Journal of Renewable Energy and Environment

Journal Homepage: www.jree.ir

Materials and Energy Research Center
MERC

Research Article

Variability Assessment of Solar Irradiance for the Safe Grid Integration of Solar Photovoltaic Power Plants

Md. Rashedul Alam [a], Iftekhar Uddin Bhuiyan [b*], Nur Mohammad [c]

[a] Sustainable and Renewable Energy Development Authority (SREDA), P. O. Box: 1000, Dhaka, Bangladesh.
[b] Institute of Appropriate Technology, Bangladesh University of Engineering and Technology, P. O. Box: 1000, Dhaka, Bangladesh.
[c] Department of Electrical and Electronic Engineering, Chittagong University of Engineering and Technology, P. O. Box: 4349, Chittagong, Bangladesh.

PAPER INFO

Paper history:
Received: 21 December 2022
Revised: 02 April 2023
Accepted; 14 April 2023

Keywords:
Assessment of Solar Irradiance,
Short-term variation of Solar Irradiance,
Integration Challenges of Variable Renewable Energy,
Voltage-frequency aspects of Solar Photovoltaic grid integration

ABSTRACT

The output power of a Solar Photovoltaic (SPV) plant depends mainly on the solar irradiance on the photovoltaic (PV) modules. Therefore, short-term variations in solar irradiance cause variations in the output power of solar power plants, making solar photovoltaic grid integration unstable. Solar irradiance variations mainly occur due to the weather conditions of a given location, especially the movement of clouds and seasonal effects. Consequently, assessing the variability of solar irradiance over the course of a year is essential to identify the extent of these variations. Geographical dispersion and cloud enhancement are two important factors affecting output power variations in a PV plant. Geographical dispersion reduces such variations, while cloud enhancement increases them. This study utilizes two ground station-based solar Global Horizontal Irradiance (GHI) datasets to assess the viability of solar irradiance in the Chittagong division of Bangladesh. The analysis reveals a significant number of days with high short-term solar irradiance variation. In addition to solar irradiance, the frequency and voltage at the interconnection point are important for safe grid integration. It was observed that the grid frequency exceeded the range specified by the International Electrotechnical Commission (IEC), but remained within the grid code range of Bangladesh. Grid voltage variation at the interconnection substation was found to be within the standard range during the daytime, but low voltage was observed at the grid level during the rest period. Therefore, it is crucial to implement necessary preventive measures to reduce short-term variations for the safe grid integration of large-scale variable SPV plants.

https://doi.org/10.30501/jree.2023.377735.1522

1. INTRODUCTION

Global irradiance, a summation of direct irradiance and diffuse irradiance (including reflected irradiances), depends on the wind speed and cloud patterns that are the driving forces of variations of solar power (Blanc et al., 2014; Järvelä et al., 2020; Keeratimahat et al., 2019). Solar photovoltaic systems collect energy from the sun in a spatial dimension (Jazayeri et al., 2017). Therefore, it is important to understand the amount of variability of solar irradiance in the area with solar power systems. Variable Renewable Energy (VRE) adaptation capability of the electricity network depends on the amount of variability of the output power of the Solar Photovoltaic (SPV) plant. The movement of the cloud creates shadows on the Photovoltaic (PV) modules and changes the incidence of solar irradiance (Ahmed et al., 2020). The output of the PV system varies accordingly and provides a great effect on the integrated electric system (Tahir & Asim, 2018). For example, the Teknaf 20MW Solar plant, connected to a 33kV distribution substation of Cox's Bazar Palli Bidyut Somity of Bangladesh, faced unexpected shutdown due to protection sensitivity, long distribution line faults, and dynamic change of load flow. The maximum load of the Teknaf area was around 25MW and connected to the Cox's Bazar grid substation through a 33kV 80km long transmission line (Kainat et al., 2021).

Geographical dispersion and cloud enhancement are two important factors. The geographic dispersion of solar-photovoltaic panels reduces variability in energy production. In the study of geographic dispersion, Van Haaren et al characterized the variability in power output of six photovoltaic plants based on minute-averaged radiation data from each plant and the output from 390 inverters. They found maximum ramp rates of 0.7, 0.58, 0.53, and 0.43 times the plant's capacity for 5, 21, 48, and 80 MW AC plants, respectively, due to geographical dispersion. The study was conducted by simulating a step-by-step increase in the plant size at the same location (Van Haaren et al., 2014). On the other hand, the Cloud Enhancement (CE) or over-irradiance or irradiance enhancement can exceed the expected clear sky irradiance value during partly cloudy days. The CE phenomenon can be observed all around the world, but the amount may vary from place to place. Järvelä et al. (Järvelä et al., 2020) measured solar irradiance on such days that might be increased up to 1.5 times the clear weather days for some time. The output power fluctuation of the SPV power plant increases due to CE.

*Corresponding Author's Email: iftekhar@iat.buet.ac.bd (I. U. Bhuiyan)
URL: https://www.jree.ir/article_171371.html

Please cite this article as: Alam, M. R., Bhuiyan, I. U., Mohammad, N. (2023). Variability Assessment of Solar Irradiance for the Safe Grid Integration of Solar Photovoltaic Power Plants, *Journal of Renewable Energy and Environment (JREE)*, 10(4), 107-118. https://doi.org/10.30501/jree.2023.377735.1522.

Variation in the amount of solar irradiance depends on the location-specific weather status and cloud pattern of that place (Sengupta et al., 2018). Solar research focuses on understanding historical solar resource patterns and making future predictions, both of which are needed to support reliable power system operations (Sivaneasan et al., 2017). As solar technologies mature, more and increasingly larger solar energy systems are installed across the country (Shuvho et al., 2019). Financing these systems requires assurance that they will produce the energy predicted through performance models (Boopathi et al., 2021; Van Haaren et al., 2014). Failing to meet the minimum energy performance requirements can result in financial penalties, requiring expensive risk mitigation measures. Accurate solar irradiance data sets include the foundation of a successful performance model and are critical in reducing the expense associated with mitigating this performance risk (Denholm & Margolis, 2007; Karthikeyan & Janarthanan, 2017). Those data are available from Satellite and Ground station-based sources (Choi et al., 2019; Zhang et al., 2017). Ground station-based solar irradiation data is more reliable than Satellite source-based solar irradiation data (Carmona et al., 2018; Wei, 2017). Pyranometer, Pyrheliometer, and sun-tracker are used in ground station-based solar radiation measurement stations (Jamil & Akhtar, 2017).

This paper aims to highlight the challenges concerning the grid integration of the SPV plant, especially analyzing the variation of solar irradiance in Bangladesh. To this end, the following issues are to be addressed:

a) Grid reliability parameters like frequency variation and voltage variation in a nearest SPV plant have been assessed to identify the interconnection aspects;
b) Daily solar irradiance scenario has been assessed for a year for two case study sites to understand the seasonal effect and variation patterns in a day;
c) Basic comparative analysis of daily solar irradiance data between two sites is conducted.

Solar irradiance studies concerning the safe grid integration of solar photovoltaic power plants are very scarce in Bangladesh, although numerous SPV plants are established in different divisions of the country. In this regard, the paper is organized in the following manners: the first section describes the need for the research, objectives, and approach. The second section describes the case study site and data source; the third section describes the research methodology in detail; the fourth section presents the important findings and discussion according to the research methodology. Section 5 discusses the comparative scenario between the two case study sites. The sixth section discusses the research findings, recommendations, and further research opportunities.

2. DATA

2.1. Kaptai 7.4MW Solar Power Plant

The Kaptai 7.4MW Solar Power Plant is located beside the Kaptai hydroelectric dam at the Rangamati district of Chittagong division, Bangladesh. The plant achieved commercial operation on 28 May, 2019 and was the 4th utility-scale solar park installed in Bangladesh (*Annual Report 2019-2020 of SREDA*, 2020). It is operated by the Bangladesh Power Development Board (BPDB), a state-owned power generation and distribution utility in Bangladesh. The latitude and longitude of the site were 22.491945 and 92.227349, respectively. The solar irradiance data were recorded by a pyranometer and datalogger at the mentioned solar plant. Calibrated pyranometers were used at the site. The recorded Global Horizontal Irradiance (GHI) data were used for understanding the solar insolation status of that place. The data averaging frequency was 10 minutes and the unit was in W/m^2. Since the less precise time-scale solar irradiance data were not available in that solar power plant, the mentioned data were obtained for this variation analysis.

2.2. National Solar Radiation Resource Assessment Station, Chittagong

The Sustainable and Renewable Energy Development Authority (SREDA), the nodal agency of Bangladesh aiming to promote Renewable Energy and Energy Efficiency in the country, has installed eight solar radiation resource measurement stations in different locations of Bangladesh under a Global Environment Facility (GEF) funded project 'Sustainable Renewable Energy Power Generation (SREPGen)'. Locations of the solar resource monitoring sites are Rangpur (Begum Rokeya University, Rangpur), Rajshahi (Rajshahi University of Engineering and Technology), Mymensingh (Bangladesh Agricultural University), Sylhet (Shahjalal University of Science and Technology), Kushtia (Kushita Police Line), Khulna (Khulna University), Patuakhali (Patuakhali Science & Technology University), and Chittagong (Chittagong University of Engineering and Technology). The resource monitoring stations of Rajshahi and Patuakhali have advanced facilities including Pyrheliometer and sun tracker systems. Most of the stations are located at public universities in different regions of Bangladesh. Out of these eight solar radiation resource measurement stations, the Chittagong division's site is located at the Chittagong University of Engineering of Technology (CUET) campus, Raojan, Chittagong. The latitude and longitude of the site are 22.463998 and 91.973298, respectively. Global Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance, and some weather data were recorded at a resource monitoring station. Only GHI data was used in this study to understand the variation analysis. This data was recorded by a Class-A calibrated pyranometer and its brand name was Kipp&Zonen. The data sampling frequency was 10 seconds and averaging frequency was 4 minutes. The maximum, minimum, and standard deviations of GHI data also were present with the average GHI data exhibiting a more precise scenario of solar irradiance variation. The locations of the selected sites are shown in Figure 1.

Figure 1. Location of the selected case study sites for irradiation assessment (*Customized Bangladesh Map - Google My Maps*, n.d.).

Figure 1 observes that the two sites are very close to each other, located in the Chittagong division of Bangladesh. According to the satellite-based solar irradiation data, developed by the Global Solar Atlas, a joint study of SOLARGIS, ESMAP, and the World Bank Group observed that the Chittagong division had the highest solar insolation among the other divisions' solar insolation in Bangladesh (*Global Solar Atlas*, n.d.). Most of the publicly published solar irradiation data are very good for expected energy calculation but not suitable for analysis of the VRE integration aspect due to the unavailability of less-than-minute time interval raw data on an open-source basis.

3. METHODOLOGY

The weather condition of any location varies from time to time due to seasonal changes, because the relative position between the sun and earth varies every day due to the change of declination angle and distance between them. There are summer solstice, winter solstice, and two equinoxes in a year. The weather conditions, especially clouds, and their patterns are different in different months due to several effects including the seasonal effect. Therefore, at least a whole year's data is needed to be taken under consideration for variability analysis of solar irradiance of any location.

The two nearest sites in Bangladesh have been selected for this analysis. The solar irradiance data (time series GHI data) of the Kaptai 7.4MW Solar Power Plant were recorded by a calibrated pyranometer and datalogger, as shown in Figure 2. The data averaging frequency was 10 minutes. Global Horizontal Irradiance (GHI) data of the CUET station were recorded by Class-A calibrated pyranometer (brand name: Kipp&Zonen). The data sampling frequency was 10 seconds and averaging frequency was 4 minutes. Collected daily time series solar GHI data were plotted to identify the daily irradiance status using MATLAB software, where the data unit is in W/m^2.

Figure 2. Data recording process.

The pyranometer mentioned in Figure 2 is a sensor device that senses solar irradiance and gives an output value in W/m^2 to the data logger through a digital communication protocol RS-485. Similarly, some other related sensors are connected with a datalogger to measure some related parameters like wind speed, wind direction, temperature, humidity, etc. A 4G-enabled sim card was connected to a data logger and the datalogger was sending the recorded data to the remote server through File Transfer Protocol (FTP). More than two power sources were connected to the datalogger to get interruption-free operation of solar irradiance data logging and transfer.

Voltage and frequency data were collected from Teknaf 20MW Solar Power Plant, located at Teknaf, Cox's Bazar, Bangladesh. Those data were recorded by an energy meter tested and installed by the power offtaker utility, Bangladesh Power Development Board (BPDB). Some voltage data of related 33/11kV substation and grid substation were collected from the respective utility recorded data. The distribution grid level data provider was Cox's Bazar Palli Bidyut Somity (PBS) and grid voltage level data were collected from the data published on the Power Grid Company of Bangladesh (PGCB) website.

Figure 3 represents the daily solar irradiance status of the National Solar Radiation Resource Assessment (NSRRA) Chittagong station of Bangladesh where the Y-axis represents the solar irradiance and the X-axis represents the number of records with 4-minute-interval averaging data. The data sampling was 10 seconds. The mean, max, min, and standard deviation data were plotted to understand the solar irradiance variation, whereas max, min, and standard deviation data gave more confidence about the variation of solar irradiance.

The daily solar irradiance data were plotted and their status was classified into four categories in the current study: Washout Days, High Variability Days, Low Variability Days, and Clear Days. The days on which maximum solar irradiance is limited to 300 W/m^2 were classified as Washout days in this study. The days on which maximum solar irradiance is greater than 800 W/m^2 but so many ramp-ups and ramp-down events occur in those days with high ramp level (more than 400 W/m^2) were defined as High Variability days. The more solar irradiance ramping gave more deep blue plots that help categorization, as mentioned above. If we expand a daily summary plot, then it will look like the following in Figure 3. If we compact this figure on X-axis, so many dark vertical lines will be observed.

The Low Variability days are similar, but the ramp level and the number of ramps per day are comparatively lower, at least one-third of the high variability days at the reference level. Clear weather days are defined, where daily short-term variations are negligible and non-cloudy days.

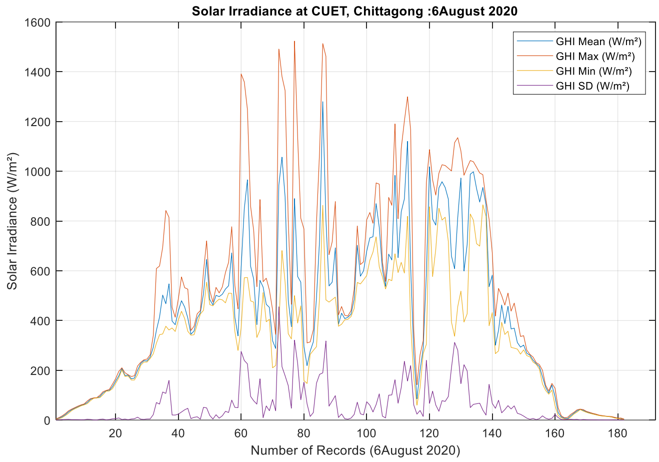

Figure 3. Daily solar irradiance with high solar ramping.

Given that we recognize the full-year solar ramping status, monthly summarized data are plotted in the result and discussion section to get the solar irradiance variation status using approximate daily classifications. Finally, monthly and yearly summary tables and bar charts are presented. This regional short-term variation analysis of solar irradiance is helpful to understand the requirement of ramp management support for safe integration of high VRE penetration into the grid.

4. RESULTS AND DISCUSSION

4.1. Voltage-frequency Status of an Interconnection Point

The variable renewable energy resources like solar irradiance are responsible for the variation of the output power of SPV plants, creating an effect in the interconnection area of the utility network. The utility network itself is subject to some variation due to its instantaneous demand-supply management. The voltage and frequency of the interconnection point have also a key role to play in this regard. Therefore, it is important to understand the real scenario of those parameters. Some of those data were collected from Teknaf 20MW Solar Power Plant, located at Teknaf, Cox's Bazar, Bangladesh.

4.1.1. Voltage records at Teknaf solar power plant

This 20-MW solar park is connected to a 33kV distribution substation operated by the Palli Bidyut Somity (PBS) of Cox's Bazar of the Bangladesh Rural Electrification Board (BREB). Data were collected from Teknaf Solartech Energy Limited (TSEL), the operating subsidiary of Joules Power Limited (JPL). The finding on the 33kV grid voltage on the plant side is given below.

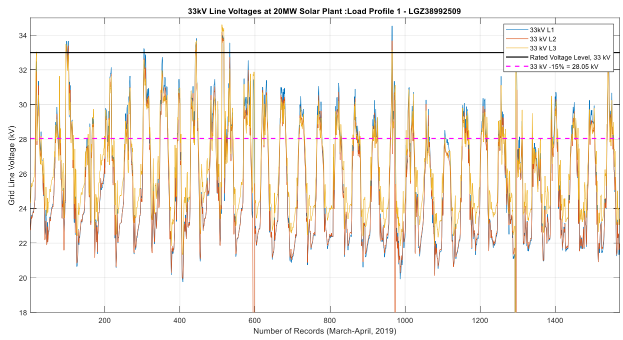

Figure 4. 33kV grid voltage at Teknaf 20MW Solar Plant; Data source: TSEL.

Figure 4 shows the 33kV grid voltage at Teknaf 20MW Solar Plant for 2 months, March-April 2019. These two months were selected as a sample among 12 months when electricity feeders were loaded with cooling loads. The grid voltage of the daytime was observed between 33kV and 28kV, which is within the -15% range. In the rest of the time of the month, the low voltage was observed at the grid level. The collected data were recorded at the energy meter of the Teknaf 20MW Solar Power plant. A sample of the daily voltage profile among these 2 months (4 April) at the plant level is shown in Figure 5 below.

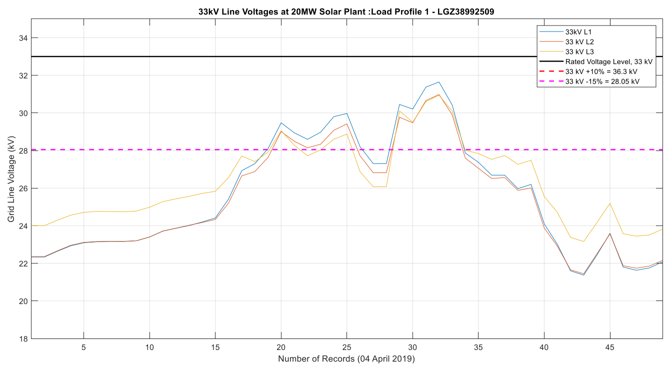

Figure 5. Grid voltage observed at Teknaf 20MW solar plant, 04 April 2019; Data source: TSEL.

According to Figure 5, grid voltage goes down beyond the standard level when the contribution of the Teknaf 20MW solar power plant is less or absent. The voltage fluctuates due to the amount of solar power generation and the load of the consumer in that area. Load change did not occur very quickly and frequently in a substation or feeder, but solar power generation changes very fast with the rapid change of solar irradiance with the time domain.

4.1.2 Frequency records at Teknaf solar power plant

After projecting the voltage data of the TSEL interconnection point, the recorded grid frequency data for the same period at Teknaf 20MW solar power plant is projected in Figure 6 below.

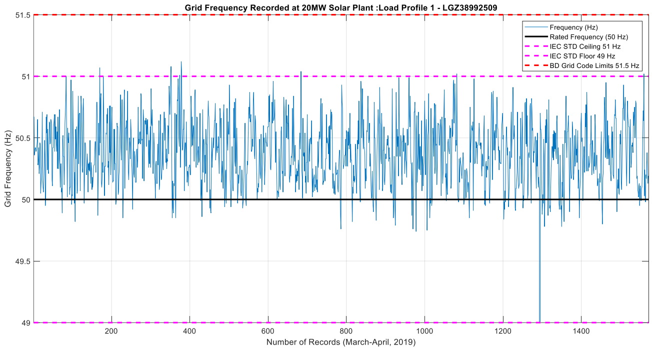

Figure 6. Grid frequency recorded at Teknaf 20MW solar power plant; Data source: TSEL.

According to the standard of the International Electrotechnical Commission IEC 61727, the utility frequency needs to be maintained within ±2% (1 Hz) for safe and continuous operation of the Solar Power Plant (*IEC 61727:2004 | IEC Webstore | Invertor, Smart City, LVDC*, n.d.). However, this limit ranges from 47.5 Hz to 51.5 Hz in the grid code of Bangladesh, which is wider than the IEC range (*Bangladesh Energy Regulatory Commission (Electricity Grid Code) Regulations, 2019*, 2020). According to Figure 6, the frequency variation remains often within the IEC range, but it crosses the IEC range, sometimes. The operating frequency range of the Bangladesh Grid Code is wider than the IEC range and this variation is always within the grid code range. Grid-tied solar inverters are capable to maintain this frequency variation. The plant operator informed us that Solar Plants frequency settings of the Teknaf 20 MW solar plant were modified after reviewing the interconnection problem (Kainat et al., 2021).

4.2 Solar Irradiance Data at Kaptai 7.4MW Solar Power Plant

According to the data recording procedure mentioned in the methodology, the time series solar irradiance data of the Kaptai 7.4MW Solar power plant were recorded into the data logger and remote server. The data quality was checked before using the collected solar irradiance data set. The solar GHI data of the Kaptai 7.4MW solar power plant were plotted on the monthly basis and observed in the daily condition as classified. Monthly plotted figures are given below:

4.2.1. *Solar irradiance observed in October 2019*

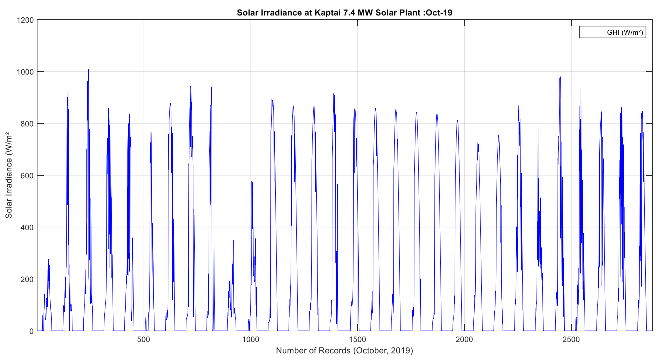

Figure 7. GHI Data of Kaptai, October 2019.

Solar irradiance observed in the Kaptai 7.4MW solar power plant for the entire month of October 2019 is represented by a single line in Figure 7. The figure reveals clear weather days when solar ramping was not present. Some days look deep blue with different levels on Y-axis. Those were partly cloudy days and solar irradiance variation was present. More deep blue represents more ramping on that day. A ramping level can be identified by the height of the deep blue lines. Some full cloudy days are also present where the peak irradiance of those days is less than 300 W/m^2. Therefore, according to the mentioned initial screening, around 50% of days are high solar resource variability, 3 days are washouts, and the rest are clear weather days. The highest solar irradiance level is around 1000 W/m^2, while the lowest is around 250 W/m^2.

4.2.2. *Solar irradiance observed in November 2019*

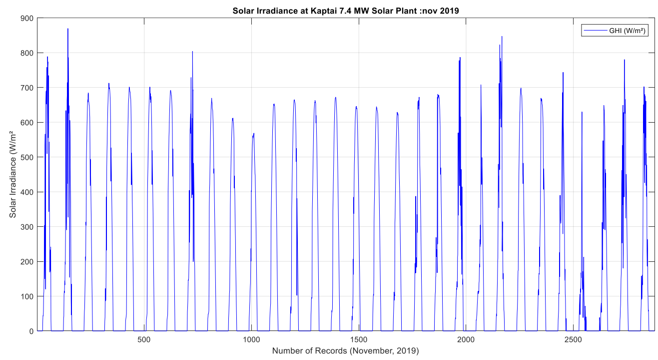

Figure 8: GHI Data of Kaptai, November 2019.

Figure 8 shows that most of the days of November 2019 are clear weather days except variability-containing days. The highest solar irradiance level is around 950 W/m^2, while the lowest is around 580 W/m^2.

4.2.3. *Solar irradiance observed in December 2019*

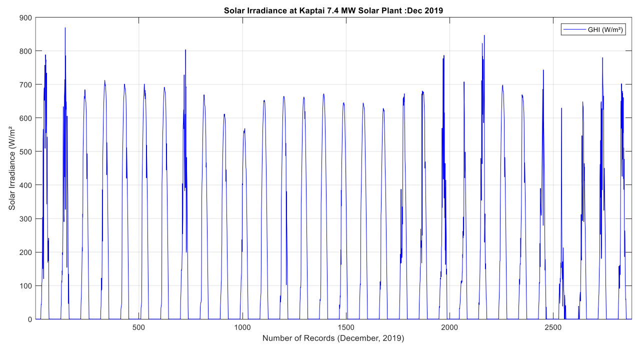

Figure 9: GHI Data of Kaptai, December 2019.

According to Figure 9, most of the days are clear weather days except for a few variability-containing days. The highest solar irradiance level is around 950 W/m^2, while the lowest is around 650 W/m^2.

4.2.4. *Solar irradiance observed in January 2020*

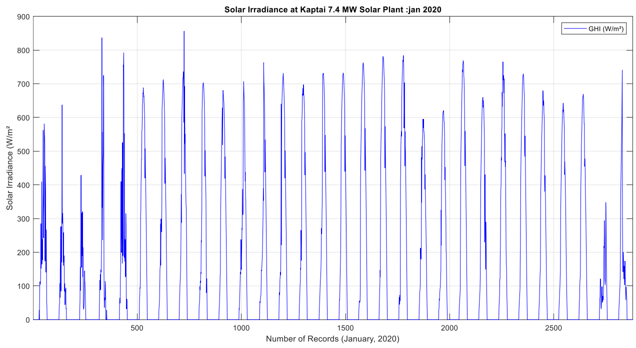

Figure 10. GHI Data of Kaptai, January 2020.

Figure 10 shows solar irradiance observed in January 2020. According to Figure 10, it is observed that most of the days are clear weather days except for a few variability-containing days and washout days. The highest solar irradiance level is around 850 W/m^2, while the lowest is around 350 W/m^2.

4.2.5. *Solar irradiance observed in February 2020*

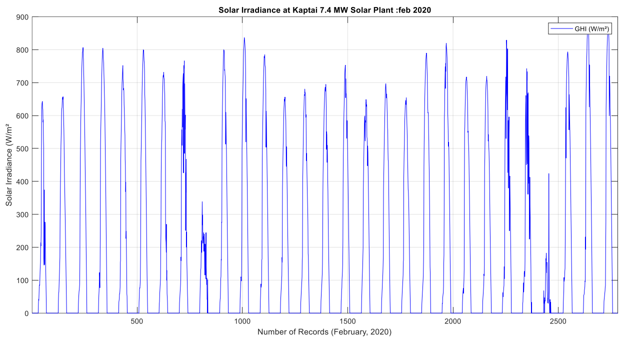

Figure 11. GHI Data of Kaptai, February 2020.

Figure 11 reveals that most of the days of February 2020 were clear weather days except few variability-containing days and washout days. Here the number of variability/washout days is lower than the previous figures. The highest solar irradiance level is around 830 W/m^2, while the lowest is around 300 W/m^2.

4.2.6. *Solar irradiance observed in March 2020*

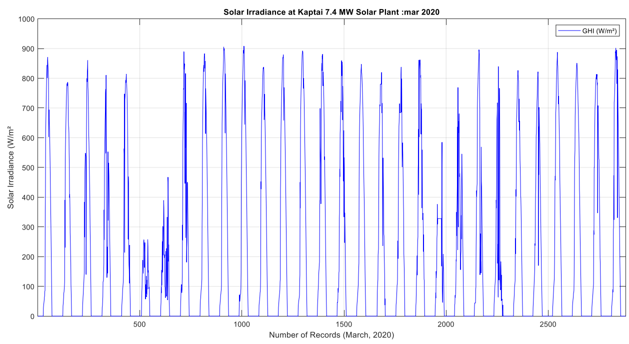

Figure 12. GHI Data of Kaptai, March 2020.

According to Figure 12, solar irradiance is observed to be clear weather days in March 2020 except few variability-containing days and washout days. The highest solar irradiance level is around 900 W/m^2, while the lowest is around 250 W/m^2.

4.2.7. *Solar irradiance observed in April 2020*

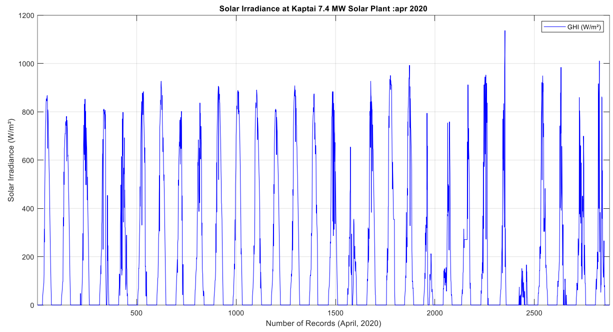

Figure 13. GHI Data of Kaptai, April 2020.

Figure 13 reveals that the number of high solar resource variable days is more than 50%, a few are washout days and the rest are clear weather days. It is observed that clear weather days are decreasing and variability days are increasing as compared to the previous months. The highest solar irradiance level is around 1150 W/m^2, while the lowest is around 150 W/m^2. The cloud enhancement is observed during the highest solar irradiance-containing day.

4.2.8. *Solar irradiance observed in May 2020*

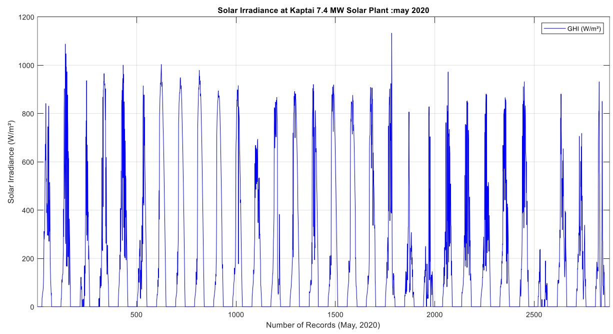

Figure 14. GHI Data of Kaptai, May 2020.

According to Figure 14, the number of clear weather days is quite small in May 2020. Most of the days are high solar resource variables, while few are washout days. The highest solar irradiance level is around 1100 W/m^2, while the lowest is around 200 W/m^2. The cloud enhancement is observed in a few days.

4.2.9. *Solar irradiance observed in June 2020*

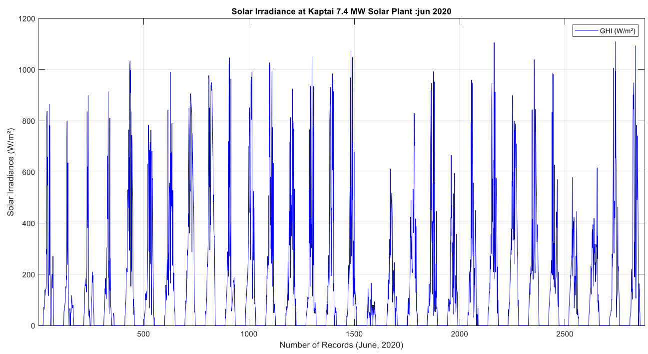

Figure 15. GHI Data of Kaptai, June 2020.

According to Figure 15, all days are high solar resource variables except a few washout days. There is no clear weather day. The highest solar irradiance level is around 1100 W/m^2, while the lowest is around 150 W/m^2. Cloud enhancement is observed on many days this month.

4.2.10. *Solar irradiance observed in July 2020*

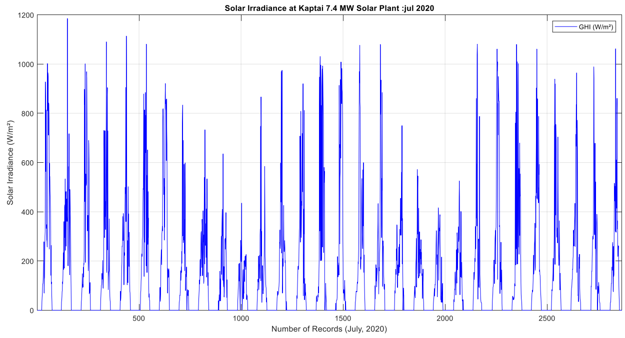

Figure 16. GHI Data of Kaptai, July 2020.

According to Figure 16, all days of July 2020 are high solar resource variables except a few washout days. There is no clear weather day. The highest solar irradiance level is around 1200 W/m^2, while the lowest is around 400 W/m^2. Cloud enhancement is observed on many days this month.

4.2.11. *Solar irradiance observed in August 2020*

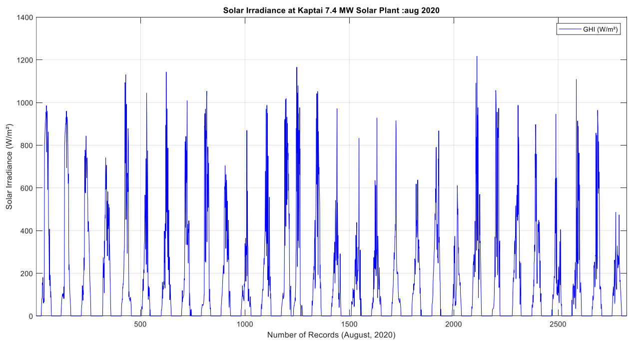

Figure 17. GHI Data of Kaptai, August 2020.

According to Figure 17, all days of August 2020 are high solar resource variables except a few washout days. There is no clear weather day. The highest solar irradiance level is around 1200 W/m^2, while the lowest is around 450 W/m^2. This month, cloud enhancement is observed on many days.

4.2.12. *Solar irradiance observed in September2020*

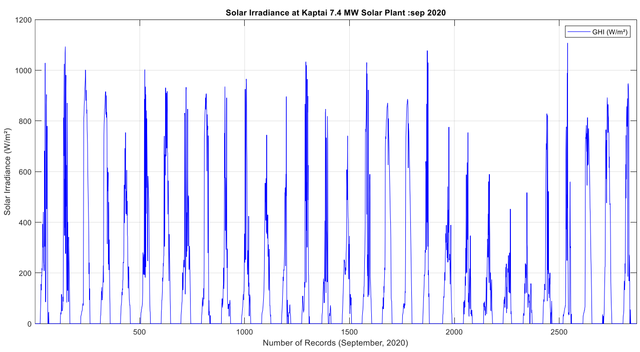

Figure 18. GHI Data of Kaptai, September 2020.

According to Figure 18, most of the days are high solar resource variable days; a few are washout days and the number of clear weather days is less than five. The highest solar irradiance level is around 1150 W/m^2, while the lowest is around 400 W/m^2. Cloud enhancement is observed on many days of this month, as well.

4.2.13. *Solar irradiance observed for a year*

The daily irradiance status summary is shown below in based on the above one-year solar irradiance data assessment of the Kaptai 7.5MW Solar Power Plant.

From, it is observed that only 105 days (29%) in a year are clear weather days, whereas 188 days (51%) are high solar resource variable days. Only 40 days (11%) are low variability days and 33 days (9%) are washout days. Given that the high solar resource variability days of a year are more than 50%, it is important to take necessary preventive measures to minimize the output power variation of solar power plants for safe grid integration and high PV penetration, because the output power of the SPV plant is proportional to the input solar irradiance. This output power variation needs to be addressed by the alternative support system connected to the grid and nearest to the interconnection areas. Washout days, high variability days, low variability days, and clear days for a year are shown in Figure **19** as a monthly bar chart.

Table 1. Yearly status of solar irradiance at Kaptai, Chittagong, Bangladesh.

Month	Total Days	Washout Days	High Variability Days	Low Variability Days	Clear Days
JAN 2020	31	3	4	4	20
FEB 2020	29	2	4	3	20
MAR 2020	31	3	9	8	11
APR 2020	30	2	17	8	3
MAY 2020	31	1	22	3	5
JUN 2020	30	3	27	0	0
JUL 2020	31	6	23	0	2
AUG 2020	31	6	22	3	0
SEP 2020	30	3	22	3	2
OCT 2019*	31	2	17	4	8
NOV 2019*	30	1	11	2	16
DEC 2019*	31	1	10	2	18
Total	366	33	188	40	105
Percentage		9%	51%	11%	29%

* Due to the unavailability of the data, the previous year's data has been considered for 3 months

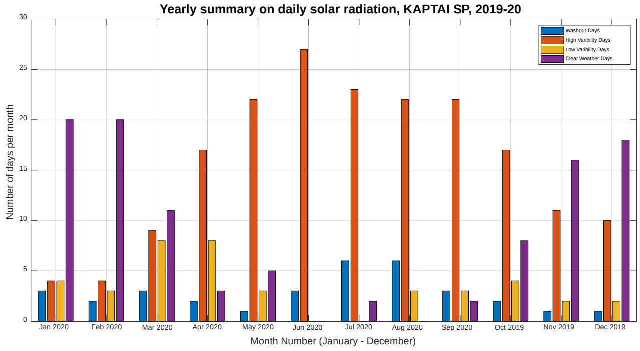

Figure 19. A yearly summary of daily solar irradiance, KAPTAI SP.

According to Figure **19** , November to February have more clear weather days, while October and March have some clear weather days. On the other hand, the months of April to October have more high solar irradiance variability days, whereas June has the peak conditions in terms of the number of days. Every month has 1-3 washout days, but it is high (6 days in each month) in July and August.

4.3 National Solar Radiation Resource Assessment Station, Chittagong

The solar GHI data of the National Solar Radiation Resource Assessment Station, Chittagong were plotted on the monthly basis and the daily condition, which is classified and mentioned in the methodology section, was observed. Monthly plotted figures are given below:

4.3.1. *Solar irradiance observed in January 2020*

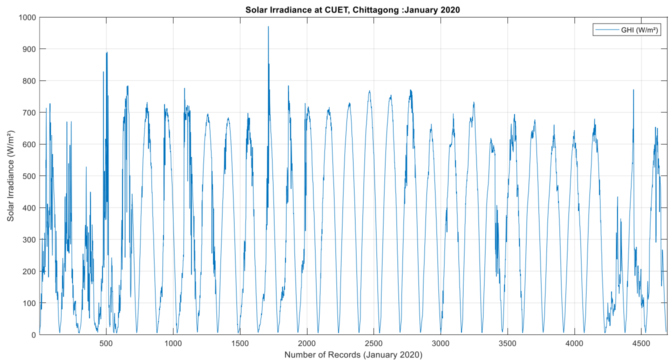

Figure 20. GHI Data of NSRRA CTG, January 2020.

According to Figure 20, in January 2020, most of the days are clear weather days with few high variability days and one washout day. The average peak solar irradiance is approximately 700 W/m^2, the highest solar irradiance level is around 1000 W/m^2, and the lowest is around 400 W/m^2. The cloud enhancement is observed in a few days of this month.

4.3.2. *Solar irradiance observed in February 2020*

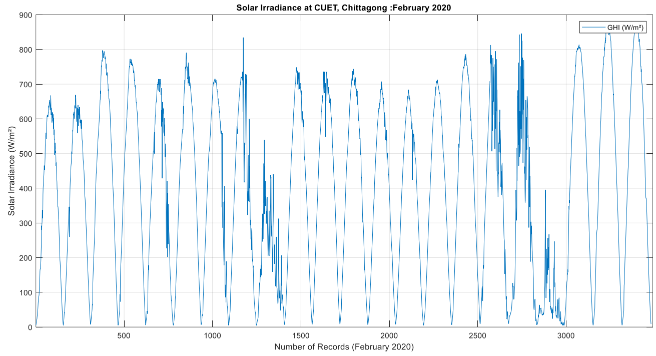

Figure 21. GHI Data of NSRRA CTG, February 2020.

In February 2020, as shown in Figure 21, most of the days are clear weather days with four high variability days and one washout day. The average peak solar irradiance is approximately 700 W/m^2, the highest solar irradiance level is around 950 W/m^2, and the lowest is around 400 W/m^2. Cloud enhancement is observed in a few days of this month.

4.3.3. *Solar irradiance observed in March 2020*

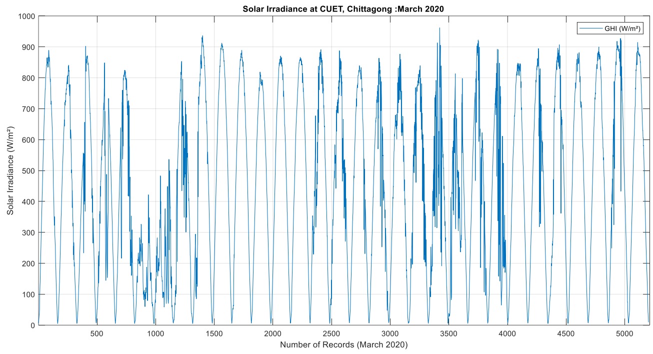

Figure 22. GHI Data of NSRRA CTG, March 2020.

According to Figure 22, in March, most of the days are clear weather days with 7 high variability days and 2 washout days. The average peak solar irradiance is approximately 850 W/m^2, the highest solar irradiance level is around 950 W/m^2, and the lowest is around 400 W/m^2.

4.3.4. *Solar irradiance observed in April 2020*

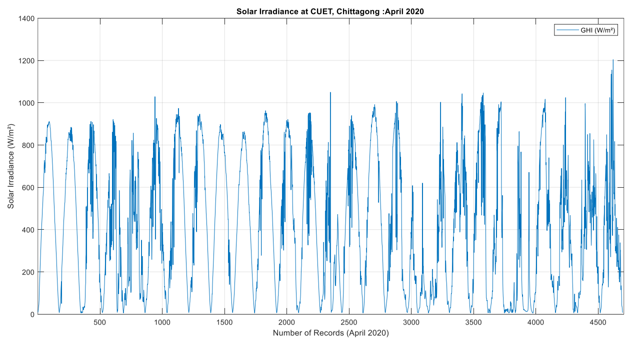

Figure 23. GHI Data of NSRRA CTG, April 2020.

In April 2020, as shown in Figure 23, only 7 days are clear weather days with one washout day and the rest of the days being high variability days. The average peak solar irradiance is approximately 900 W/m^2, the highest solar irradiance level is around 1200 W/m^2, and the lowest is around 400 W/m^2. The cloud enhancement is observed in a few days of this month.

4.3.5. *Solar irradiance observed in May 2020*

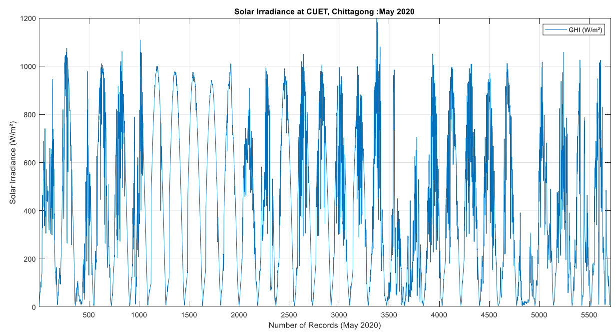

Figure 24. GHI Data of NSRRA CTG, May 2020.

According to Figure 24 (May 2020), only 5 days are clear weather days, while the rest of the days are high variability days including one washout day. The average peak solar irradiance is approximately 1000 W/m^2, the highest solar irradiance level is around 1200 W/m^2, and the lowest is around 400 W/m^2. The cloud enhancement is observed in a few days of this month.

4.3.6. *Solar irradiance observed in June 2020*

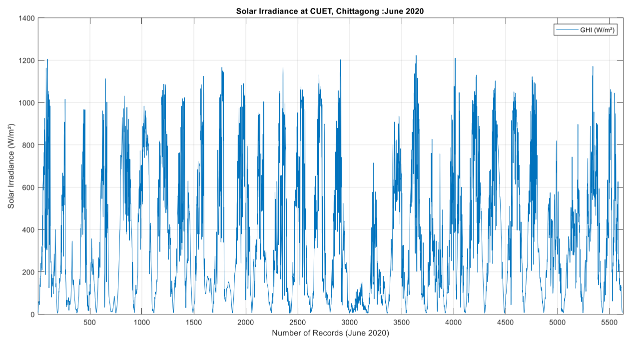

Figure 25. GHI Data of NSRRA CTG, June 2020.

According to Figure 25 (June 2020), there are no clear weather days. Most of the days are high variability days including a few washout days. The average peak solar irradiance is approximately 1000 W/m^2, the highest solar irradiance level is around 1200 W/m^2, and the lowest is around 150 W/m^2. The cloud enhancement is observed in a few days of this month.

4.3.7. *Solar irradiance observed in July 2020*

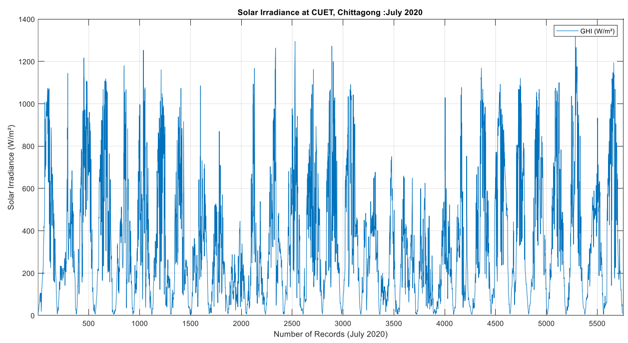

Figure 26. GHI Data of NSRRA CTG, July 2020.

According to Figure 26 (July 2020), there are no clear weather days. Most of the days are high variability days including a few washout days. The average peak solar irradiance is approximately 1000 W/m^2, the highest solar irradiance level is around 1250 W/m^2, and the lowest is around 400 W/m^2. Cloud enhancement is observed on many days this month.

4.3.8. *Solar irradiance observed in August 2020*

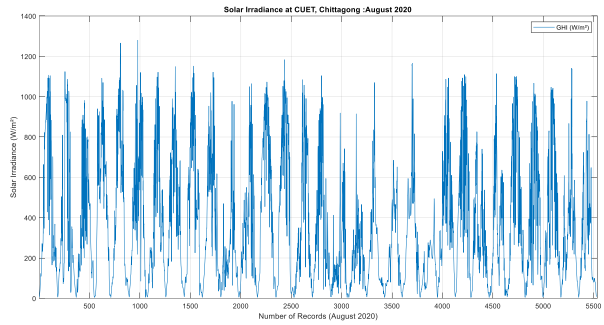

Figure 27. GHI Data of NSRRA CTG, August 2020.

According to Figure 27 (August 2020), there are no clear weather days. Most of the days are high variability days including a few washout days. The average peak solar irradiance is approximately 1050 W/m^2, the highest solar irradiance level is around 1300 W/m^2, and the lowest is around 400 W/m^2. Cloud enhancement is observed on many days this month.

4.3.9. *Solar irradiance observed in September 2020*

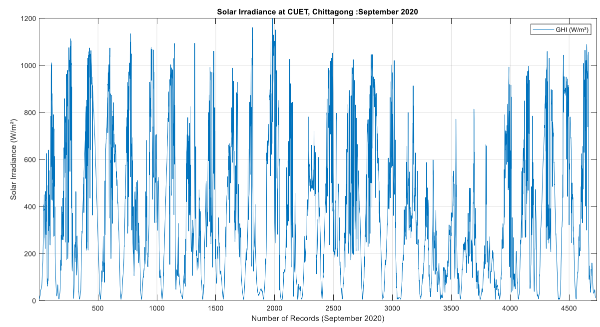

Figure 28. GHI Data of NSRRA CTG, September 2020.

According to Figure 28 (September 2020), there are no clear weather days. Most of the days are high variability days including 4-5 washout days. The average peak solar irradiance is approximately 1000 W/m^2, the highest solar irradiance level is around 1200 W/m^2, and the lowest is around 600 W/m^2. Cloud enhancement is observed on many days this month.

4.3.10. *Solar irradiance observed in October 2020*

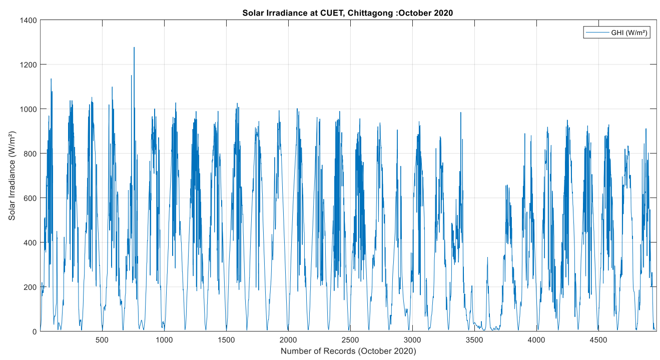

Figure 29. GHI Data of NSRRA CTG, October 2020.

According to Figure 29 (October 2020), there are no clear weather days. Most of the days are high variability days including 1-2 washout days. The average peak solar irradiance is approximately 950 W/m^2, the highest solar irradiance level is around 1300 W/m^2, and the lowest is around 350 W/m^2. Cloud enhancement is observed on many days this month.

4.3.11. *Solar irradiance observed in November 2020*

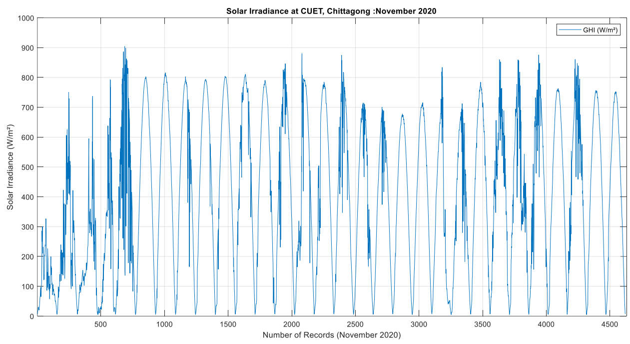

Figure 30. GHI Data of NSRRA CTG, November 2020.

According to Figure 30 (November 2020), most of the days are clear weather days and the rest of the days are high variability days including 1-2 washout days. The average peak solar irradiance is approximately 800 W/m^2, the highest solar irradiance level is around 900 W/m^2, and the lowest is around 300 W/m^2. The cloud enhancement is observed in a few days of this month.

4.3.12. *Solar irradiance observed in December 2020*

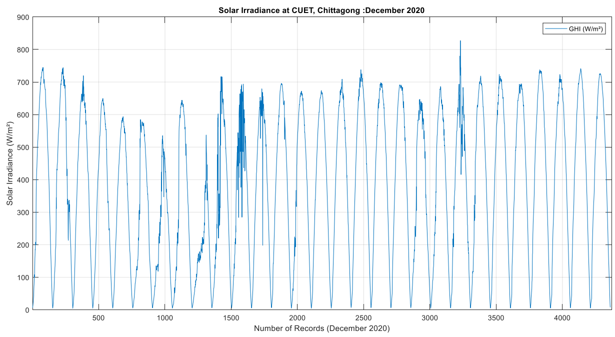

Figure 31. GHI Data of NSRRA CTG, December 2020.

According to Figure 31 (December 2020), most of the days are clear weather days and the rest 2-3 days involve a few variabilities. The average peak solar irradiance is approximately 700 W/m^2, the highest solar irradiance level is around 850 W/m^2, and the lowest is around 500 W/m^2. The cloud enhancement is observed in a few days of this month.

4.3.13. *Solar irradiance scenario for a year*

The daily solar irradiance status is given below in **Error! Reference source not found.** and Figure 32 based on the above one-year solar irradiance data assessment of the National Solar Radiation Resource Assessment (NSRRA) station, Chittagong.

Table 2. Yearly status of solar irradiance at CUET, Chittagong.

Month	Total Days	Washout Days	High Variability Days	Low Variability Days	Clear Days
JAN 2020	31	2	8	4	17
FEB 2020	29	2	3	5	19
MAR 2020	31	2	14	5	10
APR 2020	30	4	20	4	2
MAY 2020	31	4	22	2	3
JUN 2020	30	3	27	0	0
JUL 2020	31	5	26	0	0
AUG 2020	31	2	29	0	0
SEP 2020	30	0	30	0	0
OCT 2020	31	2	28	1	0
NOV 2020	30	1	13	5	11
DEC 2020	31	0	4	2	25
Total	**366**	**27**	**224**	**28**	**87**
Percentage		7%	61%	8%	24%

Table 2 shows that more than 50% of days in a year contain high solar variability. Approximately 10% contain washout days and another approximately 10% involve low variability days. Only approximately 25 – 30% of days are obtained as clear weather days.

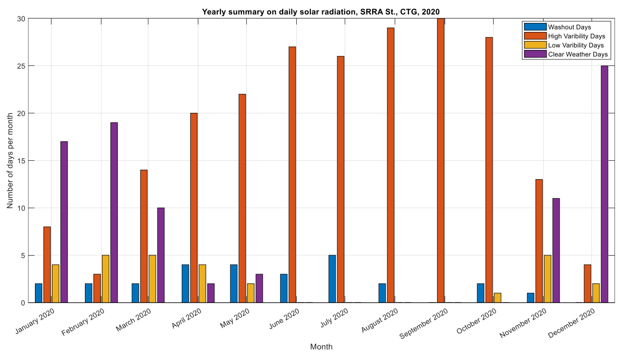

Figure 32. Yearly summary on daily solar irradiance, SRRA St., CTG.

Figure 32 shows that the months of December to February have a higher number of clear weather days, while November and March have around 10 days with clear weather. In contrast, the months from April to October have more days with high solar irradiance variability, with June to October having the highest number of such days. March and November have a similar percentage of high solar irradiance variability days, close to 50%. Each month has between 0 and 3 washout days, but April, May, and July have a higher number of washout days, around 4 to 5 days per month.

5. COMPARATIVE SCENARIO

As shown in **Error! Reference source not found.** and **Error! Reference source not found.**, the first case study site has 51% high variability days while the second case study site has 61% high variability days in a year. Similarly, their low variability days in a year were 11% and 8%, respectively. The monthly comparative analysis is presented in Figure 33.

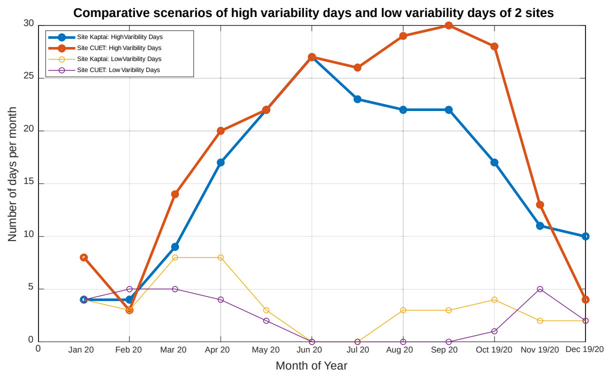

Figure 33. Comparative scenarios of the 2 case study sites on high variability days and low variability days.

According to Figure 33, the monthly high variability days of 2 case study sites are very close to each other although some significant differences are observed between August and November. In addition, monthly small variability days are very close to each other. Similarly, comparative scenarios of clear weather days and washout days are shown below in Figure 34.

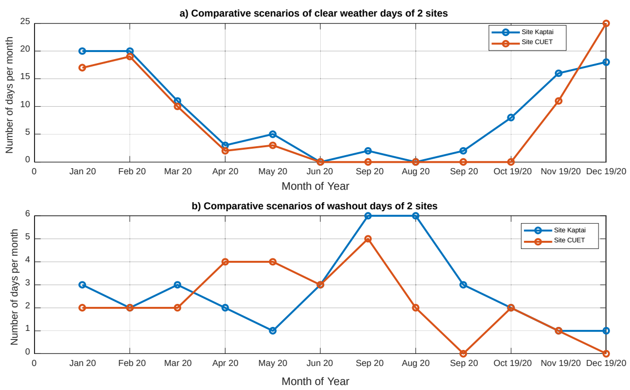

Figure 34. Comparative scenarios of clear weather days and washout days.

Figure 34(a) represents the comparative scenarios between two sites on monthly clear weather days. The monthly clear weather patterns of the two sites look almost similar with a negligible difference in January, May, June, and September and a significant difference from October to December. Figure 34(b) represents the comparative scenarios between two sites on monthly washout days. Some significant differences were observed between the two sites, although limited to monthly six days. This yearly analysis of solar irradiance gives us the scenario of variation of solar irradiance and its major variation time. The alternative support system to meet the output power variation of the SPV plant requires planning according to the variation of solar irradiance. This assessment of the two sites gives a scenario of this region.

Considering the minimum values, at least more than 50% of days in a year contain high solar irradiance variation. Around 8% of days of a year are washout days, 10% of days are low variability days, and only approximately 25–30% of days are obtained as clear weather days. As observed, since 50% of the days in a year have high solar irradiance variability, it is crucial to consider this factor in the grid integration study of any proposed large-capacity solar photovoltaic (SPV) plant, because the output power of the SPV plant is directly proportional to the input solar irradiance. Also, geographical dispersion can reduce some ramping effects and cloud enhancement increases the solar ramping effect which can change the resultant effect in a few amounts. More precision time interval data can provide more reliable solar ramp management results but still, an approximate scenario was identified.

This variable power output of the SPV plant creates a quick load flow change in the interconnection area of the utility network. Ramp rate and ramp level are important issues here. If the utility network is unable to manage such load flow in that area, then several adverse effects will be observed due to the integration of such variable renewable energy. Therefore, it is important to promote variable renewable energy like solar photovoltaic power plants in Bangladesh with safe grid integration including necessary correction measures.

6. CONCLUSIONS

Solar irradiance is variable in nature due to the weather conditions of that location. Yearly assessment is essential as seasonal variations are present in weather conditions. The important findings of this study are summarized below.

a) The variation of grid frequency at the interconnection point of the case study site was observed although higher than the IEC range, but still within the grid code range of Bangladesh. Available grid-tied solar PV inverters were capable to operate within the range.

b) Variation of grid voltage at the grid interconnection substation was found within the standard range in the daytime, but within the rest of the observed time period, the low voltage was witnessed at the grid level. However, the variation of grid voltage at the interconnection point of the case study site depended on the regional load, the generation capacity of the nearest power plant, the distance from the grid substation, the capacity of the grid transmission line, etc. It may vary based on the conditions of the interconnection points.

c) According to the information of selected two sites (Kaptai 7.4MW solar power plant and NSRRA, Chittagong), more than 50% of days in a year contain a high short-term variation of solar irradiance. Only 7% - 9% were annual washout days.

d) Only 24-29% of days in a year were clear weather days where short-term variations of solar irradiance were not present. Also, 8%-11% of days in a year contained a low short-term variation of solar irradiance.

e) Two case study sites were taken to get reliable results. The result of the two sites obtained from this study was very close to each other, which is acceptable.

Therefore, for safe grid integration of large-scale variable solar power plants into the grid with high VRE penetration, it is essential to take necessary preventive measures to reduce the solar ramping. This result is a site or region-specific scenario that can reflect the SPV integration picture of Bangladesh. This assessment was conducted using existing time series solar irradiance data. More precision solar irradiance data will give a more reliable result for further study.

7. ACKNOWLEDGEMENT

We thank the financial support from the Bangladesh University of Engineering and Technology (BUET) through Committee for Advanced Studies and Research (CASR). The editor-in-chief and reviewers of the JREE are greatly acknowledged for their comments and support.

NOMENCLATURE

BPDB	Bangladesh Power Development Board
BREB	Bangladesh Rural Electrification Board
BUET	Bangladesh University of Engineering and Technology
CASR	Committee for Advanced Studies and Research
CE	Cloud Enhancement
CUET	Chittagong University of Engineering of Technology
GEF	Global Environment Facility
GHI	Global Horizontal Irradiance
IEC	International Electrotechnical Commission
JPL	Joules Power Limited
NSRRA	National Solar Radiation Resource Assessment
PBS	PalliBidyutSomity
PGCB	Power Grid Company of Bangladesh
PV	Photovoltaic
SPV	Solar Photovoltaic
SREDA	Sustainable and Renewable Energy Development Authority
SREPGen	Sustainable Renewable Energy Power Generation
TSEL	Teknaf Solartech Energy Limited
VRE	Variable Renewable Energy

REFERENCES

1. Ahmed, R., Sreeram, V., Mishra, Y., & Arif, M. D. (2020). A review and evaluation of the state-of-the-art in PV solar power forecasting: Techniques and optimization. Renewable and Sustainable Energy Reviews, 124, 109792. https://doi.org/10.1016/j.rser.2020.109792

2. Annual Report 2019-2020 of SREDA. (2020). http://www.sreda.gov.bd

3. Bangladesh Energy Regulatory Commission (Electricity Grid Code) Regulations, 2019. (2020). http://www.berc.org.bd

4. Blanc, P., Espinar, B., Geuder, N., Gueymard, C., Meyer, R., Pitz-Paal, R., Reinhardt, B., Renné, D., Sengupta, M., Wald, L., & Wilbert, S. (2014). Direct normal irradiance related definitions and applications: The circumsolar issue. Solar Energy, 110, 561–577. https://doi.org/10.1016/j.solener.2014.10.001

5. Boopathi, K., Ramaswamy, S., Kirubakaran, V., Uma, K., Saravanan, G., Thyagaraj, S., & Balaraman, K. (2021). Economic investigation of repowering of the existing wind farms with hybrid wind and solar power plants: a case study. International Journal of Energy and Environmental Engineering, 12(4), 855–871. https://doi.org/10.1007/s40095-021-00391-3

6. Carmona, F., Orte, P. F., Rivas, R., Wolfram, E., & Kruse, E. (2018). Development and Analysis of a New Solar Radiation Atlas for Argentina from Ground-Based Measurements and CERES_SYN1deg data. The Egyptian Journal of Remote Sensing and Space Science, 21(3), 211–217. https://doi.org/10.1016/j.ejrs.2017.11.003

7. Choi, Y., Suh, J., & Kim, S.-M. (2019). GIS-Based Solar Radiation Mapping, Site Evaluation, and Potential Assessment: A Review. Applied Sciences, 9(9), 1960. https://doi.org/10.3390/app9091960

8. Customized Bangladesh Map - Google My Maps. (n.d.). Retrieved March 26, 2023, from https://www.google.com/maps/d/u/0/edit?hl=en&mid=1eKcsqjkBzI3jgVfOkJ6xpVPVU1guOtg&ll=23.608281830845563%2C92.00898324794439&z=7

9. Denholm, P., & Margolis, R. M. (2007). Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies. Energy Policy, 35(9), 4424–4433. https://doi.org/10.1016/j.enpol.2007.03.004

10. Global Solar Atlas. (n.d.). Retrieved March 27, 2023, from https://globalsolaratlas.info/download/bangladesh

11. IEC 61727:2004 | IEC Webstore | invertor, smart city, LVDC. (n.d.). Retrieved March 27, 2023, from https://webstore.iec.ch/publication/5736

12. Jamil, B., & Akhtar, N. (2017). Estimation of diffuse solar radiation in humid-subtropical climatic region of India: Comparison of diffuse fraction and diffusion coefficient models. Energy, 131, 149–164. https://doi.org/10.1016/j.energy.2017.05.018

13. Järvelä, M., Lappalainen, K., & Valkealahti, S. (2020). Characteristics of the cloud enhancement phenomenon and PV power plants. Solar Energy, 196, 137–145. https://doi.org/10.1016/j.solener.2019.11.090

14. Jazayeri, M., Jazayeri, K., & Uysal, S. (2017). Generation of spatially dispersed irradiance time-series based on real cloud patterns. Solar Energy, 158, 977–994. https://doi.org/10.1016/j.solener.2017.10.026

15. Kainat, Engr. M. G. S., Alam, Engr. Md. R., & Masud, Engr. Md. T. (2021). Towards a Sustainable Energy Future. Grid Integration of Solar Energy: A case study on 20 MW Solar Power Plant of Teknaf Solar Energy Ltd. In Towards Sustainable Energy Future (Vol. 1, Number 1). SREDA, Bangladesh. http://www.sreda.gov.bd/site/page/95b63d6e-aac2-46ae-a46d-37faae6f9e86

16. Karthikeyan, V., & Janarthanan, S. (2017). Yield factor of grid connected solar photovoltaic system-a case study. Journal of Advanced Research in Dynamical and Control Systems, 9, 206–213. https://www.academia.edu/download/62920747/635020200411-35167-11vvlag.pdf

17. Keeratimahat, K., Bruce, A., & MacGill, I. (2019). Partial curtailment to firm photovoltaic generation dispatch. 2019 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), 1–5. https://doi.org/10.1109/APPEEC45492.2019.8994464

18. Sengupta, M., Xie, Y., Lopez, A., Habte, A., Maclaurin, G., & Shelby, J. (2018). The National Solar Radiation Data Base (NSRDB). Renewable and Sustainable Energy Reviews, 89, 51–60. https://doi.org/10.1016/j.rser.2018.03.003

19. Shuvho, Md. B. A., Chowdhury, M. A., Ahmed, S., & Kashem, M. A. (2019). Prediction of solar irradiation and performance evaluation of grid connected solar 80KWp PV plant in Bangladesh. Energy Reports, 5, 714–722. https://doi.org/10.1016/j.egyr.2019.06.011

20. Sivaneasan, B., Yu, C. Y., & Goh, K. P. (2017). Solar Forecasting using ANN with Fuzzy Logic Pre-processing. Energy Procedia, 143, 727–732. https://doi.org/10.1016/j.egypro.2017.12.753

21. Tahir, Z. R., & Asim, M. (2018). Surface measured solar radiation data and solar energy resource assessment of Pakistan: A review. Renewable and Sustainable Energy Reviews, 81, 2839–2861. https://doi.org/10.1016/j.rser.2017.06.090

22. Van Haaren, R., Morjaria, M., & Fthenakis, V. (2014). Empirical assessment of short-term variability from utility-scale solar PV plants. Progress in Photovoltaics: Research and Applications, 22(5), 548–559. https://doi.org/10.1002/pip.2302

23. Wei, C.-C. (2017). Predictions of Surface Solar Radiation on Tilted Solar Panels using Machine Learning Models: A Case Study of Tainan City, Taiwan. Energies, 10(10), 1660. https://doi.org/10.3390/en10101660

24. Zhang, J., Zhao, L., Deng, S., Xu, W., & Zhang, Y. (2017). A critical review of the models used to estimate solar radiation. Renewable and Sustainable Energy Reviews, 70, 314–329. https://doi.org/10.1016/j.rser.2016.11.124