IMPROVED ELECTRICAL LOAD MATCH IN CALIFORNIA BY COMBINING SOLAR THERMAL POWER PLANTS WITH WIND FARMS

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ABSTRACT

The ability of wind and solar electrical energy generation to match the current utility electrical load in California was analyzed. We compared the renewable electrical generation and the utility load in California using actual hourly wind farm data at two different locations and predicted hourly parabolic trough solar thermal output at one location. Solar energy electrical generation better matched the utility load than wind energy electrical generation; but the best match to utility load is a combination of wind and solar with six hours of molten salt storage. Also, the difference in seasonal wind generation at different locations in California, when combined with solar generation, could result in a substantial amount of the California utility electrical load being met by wind and solar energy.

1. INTRODUCTION

1.1 Background

California is well known in the United States for its large amount of wind-generated electricity (e.g., 2439 MW of installed wind capacity in California at end of 2007 supplied enough electricity to power more than 500,000 average homes). Over the entire year, the total wind-generated electricity in California is 1.8% of the total generated electricity; but at times during the year, wind energy generates more than 5% of the total. In addition, California generates more electricity from solar energy than any other state in the United States, but at the end of 2006, only 0.2% of the electricity was from solar energy. Although significant quantities of solar photovoltaic (PV) electricity have been added during the past few years in California (~ 25 MW/year), most of the solar-generated electricity is coming from 354 MW of the solar thermal power plants that were installed in California in the late 1980s and early 1990s. As the major electrical utilities in California determine how to meet the renewable portfolio standard requirement (i.e., 20% of all electricity in California must be generated by renewable energy by 2015), we decided to determine how well electrical generation by wind farms and solar thermal power plants—and the combination of the two—match the utility electrical load.

The idea for this paper was a direct result of the work by one of the authors on a paper presented at Windpower 2007 in Los Angeles (1). Research for that paper discovered that a wind farm (WF) in Altamont Pass, CA, generated most of its electricity during the late night and early morning hours and the lowest percentage of electricity generated by that wind farm was in the afternoon. This wind-generation profile was directly opposite that of a typical utility electrical load, which has lowest loading in early morning hours and highest loading in the afternoon hours. The author was familiar with this mismatch between wind farm output to utility load due to a similar situation existing in the Texas Panhandle. In the Texas Panhandle situation, the best solution found for improving the utility-load/wind-generation match was to add solar-generated electricity to the wind farm (2). In the 2006 ASES conference, a paper was presented on adding solar thermal power plants to wind farms in the Texas Panhandle and in Central West Texas (3). Another report documents the monthly and diurnal distribution of wind-generated electricity in several states in Western United States, including California (4). The fact that wind and solar energy combine well in California is not a new concept; it was also presented in a paper in 1990 (5).

1.2 Data Used in the Analysis

Hourly electrical loading was obtained from the Federal Energy Regulatory Commission (FERC, www.ferc.gov) for the five largest utilities in California (from 2005 statistics from the California Energy Commission (CEC), www.energy.ca.gov):

1. Southern California Edison (SCE) – 32.9%
2. Pacific Gas & Electric (PG&E) – 31.7%
3. Los Angeles Department of Water & Power (LADWP) – 10.2%
4. San Diego Gas & Electric (SDG&E) – 7%
5. Sacramento Municipal Utility District (SMUD) – 4.6%.

Hourly electrical load data were gathered for four of the five utilities listed above from the FERC Web site for 2004, 2005, and 2006. We only obtained electrical load data for 2004 for SCE; but due to a near-identical daily electrical load shape between SCE and LADWP, we believe our estimate of the hourly electrical load for 2005 and 2006 for SCE is very good.

The majority of the California wind farms are in three locations (see Fig 1). Southern California has two locations; San Gorgonio Pass (near Palm Springs in the low desert) and Tehachapi Pass (between Tehachapi and Mojave in the high desert). Northern California's Altamont Pass (east of San Francisco Bay area) is the third location. Hourly wind energy electrical generation data were obtained for two wind farms located in two of the large wind farm areas – one in Altamont Pass and the other in Tehachapi Pass. Both wind farms had wind turbines rated at 600 to 800 kW and were installed on towers 50 to 60 meters tall. Three years of hourly data were obtained for the wind farm in Tehachapi Pass (2004–2006), but only two years of hourly data were obtained for the Altamont Pass wind farm (2005 and 2006), because the wind farm was being installed in 2004. No hourly wind farm data were obtained for San Gorgonio Pass, but two years of predicted hourly production data were obtained for a single large wind turbine. Some seasonal data are also shown for all wind farm regions depicted in Fig 1.

The best location for solar thermal power plants is in the high desert (Mojave Desert) where the current concentrating solar power (CSP) plants are located (see Fig 2). Hourly data are available from these CSP plants, but were not used in this paper for two reasons:

1. CSP technology has improved significantly since these plants went into operation almost 20 years ago.

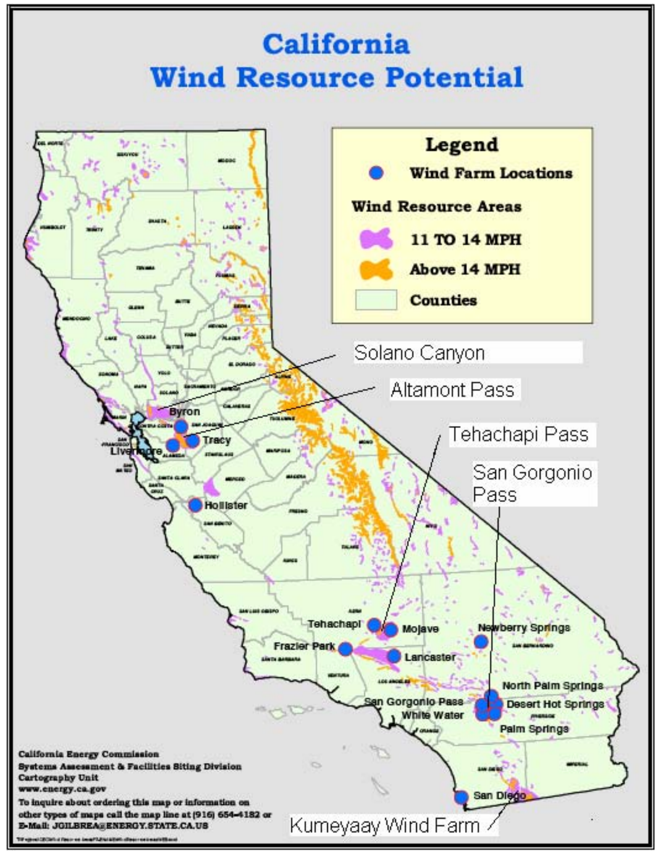

Fig. 1. Location of wind farms in California.

2. Natural gas as fuel backup is used in the generation of power at these plants to supply baseload power to the utility; so energy output due to solar thermal energy is not readily available.

Instead of using the CSP plant data, direct-normal irradiance (DNI) hourly data were obtained from a satellite dataset (6,7) and were used as input to the National Renewable Energy Laboratory's Solar Advisor Model (SAM) (8). This model is capable of predicting the output for a parabolic trough solar thermal power plant. The model allows for an oversized solar field and thermal energy storage. The satellite DNI hourly data were only available for years up to 2005, so solar thermal power plant hourly data (with no storage and with six hours of storage) were predicted for 2004 and 2005 for the Mojave Desert (Mojave Desert is the largest region with highest DNI in California). Only a parabolic trough CSP plant was considered in this paper due to most of the CSP plants in the world being this type. Other options include: Power Tower (central receiver with heliostat field), Dish Stirling, and Photo-voltaic (PV) array (with or without concentrators).

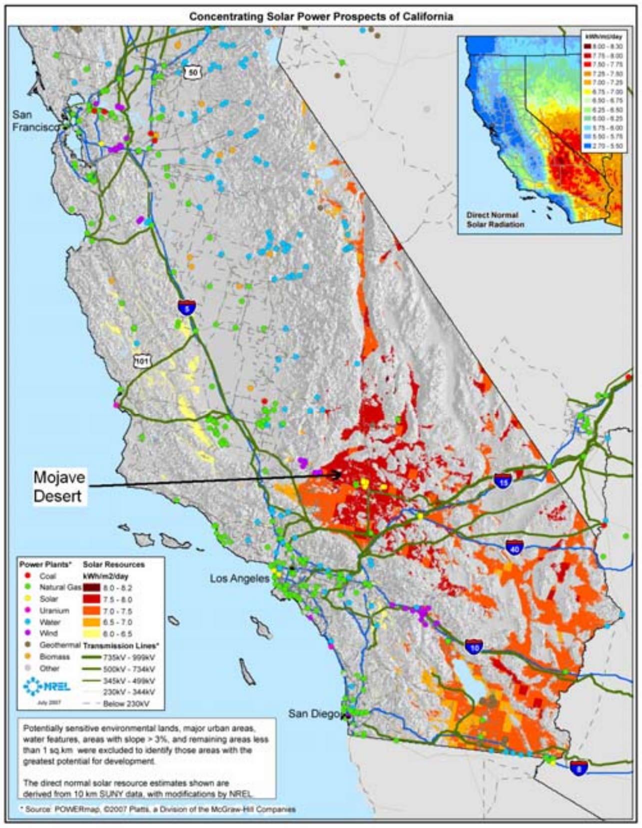

Fig. 2. Location of CSP plants in California.

2. RESULTS

2.1 California Monthly & Diurnal Electrical Loading

The average monthly utility electrical loading is shown in Fig. 3 for PG&E and SCE, the largest electrical utilities in northern and southern California, respectively. The fact that the peak electrical load month occurs in the summer is not surprising. This is when the peak occurs in most states in the southern half of the United States due to cooling and irrigation pump loads. In northern states, the peak month sometimes occurs in the winter due to heating loads. However, it is important to notice that only electrical loading over four months is elevated (June–Sept.) and the loading for the other eight months is relatively constant.

Figure 4 shows the diurnal (i.e., daily) electrical loading when the electrical loading reaches its peak at the five largest utilities in California for 2004. Most of the large utilities follow the same trend during the day, with the exception of SDG&E, which reaches its peak significantly earlier (2 p.m.) – mainly due to decrease in building electrical load. Also notice the close electrical loading shape between SCE and LADWP. Another interesting point to notice for 2004 California electrical loading is that although the average highest utility load month was July for all five utilities, none had their peak electrical load in July—it was either September or August.

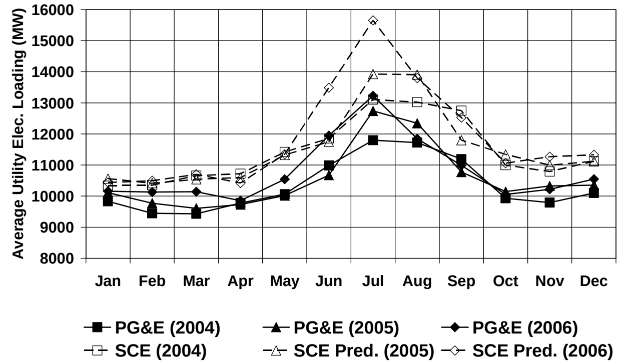

Fig. 3. Average monthly electrical loading for the two largest utilities in California (2004 – 2006).

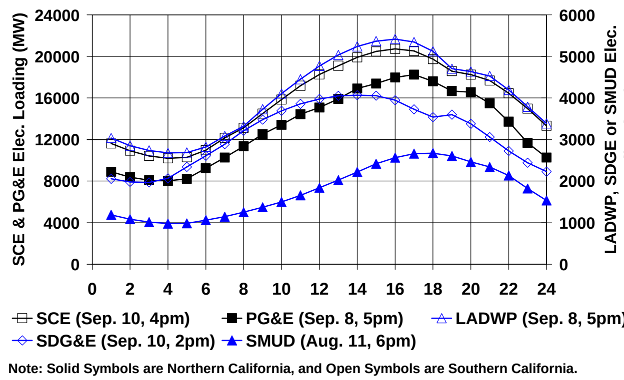

Fig. 4. Peak diurnal electrical loading during 2004 for five largest utilities in California.

2.2 Monthly Average Capacity Factors for Wind Farms and CSP Plants

Capacity factor (CF) is used as a measure of efficiency/energy output capability of power plants, where:

$$CF = \frac{\text{Energy Output (MWh)}}{\text{Rated power of Plant (MW)} * \text{hours in interval (h)}}$$

In Fig. 5, the monthly capacity factors are shown for two years (2005 and 2006) for three relatively recent wind farms installed in the three major wind farm regions. The wind farm in Altamont Pass peaks in generation in the summer, whereas the wind farms in Tehachapi and San Gorgonio Passes peak in the spring. One common characteristic of all three major wind farm areas is that they usually have their lowest output in the winter. Figure 6 shows the quarterly (or seasonal) capacity factors for individual wind farms in 2007 located in five different locations in California. It is interesting to note that the wind farm east of San Diego does best in the winter, which should help balance the wind farm electrical generation from other regions as more wind farms are installed in this area.

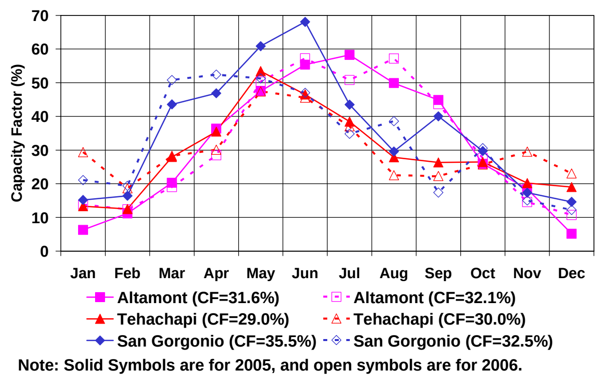

Fig. 5. Average monthly capacity factors for wind farms in major California wind farm areas (2005, 2006).

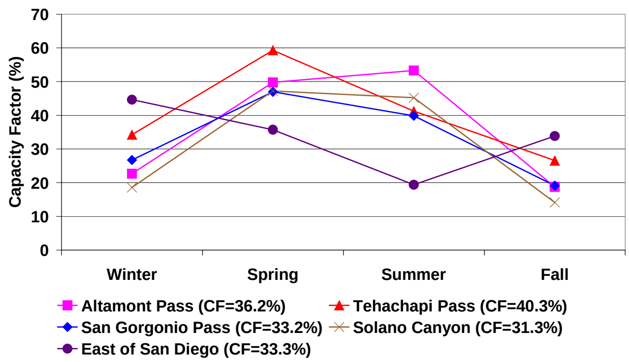

Fig. 6. Average seasonal capacity factors for wind farms at several locations in California (2007).

Figure 7 shows the predicted capacity factors of CSP plants (no storage and six hours of storage) according to NREL's CSP model and the DNI satellite data. The capacity factors peak in June, which is one month earlier than the utility load peak; but CSP plants are predicted to do well during the highest utility loading months (June–September). However, after these four months, the CSP plants decrease until a low capacity factor of 10%–20% is reached, while the utility electrical load is constant during this period. The effect of adding six hours of storage to the CSP plants is to increase the capacity factor by 50%.

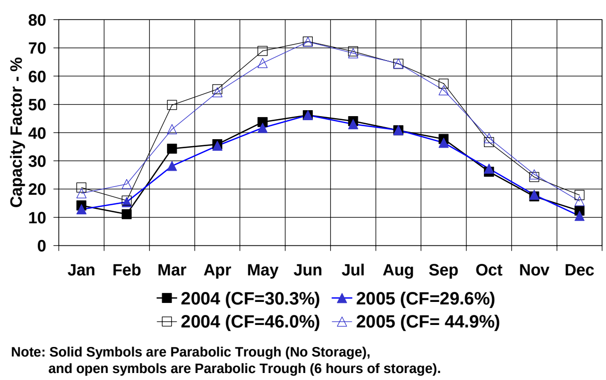

Fig. 7. Average monthly capacity factors for CSP plants in Mojave Desert of California (2004, 2005).

2.3 <u>Diurnal Renewable Energy Generation Analysis</u>

Figures 8 and 9 show the average daily capacity factors for wind farms for two years (2005 and 2006) for northern and southern California, respectively. The Altamont Pass wind farm has high capacity factors in the early morning and late night, with low capacity factors during midday—not a good match to utility load in morning and midday; but in the evening, this profile helps. Although the capacity factor is again lowest at midday for the Tehachapi Pass wind farm, it is not nearly as steep as for the Altamont Pass wind farm. Also shown is the prediction of a single larger wind turbine in San Gorgonio Pass based on hourly wind speed data obtained from the wind farm.

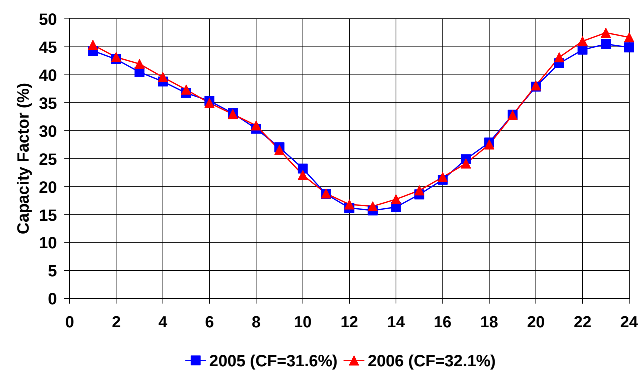

Fig. 8. Average diurnal capacity factors for wind farm in northern California (2005, 2006).

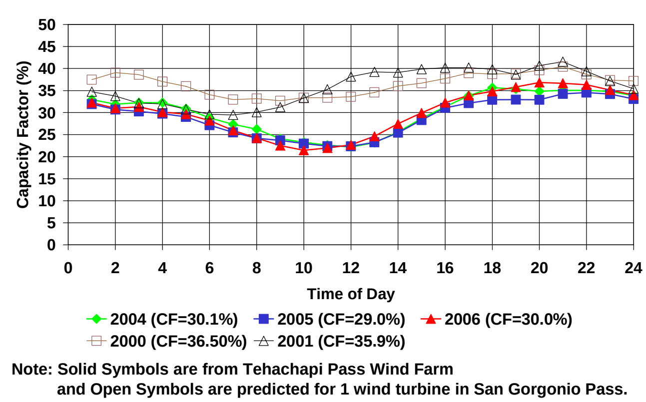

Fig. 9. Average diurnal capacity factors for wind farm in Tehachapi Pass(2004 - 2006) & single wind turbine prediction in San Gorgonio Pass (2000, 2001), both locations in southern California.

If this modeling is correct, then San Gorgonio is even more constant in output than Tehachapi (better for utility load match). However, as stated earlier, no hourly wind farm data were obtained for San Gorgonio Pass to confirm this.

Figure 10 shows the average daily capacity factor for the CSP plants with and without storage over 2004 and 2005. The mismatch with utility loading observed earlier with wind farms is compensated for by the CSP plants because the best capacity factor occurs at midday. Also, the CSP storage case improves the match significantly by adding electricity in the evening when utility electrical load is high.

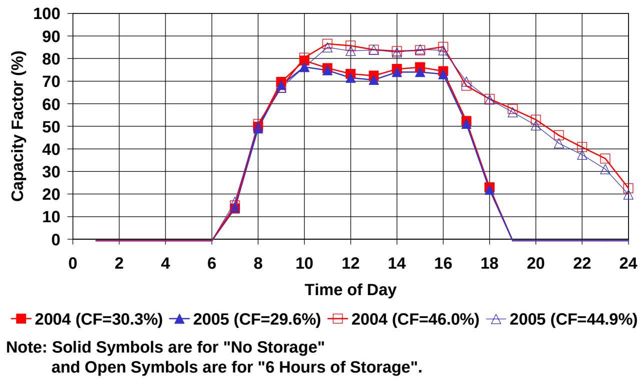

Fig. 10. Average diurnal capacity factors for CSP plants in Mojave Desert of California (2004, 2005).

The next series of figures show a comparison between southern and northern California for the following cases:

1. Wind farm alone (100 MW)
2. Solar power plant alone (100 MW)
3. Solar power plant with 6 h of storage (100 MW)
4. Wind and solar with storage (200 MW).

In Figs. 11 and 12, the comparison is made for a winter month. Very little difference is seen between northern and southern California for this month. The solar storage

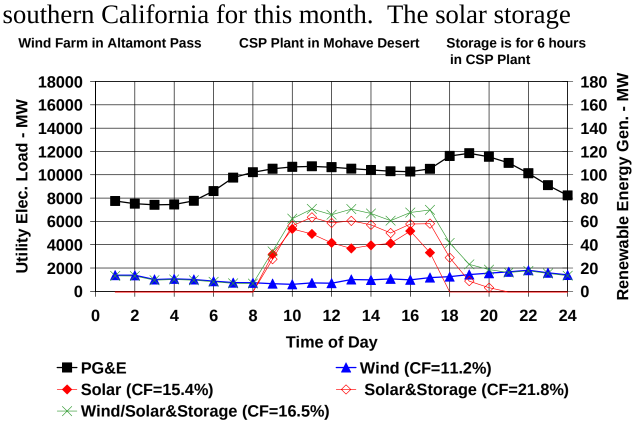

Fig. 11. Diurnal utility loading and renewable energy generation in northern California (Feb. 2005).

helped, but because the peak occurred later (in the evening, rather than in the late afternoon), it would have been better to store the energy during the day to be used in the evening when the peak demand occurred (e.g. from 10 a.m. to 4 p.m. the difference between solar and solar with storage could be added to solar from 4 p.m. to 8 p.m.). Neither wind nor solar did well during utility load increase in the morning.

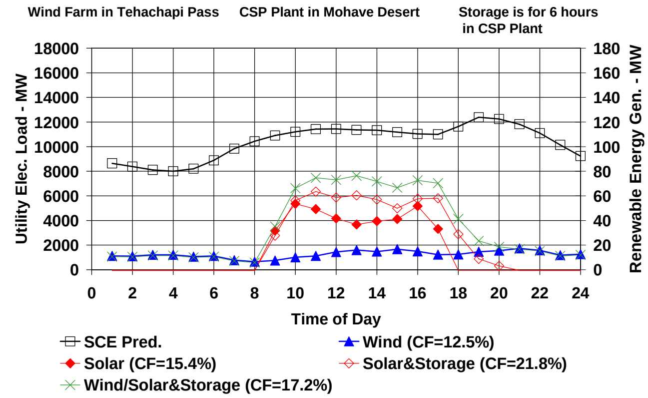

Fig. 12. Diurnal utility loading and renewable energy generation in southern California (Feb. 2005).

In Figs. 13 and 14, the solar/storage case and the wind/solar/storage case were the best match for a month in spring for both northern and southern California.

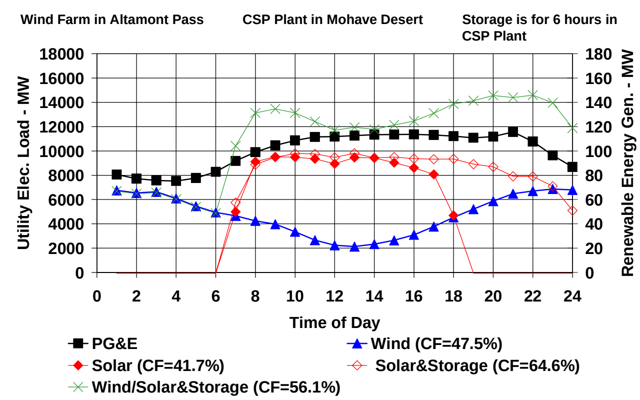

Fig. 13. Diurnal utility loading and renewable energy generation in northern California (May 2005).

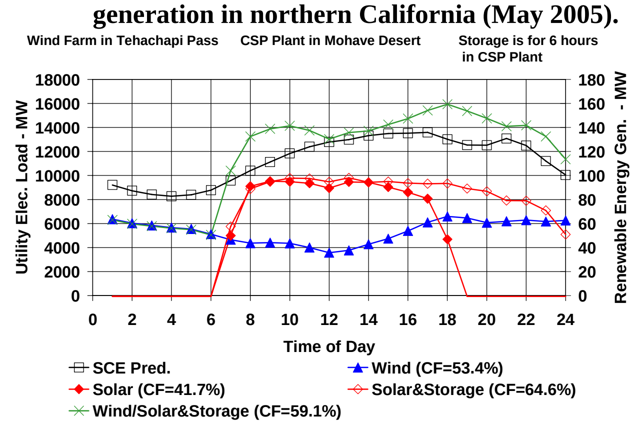

Fig. 14. Diurnal utility loading and renewable energy generation in southern California (May 2005).

It is very obvious that adding solar power plants to wind farms improved the utility load match for both northern and southern California. The failure of wind and solar energy to meet utility load well in winter was not seen in the spring. In the spring, the rise in utility load in the morning and during the day into the evening was met by the combination of wind and solar with storage for both northern and southern California.

Figures 15 and 16 show a comparison of how each renewable case does for the month with the highest average electrical load (i.e., July)—again, for northern and southern California, respectively. The higher capacity factor in Altamont versus Tehachapi in the morning and evening improved the utility load match at these respective time periods.

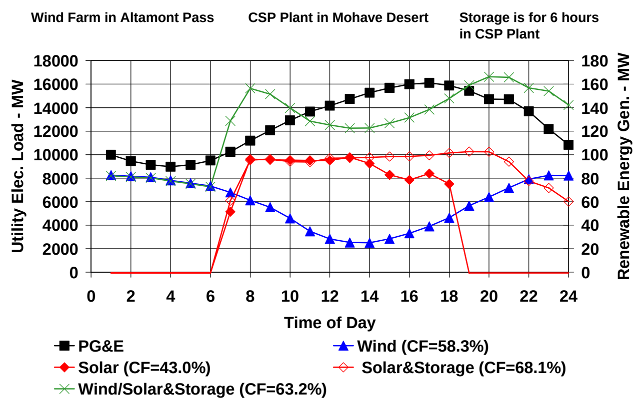

Fig. 15. Diurnal utility loading and renewable energy generation in northern California (July 2005).

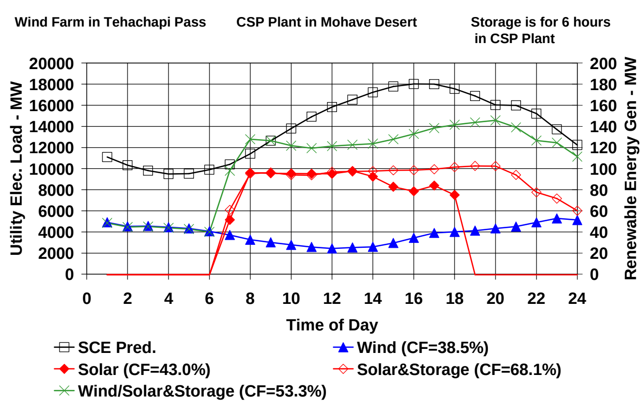

Fig. 16. Diurnal utility loading and renewable energy generation in southern California (July 2005).

No case is shown for fall since it is similar to winter.

Showing average utility electrical load and renewable energy generation during the month helps in assessing general matching of renewable energy generation to utility load, but it is always interesting to look at individual days to see what would actually happen on a particular day. Probably the best day to select out of the year from a utility perspective is the day when peak utility load was reached. This day is important to utility because they want to know how well each power plant will perform on that day because that is the day the utility is least likely to meet the load of all of its customers. Figures 17 and 18 show the hourly peak utility loading in 2005 (notice that peak electrical load occurs on different days in northern and southern California).

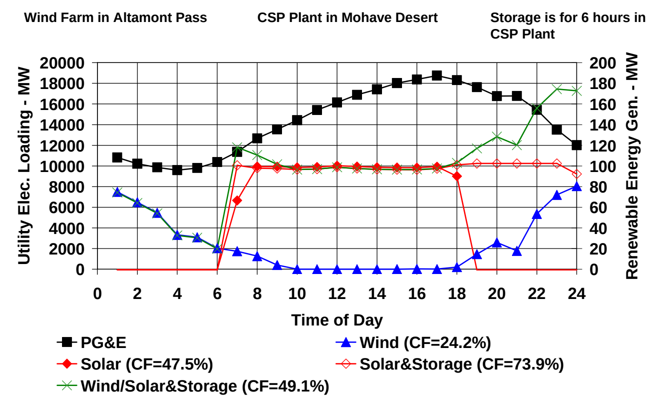

Fig. 17. Diurnal utility loading and renewable energy generation in northern California for hourly peak of year (July 14, 2005).

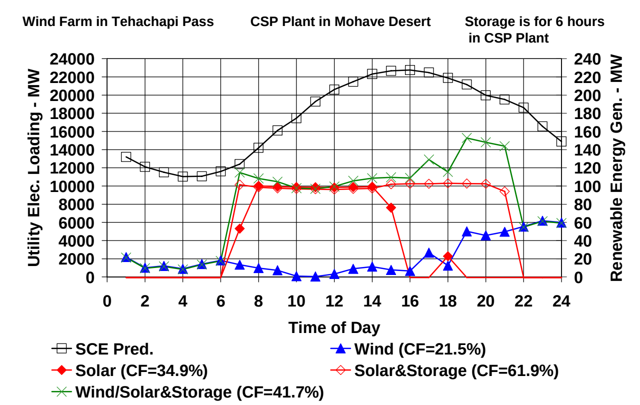

Fig. 18. Diurnal utility loading and renewable energy generation in southern California for hourly peak of year (July 22, 2005).

For northern California, the solar power plant is operating at maximum capacity at the time the peak utility load occurs (5 p.m.). Unfortunately, the wind farm is not generating any energy at the peak. However, the Altamont wind farm begins producing in the evening hours when the utility load is still high. The southern California case is significantly different because it occurred a week later. The CSP plant without storage was once again operating at full capacity until about 2 p.m. Then, over the next two hours, the solar thermal power plant dropped to zero when the peak occurred at 4 p.m.—likely due to clouds obscuring the sun. The Tehachapi wind farm, although only producing about 5 MW at the peak, was at least making a contribution. However, for the solar/storage case, there was no drop in solar power plant operating at maximum capacity during the peak and going to 9 p.m. before shutting off. For the wind/solar/storage case, the wind picking up in the evening helped to maintain renewable electrical generation (although only 50% of what it had been) up through midnight.

3. CONCLUSIONS

Solar thermal electrical generation was shown to be a better match consistently to utility electrical load than a wind farm, whether the wind farm was in northern or southern California. Adding six hours of storage to the solar thermal power plant substantially improved the utility load match in the evening, and also improved reliability in case clouds blocked the solar radiation at some point during the day. The price/kWh for a parabolic trough system with 6 hours of storage is predicted to be less than one without storage. The combination of wind farm and solar with storage was the best case for matching the utility load due to high winds helping in evening when utility load was still high. Storage also increased reliability for periods when lulls in wind energy occurred. Taking advantage of the different seasonal peaks for wind farms at different locations in California (summer peak for Altamont Pass, spring peak for Tehachapi and San Gorgonio Passes, winter and fall peak for east of San Diego) should allow for a significant percentage of electricity to be generated by wind and solar energy in California.

4. FUTURE WORK

Using a compressed air energy storage (CAES) system with a wind farm to store the excess wind-generated electricity during low utility load periods (late night and early morning) should further improve the renewable energy generation/utility load match. The efficiency of the one CAES system currently in United States is 50%, but new CAES systems are predicted to have an efficiency of 70% (9). Using CAES may violate use of production tax credit (PTC) since some natural gas is usually required. A CSP storage system efficiency of at least 95% is expected. Instead of using CAES, another possibility is to use the excess wind-generated electricity in the late night and early morning hours to power heaters to heat the liquid being used in the solar thermal power plant storage system.

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