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3.3 AVAILABILITY AND VARIABILITY OF POTENTIAL PV SOLAR AND WIND POWER PRODUCTION IN OKLAHOMA

Keith A. Brewster*[1] and Samuel K. Degelia[2]

[1]Center for Analysis and Prediction of Storms
[2]School of Meteorology
University of Oklahoma
Norman, OK 73072

1. INTRODUCTION

Renewable energy sources, including wind, solar, biomass, and hydropower are all becoming increasingly important in the world's power production (Li et al. 2011).

Wind energy has seen a recent growth in capacity and production, especially in the Great Plains states, including Oklahoma, as reported by the regional grid operator, Southwest Power Pool (SPP). Wind power rated capacity in the SPP is more than 8 GigaWatts (GW), and actual wind power production had grown to 15.8% of total production by Fall 2015 (SPP, 2015).

Two issues with wind as a power source are that it is variable and it is not always strong at the time of peak power demand. Variable power presents challenges to the power grid, requiring relatively expensive fast-response generators and/or increased reserved power requirements to provide a steady voltage on the grid. In 2015 the two lowest wind production months in the SPP were July and August (SPP, 2015), months with high cooling demand. Furthermore, wind power in the Great Plains tends to be concentrated in certain areas of the western Great Plains distant from population and demand centers, creating congestion on transmission lines when the wind is strong in these areas.

Combining solar photovoltaic (PV) power with wind power in a hybrid system has the potential to reduce variability and increase reliability in renewable electrical energy production. Such a combination could aid power grid operators in planning and help power companies with critical investment decisions (Blumsack and Richardson 2012). Furthermore, if PV energy is available at peak demand times, it has the potential to maximize revenue for PV producers while providing the grid and consumers with reliable power that can grow with the increasing population and economic growth, thus reducing the need for building additional fossil-fuel power plants.

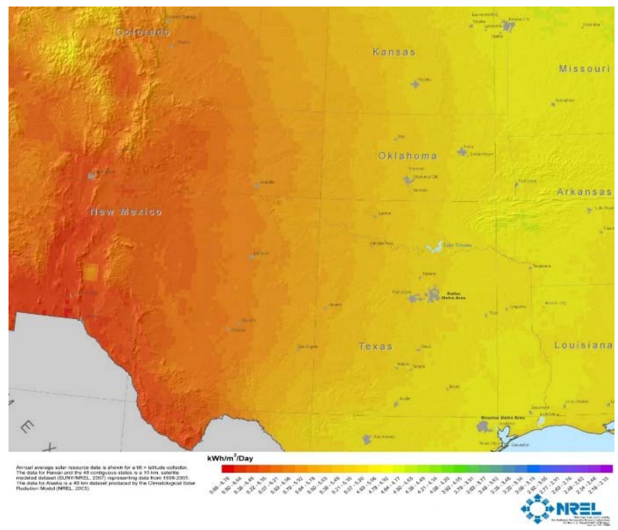

Figure 1. Solar Power availability over the Southern Great Plains from the National Renewable Energy Laboratory.

With the recent steep decline in costs for PV solar panels, support in the form of Federal tax incentives, and a low interest rate environment providing low cost of capital, production of solar power on the utility scale (1-100 MW) and on the rooftop scale (5-500 kW) has become economically feasible in many places in the United States, as well as elsewhere in the world.

With a large number of sunny days per year, Oklahoma has abundant incident solar energy (Fig 1), ranging from 2.4 MWh/m^2 at Kenton in the Oklahoma panhandle to 1.6 MWh/m^2 near the eastern border with Arkansas. These are greater

*Corresponding author address: Keith Brewster, PhD,
120 David L. Boren Blvd., Suite 2500,
Norman, OK 73072, kbrewster@ou.edu

than many east coast states that have made fairly large commitments to PV production. Pressure to reduce air pollution from older coal-fired plants and to reduce carbon dioxide emissions provides urgency to looking at options to increase clean electric power generation in Oklahoma. In this environment we are motivated to examine the possible addition of PV solar projects to the power production suite in Oklahoma where it is currently less than 1% of generation.

Oklahoma is home to several large wind power production sites, commonly known as wind farms. It is of interest to study co-location of solar PV production at or near these sites which already have grid interconnect systems, access roads and other infrastructure. Using collocated PV, it might be possible to not only supplement the power production, but to also reduce the variability of the total power produced at these sites.

In this study we examine the availability and variability of electric power that could be produced in two scenarios: 1) utility-scale projects to supplement wind power production at or near current large wind farms in Oklahoma, 2) distributed power produced in Central Oklahoma. The study will consider production in four regions, three representing current areas of wind power production (Fig. 2), Woodward, Medicine Park, and Blackwell, and the Oklahoma City metropolitan area for distributed power.

2. METHOD OF ESTIMATING POWER PRODUCTION FROM OBSERVATIONS

Because production data is considered proprietary information by the producers; here we estimate the wind power production using wind data from the Oklahoma Mesonet. The Mesonet is a well-maintained network of 120 high-quality automated observing stations deployed across Oklahoma that reports weather data every 5 minutes (Brock et al., 1995; McPherson et al., 2007). In order to study potential wind power, turbine-height winds were estimated from the 10-m wind observations from the Oklahoma Mesonet stations. Newman and Klein (2013), among others, noted that winds at turbine height (80 meters) can be approximated from 10-m observations using the power law method:

$$u(z) = u_{ref}\left(\frac{z}{z_{ref}}\right)^p \qquad (1)$$

where u(z) is the desired wind speed at turbine height, z is 80 meters, z_{ref} is 10 meters, u_{ref} is the wind speed at 10 meters, and *p* is a shear parameter.

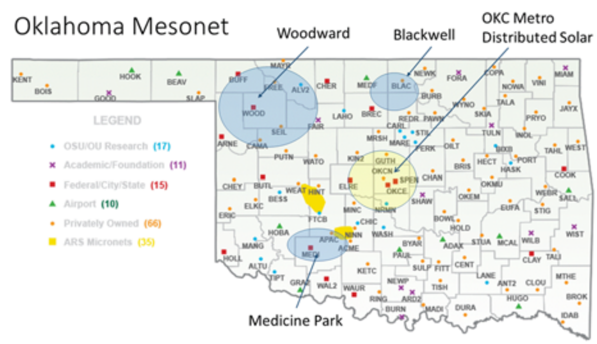

Figure 2. Oklahoma Mesonet site locations annotated with major wind production areas of the state (blue ovals), plus the Oklahoma City metro area (light yellow oval).

Previous studies, including Blumsack and Richardson (2012), have used a constant shear parameter. However, we selected from parameters given by Newman and Klein (2013) corresponding to different stability classes calculated using the gradient Richardson number (Eq. 2), which is expected to produce more realistic approximations.

$$Ri = \frac{g[(T_{9m} - T_{1.5m})/(\Delta z_T + \Gamma_d)]\Delta z_u^{\;2}}{T_{1.5m}(u_{10m} - u_{2m})^2} \qquad (2)$$

This method performs well under unstable and neutral conditions, but less so under stable conditions (Newman and Klein 2013). Given that the highest demand for power is during the daytime, generally in unstable or neutral conditions, this is acceptable for this study.

The turbine height winds were then used to compute wind power using a wind power curve formula derived from power generation data typical of a utility-scale wind power turbine utilized in the Great Plains and fit to a hyperbolic tangent curve. The power curve specifies that no power is generated when the wind speed is below the cut-in wind speed of 3 m s^{-1}. When the wind speed is between the cut-in speed and the rated speed of 16 m s^{-1}, the wind power production depends on a hyperbolic tangent function of the wind speed. Between 16 m s^{-1} and the cut-out speed of 25 m s^{-1} the turbine generates maximum power. Once the wind speed exceeds the cut-out speed, no power is generated because the turbines must be shut-down to prevent damage. These values are then multiplied by the rated capacity of the site to obtain total power output. Large wind turbines typically output AC electricity so a DC-to-AC conversion factor is not required (Sims 2014) before transforming to transmission voltage.

The power production from a hypothetical new solar installation is estimated from solar observations also obtained from the Oklahoma Mesonet. The Mesonet stations provide solar irradiance data from pyranometers in the form of global downwelling solar radiation averaged over five minute intervals (Mesonet 2016). Since the pyranometer measures total sky radiation, it was necessary to include calculations to distinguish between diffuse and direct radiation as tilting the PV panel toward the sun acts to increase the capture of direct radiation but not diffuse radiation (Duffie and Beckman 1980). Following the method of Jacovides et al. (2005), the diffuse radiation was determined from the clearness index (Eq. 3), where k_d is the diffuse radiation fraction and k_t is the clearness index.

$$k_d = 0.94 + .937 * k_t - 5.01 * k_t^2 + 3.32 * k_t^3 \quad (3)$$

The clearness index is the ratio of observed downwelling radiation to extraterrestrial radiation (which is a sinusoidal function of the solar constant and the day of year) (Jacovides et al. 2005). Once the diffuse radiation values were calculated using Eq. 3, the diffuse component was subtracted from the total radiation measured at the Mesonet sites to find direct radiation. At this point in the calculation, the tilt of the PV panel was taken into account. The amount of solar radiation reaching the tilted panel is given by Eq. 4, where S_{panel} is the direct radiation on the PV panel surface, $S_{horizontal}$ is the downwelling global horizontal radiation from the Mesonet pyranometer, α is the elevation angle (which is dependent on the declination angle), and β is chosen fixed tilt (Duffie and Beckman 1980).

$$S_{Panel} = \frac{S_{borizontal} \sin(\alpha + \beta)}{\sin \alpha} \quad (4)$$

With the direct radiation orthogonal to the tilted panel known, the diffuse radiation was added back to give total radiation. It is assumed the capture of diffuse radiation is constant with variation in tilt angle. Tina and Gagliano (2010) showed that there is an advantage to employing a PV tracking system to the solar power system. However, they found that the overall collection improvement of a two-axis system over a single-axis system is marginal. Thus, similar to Blumsack and Richardson (2012), we will assume collection from a flat-plate, fixed-axis collector.

Typical power calculation methods for PV systems will be applied to convert solar radiation values into power output. The efficiency of the panels is taken into account because the power rating in Watts of the PV panel surface is given relative to 1000 W m^{-2} incident solar irradiance. Specific panel brands or models were not selected, only utility-scale plant total rated power was considered. Various solar power plant sizes are outlined in the results section. The panels output power in DC whereas the power grid carries AC electricity, so a conversion factor of 91.81% was applied to the generated power values to account for conversion loss and to arrive at grid-ready power (NREL and DOE 2014).

For this study we examined the estimated mean hourly production of wind and solar for each month of the year over a 20-year study period (1996-2015). We also computed variability by considering the variation from the monthly mean. The focus is on the month of July, one of the high-demand summer months in Oklahoma.

For the purposes of calculating the variation of renewable power to the grid we need to consider the natural diurnal variation in potential power from both wind and solar sources. In the case of solar power this variation is due to the motion of the sun across the sky and seasonal variation in the elevation of the sun in the sky. For wind there is also a typical variation throughout the day due to mixing of generally stronger winds aloft toward the surface in the afternoon, decoupling in the evening, and other diurnal dynamic effects. The assumption is that the natural, expected, variations can be accommodated in day-ahead grid power planning and scheduling, and the more irregular power variations require the use of more expensive quick-response on-demand power sources or additional reserve generation to ensure a steady voltage on the electric grid.

A monthly mean power generation for each hour of the day is constructed from the 20-year Mesonet dataset. This climatological average represents the expected hour-by-hour variation through the day. The unsteady variation is calculated using a difference from this mean and is expressed in two ways, 1) as a standard deviation of power and 2) a relative power standard deviation as a percent of the hourly climatological mean (%RSD)

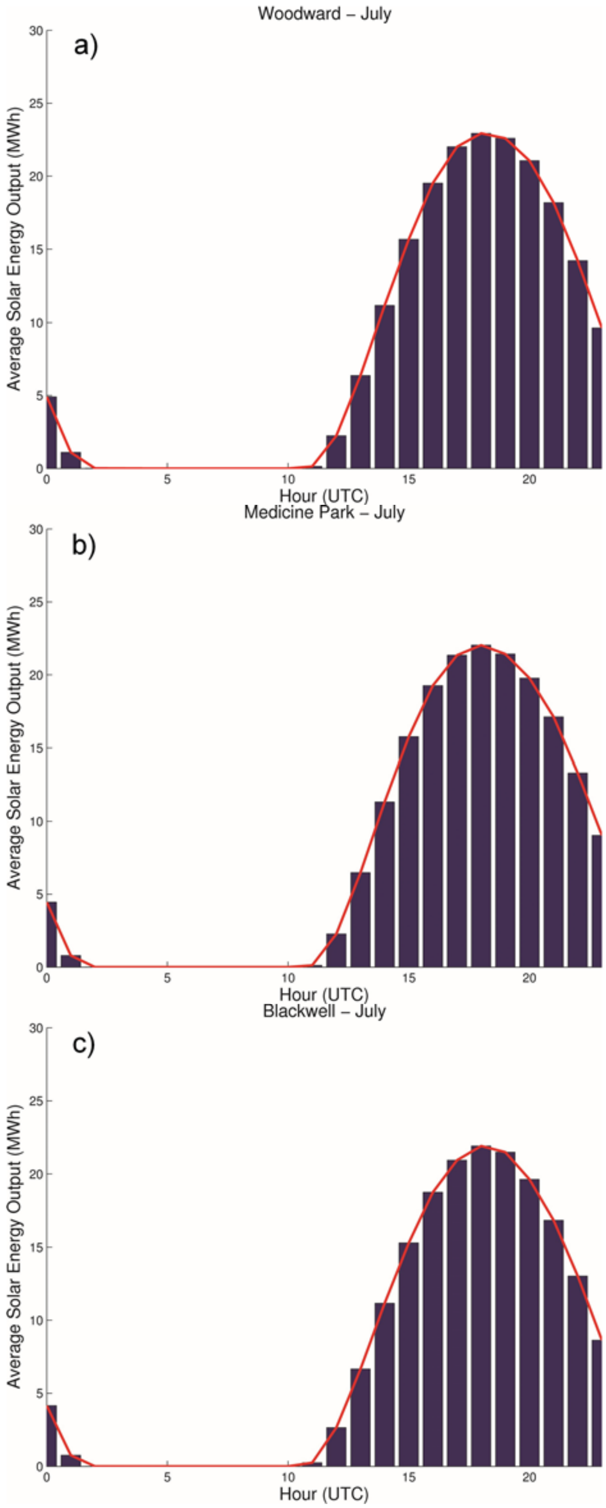

Figure 3 Average solar energy output (MWh) for each hour (UTC) during the month of July, for a) Woodward, b) Medicine Park, c) Blackwell, Oklahoma for a 30 MW rated system (with fixed tilt of 35°) over the period 1996-2015.

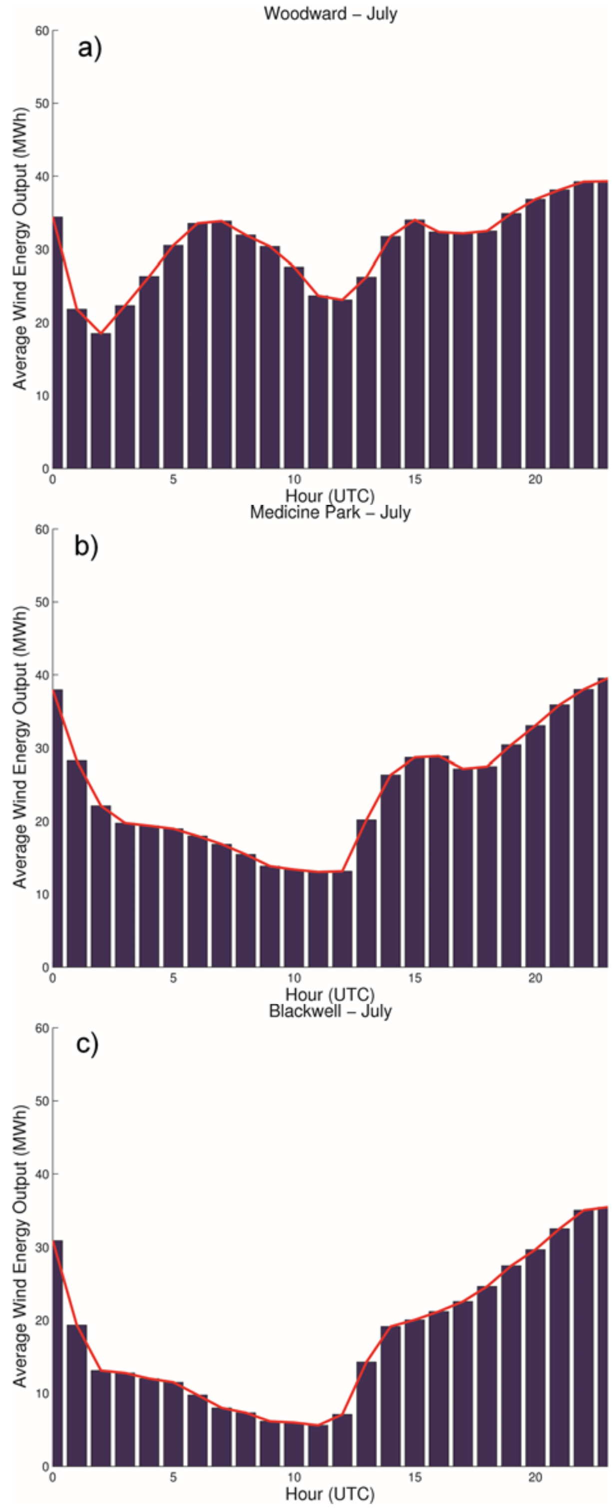

Figure 4 Average wind energy output (MWh) for each hour (UTC) during the month of July, for a) Woodward, b) Medicine Park, c) Blackwell, Oklahoma for a 100 MW rated system over the period 1996-2015.

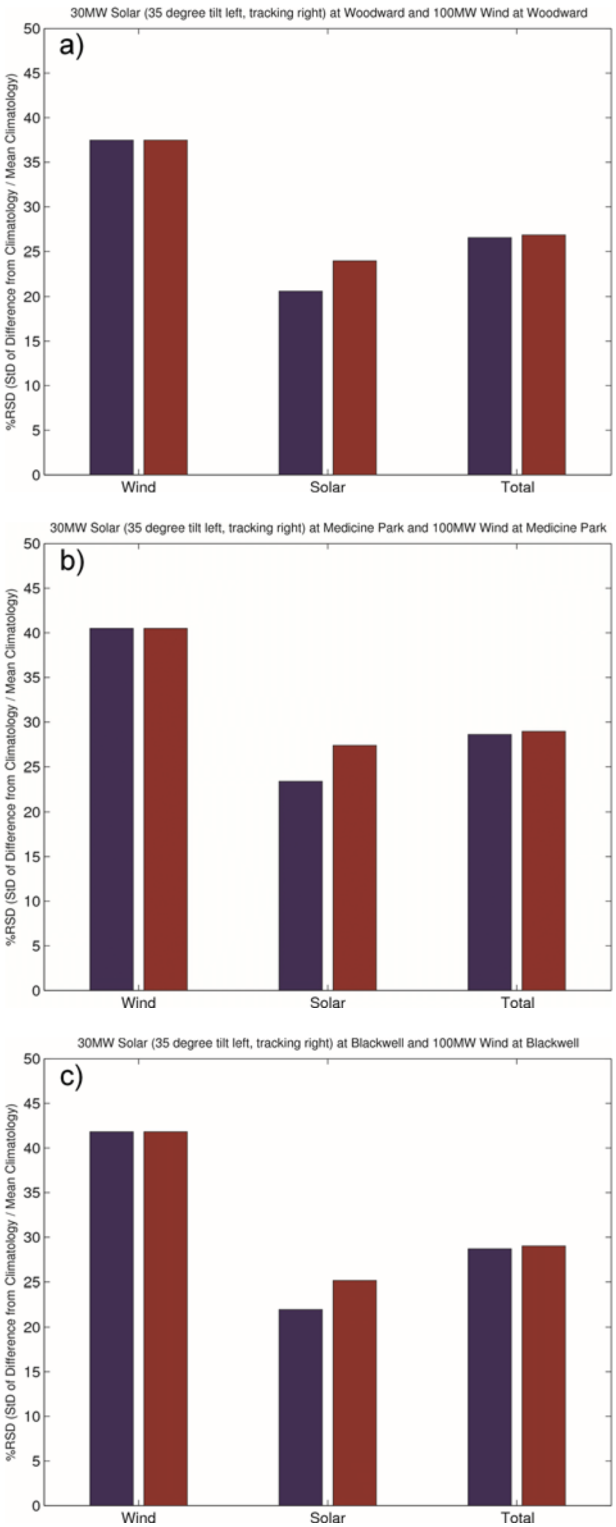

Figure 5 Power variability as percent relative standard deviation for wind, solar and hybrid wind and solar, collocated at three sites, a) Woodward, b) Medicine Park, and c) Blackwell. The blue bar for each represents solar panels fixed at 35 angle, and the red bar for single axis tracking.

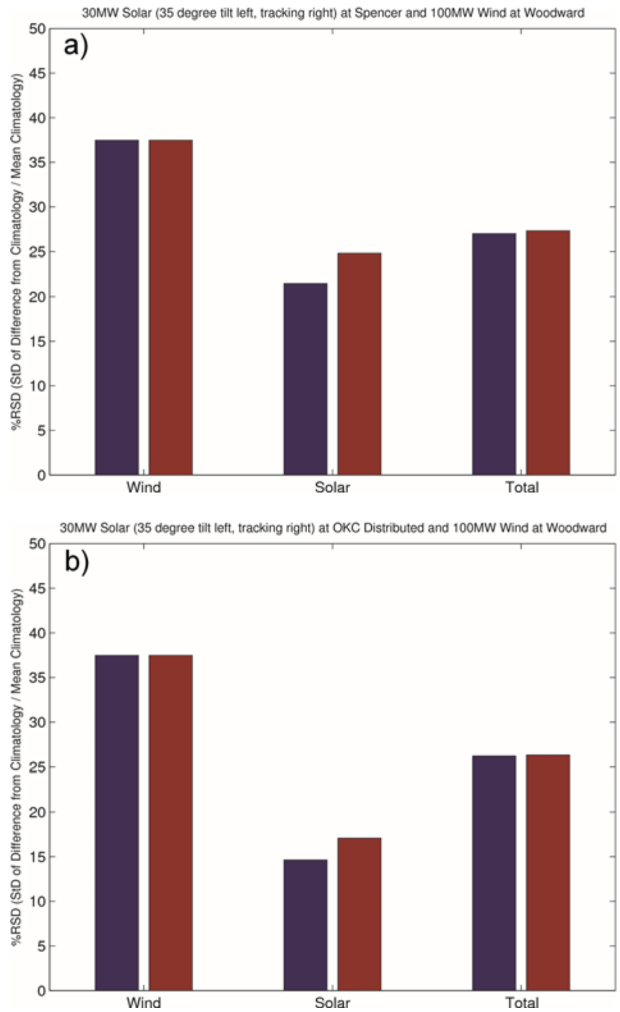

Figure 6. Power variability as percent relative standard deviation for wind, solar and combined wind and solar, a) Woodward wind and Spencer (Oklahoma City) solar, b) Woodward wind and Distributed solar power over the Oklahoma City metro area.

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3. RESULTS FOR COLLOCATED WIND-PV POWER PRODUCTION

Figure 3 shows the average potential PV solar power production for a 30 MW rated system in July. Because it is a generally sunny month across the entire state there is little difference among the three locations considered. As expected, the peak production is near solar noon, 1 pm CDT, and remains above 9 MW through 23 UTC (6 pm CDT), except at Blackwell which falls to 8.6 MW at 23 UTC. Wind power shows more difference among the sites, with Woodward showing higher production. Wind production grows throughout the afternoon and generally peaks at late afternoon (22-23 UTC). Woodward also has a secondary overnight peak (6-7 UTC, 1-2 am CDT) likely due to the low-level jet, which remains active through July in this area.

The variability in power production is shown in Fig. 5 at each of the three wind farm regions considered. The variability, in terms of standard deviation relative to the mean (%RSD) is lower for solar production than for wind production, with the fixed solar panels having about half the relative variation of wind power plants. The combined production has lower variability than the wind production mainly due to the low variation in the solar production. There is a small difference in variation between the fixed and single-axis tracked solar with the tracking having slightly higher variation. The tracked solar does tend to have about 10% higher daily production and falls-off less quickly during the afternoon compared to the fixed-tilt solar so that benefit might offset the downside of slightly higher variation.

4. DISTRIBUTED POWER IN CENTRAL OKLAHOMA

Solar panels installed on rooftops or over parking lots by individual homeowners, businesses, schools, churches and other entities can provide the owners with significant daytime power production. Excess power beyond the needs of the owners can be fed to the grid using common grid interconnect equipment. Although the capacity of an individual installation can vary from a few kW on a house to few hundred kW for school or warehouse rooftops, collectively this power, known as distributed power production, can be as large as a utility-scale project and provide a significant source of power to the grid. This power can reduce the need for peak daytime generation on the grid both through the reduction in demand and use of the distributed excess power.

To study the potential impact of distributed power in Oklahoma we consider the Oklahoma City (OKC) metropolitan area, being a region with high power demand and also having a significant number of candidate rooftops and parking lots. Data from the Oklahoma Mesonet sites at El Reno (representing potential production in Canadian Co.), Norman (Cleveland Co.), Spencer (Oklahoma Co.) and Guthrie (Logan Co.) are used to estimate distributed power in the OKC metro. We don't know what the ultimate distribution of sites might be, but, for simplicity, a simple average of production from the four Mesonet sites is used to represent the combination of production from all OKC metro area sites, and the total capacity in each county is assumed to be 7.5 MW, summing to 30 MW.

When looking at solar power variability (Fig. 6) we see a strong smoothing effect of combining solar production from four separate sites in that the variability of the combined production (14%, Fig 6b, middle bar) is reduced by one-third from that of a single OKC metro site (21%, Fig. 6a, middle bar). This, incidentally, is about the same as the variability at Woodward of collocated wind and solar site (22%, Fig. 5a).

5. CRITICAL DEMAND DAYS

To assess the availability of power during critical power demand days we examine the estimated production from the distributed power and collocated wind-PV power sites during the critical demand days declared and billed by OGE Energy (OG&E) to consumers in their SmartHours program. There were 38 of these days over the course of 4 years of data (2010-2013) provided by OG&E. We look at the ability of different renewable power sources to generate certain levels of energy during the 6-hour afternoon period 1 pm to 7 pm CDT (18-00 UTC) during the days when day-ahead projected demand was highest. Table 1 shows the estimated generation on critical days for wind power production sites and Table 2 shows the estimated generation for hypothetical

Table 1. Ability to Produce Energy at Different Thresholds at 100 MW Wind Power Sites

Location	60 MWh	70 MWh	80 MWh	90 MWh	100 MWh
WOOD	76%	74%	68%	61%	55%
MEDI	79%	76%	74%	71%	66%
BLAC	74%	68%	63%	58%	50%

Table 2. Ability to Produce Energy at Different Thresholds at 30 MW Solar Power Sites With Panels Fixed at 35 degrees

Location	60 MWh	70 MWh	80 MWh	90 MWh	100 MWh
SPEN	97%	97%	92%	87%	76%
ELRE	100%	95%	92%	84%	79%
GUTH	100%	100%	100%	92%	79%
NRMN	100%	100%	95%	92%	82%
Distributed	100%	97%	95%	89%	82%

solar power sites either collocated at the wind power sites or distributed within the OKC metro area.

It is noted that despite the higher rated maximum capacity, the wind power sites are less able to meet energy production needs on critical high demand days than the solar power sites. This is because nearly all critical demand days are very sunny, but it is not necessarily windy on those days. There is a slight advantage to the distributed power as its ability to meet critical demand levels is at or better than the individual sites for nearly all sites and threshold levels considered here.

6. SUMMARY AND CONCLUSION

Using observed data from the Oklahoma Mesonet we have shown the potential of adding PV solar production to the power grid serving Oklahoma. It was demonstrated that solar power would have a positive impact on the grid, not only adding capacity without the air pollution of burning additional fossil fuels, but also in reducing the variability of the renewable power produced. This result is found for hypothetical solar power plants collocated with current large wind farms in the state as well as for distributed power produced at sites across the Oklahoma City metro area. Distributed power has the additional advantage of lower power variance than large scale production from a single site, and also has a slight advantage over the utility scale solar production on the high demand days for the OG&E distribution area.

Future work will include examining the actual power demand for some of the days that were declared critical and the estimated solar production fell short of targets; it is possible that some of these days had less demand than expected in the day-ahead declaration of critical day due to more clouds or cooler conditions than forecasted. We also intend to look at the demand curve with time and how orienting solar panels might change the production curve to better match the diurnal demand curve.

7. ACKNOWLEGMENTS

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