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TOTAL SOLAR FIELD DIRECT NORMAL INSOLATION MEASUREMENT METHOD UNDER INVESTIGATION FOR ASME PTC 52

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ABSTRACT

With an overwhelming push for “green” renewable energy in the recent years, the American Society of Mechanical Engineers (ASME) Performance Test Codes (PTCs) are being called upon to develop standards for testing solar power facilities. To meet the challenge, ASME formed a committee to develop PTC 52, Performance Test Code on Concentrated Solar Plants.

It was recognized early on by the PTC 52 committee that there is a critical need in the Power Generation Industry to develop a commercial grade test method for the measurement of Total Solar Field Direct Normal Insolation (TSFDNI) that may be used for performance testing. The TSFDNI measurement is important because it is the fuel source (input) for solar power technologies, and is therefore a primary measurement parameter that enters into the solar-to-thermal conversion efficiency calculations.

To meet the recognized need, ASME engaged McHale & Associates, Inc. (McHale) in a research project to investigate a solution to this issue so that the industry may be provided with guidelines that can be included in ASME PTC 52 for the accurate determination of TSFDNI. The product of this effort is a conceptual measurement technique, or method, that utilizes a combination of currently available terrestrial point measurements, aerial photography, and pixel contrast recognition software that allows for a visualization of the entire solar field to provide an accurate determination of TSFDNI by "filling in the gaps" between the point measurements while keeping the number of terrestrial point measurements practical.

This paper will illustrate the conceptual TSFDNI measurement technique and how it can effectively combat the issues associated with performance testing on days when the field may see areas of haze, dust, aerial obstructions with shadows, or cloudiness which are not visible from the ground by the testing personnel or unavoidable by commercial/contractual constraints; thus allowing performance testing to be conducted on partially cloudy days which would allow facilities to be commercially accepted with confidence at an earlier date than if they had to wait for a “clear solar day”. Guidance on the best practices for deployment in a grid style system in combination with an aerial photography pixel analysis method will be presented along with discussion on how the method will result in acceptable predicted error of the TSFDNI measurement through reducing error associated with the spatial components of the field measurements.

This paper will further discuss how this method can be used beyond performance testing by providing the key boundary

information for performance models, performance monitoring systems, dispatch models, etc. Ultimately the paper will not only present just how important this measurement technique is for the development of ASME PTC 52, but also to the industry and technology itself, by presenting a way to overcome the current industries short falls in accurately determining TSFDNI.

INTRODUCTION

Since its formation, the ASME PTC 52 committee has made great progress on its mission to provide procedures, methods, and definitions for the performance testing of the primary solar to thermal conversion systems and thermal storage systems associated with Parabolic Trough, Linear Fresnel, Power Tower, and Dish/Engine Concentrated Solar Power (CSP) plants. Yet, based on current engineering knowledge and practices, one area that continues to be difficult to determine with a high level of accuracy is the solar to thermal and/or solar to electrical conversion efficiency for CSP facilities; while taking into account the costs of the test and the value of the information obtained.

As Direct Normal Insolation (DNI) is the fuel source (input) for solar power technologies (Photovoltaic and Concentrating Solar Power), it is therefore a primary measurement parameter that enters into to the solar to thermal and/or solar to electrical conversion efficiency calculations. Current guidelines outside of the ASME state that performance testing should be conducted on a “clear solar day” [1] and that the Total Solar Field Direct Normal Insolation (TSFDNI) measurement can be based on a single measurement point of DNI. During meeting deliberations on this topic, the discussions continue to revert back to the question of how solar-to-thermal energy conversion efficiency is determined if testing does not occur on a clear solar day and there is not uniform solar exposure to the solar field. As the demographic of people that make up the committee are all technical experts in the industry, and agreement on this most fundamental measurement of TSFDNI cannot be reached with current industry experience, practices, or expertise, it was recognized early on that there is a critical need in the Power Generation Industry to develop a commercial grade test method for the measurement of TSFDNI that may be used for performance testing.

In order to create a new method for determining TSFDNI, an evaluation of the current methods and techniques must be completed [2]. This paper is intended to discuss the shortfalls of the current techniques, which will allow for a better understanding of the exact hurdles that need to be overcome in a new method. Once these hurdles are identified, a new method can be created which obviates their existence.

CURRENT METHODS FOR TSFDNI MEASUREMENT

Current guidelines indicate that testing should be conducted on “clear solar days” only [1], utilizing a single point DNI measurement. Initially, this doesn’t seem like a problem, as these technologies were created to be in sunny places, which would indicate that a clear solar day can be obtained easily. But, as solar energy becomes more popular in the power industry, it will be summoned upon to be placed in areas that do not have ideally clear solar days for the majority of the year. Additionally, they will have commercial obligations and implications if they cannot prove their guarantees in a set amount of time.

Regardless of where these technologies are placed, if they cannot be evaluated properly during times of shading, then it will be very difficult for them to move forward. Placing a clear solar day requirement on solar facilities is a limiting factor that reduces their availability to the power market. More can be learned from solar facilities and their efficiencies if more were known about their fuel source during all times, clear and cloudy. Let’s consider a single DNI measurement point method for determining TSFDNI. Assuming the TSFDNI is known to be 1000 W/m^2 during zero percent shading and zero W/m^2 during 100 percent shading of the entire solar field, an error analysis can be created for the method itself. As can be seen in the graph below (Figure 1), a single measurement point is not an effective way to measure TSFDNI over a solar field when shading is present.

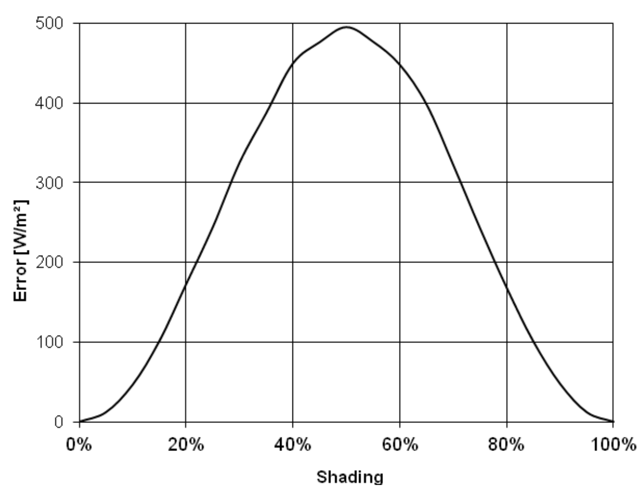

Figure 1. Results of Monte-Carlo Simulation Error vs. Shading with a single instrument

Figure 1 indicates that as the amount of shading increases, so does the amount of error associated with the measurement method of TSFDNI. Note that this error analysis focuses only on the method, not the error associated with the instrumentation used, as instrumentation error is not in question due to its overall development and research. On zero percent shading of the field, there is zero error in the reading, and the same for one hundred percent shading. Notice that the error associated with the single measurement method creates a bell curve. This bell curve signifies an increase, peak, and then decrease of error as the shading is increased across the field. This is an expected result as error associated with TSFDNI is affected by area coverage and the location of measurements in the field.

With a potential of 50 percent error in the TSFDNI measurement utilizing a single instrument method, it is difficult to determine actual performance of the unit. It is even more difficult to model a facility over a period of time, say a year; as this period of time, one year, will certainly have some periods of shading. A new question now arises; how can the error associated with the measurement of TSFDNI be reduced?

TERRESTRIAL GRID SYSTEM

The first train of thought is to increase the number of instruments used in the measurement field; measuring DNI in multiple places across the solar field in order to obtain a more accurate determination. This comes at a cost, as a single point DNI measurement is currently around the $20,000 to $25,000 range. And even then, how much does it impact the error associated with the measurement? Figure 2 gives an example of five DNI measurement points for determining TSFDNI, one stationed in the center of the field and the remaining four at each corner of the field (assuming a square field).

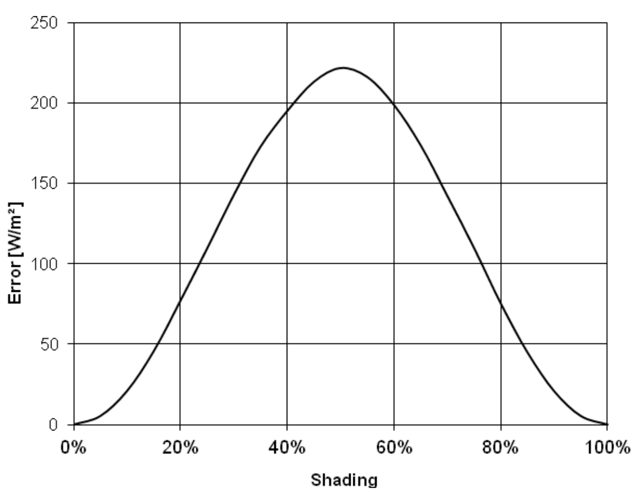

Figure 2. Results of Monte-Carlo Simulation Error vs. Shading with five instruments

Figure 3 shows both the single point measurement method and terrestrial five point grid measurement method on the same scale.

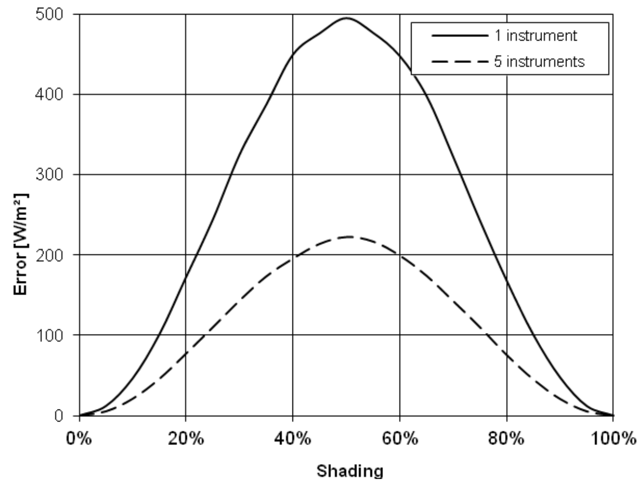

Figure 3. Results of Monte-Carlo Simulation Error vs. Shading with a single instrument and five instruments

In comparison to a single instrument, it can be seen that a terrestrial grid of five instruments may reduce the error of TSFDNI by over half at the peak of the bell curve. This reduction is substantial with only the addition of 4 instruments, but the error is still significant to the TSFDNI measurement, which at the peak of the curve can be in the order of over 20 percent error. By adding more instruments, the obvious expected result is a lower error; Figure 4 shows a graph indicating the measurement error vs. number of DNI instruments during a 25 percent shading period.

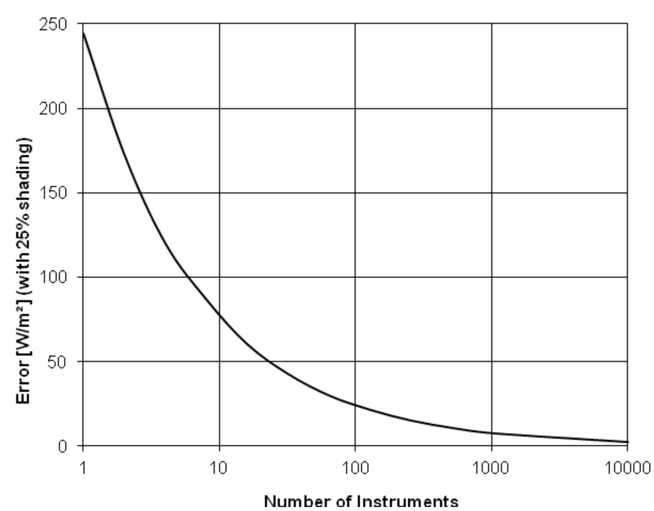

Figure 4. Results of Monte-Carlo Simulation Error vs. Number of Instruments with 25% shading

By adding more and more instruments to the solar field, the spatial error in the measurement is reduced. This error is associated to the unknown DNI which is between the measurement points and not actually measured. If the DNI measurement plane is not uniform, the error associated increases drastically. From Figure 4, it is easy to see that as more instruments are placed in the field, the measurement error decreases. But again, cost is the limiting factor; the estimated cost of 100 DNI instruments is approximately 2.5 million dollars, which would allow for a possible error in the order of 25 W/m^2. Another look at the terrestrial grid system shows that a different approach can be taken with minimal effect on the error of the TSFDNI measurement. To help reduce cost, only a single DNI instrument could be used in conjunction with lower cost GHI instruments. The reduced cost also comes with lower instrument accuracy. Typical accuracies of DNI instruments are in the order of two percent, where GHI instruments are between three and five percent. In comparison to an all DNI instrument grid system, it can be assumed that a hybrid grid of DNI and GHI instruments would result in a small TSFDNI error difference in the favor of the all DNI instrument grid. However, the projected cost reduction of using 100 GHI instruments (total cost estimated at $250,000) in place of 100 DNI instruments (total cost estimated at $2,500,000) is approximately $2,250,000 in instrumentation alone.

Even with a terrestrial grid system, utilizing DNI and GHI instruments in combination, there is a point which the cost outweighs the benefit and it is very impractical to place 10,000 instruments out for a performance test. As a result, the next question must be answered; how can the spatial component of the error be reduced while keeping the costs down using multiple instruments?

AERIAL DISTANT OBSERVER METHOD (ADOM)

Placing more terrestrial instruments in a grid pattern across a solar field is a great way to reduce the error in the TSFDNI measurement; however, it is simply not enough reduction in error within a cost effective means. There is, however, a way to reduce the spatial error component by utilizing a terrestrial grid system in conjunction with aerial photography [3] and pixel contrast recognition software; which results in the Aerial Distant Observer Method or ADOM [4]. ADOM is unique in that it utilizes current measurement technologies but applies them in a different technique.

By taking photographs of an entire solar field, the field can be analyzed for the entire area across the field; even those not being measured directly with terrestrial instruments. The idea is simple; implement a terrestrial instrument grid system across the field, take photographs of the field during testing, analyze the photograph with digital pixel recognition software in order to obtain a true TSFDNI measurement. An example of the testing set up can be seen in Figure 5.

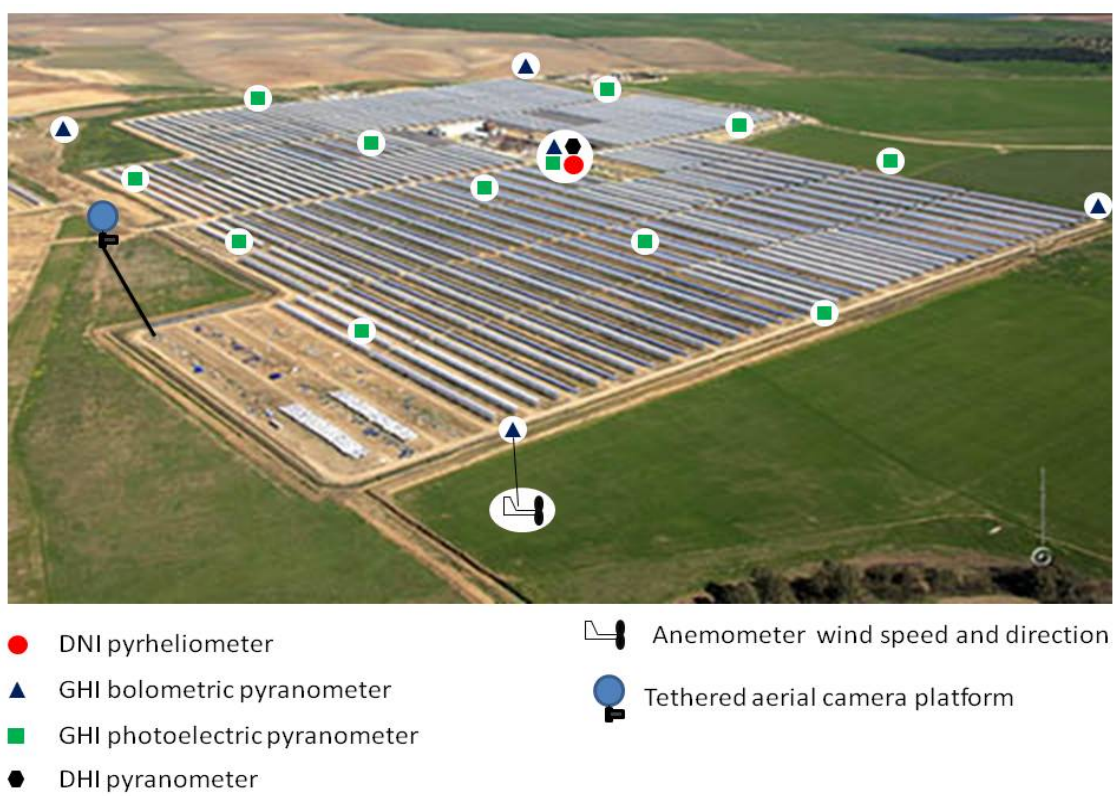

Figure 5. Example of ADOM deployment depicted on Abengoa's solar trough field near Seville, Spain

The pixel recognition software would mimic software already being used today in the "sensitive papers" method of determining drift for cooling towers. A photograph of the field would be input into the software and known points of DNI and GHI would be compared to the photographs contrast at those points. These known points would then be compared to the entire photograph which would then calculate a value for TSFDNI. This value of TSFDNI would have little to no effect from spatial error as all space will have been accounted for. Figure 6 shows the bell curve for the ADOM error.

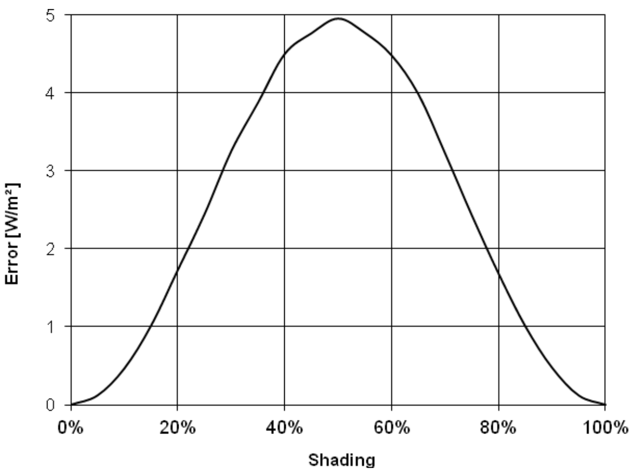

Figure 6. Results of Monte-Carlo Simulation Error vs. Shading with ADOM

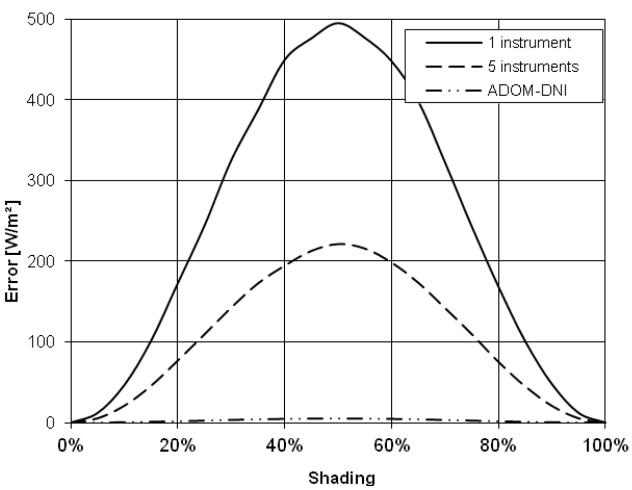

Figure 7. Results of Monte-Carlo Simulation Error vs. Shading with all three methods

It is clear in Figure 7 that this method, utilizing five terrestrial instruments, decreases the percent error by a significant amount. The figure above only utilizes a single DNI instrument in the center of the field and four GHI instruments on each corner of the field for terrestrial measurements. To help aid in the cost reduction and error reduction, ADOM can employ point sticks. Point sticks would consist of a large flat disc of known color and reflectivity on a pole of known height. These point sticks would be placed next to terrestrial instrumentation for correlation and also scattered throughout the solar field. These point sticks would allow for a lower error in the overall TSFDNI measurement. The pixel recognition software would be able to more readily identify these point sticks of known color and reflectivity to determine contrast and correlate them with known measurements of DNI and GHI. By utilizing current technologies in a unique way, a more accurate determination of TSFDNI can be made; this is evident in the prior information portrayed in this paper. But how does this help the solar industry move forward?

THE BENEFITS OF ADOM

The most obvious benefit of ADOM is to performance testing. While this is important and is also the reason for ADOM's invention, it is not the most significant benefit. Solar energy advancement in the power industry is a substantial achievement. Breaking into an established market is not an easy undertaking, and if the technology doesn't meet the current market expectations, then breaking into that market can be almost impossible.

ADOM can help solar energy break into the current power market by assisting in the development of commercial availability, modeling, and performance monitoring to name a few. One of the greatest hurdles for the solar industry to overcome is commercial availability. This hurdle can be reduced with advancements in prediction models for solar facilities and performance monitoring, along with a better understanding of how solar fields react to conditions other than a "clear solar day".

Having an accurate measurement of TSFDNI during many different types of days (clear, hazy, partly cloudy, and cloudy), will allow for a better understanding of solar facilities by modeling. Current industry models typically only utilize clear solar day information in predictions of unit output and efficiency. Using ADOM over a range of daily solar conditions would give an indication of how the unit will perform in "normal plant operation". This information would then provide a better understanding of availability over a range of daily solar conditions, meeting the market need for availability information.

Performance monitoring is important to the current power market and should therefore be important to the solar industry. Without a system like ADOM, monitoring performance of a solar facility over a period of time, whether it is days or a year, would be highly inaccurate. The more accurate the TSFDNI measurement is on partly cloudy days, the more accurate the performance monitoring, the more accurate the prediction modeling, and the more accurate the financial forecasting is.

CONCLUSION

It's easy to see that for a clear solar day, a single DNI measurement point is sufficient for determining TSFDNI to be used in performance modeling. However, it is also easy to see that an accurate TSFDNI measurement, using ADOM, during partly cloudy conditions is important for the advancement of the solar industry. These data points on less than ideal solar days allow for a much better understanding of the solar facility's performance and efficiency. This better understanding will certainly move the industry forward with equipment design and manufacturing, deployment, and commercial availability predictions to name a few.

Don't let current guidelines and requirements stand in the way of a better understanding of solar energy. Move past the restrictions to a better tomorrow by allowing solar energy to flourish in areas that no one ever expected.

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