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# Evaluation of the Potential for Photovoltaic Power Generation in Illinois

by

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A Division of the Illinois Department of Natural Resources

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# Abstract

Solar power production was estimated from hourly solar insolation data collected at 19 sites across Illinois from 1991-2004 by the Illinois State Water Survey (ISWS). Values were compared with more limited, experimental data and a solar radiation model reported in the literature. All prior data sources are in good agreement with the ISWS values with discrepancies noted. Based on analyses of the current Illinois data, an estimate was made of potential power production from small to medium-sized photovoltaic modules and systems in Illinois. ISWS insolation data were converted from observed values using flat-plate pyramometers oriented horizontally, to expected values from south-facing sensors tilted from horizontal by the latitude of each station, a typical orientation of photovoltaic systems. Champaign, Illinois, centrally located in the state, was chosen as a hypothetical solar power array site. A large operational array in Arizona was used as a model of photovoltaic system performance. Expected differences in power production due to technologies chosen for the hypothetical array and climatological conditions in Illinois as compared to the model array were considered. The use of concentrated solar collectors was not explored.

The expected power output based on two array designs was calculated to be 134-180 kilowatt hours per square meter of array per year. Considering the unsubsidized cost of a photovoltaic array necessary to provide power for an individual dwelling, the system cannot expect to match grid power on a cost basis at this time. However, the comparison becomes more favorable in relatively remote locations where transmission lines for grid connection must be established. That is, photovoltaics may be cost effective for small remote applications such as powering billboards, but generally not for homes or businesses. Cost effectiveness of photovoltaics increases significantly when major subsidies and economy-of-scale discounts in both module and balance-of-system costs are available to reduce the initial system price and with designs of large-scale array systems. Photovoltaics also may be worth considering to offset the most expensive power produced by utilities, peak power, and for distributed power generation providing grid support.

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## Introduction

Sharp increases in the cost of fossil fuels, falling prices on sources of renewable energy, and potential security threats to the national power grid all provide impetus to a renewed interest in renewable energy potential across the Unites States. Wind power, for example, has been expanding very rapidly and already is cost effective in some markets. Wind power has extended times of low productivity, however, especially during the hot summer months when typical wind velocities are low and electric power demand is high. In addition, wind power does not match the daily demand cycle well because wind speeds at typical turbine heights maximize at night and demand is highest during the day. Photovoltaics, devices commonly referred to as solar cells, match well with daily and annual power demand cycles and require relatively little land area to meet consumer power demands

This study presents analyses of long-term solar insolation (solar power density) data in Illinois and also provides an estimate of the practical application of photovoltaics for power generation in the state. While not currently economically viable when compared with existing commercial power sources, where subsidized, there are situations in which photovoltaics currently are competitive and worthy of consideration. Indeed, the combination of high energy costs and aggressive subsidies are driving the market for photovoltaics in Germany and Japan, an activity consuming much of the world's current production capacity.

## Acknowledgments

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## Solar Insolation in Illinois

The Illinois State Water Survey (ISWS) has maintained observations on global solar radiation from the automated 19-site Illinois Climate Network (ICN) since approximately 1991 (Figure 1). Data were collected using Eppley model 8-48 black and white pyranometers mounted on 2.7 meter (m) arms, extending south from each monitoring tower at a height of approximately 2 m above the ground (Hollinger et al. 1994). The pyranometers were factory calibrated from 295 to 2,800 nanometers to a National Institute for Standards and Technology traceable blackbody. Pyranometer output is 9 to 10 microvolts per watt per meter squared with a temperature dependence of ±1.5 percent over a temperature range of -20 to 40°C, with a linear response within ±1 percent over its rated intensity range and a response time of 4 seconds. Cosine response exceeds ±5 percent from normalization at zenith angles of 70 to 80 degrees and exceeds ±2 percent for zenith angles of 0 to 70 degrees. Assuming the sun is between zenith angles of 0 to 70 degrees 67 percent of the day, the accuracy would be within ±5.5 percent. All results fall outside the expected worst-case errors of the pyranometers and, therefore, should not be due to pyranometer measurement errors.

Pyranometer output is "global" solar radiation data, collected from all parts of the sky simultaneously. This is similar to collection of energy by a flat-plate solar array oriented horizontally. These data are not directly relevant to a concentrating solar collector, which uses reflectors to concentrate solar

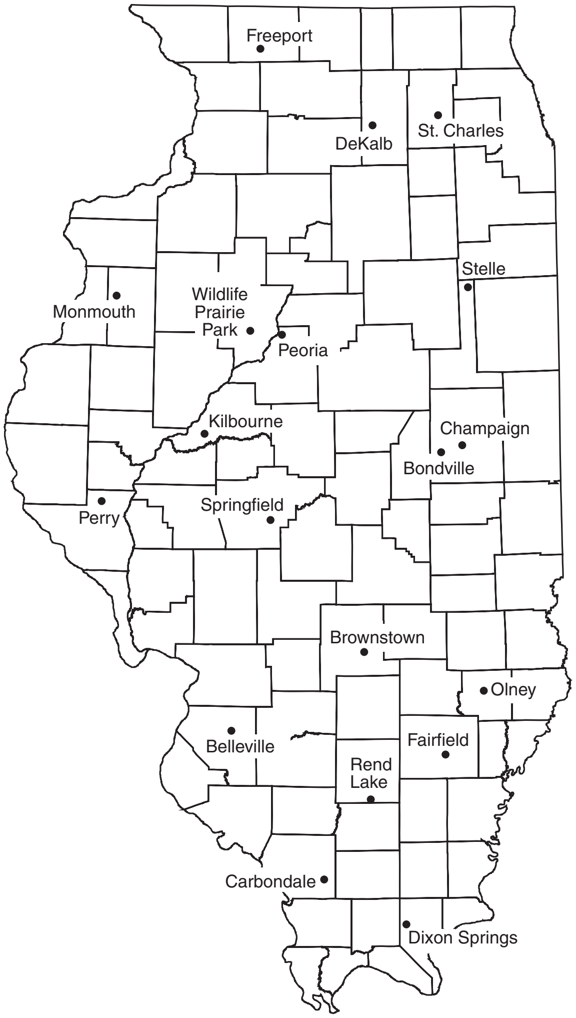


Figure 1. The Illinois Climate Network monitoring sites.

radiation on an absorber and, thus, relies on unobstructed exposure to the sun (including obstruction by clouds). Global data include diffuse radiation measured during cloudy weather. This study did not consider concentrating solar collectors.

Monthly averaged ISWS solar insolation data were computed for all years in the study period (1991-2004). Data were converted to equivalent numbers for a flat-plate collector oriented south and tilted relative to the horizontal by the latitude at the observation site. This corrected value would be most representative of solar flux on a well-designed photovoltaic system. Conversion was based on data published by Marion and Wilcox (1994), which provided experimental numbers for both tilted flat-plate and global solar insolation values at five locations in Illinois: Springfield, Rockford, Peoria, Chicago, and Moline. The ratios of the horizontal to tilted array insolation values at all locations and for all years were averaged by month. The specific conversion factors used are given in Table 1.

Thus, ISWS data given in Table 2 are monthly averages of solar insolation in kilowatt hours per square meter per day (kWh $m^{-2}$ $day^{-1}$) converted to estimated values for a flat-plate collector tilted 40

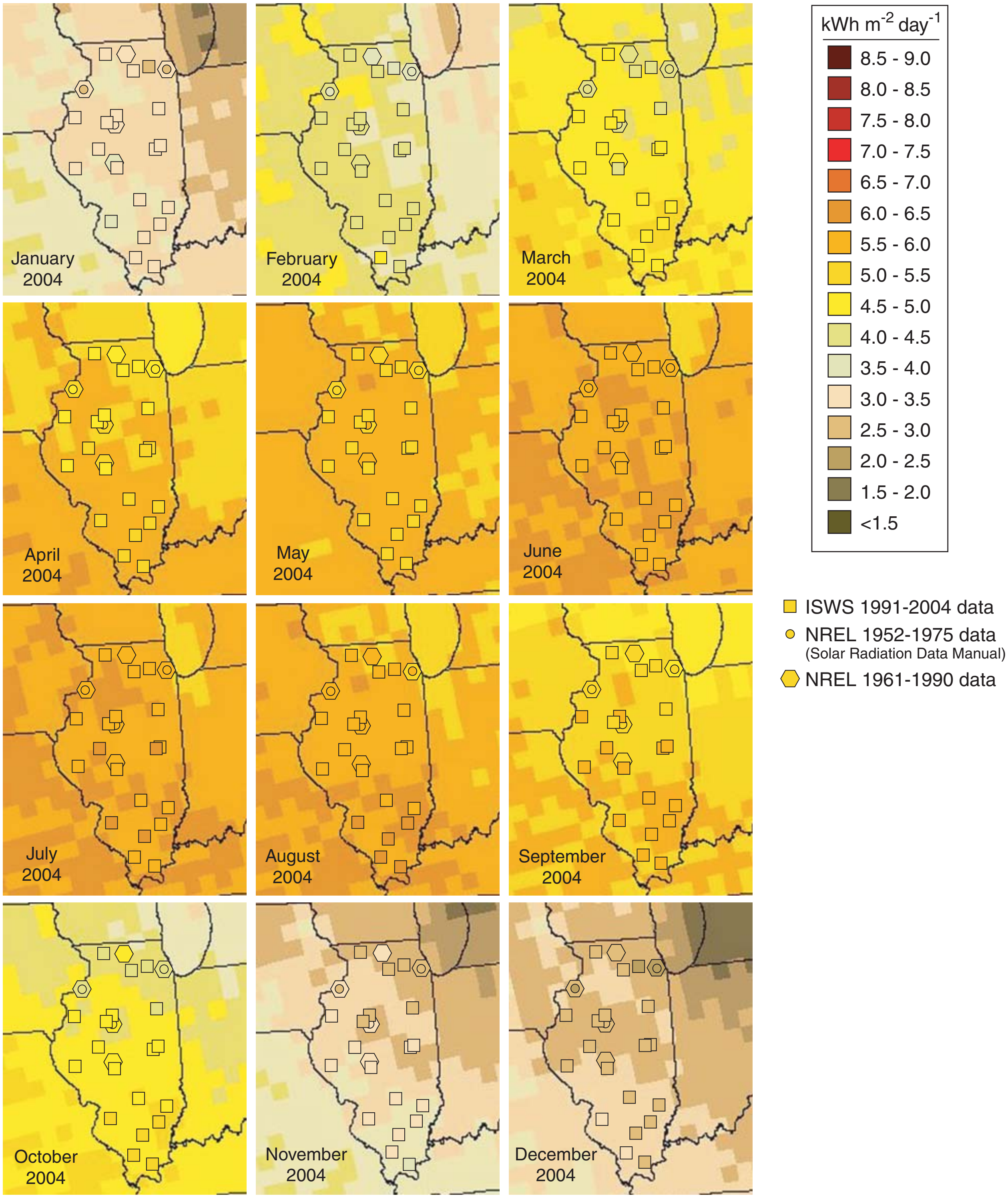
**Table 1. Tilt Correction Factors**

| *Month* | *Tilt Correction* |
|---|---|
| January | 1.711 |
| February | 1.475 |
| March | 1.219 |
| April | 1.054 |
| May | 0.948 |
| June | 0.900 |
| July | 0.923 |
| August | 1.023 |
| September | 1.179 |
| October | 1.406 |
| November | 1.558 |
| December | 1.706 |

**Note**: Tilt correction factors were computed at five locations in Illinois with and without tilt and averaging resulting ratios.

degrees to the horizontal (the approximate latitude of central Illinois) using the multipliers in Table 1. These resulting values were compared with three other solar insolation datasets for central Illinois. The first dataset from the *Insolation Data Manual and Direct Normal Solar Radiation Data Manual* (Riordan and Hulstrom 1990) by the Solar Energy Research Institute (now National Renewable Energy Laboratory [NREL]) was based on 1952-1975 data from three Illinois monitoring stations at Chicago, Springfield, and Moline. Global solar radiation values were converted to kWh $m^{-2}$ $day^{-1}$. Ratios listed in Table 1 were used to convert to equivalent values for a latitude-tilted flat-plate collector. The second dataset, published in *The Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors* (Marion and Wilcox 1994), can be downloaded from the Web (rredc.nrel.gov/solar/old_data/nsrdb/redbook/mon2/state.html). Data (in kWh $m^{-2}$ $day^{-1}$) cover 1961-1990 at the five Illinois locations, and were derived from a variety of solar collector geometries rather than global solar radiation values. Specific data selected for comparison were those for a flat-plate collector facing south with a fixed tilt equal to the latitude of the collector. The third dataset was the result of a calculation based on the Climatological Solar Radiation (CSR) model (George and Maxwell 1999), which uses cloud cover, water vapor, trace gas, and aerosol information to obtain estimates of global radiation. Model data are in kWh $m^{-2}$ $day^{-1}$ for a south-facing flat-plate collector at a tilt equivalent to the site's latitude.

A comparison of the four datasets for each month is shown in Figure 2. There is general agreement among all data, although the ISWS data are the most detailed. Less statewide variability exists in the ISWS data than in CSR model data. Comparison of all experimental datasets shows that the model appears to overestimate insolation in April and May. Moderate discrepancies may be due to noise or to the corrections applied to make all values comparable. The impact of cloud cover variability during the period of observations of these datasets was not considered.



Background plots with tilted pixels are NREL projected solar insolations (Climatological Solar Radiation Model). [www.nrel.gov/gis/solar.html] (Geographic Information System PV Solar Radiation Maps)

Figure 2. Comparison between the NREL solar radiation model and three Illinois insolation datasets.

## Photovoltaic Power Generation in Illinois

Given the above results, estimates of power generation by a hypothetical photovoltaic array in Illinois were derived. Due to its central Illinois location, Champaign was chosen as a representative array site, and solar insolation data from that site were used to evaluate the potential performance of such an array. The expected solar insolation values for Champaign, given in Table 2, were used for this estimation. Values by day of year at 1200 hours averaged over the period of record are given in Figure 3. (**Note:** The ISWS data observations at a specific time represent an average of values collected within the preceding hour from 10-second polling of solar radiation sensors. In addition, time at ICN sites is recorded in Central Standard Time throughout the year.)

Several observations can be noted from these data. First, when converting from a horizontal collecting surface (global radiation value) to a tilted surface, power is lost in summer and gained in winter, resulting in more constant insolation values throughout the year than for the flat collector. In this analysis, the months of the vernal and autumnal equinoxes display highest values because the collector is most perpendicular to the sun's rays. Nonetheless, November-January data are significantly lower than during the rest of the year because the tilt effect cannot overcome lower sun angles and reduced daylight hours during these months. November is also one of the cloudiest months in Illinois, which may account for the sudden decrease in insolation about Day 300. Second, there is considerable noise in the data. Noon solar insolation values exhibit a standard deviation of ~0.3 kW $m^{-2}$ year round even upon averaging over 14 years of data. Thus, substantial periods of low power output may be anticipated. A nongrid-connected system would require a substantial energy storage system, such as batteries, or an alternate power source, such as a generator, and perhaps a scheduled reduction of power usage on darker days.

Performance of a photovoltaic array depends greatly on the type of module purchased, type of power inverter used, methods for tracking the maximum power operating point of the array at different solar insolation values, and the actual reliability of the array. To obtain a reliable estimate for a model system, data were obtained from an existing, large-scale operational array. Such a system is the Springerville, Arizona array, operated by Tucson Electric Power Company (2002), which includes 4.5 megawatts (MW) of installed capacity. The array includes 11,700, approximately 12 percent efficient, ASE-300 solar modules manufactured by RWE Schott Solar rated at 300 W per module, covering an area of 28,400 $m^2$. In addition, the array has 12,000 Solarex MST-43 modules with a rated power of 43 W per module. These modules cover 9,820 $m^2$, resulting in a rated power conversion efficiency of 5.3 percent. The array is completed by 11,280 First Solar FS-45 and FS-50 modules with rated capacities of 45 W and 50 W per module, respectively. The total rated power is 564 kW for an array area of 8,122 $m^2$, corresponding to a 6.9 percent efficiency.

The First Solar modules use cadmium/tellurium-based (CdTe) technology while all other modules are crystalline silicon (Si) based. The former perform best under mid-day conditions, while the latter work best during morning or evening settings. The CdTe modules are less sensitive to temperature. Due to inclusion of the Solarex and First Solar modules, efficiency of this array is significantly lower than with the ASE modules alone. Nevertheless, the general behavior of the array should be representative.

Array output and meteorological variables of solar insolation, ambient temperature, and wind speed are downloaded from the Springerville array continuously onto a Web site every two minutes (http://www.greenwatts.com/pages/solaroutput.asp), making data availability relatively straightforward (Tucson Electric Power Company 2002). Figure 4 shows power output as a function of solar insolation and its corresponding efficiency based on data from the Web site recorded over several days in August 2005. In general, the trend in array performance is roughly constant down to insolation values as low as

## Table 2. Solar Insolation (kWh $m^{-2}$ $day^{-1}$) in Illinois

| *Location* | *Latitude (°N)* | *Longitude (°W)* | *Altitude (m)* | *Jan* | *Feb* | *Mar* | *Apr* | *May* | *Jun* | *Jul* | *Aug* | *Sep* | *Oct* | *Nov* | *Dec* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Freeport | 42.28 | 89.67 | 265 | 3.342 | 4.299 | 4.666 | 4.991 | 5.316 | 5.775 | 5.867 | 5.776 | 5.496 | 4.425 | 2.845 | 2.662 |
| St. Charles | 41.90 | 88.37 | 226 | 2.941 | 3.759 | 4.187 | 4.665 | 5.062 | 5.654 | 5.798 | 5.559 | 5.322 | 4.183 | 2.595 | 2.334 |
| De Kalb | 41.85 | 88.85 | 265 | 3.377 | 4.131 | 4.434 | 4.755 | 5.037 | 5.529 | 5.691 | 5.498 | 5.285 | 4.332 | 2.767 | 2.643 |
| Monmouth | 40.92 | 90.73 | 229 | 3.639 | 4.257 | 4.829 | 4.998 | 5.287 | 5.731 | 5.893 | 5.808 | 5.666 | 4.639 | 3.070 | 2.932 |
| Stelle | 40.95 | 88.17 | 213 | 3.344 | 4.073 | 4.474 | 4.786 | 5.035 | 5.579 | 5.784 | 5.647 | 5.480 | 4.469 | 2.777 | 2.653 |
| Wildlife Prairie Park | 40.73 | 89.75 | 186 | 3.223 | 4.031 | 4.600 | 4.905 | 5.223 | 5.733 | 5.922 | 5.742 | 5.496 | 4.559 | 2.941 | 2.643 |
| Peoria | 40.70 | 89.52 | 207 | 3.271 | 4.109 | 4.642 | 4.921 | 5.239 | 5.740 | 5.880 | 5.727 | 5.639 | 4.562 | 2.957 | 2.721 |
| Killbourne | 40.17 | 90.08 | 152 | 3.300 | 4.087 | 4.697 | 5.051 | 5.333 | 5.757 | 6.059 | 5.915 | 5.729 | 4.636 | 3.046 | 2.798 |
| Champaign | 40.08 | 88.23 | 219 | 3.194 | 4.170 | 4.584 | 5.016 | 5.253 | 5.720 | 5.964 | 5.800 | 5.781 | 4.824 | 3.109 | 2.787 |
| Bondville | 40.05 | 88.22 | 213 | 3.439 | 4.308 | 4.660 | 5.086 | 5.299 | 5.769 | 6.091 | 5.948 | 5.773 | 4.870 | 3.143 | 2.890 |
| Perry | 39.80 | 90.83 | 206 | 3.482 | 4.218 | 4.732 | 4.996 | 5.272 | 5.648 | 5.957 | 5.879 | 5.684 | 4.735 | 3.186 | 2.933 |
| Springfield | 39.52 | 89.62 | 177 | 3.234 | 4.079 | 4.481 | 4.925 | 5.190 | 5.601 | 5.875 | 5.768 | 5.589 | 4.666 | 3.028 | 2.821 |
| Brownstown | 38.95 | 88.95 | 177 | 3.188 | 4.123 | 4.567 | 5.072 | 5.212 | 5.619 | 5.876 | 5.859 | 5.695 | 4.938 | 3.245 | 2.836 |
| Olney | 38.73 | 88.10 | 134 | 3.276 | 4.218 | 4.568 | 5.119 | 5.280 | 5.582 | 5.938 | 5.757 | 5.649 | 4.869 | 3.271 | 2.785 |
| Belleville | 38.52 | 89.88 | 133 | 3.571 | 4.418 | 4.848 | 5.281 | 5.487 | 5.666 | 6.178 | 6.222 | 5.982 | 5.200 | 3.481 | 3.154 |
| Fairfield | 38.38 | 88.38 | 136 | 3.320 | 4.227 | 4.642 | 5.153 | 5.251 | 5.580 | 5.885 | 6.004 | 5.758 | 5.003 | 3.362 | 2.918 |
| Rend Lake | 38.13 | 88.92 | 130 | 3.375 | 4.325 | 4.766 | 5.329 | 5.455 | 5.916 | 6.212 | 6.170 | 5.842 | 5.128 | 3.482 | 2.992 |
| Carbondale | 37.72 | 89.23 | 137 | 3.388 | 4.631 | 4.783 | 5.377 | 5.382 | 5.777 | 5.983 | 6.019 | 5.737 | 5.001 | 3.455 | 3.063 |
| Dixon Springs | 37.45 | 88.67 | 165 | 3.447 | 4.327 | 4.746 | 5.308 | 5.324 | 5.731 | 5.997 | 6.013 | 5.776 | 5.136 | 3.538 | 2.988 |

**Note**: Values simulate measurements from a south-facing flat plate collector tilted relative to horizontal at the latitude of the station.

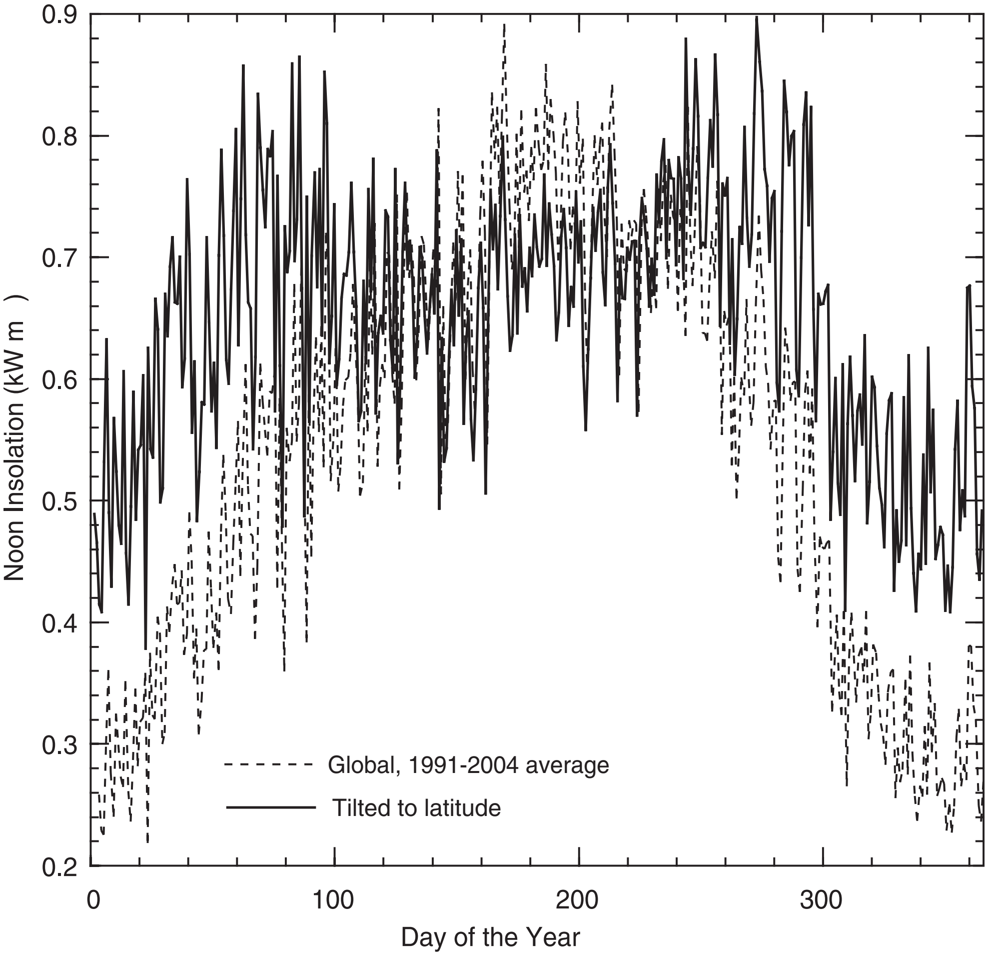


Figure 3. Solar insolation between 1100 and 1200 CST at Champaign, Illinois.

10 Wm$^{-2}$, while efficiency increases as light levels fall (Figure 4b). Performance correlates well with solar insolation, but only slightly with ambient temperature (not shown). The most likely explanation for the decrease in efficiency with increasing insolation is solar heating of the photovoltaic devices themselves. These solar cells are ≤12 percent efficient, but are nearly 95 percent absorbing. Therefore, one may expect well over 800 Wm$^{-2}$ of heating of the devices under full sun. This heating is concentrated at the photovoltaic junctions, yielding mid-day junction temperatures, perhaps in excess of 50°C, even in low ambient temperatures. This conclusion about solar heating of the system is further supported by the observation that wind speed, which can provide cooling, increases the array efficiency (not shown). Overall, performance of a hypothetical array in central Illinois should be similar, in general, to the Springerville array even though the ambient temperature at Springerville is significantly higher on average throughout the year.

Average performance of the Springerville array appears to fall from ~11 percent efficiency at 15 Wm$^{-2}$ insolation to ~7 percent efficiency at 1,000 Wm$^{-2}$ (Figure 4b). This efficiency includes all power inversion, wiring, inoperative modules, and blocking diode losses. It is expected that modules with lower performance, representing the majority of the array, influence these results, whereas an array consisting entirely of ASE modules would have higher performance. Therefore, options considered for the

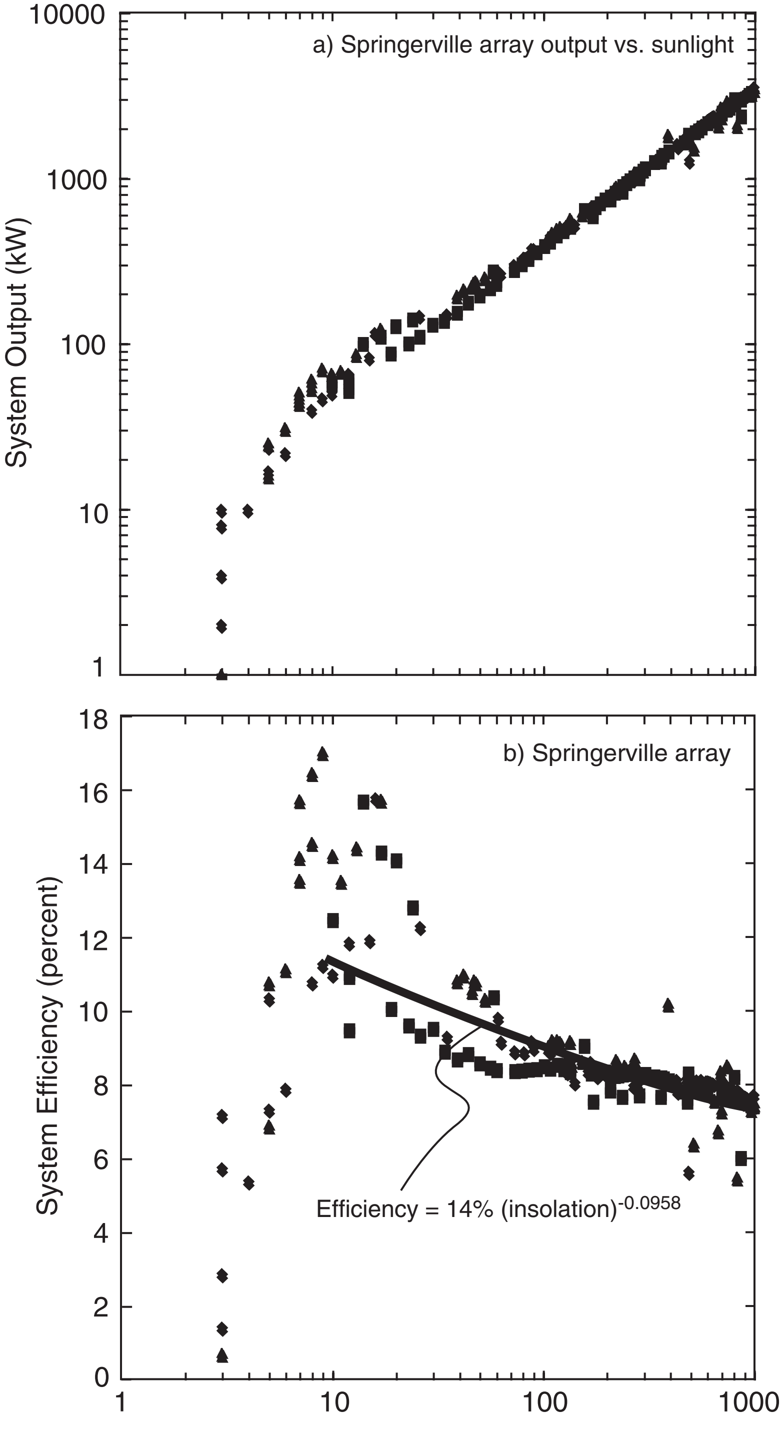


Figure 4. (a) Power output of the Springerville, Arizona photovoltaic array as a function of solar insolation during August 2005 (Tucson Electric Power Company 2002), and (b) net energy conversion efficiency of the system. The equation is the best fit power law for the data. The array ceases operation below ~10 $Wm^{-2}$.

hypothetical array in Champaign included: (1) an array following the Springerville array efficiency as a function of insolation and (2) an array with a constant 12 percent efficiency. The latter array was downgraded slightly using 88 percent efficiency for the balance of the system (a value recommended by NREL for comparison). Net efficiency for system (2) then was 10.6 percent. No correction was made for higher or lower light levels.

Taking hourly averaged solar insolation values (see, for example, Champaign data for noon and 9 a.m. in Figure 5), power output was calculated for an array performance equal to the Springerville array properties and for a constant array efficiency of 10.6 percent. The integrated areas under these curves (assuming no array output in both cases for insolation below 10 $Wm^{-2}$) gave the total power produced by the arrays, 134 or 180 kWh $m^{-2}$ of array per year, respectively. Note also that were the array efficiency to increase at low light intensities and decrease at high intensities, as suggested by the data in Figure 4b, the curves in Figure 5 would vary less both in terms of scatter and with day of year.

## Economic Considerations

Having an approximation of the power expected from a square meter of solar array allowed estimation of the effective cost of the power and an assessment of the conditions when photovoltaic power may be economically viable in Illinois. Assumptions included sole use of RWE Schott Solar ASE-300 modules purchased at a current retail price (from a Web site in October 2005) of $1,200 per

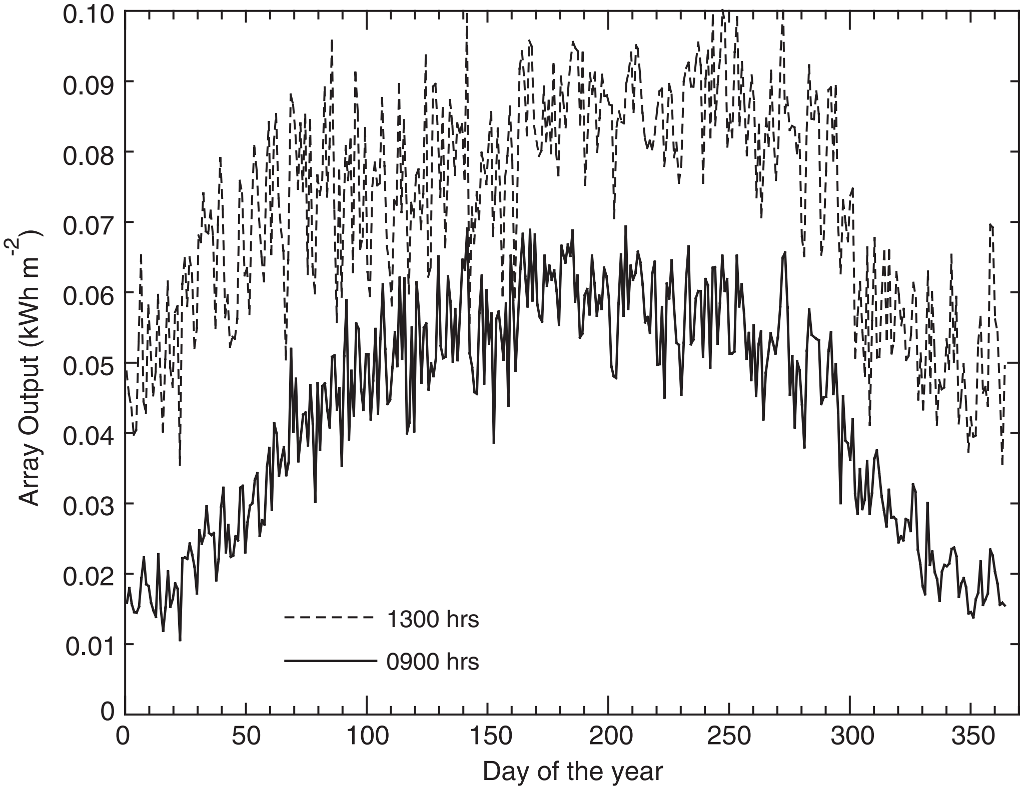


Figure 5. Sample hours of average solar insolation (1991-2004) at Champaign, Illinois corrected to simulate a 10.6 percent efficient flat-plate solar power system at a tilt equal to the latitude of the station.

module, and a constant 10.6 percent efficient array performance. Other manufacturers produce equivalent products for equivalent prices. At the time of this writing, higher efficiency modules are available than the ASE-300 modules considered here, but because their price is greater, the price per watt of installed capacity is equivalent. Because data are available on the performance of an array using the ASE-300 modules, these data were used for comparison.

The RWE ASE-300 modules have an area of ~2.43 m$^2$ and are warranted for 20 years. In central Illinois, this translates to expected production of 437 kWh per year or 8730 kWh over the lifetime of each module. If there were no other cost than the purchase price of the module, this would amount to $0.14 per kWh.

Unfortunately, the true price is higher. A typical way to discuss this is to consider the cost per watt of rated power (the power produced by the module under air mass 1.5 full sun conditions at 25°C). Air mass 1.5 full sun is a standardization factor that represents the longer path length and assumed light degradation solar insolation makes through a clear atmosphere for central latitudes. The RWE ASE-300 modules are available based on a current Web listing at \$4 W$^{-1}$ rated power. The balance-of-system costs including rack mount, cabling, power conditioning, direct current to alternating current inversion, and circuit breakers can be expected to cost roughly another \$4 W$^{-1}$ rated power, for a total of \$8 W$^{-1}$ installed capacity, a value that can vary significantly. A very large system, for example, may reduce the total cost to as little as \$5 W$^{-1}$ installed capacity.

With current technology for a grid-connected system, a conservative estimate for these costs is approximately \$8,000 kW$^{-1}$ of rated array capacity. For ASE-300 modules, 1 kW of capacity corresponds to 8 m$^2$ of array (3.3 modules per kW). Such an array in Champaign, operating at 10.6 percent efficiency, would produce approximately 28,750 kWh over its 20-year warranted lifetime. Maintenance for large well-designed arrays should be minimal, but will be required.

The capital cost is not trivial. A 20-year loan of $8,000 at 5 percent interest has a total cost of $12,672. Therefore, accounting for the complete system cost with a loan, power produced by the above array could be expected to cost $0.44 per kWh. Including maintenance, the costs may approach $0.50 per kWh. The price would be higher for a system with battery storage, depending on the storage technology used, capacity required, and use conditions.

It is valuable to compare this cost with grid power for urban applications. Based on a typical residential power cost of \$0.11 per kWh in central Illinois, the anticipated annual output of 180 kWh m$^{-2}$ corresponds to ~\$20 m$^{-2}$ annually in retail power or ~\$400 m$^{-2}$ over the lifetime of the device. Typical annual household electric loads are ~9,000 kWh. A medium-sized photovoltaic array (6 kW or 20 ASE modules) can produce this level of power, as discussed previously. One could expect to pay roughly \$48,000 for such an installation. At \$0.11 per kWh, this installation would offset \$19,400 in purchased power over the array lifetime.

However, practical application of such an array assumes net metering and a grid connection, where power is bought from the grid when the array is not operating and sold to the grid when it is operating in excess of the household requirements. Not all states and regions require utilities to permit net metering, but some do. For example, one major power producer for northern Illinois allowed net metering up to 40 kW of power until recently, but now buys excess power at a lower "avoided cost" rate (roughly the wholesale rate for power). Another large utility, serving primarily central Illinois, does not currently allow net metering and does not buy back power. Regardless, even with net metering, for the $48,000 price, photovoltaics are not economically competitive for grid-connected consumers.

Utility-scale "baseline" power production is less expensive than the retail price a typical consumer pays, being between $0.02 and $0.05 per kWh or between $3.6 and $9 annually for the 180 kWh produced by a square meter of efficient solar cell. At this price, photovoltaic-generated power does not even cover the interest on the system purchase cost. However, baseline power is not a good comparison for photovoltaics. Rather, consideration should be given to peak power and, in particular, summertime peak power, the most expensive power for utilities to produce because their generator for that power is idle most of the year. Summer peak power can cost more than \$0.20 per kWh and, in certain crises, has been known to exceed \$1 per kWh. Under these considerations, photovoltaics may become cost effective through an application known as peak shaving, which reduces generating capacity to meet peak demands. Because the maximum daily production of power by a photovoltaic array well matches the daily highest peak demands on the grid, it is a natural choice for peak-shaving applications. Note that a solar array designed for summertime peak shaving should be mounted at a tilt of latitude minus 15 degrees relative to the horizontal to maximize summer output. This alteration reduces power output the remainder of the year.

Another issue facing utilities is the capacity of the grid itself, as evidenced by recent power blackouts. Maintaining a grid capable of supporting peak loads during the summer is far more expensive than maintaining a grid capable of supporting average peak loads. Furthermore, the larger the power capacity of the grid, the more vulnerable it becomes to localized failures, physical attack, and sabotage. Use of a distributed generating technique such as photovoltaics provides grid support that significantly can decrease peak loads on the grid, thus reducing costs and improving reliability. Photovoltaics are very well suited to grid support roles, although it is difficult to quantify the cost effectiveness in detail without data on the cost of transmission lines.

The above discussion includes some assumptions that deserve further consideration. The advertised price of \$1,200 per 300 W module likely would be less if purchased in large quantities. With some effort, efficiency higher than 10.6 percent also may be achieved: an upper limit of 11.4 percent with a 12 percent efficient module, a 95 percent efficient inverter, and no other losses. Springerville data suggest that higher efficiency may be achieved at low light levels where modules are significantly cooler. Furthermore, given subsidies or tax incentives to reduce capital costs, the price of power may be substantially lower than \$0.44 per kWh. Because the power itself costs no more than the maintenance cost of the array, reducing the initial expense through grants can make a photovoltaic array worthwhile, even for a grid-connected homeowner. For example, if a consumer could get a one-to-one match on purchase of a system, then the break-even cost for a grid-connected, net-metered system would be \$0.22 per kWh.

Clearly, the current economical application of photovoltaics is for low-power systems in remote locations, due to the cost of grid connection. One utility serving central Illinois currently quotes \$10-12 per foot of power line for a new grid connection (that is, a "primary connection") requiring a step-down transformer and utility poles. Thus, a half mile of transmission line would cost an estimated \$26,000-\$31,000. Using \$30,000 as a representative cost, this would offset the price for approximately 30 m$^2$ of photovoltaic array with the above estimated cost (ignoring interest because it is assumed that this price would be paid regardless). One then must include the generation cost of power the array would produce purchased from the local utility company. A 30 m$^2$ array may produce an expected 108,000 kWh over 20 years. At \$0.11 per kWh, this would represent another \$12,000 of power beyond the \$30,000 line cost. Because this power is paid over 20 years, interest must be included in evaluating its value. Much of this income can be counted in the initial funds available to purchase an array relative to the grid connection cost.

For the resulting system, an estimated 42 m$^2$ of array can be purchased for the cost of a half mile of power line even at the simple retail price of the modules and without figuring in inflation in the cost of electricity. Thus, a load consuming, on average, 7,500 kWh per year would break even against a half mile long grid connection. A year consists of 8,766 hours (accounting for leap year), so the average load could be as great as 860 W if sufficient efficient storage were available to provide power to the load. The price benefit becomes significantly higher further from the grid and for lower power loads. These calculations and estimates require several caveats. They are based on an undiscounted retail module cost for a particular relatively high-performance module, but they do not include the cost of a battery backup, incentives, or maintenance costs. It is possible that most of these points are roughly offsetting; thus, the break-even point may be approximately correct.

Other issues deserve note with respect to use of photovoltaics by the power industry. Utilities are very conservative businesses. Their mission is to supply reliable power at the lowest cost by procedures not necessarily supported by environmentalists or current public opinion. Investments in new technologies must show reasonable options for profit. Photovoltaics may have been avoided for many years just for this reason. Furthermore, both grid support and peak shaving applications require photovoltaic installation on a scale that currently exceeds world photovoltaic production. From a purely operational perspective, further improvements in design and demonstrated performance will be necessary before utilities may consider photovoltaics more seriously as a viable power source.

## Summary and Conclusions

Fourteen years of hourly solar insolation values at 19 sites across Illinois collected by the ISWS provide a valuable addition to existing sources of solar radiation data and afford a significantly denser dataset than previously has been available, especially for downstate Illinois locations. These data should improve modeling of solar insolation in Illinois. Based on these data, annual power output from a hypothetical, relatively efficient photovoltaic array in Champaign, Illinois, was estimated as 134-180 kWh m$^{-2}$ of array per year. Output would vary with latitude, being higher in southern Illinois and lower in northern Illinois. Considering current photovoltaic technology, as well as capital costs to purchase the system, the estimated cost of photovoltaic power would be roughly $0.44 per kWh. Incentives, tax benefits, and grants could reduce this price significantly.

Based on these arguments, there is current value of photovoltaic technology for low-load remote applications such as powering billboards, emergency phones, sectioning switches on power lines, etc. Higher loads become increasingly costly, while more remote sites can offset a larger photovoltaic array cost. In certain cases, photovoltaics also may make economic sense when considering peak-shaving and grid-support issues. Nevertheless, without major subsidies, it will be difficult in the near future to compete with electrical power from an existing utility grid. As prices on photovoltaic modules decrease and as these devices become more efficient, installing photovoltaic arrays should become increasingly favorable.

Results in this report were calculated for small to medium photovoltaic array designs. A larger, 100 kW array may be expected to produce power at $0.27 per kWh over a 20-year lifetime, without subsidy, but given economy-of-scale discounts in both module and balance-of-system costs, installed at $5 W$^{-1}$ rated capacity with a 5 percent interest loan of the purchase price. This price is approaching the current cost of nuclear power and typical peak power generation costs. Any significant discount on the purchase price or capital cost would make photovoltaics cost effective in the current marketplace for peak power.

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