Increasing the Percentage of Renewable Energy in the Southwestern United States

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ABSTRACT

An analysis was performed on the states in the Southwestern United States to determine methods to increase the proportion of wind and solar generated electricity in those states to levels as high as 40% of total electricity used. This analysis was performed by comparing the monthly and diurnal electrical load in each state to the electrical generation by wind farms and to the solar resource. Electrical utility loading was also compared to electrical generation by concentrating solar power (CSP) plants with and without storage for California. In order to meet the high electrical load in the evening for most states, CSP plants with storage capability (i.e. parabolic trough and power tower) are required. In addition, wind energy generated during the late night and early morning hours needs to be stored to match electrical loading. There are some locations in the Southwestern United States where the wind and solar resources are both excellent (capacity factors above 40% for both), so the efficient CSP plant storage system (97% efficiency) can be used to compensate for the intermittent production of electricity by both systems, but normally this is not the case. However, establishing a procedure/policy of supplying to the utility grid excess energy from wind farms during utility low load periods (e.g. late night and early morning) and extracting it for storage systems should help in achieving a high percentage of renewable energy use in the Southwestern United States. Also, if high renewable energy proportion is to be achieved, two-axis tracking systems like Dish Stirling and photovoltaic (PV) arrays will be required to add additional solar energy in the fall and winter when the parabolic trough method is insufficient for meeting utility electrical load requirement.

INTRODUCTION

Wind energy electrical generation has been the fastest growing electrical energy source in the United States for the past several years. The Energy Information Agency (EIA) reported "While electricity generation from the primary fuel sources decreased in 2008 (coal by 1.5%, natural gas by 1.5%, and nuclear <by> 0.03%), generation from all renewable sources increased … Most notably, wind generation increased 60.7%, from 34.5 million MWh in 2007 to 55.4 million MWh in 2008. For the first time, wind generation constituted a larger share of total electric generation than either petroleum or wood and wood-derived fuels." (http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html). This growth is mainly due to: (1) the low price for wind generated electricity (usually sold to the utility for less than $60/MWh), (2) renewable portfolio standards in 24 states which encourage the development of renewable energy (http://apps1.eere.energy.gov/states/maps/renewable_portfolio_states.cfm) , (3) the

federal production tax credit (PTC) which is about $20/MWh (http://www.dsireusa.org). The decrease in the price of wind farm generated electricity was due to the improvements in technology of wind turbine components (blades, generators, gearboxes, controllers, etc), and also to taller towers which have increased the annual capacity factors in United States from the 15 to 40% range to the 25 to 55% range. Capacity factor is defined as:

Capacity Factor = Energy Produced during Time Interval/[Rated Power x Time Interval] (1)

As larger amounts of electrical generation in the Southwestern United States (Fig. 1) are being replaced by renewable energy, the match between the renewable energy generation and the electrical utility loading must be evaluated. For each of the six southwestern states analyzed in this paper (Arizona, California, Colorado, Nevada, New Mexico, and Utah), we analyzed how wind and solar energy matched the:

1. monthly utility electrical load,
2. average diurnal utility electrical load, and
3. peak utility electrical load day during the year

In addition, the effect of combining wind farms with parabolic trough CSP plants was analyzed for California.

Fig. 1. Map of Southwestern United States.

The utility electrical loading for this paper was obtained from the EIA website (www.eia.gov) and the Federal Energy Regulatory Commission (FERC) website (www.ferc.gov). The wind farm data for all the states but California were obtained from the National Renewable Energy Laboratory (NREL) website (http://www.nrel.gov/wind/systemsintegration/) under the Western Wind and Solar Integration Study (WWSIS). The 10-minute wind farm data predicted on the NREL website were estimated at a 100 meter hub height, while the hourly wind farm data for California were obtained from the FERC website for a wind farm in northern California (hub height of 60 meters). According to the NREL web site, the average wind speed prediction could be off by as much as 1 m/s (large error occurred mainly for complex terrain), but for trends shown in this paper these data are sufficient. While there has been significant wind farm development (www.awea.org) in California (2723 MW), Colorado (1246 MW), and New Mexico (597 MW), wind farm development is just beginning in Utah (223 MW), Arizona (63 MW), and Nevada (0 MW). The hourly and monthly direct normal irradiation (DNI) data (i.e. DNI required to estimate performance of CSP plant) were obtained from NREL

(http://rredc.nrel.gov/solar/). The estimated CSP parabolic trough output for California (with and without six hours of storage) was estimated[1] using the Solar Advisory Model (SAM). This software is available for free from the NREL website. CSP solar plant data with 6 hours of storage had been estimated for several locations in the other five southwestern states, and were available on NREL web site, but did not discover this in time to include in paper. The solar resource is especially good in the Southwestern United States, and the wind resource varies from fair to excellent (Figs. 2 and 3). The monthly electricity usage and the electricity distribution (in percent) are shown below for states in the Southwestern United States (Figs. 4 and 5).

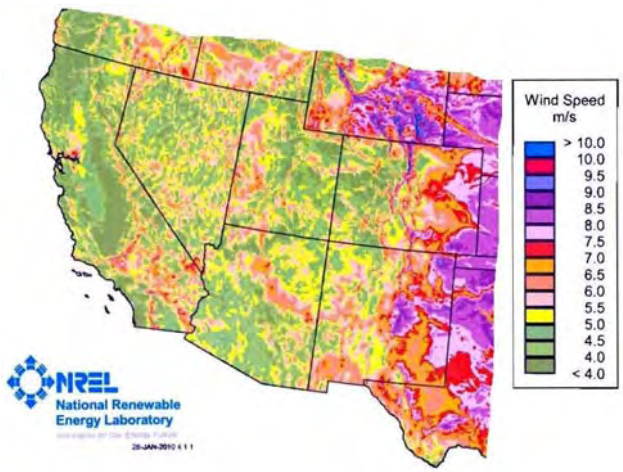


Fig.2. Wind Resource (80 m height) in Southwestern United States.

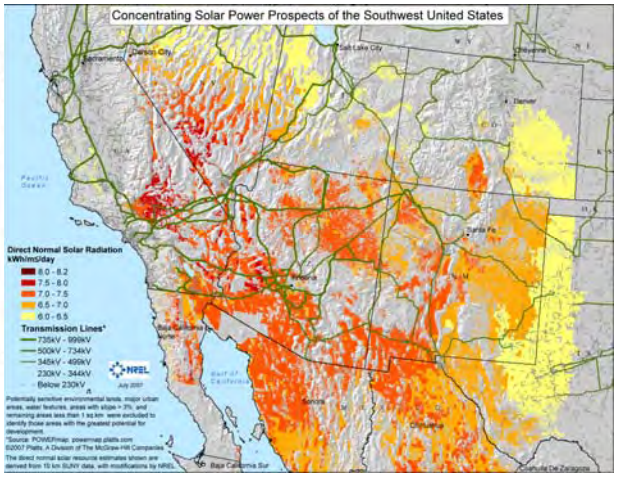


Fig. 3. Direct Normal Irradiance Solar Resource in Southwestern United States.

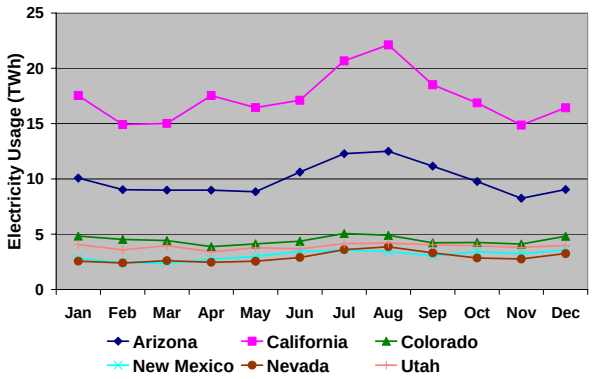


Fig.4. Electricity usage in Southwestern United States (2008, source: EIA).

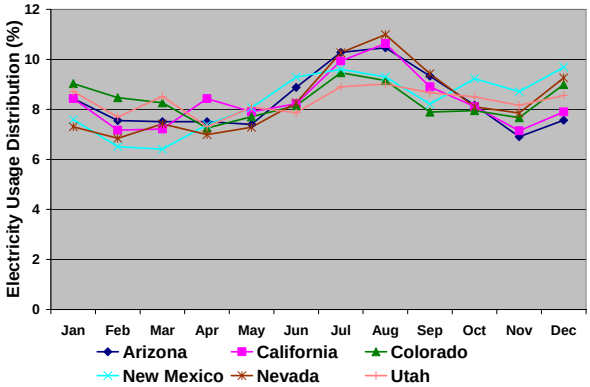


Fig. 5. Electricity Proportion in Southwestern United States (2008, source: EIA).

California uses the most electricity (17.5 TWh/month average) followed by Arizona (10 TWh/month average); the four other states average from 3 to 4.5 TWh/month. When viewing the usage distribution for each state, most of the electricity is used in the summer, but some states like Colorado, New Mexico and Utah have a secondary peak in the winter.

[1] Personal communication with Mark Mehos at NREL.

Background

In 2004, researchers at the USDA-Agricultural Research Service Conservation and Production Research Laboratory (CPRL) at Bushland, Texas became aware that in addition to the seasonal mismatch of utility electrical load requirement to wind farm generation in the Texas Panhandle, there was also a diurnal or hourly mismatch as well. At the time, additional transmission lines to carry the excess wind farm generated electricity to other locations seemed cost prohibitive, so an analysis of the problem was done to see how the renewable energy percentage could be increased without causing a decrease in reliability of the Xcel Energy subsidiary Southwestern Public Service (SPS) Company's electrical distribution system. At that time, the only conceivable storage system for wind farms in the Texas Panhandle was compressed air energy storage (CAES), but CAES was felt to be too costly. A report, published in 2005, also confirmed that CAES systems were too costly in the Texas Panhandle at that time (http://www.seco.cpa.state.tx.us/zzz_re/re_wind_projects-compressed2005.pdf). We knew that the diurnal (e.g. hourly) wind energy below a 40 m hub height matched the utility loading well (e.g. high wind energy in afternoon when utility load high, and low wind energy at night when utility load low), but we did not know why the diurnal match was poor (e.g. highest wind energy at night and lowest wind energy in afternoon) for hub heights in the 60 to 80 m hub height range. A local meteorologist (Jose Garcia) at the Amarillo National Weather Service told us that it was due to the sun causing mixing between the high wind energy aloft and the air closer to the ground. It then seemed logical to us that if the sun caused the diurnal mismatch, then it should help improve the diurnal mismatch. Not only did combining solar with wind improve the diurnal mismatch, we also found solar would improve the seasonal match and the utility peak loading as well (Vick et al, 2004). In 2006, we looked at other parts of Texas (west and far west), and found that there could be similar improvements in utility load matching by adding CSP power plants to wind farms (Vick and Clark, 2006). In 2007 we were collecting data on wind farms in the United States and discovered that the same diurnal mismatch between utility load and wind farm generation which is prevalent throughout the entire Great Plains (Schwartz and Elliott, 2006), also occurs in California (Vick et al, 2007). Again, we investigated if adding CSP power plants to wind farms would improve the diurnal mismatch and it was successful (Vick et al, 2008). While the diurnal mismatch for wind generation in Arizona is not as pronounced as most locations in the Southwestern United States, the loss in wind energy in the summer is worse, and CSP plants would definitely help the wind generation match to utility loading (Acker, 2007). NREL plans to release a Western Wind and Solar Integration Study to the public on May 20, 2010, which includes the southwestern states, as well as Kansas, Nebraska, Oklahoma, Texas, and Wyoming (http://www.nrel.gov/wind/systemsintegration/wwsis.html). A preliminary assessment of the results is available (Lew et al, 2009).

RESULTS

Parabolic Trough CSP Plant Analysis

Currently there are four types of solar energy being considered for utility scale electricity generation: parabolic trough CSP, power tower or central receiver CSP, Dish Stirling CSP, and photovoltaic (PV) – both concentrated and regular PV modules. Photovoltaic is also being considered on a large scale for distributed generator systems (e.g. agriculture, business, and

residential). Currently only utility scale PV, parabolic trough systems, and Dish Stirling are installed, but parabolic trough CSP is the largest in terms of installed MW. There are 11 parabolic trough CSP plants in the United States (nine plants totaling 354 MW in California installed in 1984-90, one plant rated at 1 MW in Arizona installed in 2006, and one plant rated at 64 MW in Nevada installed in 2007), but there are thousands of MW of parabolic trough CSP plants being planned for in the next five years in California, Arizona, Nevada, and New Mexico (http://www.nrel.gov/csp/solarpaces/by_country_detail.cfm/country=US).

Figure 6 shows the monthly average DNI solar resource for parabolic trough CSP plants at good solar sites in Southwestern United States over a 30 year period (1961-1990). Figure 6 shows that California and Nevada have excellent DNI solar resources, but the other states have good DNI solar resources too. Although the DNI solar resource in Arizona is not as good as California and Nevada due to monsoons occurring in late summer, the larger land area with good DNI solar makes it likely for extensive parabolic trough CSP plants in the future. Figures 7 and 8 show the solar resource for Dish Stirling and PV, respectively.

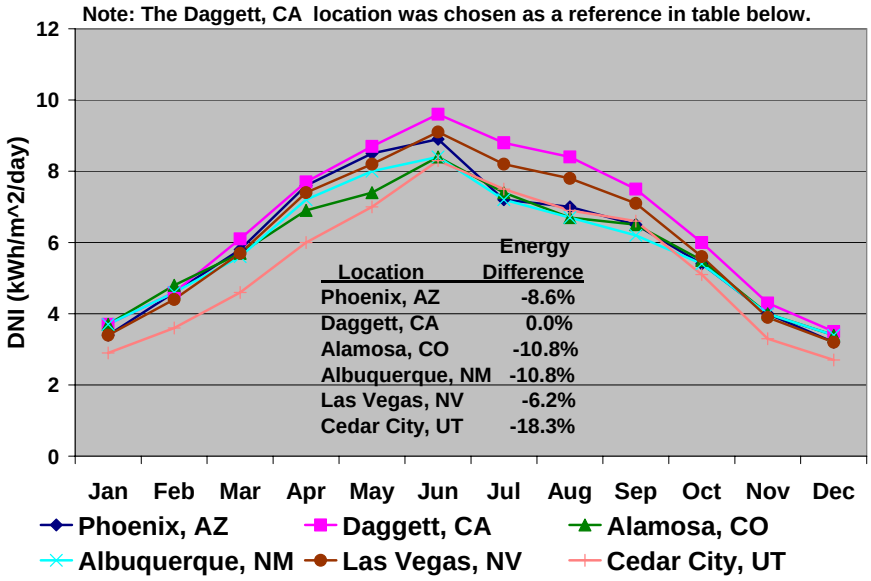


Fig. 6. DNI for horiz. N-S single-axis tracking east-west (1961-1990) – parabolic trough.

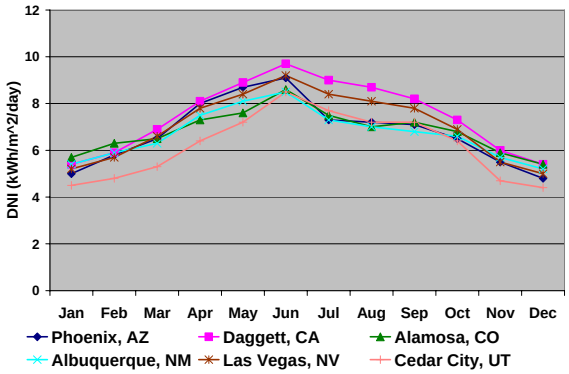


Fig. 7. DNI (two-axis) – Dish Stirling (1961-1990).

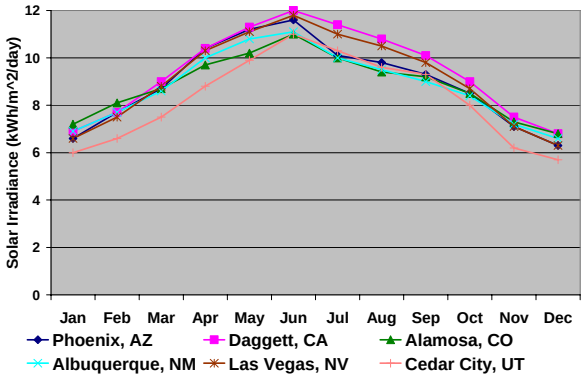


Fig. 8. Solar Irradiance (two-axis) – PV (1961-1990).

There are advantages and disadvantages with all the solar options. The parabolic trough systems have a long operational history (since the 1980's). The power tower/central receiver method is more efficient than the parabolic trough method because higher temperatures of the working fluid can be achieved due to higher concentration ratios. Both the parabolic trough and power tower have very efficient (97%) thermal storage capability. Parabolic Trough and Power Tower have a design point efficiency (DPE) in range of 25%, but Dish Stirling has a DPE above 30%. Crystalline silicon (c-si) PV has a DPE range between 14 and 18%, and that of thin film cadmium telluride (ca-te) is 9%. Also, both c-si and ca-te PV have decreased in price significantly in the past few years. Typically parabolic trough and power tower use water for both working fluid and for cooling, but since the best sites would be located in the desert, water availability is of concern. However, these plants can be designed with dry cooling resulting in a 90% reduction in water use at only a slight cost penalty. While Dish Stirling and PV do not require water, they also both do not have the capability of storing energy thermally, and although batteries, CAES, and pumped storage[2] could be considered, the energy loss can be as high as 30 to 50%.

The electricity production from parabolic trough CSP plants in California (SEGS I – IX) and Nevada (Nevada Solar 1) are shown in Figs. 9 and 10, respectively. These CSP plants use conventional boilers for electricity production like any natural gas, coal, or nuclear power plant. The SEGS plants (Price and Kistner, 1999) that provide power to California are hybridized, so when there is not enough solar heat available, natural gas can be used. Only 10% of the energy produced during 2008 was from natural gas, but in 2009 about 30% was natural gas. The Nevada Solar 1 plant has no fossil fuel backup or thermal storage capability. Initially when one of the first CSP plants was installed in California, a solar thermal storage system was also installed, and 97% efficiency was measured (Sargent and Lundy, 2003). In Spain several parabolic trough CSP plants have been installed with 7.5 hours of solar thermal storage. Capacity factors in the 40% range are predicted for parabolic trough power plants which have six hours of storage capability and are scheduled to be installed in sunny areas of the Southwestern United States.

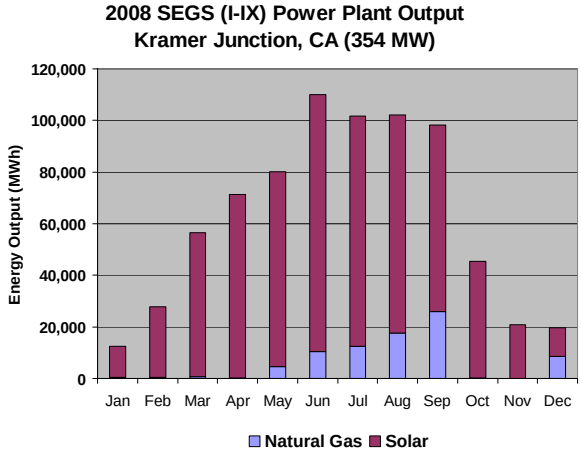


Fig. 9. Parabolic Trough (1990 installed).

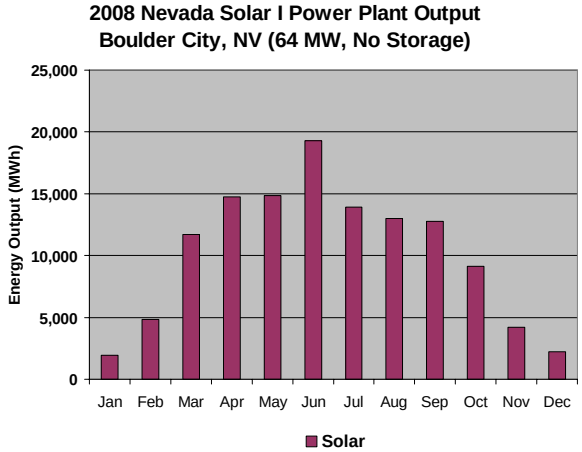
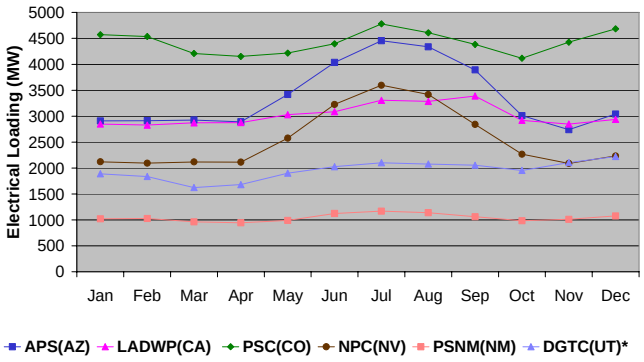


Fig. 10. Parabolic Trough (2007 installed).

[2] Pumped hydro is a system in which electricity generated during periods of low electrical load is used to pump water to an elevated reservoir, and then during hours of high electrical load, electricity generated via a hydroelectric power plant.

Utility Load Match to Wind Farm Output & Solar Energy Resource in Southwestern United States

Figures 11 to 13 present the monthly utility electrical loading, predicted wind farm capacity factor, and estimated DNI solar resource for select utilities and locations in each of the states in the Southwestern United States during 2004. The electrical loading shows a definite rise in the summer for Nevada and Arizona, but the rise is not as pronounced for the other southwestern states. It should be noted that the utility electrical loading for Utah was increased by a factor of 10, in order to be comparative visually to the other states' utilities.



*In order to see monthly trend of Utah utility, MW values were increased by factor of 10

Fig. 11 Monthly Avg. Elec. Loading for Utilities in Southwestern United States (2004).

In Fig. 12 the estimated wind farm capacity factor at a 100 m hub height (with the exception of California which is based on actual wind farm data at a 60 m hub height) is shown for various sites in the Southwestern United States. All of the wind farms show a drop in capacity factor below 25% during the summer months with the exception of California. Estimated wind farm capacity factor peaked in September for Colorado, which is atypical, but compared well with actual wind farm data. In Fig. 13 the DNI solar resources (derived from SUNY satellite for 2004) are shown for select locations in the Southwestern United States. These data are similar to data shown previously from the period 1961-1990 in Fig. 7. Colorado DNI is low, compared to other states, which may be due to forest fires occurring that year. Although electrical generation from the wind farms had the opposite trend from the electrical loading trend, if wind and solar power are combined, the combination should meet a larger percentage of utility loading in these states.

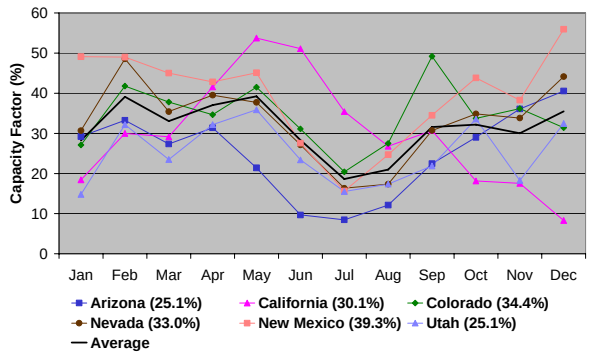


Fig. 12. Est. Wind Farm Capacity Factor for Southwestern United States (2004).

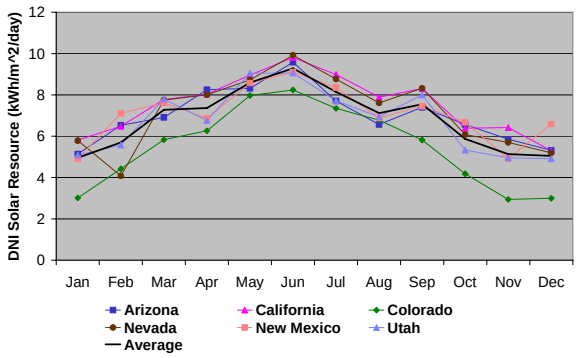
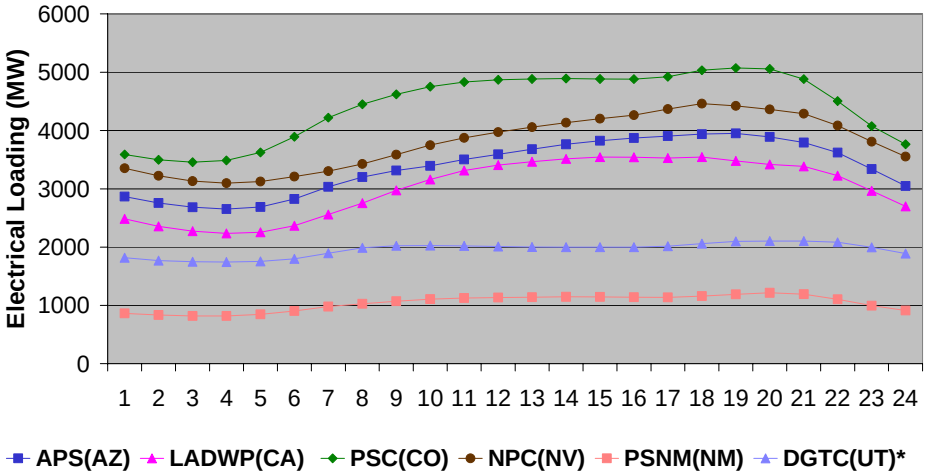


Fig. 13. Est. DNI Solar Resource for Southwestern United States (2004).

Figures 14 to 16 present the average diurnal: utility electrical loading, estimated wind farm capacity factor (again, actual wind farm capacity factor for California), and the estimated DNI solar resource for the Southwestern United States during 2004. The electrical loading is lowest in the early morning hours and peaks either in the late afternoon or evening for all the utilities selected (Fig. 14).



*In order to see diurnal trend of Utah utility, MW values were increased by factor of 10

Fig. 14. Diurnal Avg. Elec. Loading for Southwestern United States Utilities (2004).

Figure 15 shows the estimated diurnal wind farm capacity factor (again, actual wind farm data shown for California) for the Southwestern United States in 2004. New Mexico and Colorado had the highest capacity factors, but all the states had at least fair capacity factors (above 25%). New Mexico showed the best probability in terms of matching the utility electrical loading (e.g. high capacity factor in late afternoon and evening). Figure 16 shows the estimated diurnal average DNI solar resource for the Southwestern United States in 2004. The DNI solar resources for all the states match the utility loadings well with the exception of the evening hours. In the next section, it will be shown that the addition of solar thermal storage can correct that deficiency.

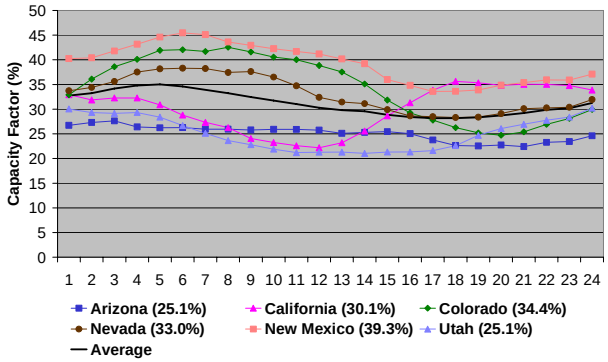


Fig. 15. Est. Wind Farm Capacity Factor for Southwestern United States (2004).

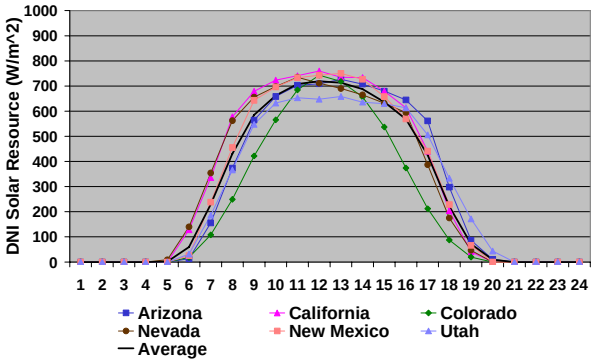


Fig. 16. Est. DNI Solar Resource for Southwestern United States (2004).

Figures 17 to 19 show the utility electrical loading, estimated wind farm capacity factor (actual capacity factor for California), and the estimated DNI solar resource for peak utility loading day for each state in the Southwestern United States in 2004. Peak utility loading occurs in late afternoon and in the summer months (July, August, and September) for all of the utilities (Fig 17).

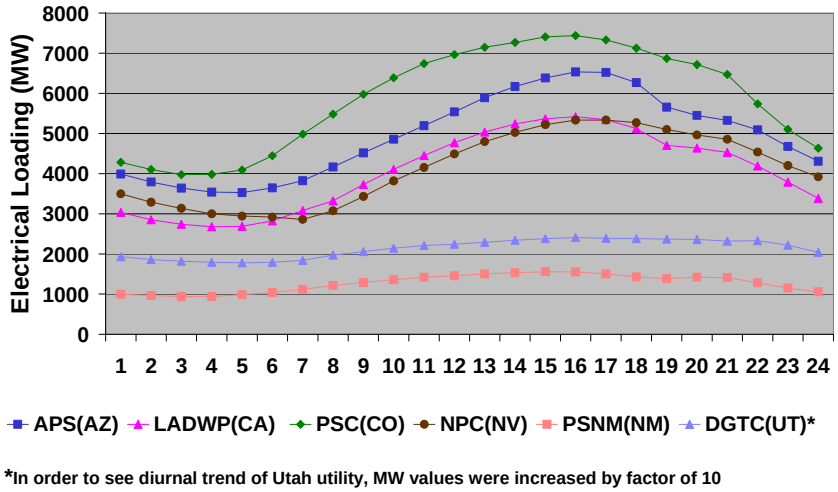


Fig. 17. Diurnal Elec. Loading on Peak Load Day for Southwestern United States (2004).

Figure 18 shows the predicted wind farm capacity factor (again, actual wind farm data for California) for the Southwestern United States on peak utility load day for each state in 2004. Unfortunately the minimum capacity factor for all wind farms occurs in late afternoon when the peak utility electrical load is reached. The wind speed picks up in the evening in California, so it would help when solar resource is declining. Figure 19 shows the estimated diurnal DNI solar resource on the day when utility load peaks. The solar resource is high for most of the states during the afternoon with the exception of Utah.

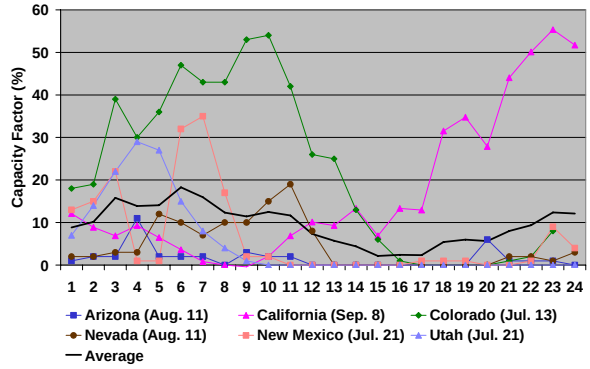


Fig. 18. Est. Wind Farm Capacity Factor on Peak Load Day for Southwestern United States (2004).

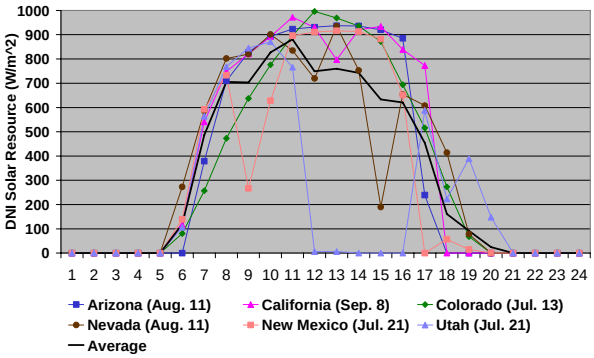


Fig. 19. Est. DNI Solar Resource on Peak Load Day for Southwestern United States (2004).

The DNI solar resource picked for Utah was Cedar City, a city located in the southwestern corner of the state, while the population centers are located in the center part or the state. The DNI solar resource for Salt Lake City was high on this particular day, but significantly less than Cedar City for the annual average.

Utility Loading Versus Wind Farm and Parabolic Trough CSP Plant with and without Storage for California

The next series of figures show a comparison in California of utility load match to various rated amounts of renewable energy (RE). The RE cases analyzed were:

1. Wind farm alone (100 MW),
2. Parabolic trough CSP plant alone (100 MW),
3. Parabolic trough CSP plant with 6 h of storage (100 MW), and
4. Wind farm and parabolic trough CSP plant with 6 h of storage (200 MW).

In Fig. 20, a comparison of RE generation to utility loading is presented for a winter month. The solar storage helped in RE generation/utility loading match in the afternoon, but because the peak utility load occurred in the evening, rather than in the afternoon, very little RE generation was available at the peak. Neither the wind farm nor the parabolic trough CSP plant would be a good match for utility load increase in the morning or in the evening where the peak load occurred. A two-axis tracking solar system could help in the evening and somewhat in morning, but wind energy from another location with a higher capacity is needed for utility loading rise at 6 a.m. in morning. In Fig 21, the wind farm/solar power plant/storage case was the best match to the utility loading for a month in the spring. The wind farm by itself does not match the utility loading well, but when combined with the solar power plant with storage, the wind farm helps from 6 a.m. to 9 a.m. and then again in the evening from 6 p.m. to 10 p.m. Without storage, the wind farm would improve the utility load match from 3 p.m. to 10 p.m.

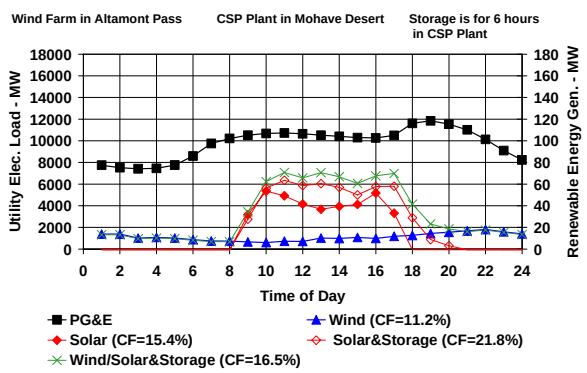


Fig. 20. Utility Load Match to RE for a Winter Month (Feb, 2005).

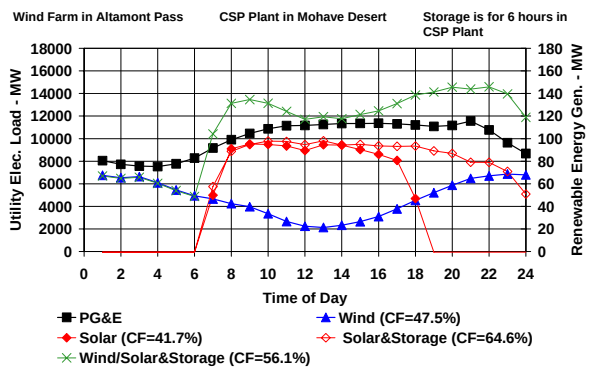


Fig. 21. Utility Load Match to RE for a Spring Month (May, 2005).

Fig 22 shows a comparison of how each RE case does for the month with the highest average electrical load (i.e., July). The solar/storage and the wind/solar/storage cases do a good job in matching the utility loading in July. No case is shown for fall since it is similar to winter. Fig 23 shows the hourly peak utility loading in 2005. While not producing power at the peak hour of 5 p.m., the wind farm output would be most effective in the morning and evening. The solar power plant, with storage, produced energy at rated power from 8 a.m. to 11 p.m. This analysis shows that adding a solar power plant to a wind farm would improve the utility load match for California. While RE generation and utility load during a winter month was not a good match, the RE generation was a good match to utility loading for spring and summer months. In the spring and summer, the rise in utility load in the morning, during the afternoon, and in the evening was met by the combination of wind farm and solar power plant with storage. On the

peak load day, the wind farm did not match the utility load well while the solar power plant with storage was a very good match. For more information on how well wind farms and parabolic trough CSP plants matched utility loading in California, see (Vick et al, 2008).

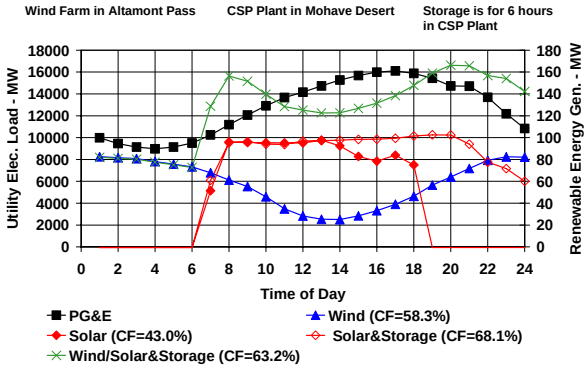


Fig. 22. Utility load Match to RE for a Summer Month (Jul, 2005).

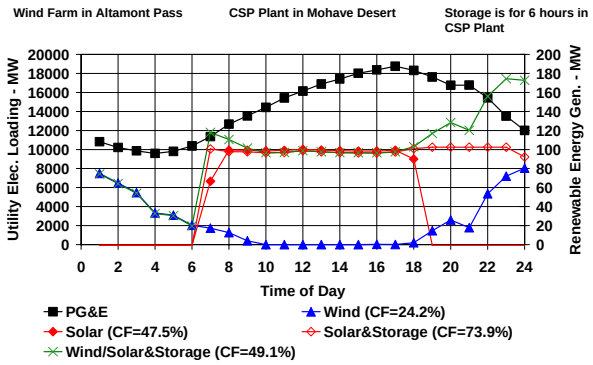


Fig. 23. Utility Load Match to RE on Peak Load Day (Jul 14, 2005).

Final Thoughts on Achieving High Percentage of Renewable Energy Penetration

A key to achieving a high renewable energy proportion is generating electricity with a combination of wind farms, solar power plants, and distributed solar/wind smaller systems dispersed over a large geographic area with efficient energy storage. For the parabolic trough and power tower CSP systems, it is convenient to store the thermal energy at the site. However, storing the excess renewable electricity in batteries, CAES, or pumped hydro at each location will probably be inconvenient. Figure 24 shows the electrical grids in the United States and Canada.

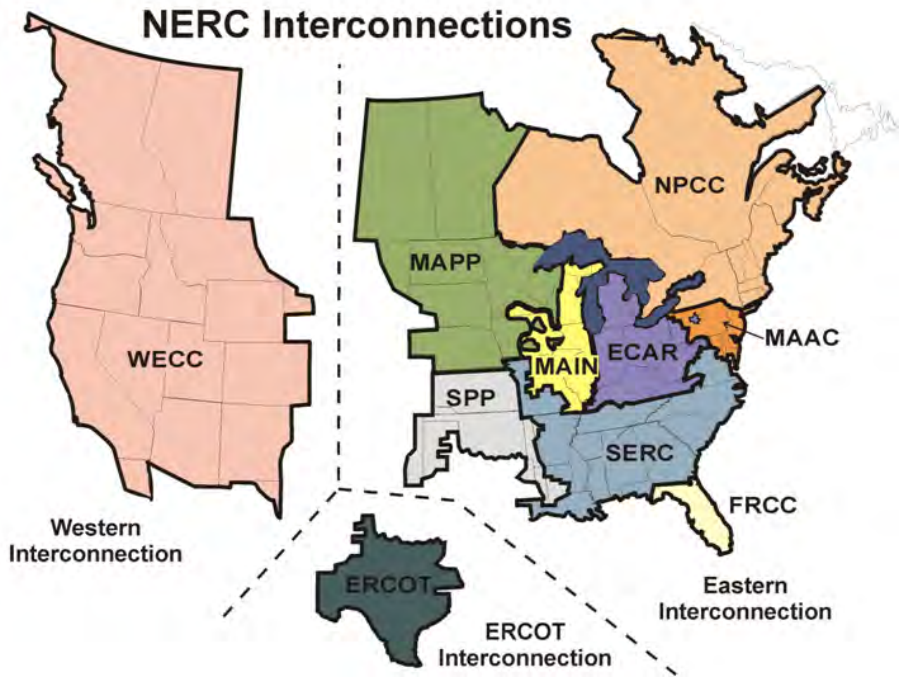


Fig. 24. The Three Electrical Grids in the Mainland United States and Canada.

Since the Southwestern United States is entirely on the WECC electrical grid (with exception of some land in eastern New Mexico which unfortunately for Southwestern United States has some of best combined solar and wind resources), the excess renewable energy generated electricity can be pumped into the grid, and then taken out at storage locations at other locations without excessive operational changes in utilities' steam power plant operations. If a cost effective procedure/policy is implemented in the Southwestern United States for transferring excess renewable energy electricity from generation point to a storage point on the utility grid, then more than likely a high renewable energy proportion can be achieved.

CONCLUSIONS

The solar resource used for estimating CSP plant output was shown to improve the match to utility electrical loading in all of the Southwestern United States (Arizona, California, Colorado, Nevada, New Mexico, and Utah) versus just the use of wind farms alone. The installation of parabolic trough CSP plants will improve the utility load match monthly, diurnally, and on peak load days for all six southwestern states compared to using wind farms alone. However, high wind energy occurring in winter and spring and at night time at several locations in the Southwestern United States will actually compliment the high solar energy in the summer and during the daylight hours. Adding solar thermal storage to parabolic trough CSP in California greatly compensates for the intermittence of wind and solar energy generated electricity which is the main complaint from utilities with wind or solar energy on their systems. Another complaint by utilities about wind farm output is that frequently wind farms do not help at the peak utility load hour during the year, and this was seen for all six states analyzed in 2004. The solar energy at this peak hour was normally high during the peak load period. When the match was not good, it was due to the solar resource location being a long distance from electrical load center. In this paper we indicate that most states in the Southwestern United States had a high average utility load in the evening which could be accommodated by adding six hours of solar thermal storage. Wind energy also usually helps with the high utility load in the evening. Other forms of solar energy (power tower, Dish Stirling, and/or PV) would also be needed in the fall and winter to be able to increase the total percentage of renewable energy in the Southwestern United States. To achieve a high percentage of renewable energy generation, the following objectives would have to be achieved: add parabolic and power tower CSP plants with storage, develop a highly efficient way of storing solar (PV or Dish Stirling) and wind generated electricity, and implement a cost effective procedure/policy to upload excess renewable electricity from the generation point and transfer it to remote storage plants via the WECC utility grid.

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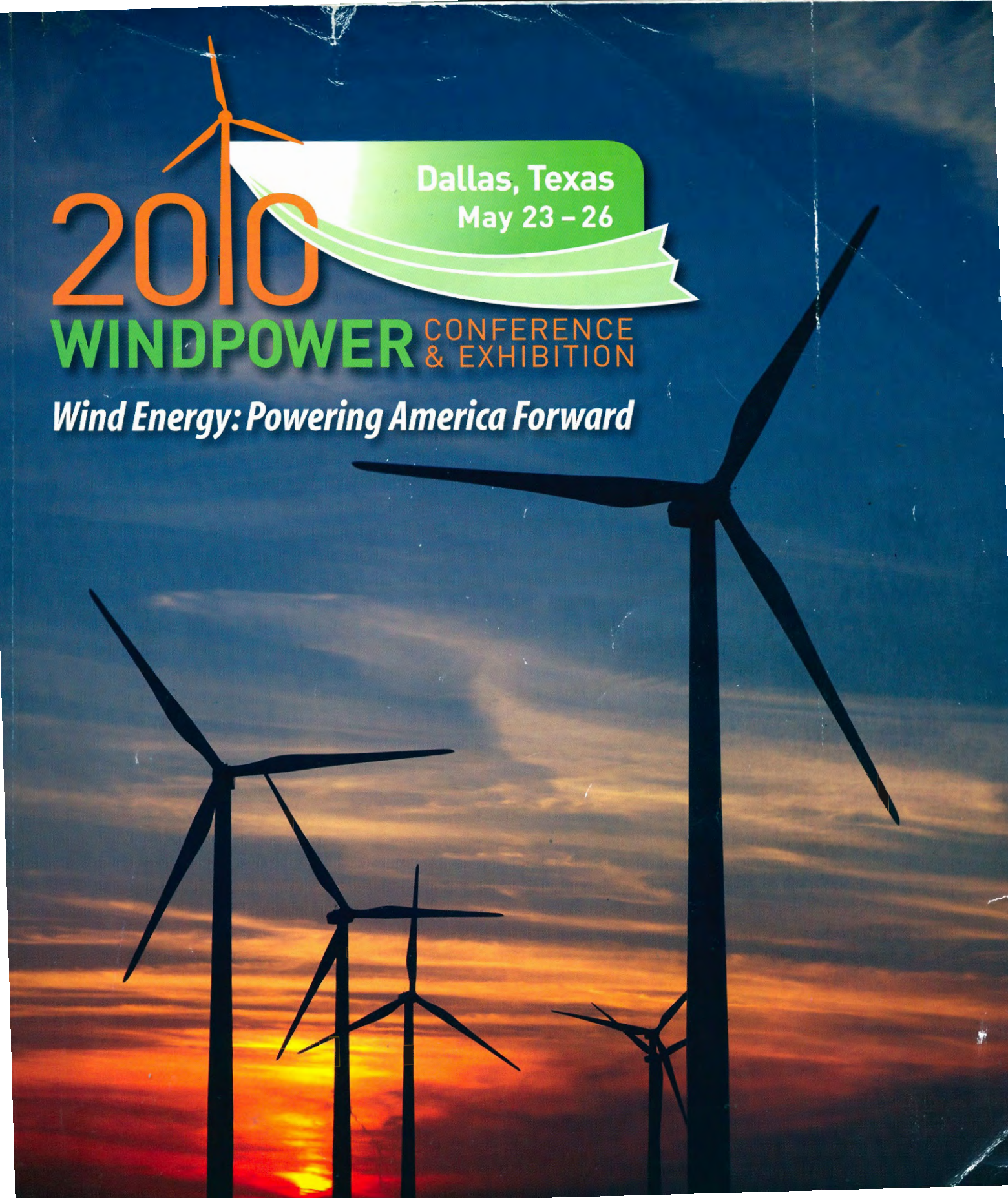
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