Side-by-Side Comparison of Subhourly Clipping Models

Preprint

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Side-by-side Comparison of Subhourly Clipping Models

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Abstract — **Over the past several years there have been numerous attempts at quantifying the inherent power clipping of inverters due to subhourly irradiance variability that is not captured in hourly PV performance models. Different models have been proposed to correct for these clipping losses in PV performance estimates, including matrix lookup models, distribution modeling of the PV power performance within a given hour, and machine learning methods. To date, there have been few comprehensive quantitative comparisons of these inverter clipping correction modeling approaches to evaluate the effectiveness of these approaches in predicting the actual behavior of PV system inverter clipping. In this study, we perform such a comparison, evaluating the Allen and Walker correction loss modeling approaches recently implemented in the System Advisor Model (SAM) against clipping losses modeled with 1-minute climate data. These comparisons were performed across a variety of climate locations and inverter loading ratios to thoroughly analyze the effectiveness of these modeling approaches relative to each other. Results from this analysis reveal that both clipping correction approaches improve annual energy accuracy to within 2% of 1-minute modeled energy yield. The two models predict annual clipping loss more accurately than simple hourly power limit clipping, with the Allen method typically being slightly more accurate at typical ILR values and the Walker method often being slightly more accurate at high ILR values The models can improve accuracy over the status quo clipping approach up to 3 percentage points in systems with ILR of 2.0, showing the importance of this modeling factor in energy yield estimates.**

I. Introduction

An inherent drawback of performing hourly power performance modeling of PV systems is the inability to account for subhourly variation in ambient conditions and subsequent PV power output. While hourly averaging of components such as incident irradiance and ambient temperature may be sufficient to capture the DC system behavior, hourly averaging is less effective when considering inverter power clipping of power in excess of the inverter power limit, as this introduces significant non-linearity that isn't represented well in an average. As the DC power input to the inverter fluctuates within the hour, the inverter will clip power that exceeds the maximum rated DC input power of the hardware. Averaging the DC power over the hour often leads to underestimation of inverter clipping relative to actual measured system behavior, and thus results in overestimation of annual energy in system performance estimates. Several studies have been conducted over the past several years investigating this phenomenon [1,2], and numerous models have been developed to correct this underestimation of inverter clipping within the performance model chain for hourly models. Two such models are the Allen method [3], which uses a lookup table to find loss factors for inverter clipping at each time step, and the Walker method [4], which models the PV power output on a time distribution over the relevant hourly timestep. Another model developed at NREL uses a machine learning approach to account for subhourly clipping, but is not analyzed in this paper due to the intensive amount of data required [5]. These corrections are applied in the performance model, and are distinct from corrections applied to the input resource data, as were evaluated in [6]. While there have been numerous publications detailing the construction of these models and analyzing their effectiveness, there has been no published study to have a side-by-side comparison of these models against the "status quo" approach of clipping hourly average power, and the more realistic use of 1-minute data. This work addresses that gap by using the System Advisor Model's recent implementations of these modeling methods to perform a comparison of the methods to each other, and to the more representative 1-minute simulation of inverter clipping estimates, across a variety of sites for a theoretical PV system.

II. Background

The two subhourly clipping correction models investigated in this paper have very different approaches to estimating the clipping loss missed by using hourly averages of PV array performance. The Allen method is an empirically driven approach, with years of data from multiple ground measurement sites being used to classify PV clipping correction factors into a lookup matrix of clipping correction factors that is indexed based on the relative clearness of the incoming direct normal irradiance (DNI) and a newly defined "clipping potential" metric, derived from the inverter power capacity and nominal clear sky system DC output at each timestep [3]. The DNI index and clipping potential metrics that are calculated at

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each timestep and used to index the matrix of clipping loss factors are derived from the following equations [3]:

$$\gamma_{DNI} = \frac{DNI}{DNI_{DryClean}} \quad (1)$$

$$CP = \frac{P_{dc,DryClean} - P_{ac,0}}{P_{ac,0}} \quad (2)$$

In (1) and (2), γ_{DNI} is the DNI index, DNI is the direct normal irradiance from the weather file in W/m^2, $DNI_{DryClean}$ is the direct normal irradiance calculated from a clear sky model, CP is the clipping potential, $P_{dc,DryClean}$ is the DC power in the timestep calculated from the clear sky assumptions, and $P_{ac,0}$ is the inverter AC power capacity. Allen's approach to subhourly clipping correction stipulates a Linke turbidity value of 1.0 for all clear-sky calculations [3]. An important distinction in applying the Allen method is that the clipping correction factors indexed in the matrix apply clipping losses based on the calculation of hourly average AC power after inverter clipping has already been applied to average hourly DC power in the model chain, and thus serves as an additive loss factor on top of the existing clipping correction losses in SAM or other models. Work is currently underway by Allen to publish open-source Python code to reproduce some of the work in [3], including creating the correction matrix. This could allow modelers to create an updated matrix using data from additional years and/or sites. This work is forthcoming and will be available at [7].

The Walker method takes a more mathematical approach to evaluate the amount of clipping that could happen within the given hour. This method considers the amount of DC power input to the inverter at a given time step as a distribution on an integral, bounded by a maximum power derived from clear sky calculations, and a minimum derived from the same clear sky conditions and the atmospheric thickness at the given timestep [4]. Using this distribution of potential DC power output within a given hour, the clipping limit of the specified inverter model can be used in integration to determine the percentage of the hour that is expected to have instantaneous power greater than the inverter power limit. The calculations to find the DC power output of the distribution, and the amount of time where the distribution exceeds the inverter power limit, are shown below [4]:

$$P_{solar} = P_{solar,min} + \left(P_{solar,max} - P_{solar,min}\right) * \left(1 - \left(\frac{t}{T}\right)^{\frac{CF}{CF-1}}\right) \quad (3)$$

$$CF = \frac{P_{solar} - P_{solar,min}}{P_{solar,max} - P_{solar,min}} \quad (4)$$

$$t_{lm} = Te^{\left[\frac{\ln\left(1 - \frac{L - P_{solar,min}}{P_{solar,max} - P_{solar,min}}\right)}{\frac{CF}{CF-1}}\right]} \quad (5)$$

In (3), P_{solar} is the average DC power output, $P_{solar,max}$ is the maximum DC power output calculated from clear sky conditions, $P_{solar,min}$ is the minimum solar output calculated from a fraction of the maximum solar output, t is the integration variable, and T is the time step of 1 hour. In (5), L is the inverter power limit above which all power is clipped, and t_{lm} is the fraction of the hour in which clipping occurs. The calculations for the fraction of the timestep in which clipping occurs can then be used to estimate the clipping loss within the hour [4]. Walker's approach does not stipulate a particular Linke turbidity factor for clear-sky calculations of the maximum theoretical solar output. An annual average Linke turbidity factor calculated from Sandia's pvlib function library is used when applying the Walker model in this study [8]. This method replaces the modeled clipping loss of the average hourly DC input power that occurs in PV performance models and is not an additive loss like the Allen method.

III. Methodology

The comparison of the Allen method and Walker method is performed using the implementation of the models in the System Advisor Model (SAM) [9]. SAM is a technoeconomic analysis tool that combines detailed PV (and other renewable energy system) performance models with rigorous discounted cash flow analyses evaluated from a variety of financial perspectives [9]. Previously, SAM's performance models simply clipped excess DC power based on hourly average weather data. The Allen method was introduced as a modeling option for SAM's detailed PV performance model in the 2023.12.17 version, while the Walker method is currently in development as an additional modeling feature that will be publicly accessible in SAM's Python wrapper PySAM in a future update [10]. A 1.0 MW single-axis East-West tracking PV system is modeled in SAM to be used throughout all the comparison cases. The base inverter model chosen for this comparison is the Sandia inverter model [11], which is the standard inverter model used in SAM and is widely used in the PV modeling industry.

The representative system was modeled for a variety of different climates using hourly and 1-minute data from the Surface Radiation Budget Network (SURFRAD), a National Oceanic and Atmospheric Administration (NOAA) database of surface radiation over the U.S. [12]. SURFRAD sites are chosen to cover a wide spectrum of different climate conditions in the U.S. 7 SURFRAD sites are analyzed in this paper, and each site is evaluated for the weather years of 2010 - 2020 (outside of data formatting issues for select sites). The Allen method was developed with data from 9 sites, including 3 SURFRAD sites with data through 2016, so the potential exists for those sites to have been overfit. For each weather year, 1-minute solar resource and ambient weather data is aggregated to hourly data using Python code, and the 1-minute weather data is aggregated into averages to generate hourly weather files to be used with the clipping correction models. Additionally, inverter loading ratios (ILR), or DC:AC ratios, ranging from

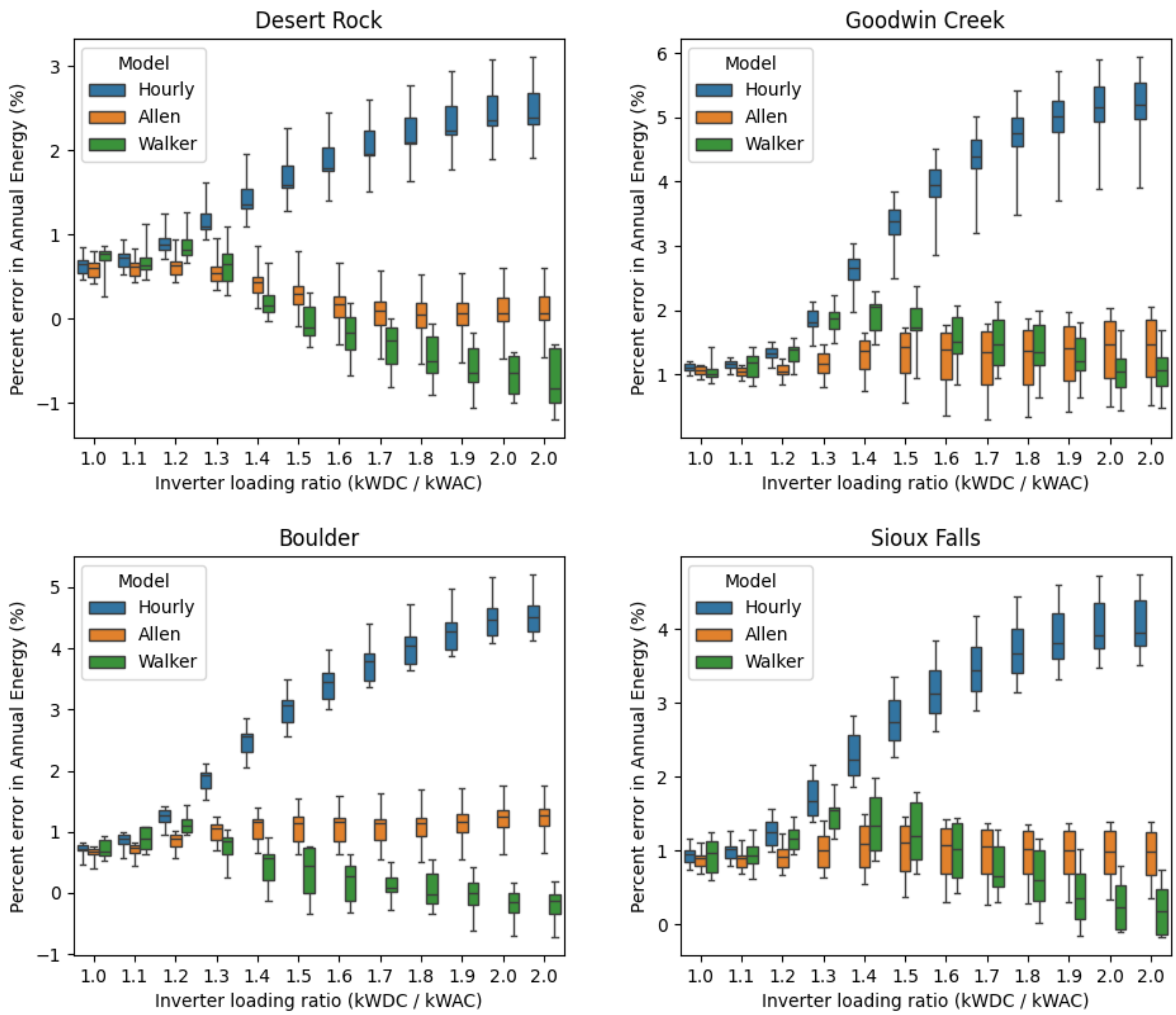

Figure 1. Percentage error in annual energy for 4 SURFRAD sites. Box and whisker plots represent weather years 2010-2020. Colors represent different hourly clipping models compared against 1-Minute clipping model

1.0 to 2.0 are modeled at each site. This is achieved by changing the maximum AC output power of the theoretical inverter, which changes the maximum inverter DC input power using the assumed inverter efficiency of 96%.

The SAM model cases analyzed in this paper are split into four categories: hourly performance models with only the status quo AC power limit clipping applied ("Hourly"); hourly performance models with AC power limit and the Allen method applied ("Allen"); hourly performance models with the Walker method applied ("Walker"); and 1-minute performance models with AC power limit applied ("Minute"). The energy and clipping loss results from the "Minute" cases serve as the basis for comparison for the other models, since the 1-minute models can more accurately estimate the granularity in inverter input power fluctuations and subsequent clipping instances. The clipping losses from the Allen method are summed with those clipping losses calculated from the status quo hourly power limit clipping in SAM. .

IV. Results and Discussion

A. Annual Energy Results

Box and whisker plots showing percentage error in annual energy to compared the Minute model's predicted annual energy yield (what is remaining after inverter clipping) are shown for 4 of the selected SURFRAD sites in Figures 1. The percentage error shown for the different models in each plot is calculated from the following equation:

$$\%\ error = \left(\frac{E_{model} - E_{minute}}{Eminute}\right) * 100\% \qquad (6)$$

TABLE I. PERCENTAGE ERROR IN ANNUAL ENERGY FOR 7 SURFRAD SITES.

	Bondville (IL)			Boulder (CO)			Desert Rock (NV)			Fort Peck (MT)			Goodwin Creek (MS)			Penn State (PA)			Sioux Falls (SD)		
ILR	H	A	W	H	A	W	H	A	W	H	A	W	H	A	W	H	A	W	H	A	W
1	0.67	0.61	0.77	0.71	0.65	0.72	0.63	0.59	0.71	0.54	0.48	0.47	1.12	1.06	1.07	0.82	0.76	0.84	0.94	0.89	0.93
1.1	0.75	0.61	0.67	0.86	0.71	0.89	0.71	0.61	0.69	0.63	0.51	0.62	1.15	1.05	1.14	0.93	0.80	0.82	1.01	0.89	0.93
1.2	1.02	0.66	1.07	1.24	0.85	1.12	0.92	0.63	0.88	0.93	0.60	0.92	1.34	1.07	1.32	1.27	0.96	1.24	1.24	0.92	1.17
1.3	1.58	0.78	1.40	1.85	1.01	0.75	1.19	0.57	0.64	1.46	0.73	0.99	1.85	1.18	1.85	1.94	1.25	1.74	1.71	1.00	1.48
1.39	2.24	0.85	1.38	2.48	1.08	0.44	1.46	0.43	0.20	2.05	0.79	0.72	2.61	1.30	1.92	2.76	1.53	1.68	2.30	1.05	1.37
1.49	2.84	0.82	1.10	3.03	1.10	0.36	1.71	0.31	-0.04	2.56	0.78	0.37	3.33	1.32	1.81	3.51	1.71	1.45	2.78	1.03	1.23
1.59	3.31	0.76	0.96	3.45	1.09	0.19	1.90	0.17	-0.19	2.96	0.76	0.05	3.91	1.26	1.55	4.12	1.79	1.25	3.18	0.99	1.00
1.69	3.66	0.71	0.69	3.79	1.07	0.10	2.07	0.09	-0.33	3.26	0.73	-0.23	4.36	1.23	1.49	4.59	1.85	1.14	3.49	0.96	0.76
1.78	3.92	0.68	0.48	4.07	1.10	0.08	2.22	0.06	-0.46	3.48	0.72	-0.26	4.71	1.25	1.39	4.96	1.90	0.96	3.73	0.95	0.63
1.88	4.10	0.68	0.32	4.31	1.14	-0.05	2.36	0.07	-0.59	3.65	0.72	-0.46	4.96	1.31	1.29	5.24	1.95	0.85	3.90	0.94	0.38
1.98	4.24	0.69	0.15	4.51	1.21	-0.20	2.47	0.11	-0.67	3.78	0.73	-0.68	5.14	1.38	1.04	5.44	1.98	0.68	4.03	0.94	0.26
2.01	4.27	0.69	0.08	4.56	1.23	-0.20	2.50	0.13	-0.73	3.80	0.73	-0.76	5.18	1.40	1.06	5.48	1.98	0.62	4.06	0.94	0.20

Where E_{model} is the respective hourly modeled annual energy from the Hourly, Allen, or Walker results and E_{minute} is the modeled annual energy yield from the Minute results.

The Desert Rock, NV results, which show the highest annual clipping loss, still show that the Allen and Walker methods are accurate to within $\pm$ 1% of the Minute annual energy yield due to improved accounting of the subhourly clipping occurring in the modeled system as the system ILR reaches 1.4 and beyond. Locations with more solar resource intermittency that are prone to more individual subhourly variability also show improved model accuracy with the introduction of the Allen and Walker clipping models. The Goodwin Creek, MS location shows that both models are within $\pm$ 2% of the annual energy yield predicted from the 1-minute simulations, which is a vast improvement from the simple hourly modeling which has errors approaching 5% for very high ILR values. The findings are similar for the Boulder, CO and Sioux Falls, SD locations, with the Allen model showing slightly lower error in annual energy yield in typical ILR operation ranges and the Walker method having slightly lower error at higher ILR values. Both models offer significant improvements of multiple percentage points over simple hourly AC power limit clipping.

For each site, as the ILR increases and more DC input power is provided for the same AC power limit, the "Hourly" model with averaged inverter input power diverges from the true "Minute" yield exponentially. In contrast, both approaches to inverter clipping dramatically reduce the error in annual energy yield while showcasing different behavior for increasing ILR. Both Allen and Walker results predominantly under-predict clipping, with only some years in places with relatively uniform weather conditions such as Desert Rock, NV having overprediction of the Minute clipping results. The mean annual energy yield prediction error across all 7 analyzed SURFRAD sites, all weather years, and all modeled ILR values is shown in Table I. For each site, the percentage error is color coded from white for 0% error to red for increasing error due to underprediction of clipping and blue for overprediction. The sites are also separated into "H", "A", and "W" columns for the Hourly, Allen, and Walker models runs respectively. Inspection of this table reveals that for all climates, the introduction of these subhourly clipping correction models can have a meaningful impact on annual energy yield accuracy even for relatively low ILR values where not much clipping occurs.

The hourly performance model slightly overpredicts annual energy relative to the 1-minute calculations, as evidenced by the percent error of around 0.5-1.0% at ILR=1.0, where virtually no clipping occurs. This overprediction can be attributed to higher plane-of-array irradiance for the hourly weather files due to weather file processing when going from minute data to hourly averages. The data was processed into weather files without a specified minute within the hour, which led to the solar position at sunrise or sunset times being assumed to be at the midpoint between the sunrise time and end of the time step or sunset time and beginning of the time step rather than the midpoint of the hour. Subhourly variability in the resource not being fully accounted for in hourly averages also impacts this initial bias error. Future work is planned to investigate these biases in more detail.

B. Inter-annual Variability

Analysis was also done on the individual weather years for each site to investigate the effect of inter-annual resource variability on the clipping loss and model accuracy. Figure 2 shows the year-to-year variation in model error across the entire

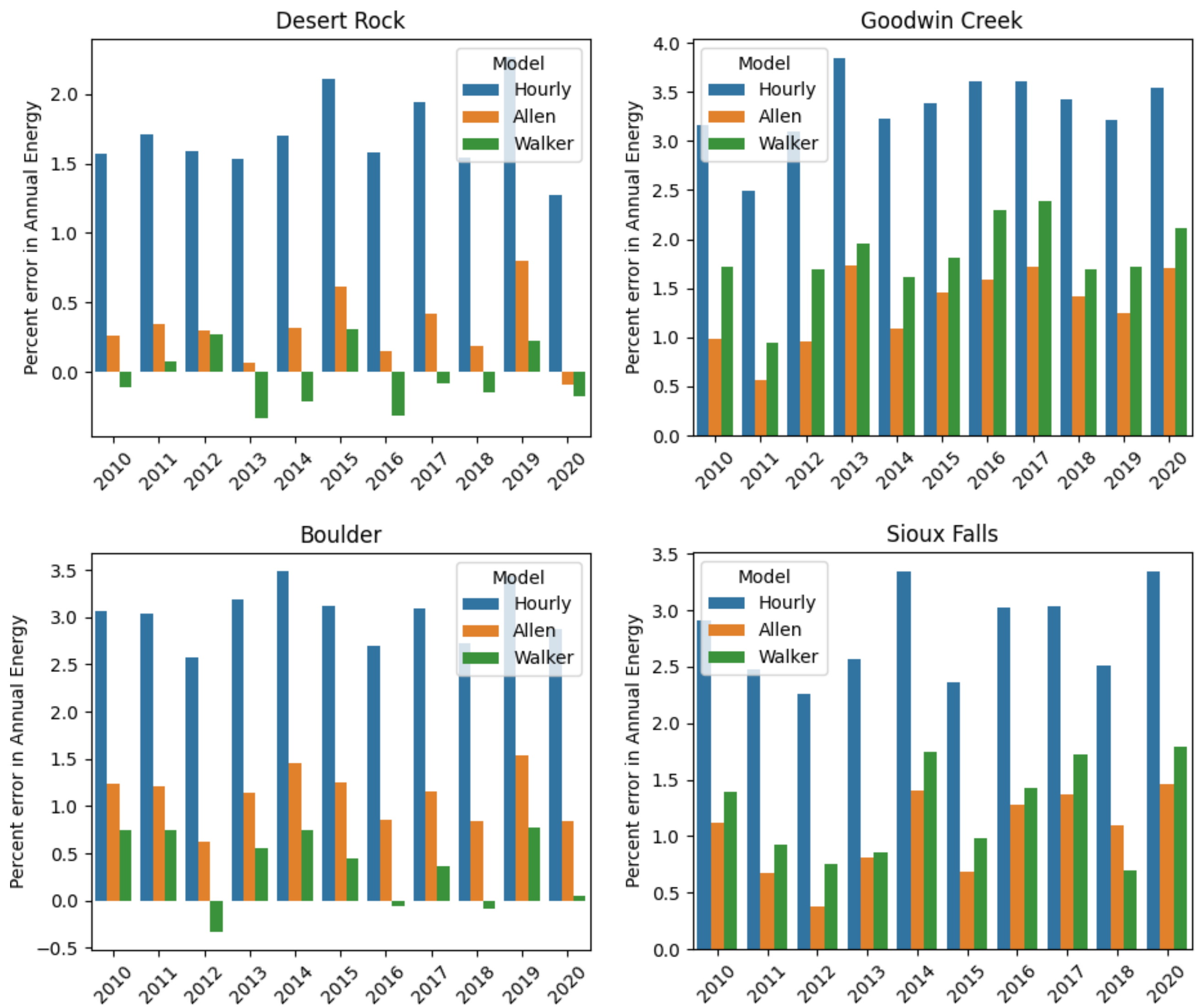

Figure 2 Percentage error in annual energy for 4 SURFRAD site for Weather Years 2010-2020 at an ILR=1.5. Colors represent different hourly clipping models compared against 1-Minute clipping model

range of weather data examined in this paper for the 4 SURFRAD sites shown in previous figures. The results show the modeled clipping behavior is roughly uniform in magnitude, with the highest and lowest modeled errors for all models occurring in the same respective years. The roughly 0.5% percent difference between the upper and lower bounds of the annual energy error across weather years highlights the importance of accounting for this inter-annual variability in subhourly clipping correction modeling. Both the Allen and Walker methods are advantageous in this regard in that they apply to hourly weather data, which allows for easier application of the model to multiple years of weather data. Other models rely on commercial satellite datasets with synthetic subhourly resource variability or time-consuming ground measurement campaigns to attempt to address this inter-annual variability in clipping behavior.

C. Clipping Loss Results

The annual clipping loss in kWh predicted by each model approach is shown for 4 SURFRAD sites in Table II. The table has labeling similar to Table I, with an additional "M" column for the 1-minute model runs. All values in the table represent the mean annual clipping loss predicted by the clipping models across all years of weather data. Isolating the predicted energy lost to clipping over the year allows for a better understanding of how the Allen and Walker models are improving upon the annual energy yield predicted by the Hourly model. Analysis of Table II shows that as the ILR increases, overall clipping increases and the two model approaches approximate the Minute clipping loss predictions much more closely than the Hourly results.

TABLE II. ANNUAL CLIPPING LOSS FOR DIFFERENT CLIPPING MODELING APPROACHES AT 4 SURFRAD SITES (ALL VALUES IN KWH).

	Desert Rock				Goodwin Creek				Boulder				Sioux Falls			
ILR	H	A	M	W	H	A	M	W	H	A	M	W	H	A	M	W
1	3.0E+00	8.9E+02	3.5E+02	3.0E+00	0.0E+00	8.3E+02	7.7E+01	0.0E+00	9.6E+00	1.1E+03	5.6E+02	9.6E+00	0.0E+00	8.3E+02	2.0E+02	0.0E+00
1.1	4.3E+02	2.8E+03	2.7E+03	4.6E+02	9.5E+00	1.8E+03	7.5E+02	9.5E+00	4.6E+02	3.3E+03	3.9E+03	4.8E+02	3.0E+01	2.1E+03	1.4E+03	3.0E+01
1.2	1.1E+04	1.8E+04	1.8E+04	1.3E+04	4.9E+02	5.5E+03	4.7E+03	5.1E+02	4.8E+03	1.3E+04	1.6E+04	8.1E+03	1.2E+03	6.9E+03	6.8E+03	1.2E+03
1.3	5.7E+04	7.4E+04	7.2E+04	7.3E+04	5.9E+03	1.9E+04	2.0E+04	6.8E+03	2.5E+04	4.3E+04	5.0E+04	4.8E+04	1.0E+04	2.4E+04	2.5E+04	1.4E+04
1.39	1.4E+05	1.7E+05	1.7E+05	1.8E+05	2.8E+04	5.5E+04	5.9E+04	4.1E+04	7.0E+04	1.0E+05	1.1E+05	1.1E+05	3.8E+04	6.3E+04	6.5E+04	5.7E+04
1.49	2.6E+05	3.0E+05	2.9E+05	3.0E+05	7.1E+04	1.1E+05	1.2E+05	1.0E+05	1.4E+05	1.8E+05	1.9E+05	2.0E+05	8.7E+04	1.2E+05	1.2E+05	1.2E+05
1.59	3.9E+05	4.4E+05	4.3E+05	4.5E+05	1.3E+05	1.9E+05	2.0E+05	1.8E+05	2.2E+05	2.8E+05	2.9E+05	3.0E+05	1.5E+05	2.0E+05	2.0E+05	2.0E+05
1.69	5.4E+05	6.0E+05	5.8E+05	6.1E+05	2.1E+05	2.9E+05	2.9E+05	2.8E+05	3.2E+05	3.9E+05	4.0E+05	4.1E+05	2.3E+05	2.8E+05	2.8E+05	2.8E+05
1.78	7.0E+05	7.7E+05	7.5E+05	7.8E+05	3.0E+05	3.9E+05	3.9E+05	3.8E+05	4.3E+05	5.0E+05	5.1E+05	5.2E+05	3.1E+05	3.7E+05	3.7E+05	3.8E+05
1.88	8.7E+05	9.4E+05	9.2E+05	9.6E+05	4.1E+05	5.0E+05	5.0E+05	4.9E+05	5.4E+05	6.2E+05	6.3E+05	6.5E+05	4.0E+05	4.7E+05	4.7E+05	4.8E+05
1.98	1.1E+06	1.1E+06	1.1E+06	1.1E+06	5.2E+05	6.1E+05	6.1E+05	6.1E+05	6.6E+05	7.5E+05	7.6E+05	7.8E+05	5.0E+05	5.7E+05	5.7E+05	5.8E+05
2.01	1.1E+06	1.2E+06	1.2E+06	1.2E+06	5.5E+05	6.4E+05	6.4E+05	6.4E+05	7.0E+05	7.9E+05	8.0E+05	8.2E+05	5.3E+05	6.0E+05	6.0E+05	6.1E+05

CONCLUSIONS

This study investigates three different models for PV inverter subhourly clipping in hourly performance models. The models take different approaches to calculating clipping losses, with the Allen method using an empirically derived matrix of clipping loss factors and the Walker method using integration over a range of potential PV power output to define the potential clipping within the hour. Initial analysis shows that both methods are accurate to within 2% of predicted annual energy yield found from 1-minute SURFRAD data across 7 different locations and 11 years of weather data. Applying either of the clipping correction models can result in as much as a 3 percentage point reduction in annual energy yield prediction error at high ILR values. Both models track the predicted total clipping loss much more accurately than simple hourly AC power limit clipping, with the Allen method typically being slightly more accurate at typical ILR values and the Walker method often being slightly more accurate at high ILR values. The models also allow for accounting for inter-annual variability in solar resource, which was found to have as much as a 0.5% variation in annual energy yield prediction error. This work shows the magnitude of error that can occur from subhourly clipping losses using hourly models and confirms that using either the Allen or Walker model is crucial in correcting these errors in single year model error as well as multiyear analyses. Further work in this area will include open-source scripts used to conduct this analysis, inclusion of both methods in the SAM desktop tool, and the creation of resources to help use these models in SAM simulations.

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