear and non-linear regression analyses. Access to data processing capabilities such as these will greatly facilitate operational field research.

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Table 1. Monthly normal power generation in kWh from one PV cell and a wind turbine. Totals may vary slightly due to rounding.

	1 PV Cell	1 Wind Turbine	Total
January	7.0	141.4	148.4
February	9.2	127.7	136.9
March	14.2	151.1	165.3
April	17.5	141.5	159.1
May	21.4	98.9	120.3
June	22.6	54.1	96.2
July	23.3	54.1	77.3
August	20.2	52.1	72.4
September	15.3	63.0	78.3
October	11.0	89.3	100.3
November	6.6	122.5	129.1
December	5.6	134.1	139.7
Annual	173.9	1249.3	1423.3

Table 2. Modified monthly normal power generation in kWh from 5 PV cells and a wind turbine. Totals may vary slightly due to rounding.

	5 PV Cells	1 Wind Turbine	Total
January	35.0	141.4	176.4
February	46.0	127.7	173.7
March	71.0	151.1	222.1
April	87.5	141.5	229.0
May	107.0	98.9	205.9
June	113.0	54.1	186.6
July	116.5	54.1	170.6
August	101.0	52.1	153.1
September	76.5	63.0	139.5
October	55.0	89.3	144.3
November	33.0	122.5	155.5
December	28.0	134.1	162.1
Annual	869.5	1249.3	2118.8

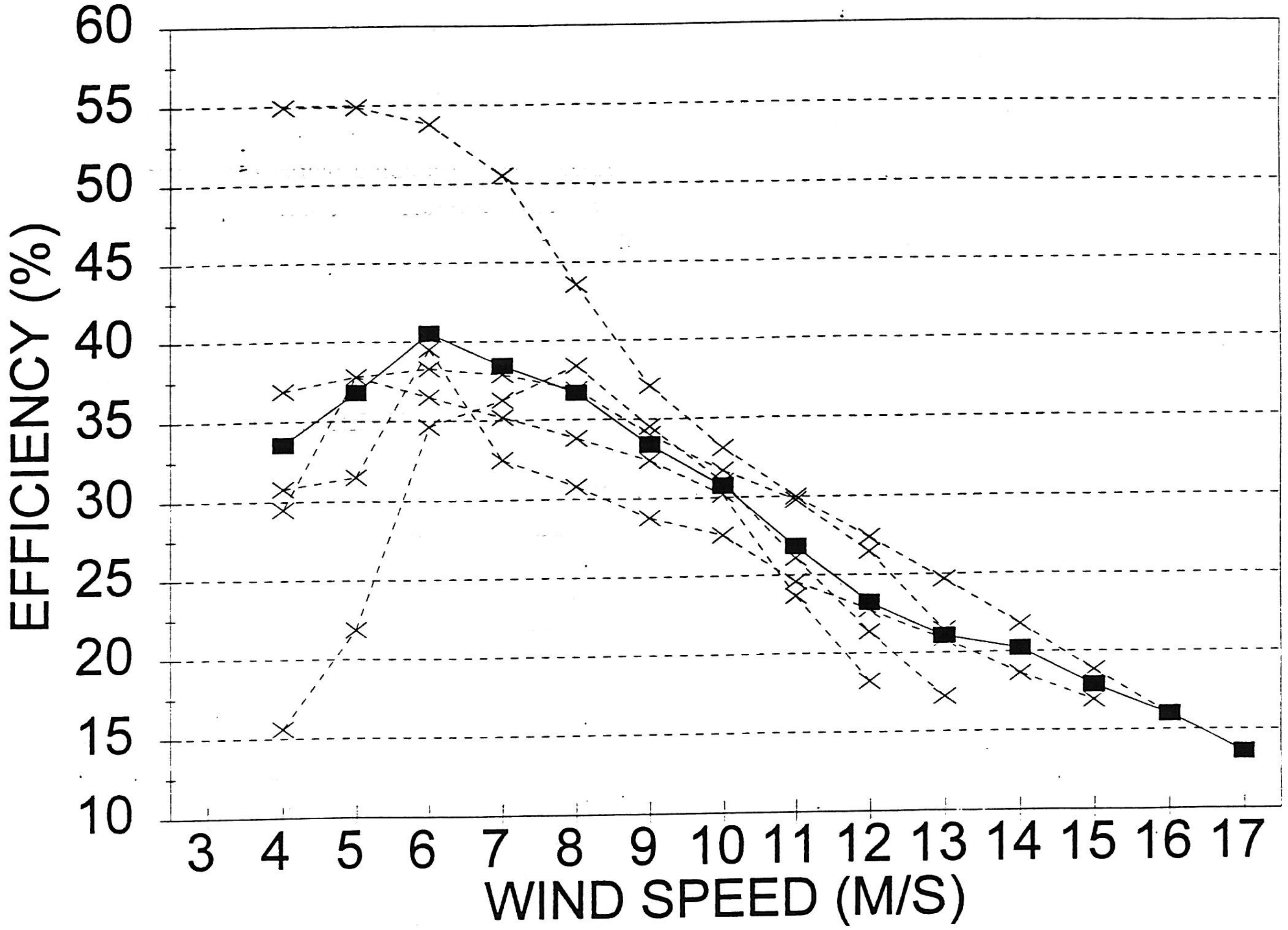

Figure 1. Overall efficiencies of 5 commercially available wind turbines in converting available wind power into electrical energy. The curve denoted by the dark boxes represents the average overall wind turbine efficiency.

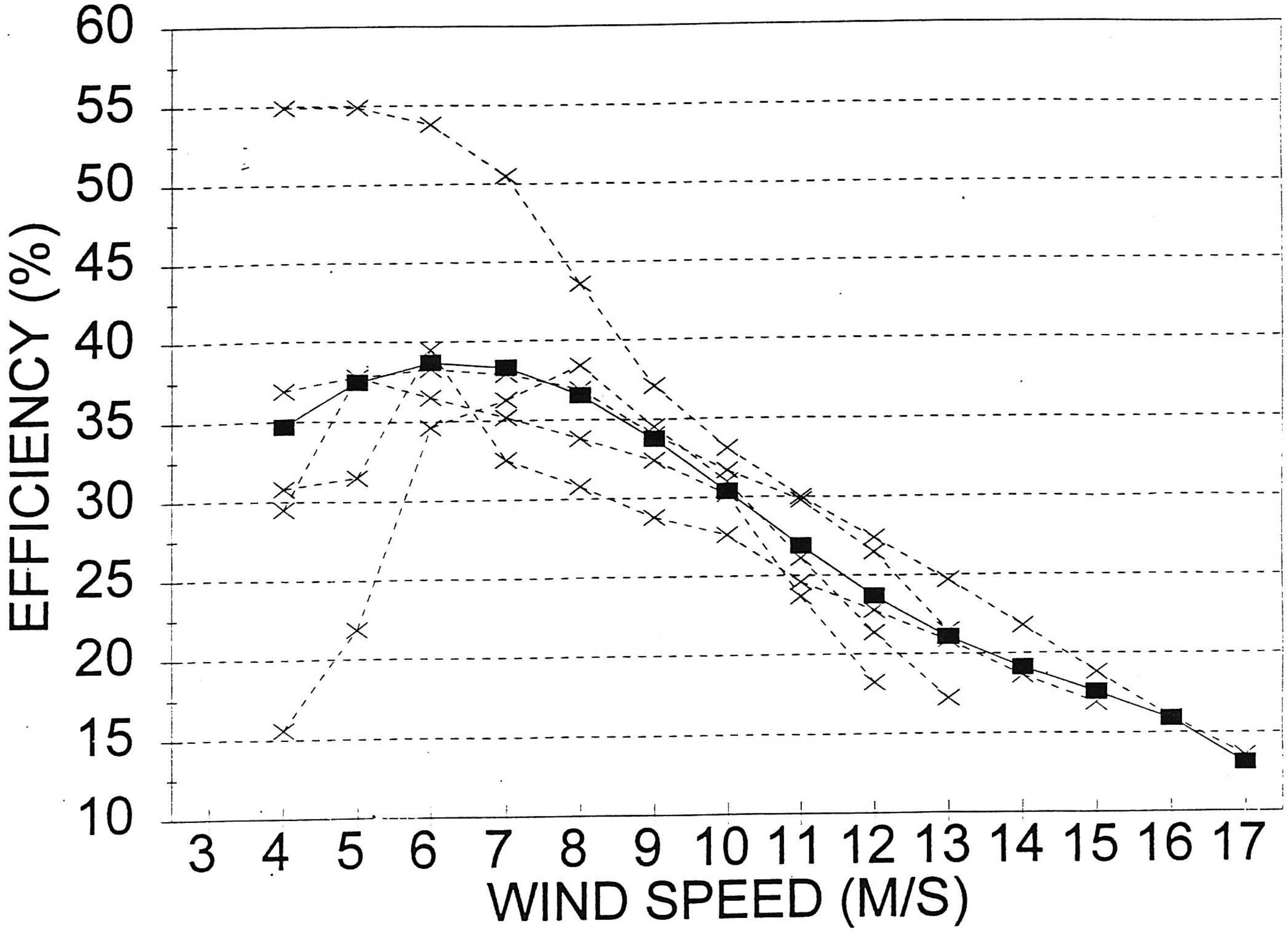

Figure 2. As in Figure 1, except with an overlay of the SCORE generated average overall wind turbine efficiency curve.