A FEASIBILITY STUDY OF SOLAR PHOTOVOLTAIC POWER SMOOTHING USING FUZZY LOGIC APPROACH

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Abstract - Penetration of Variable Renewable Energy (VRE) is a challenge for safe grid integration. The short-term variation of solar irradiance, which is initiated by moving clouds, causes fluctuations in Solar Photovoltaic (SPV) power generation and can jeopardize grid stability. The fluctuations in the output power of the SPV plants are the reason for the dynamic change of load flow in the interconnection area of the utility network. To assess the short-term variation of solar irradiance, 1-year time-series solar irradiance data have been collected from a Solar Irradiance Measurement Station; located at Chittagong University of Engineering and Technology (CUET), Chittagong, Bangladesh. The collected data from the case study site reveals that the short-term variation of solar irradiance is significant especially from April to September. Furthermore, a feasibility study of SPV power smoothing has been conducted using the Fuzzy Logic approach to identify the requirement of the Energy Storage System (ESS) as well as to minimize the solar ramp rate and ramp level. An 8 MWh ESS with an 8 MW power capacity has been identified as the capacity of the ESS support system for smoothing a 20 MWp solar plant. The daily support amount and the surplus amount have been calculated for solar power smoothing and that found identical in terms of energy and power. Although this feasibility study gives a directive on grid integration aspects before establishing a large utility-scale SPV plant, the actual scenarios may be slightly different due to the geographical dispersion, cloud enhancement and similar other effects.

Keywords: Solar Irradiance, Variable Renewable Energy, Short-term Variation, Solar Power Smoothing, Fuzzy Logic, Feasibility Study, Energy Storage.

1. INTRODUCTION

Solar irradiance is variable in nature due to environmental conditions like cloud patterns and their movement [1,2]. As it is the input of the Solar Photovoltaic (SPV) power plant, the output power of the plant depends on it [3,4]. The short-term variability of solar irradiance, originating from moving clouds, causes fluctuations in the SPV power generation and can negatively affect grid stability [5]. The Ramp-rate (RR) statistics, a quantifying parameter of solar power variability; is widely used, most common and practical quantities [6]. The power ramp-rate control (PRRC) strategy is employed to limit the fluctuation rate in the photovoltaic (PV) output power under dynamically changing irradiance conditions [7]. It has been observed that more than 50% of the days in a year in Bangladesh experience high solar irradiance short-term variability [8].

To address this short-term variability, grid codes of several countries have incorporated ramp-rate limitations to inject variable renewable energy (VRE) like SPV plants [9,10]. In Bangladesh, there are no such specific requirements of ramp-rate limitations in the conditions of the power purchase agreement of utility-scale solar power plants as well as in the national grid code of Bangladesh [11]. The fluctuations in the output power of the plant are the reason for the dynamic change of load flow in the interconnection area of the utility network [12]. There are some issues like cloud enhancement and geographical dispersion but still, such intermittency poses significant challenges [13–15]. Increasing penetration in the interconnected power network impacts system frequency response. Therefore, it is difficult for the Transmission System Operator (TSO) to address the frequency regulation. Understanding the nature of this intermittency is important as it can unstable system inertia and stability. Some important issues are discussed below.

1.1. Geographical Dispersion

The geographic dispersion of solar-photovoltaic panels reduces variability in energy production. A study result was published in [16] that characterized some plants' power output variability based on minute-averaged irradiation data from each plant and the output from 390 inverters. The result of that study was observed 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 Alternating Current (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 [16]. The study was based on the United States of America (USA) and Canada although the scenario may be different in Bangladesh with some positive effects of geographical dispersion.

1.2. Cloud Enhancement

The solar irradiance can exceed the level of expected clear sky irradiance for a very short time during partly cloudy days. This is known as cloud enhancement (CE) or over irradiance or irradiance enhancement. The CE phenomenon can be observed worldwide but the amount may vary from place to place. According to [17], solar irradiance on such days may be increased to 1.5 to 1.6 times more for a short time than the clear weather days level. It also increases the output power fluctuation of the SPV power plant.

1.3. Application of Energy Storage to Minimize this Variation

The power electronic inverters are capable of operating with grid-friendly features like volt-VAR control, ramp-rate control, high-frequency power curtailment, and event ride-through [18]. To minimize the ramp rate of the SPV power plant, it is essential to provide support from alternative sources [9,19]. Utility-scale storage Li-Ion Battery is widely used for this purpose due to their first response [20]. Some other storage technologies like large Vanadium Redox flow batteries, Polysulphide Bromine flow batteries, and Zinc Bromine flow batteries are parallelly used [21,22]. Recently, energy storage, Superconductive magnetic energy storage, Sensible thermal energy storage, Latent-phase change material, Thermochemical storage, and Pumped hydro storage have also been explored as utility-scale storage [23,24]. However, the cycle life of energy storage is a challenge for ramp management of SPV applications [25]. Moving Average, Exponential Moving Average, First Order Low-Pass Filter, Second-Order Low-Pass Filter, and Fuzzy Logic Controller are investigated as control technologies to minimize the ramp rate [26–28]. The fuzzy logic controller is familiar among them and comprehensively studied in [29,30]. Energy storage may be a good solution to deal with the intermittency however, the associated cost and its disposal mechanism and maintenance are a few major concerns [31,32].

The short-term variation of solar irradiance, generated from moving clouds, is very much location-specific and depends on the weather conditions of that area. Therefore, a detailed grid integration study is essential for a large-scale SPV plant to understand the integration effect on the utility interconnection point. In this paper, a feasibility study of SPV power smoothing has been conducted using the Fuzzy Logic approach. This analysis is based on a proposed capacity of 20 MWp SPV plant for the location of Chittagong University of Engineering and Technology (CUET), Bangladesh, where a solar radiation resource monitoring station is present. The study is divided into a few parts. Those are, (a) Solar Irradiance data collection for the case study site, at least for a year; (b) Data checking, filtering and finalizing the dataset for the study; (c) Developing a fuzzy model for power smoothing analysis; (d) Apply this model with input dataset and find out the power and energy scenario of each day; (e) Finalize the results and make some recommendation to overcome the challenges. As the input data set is site or region-specific, a such study in Bangladesh is pivotal and it's the demand of the future. The smoothing level may be adjusted by changing the degree of membership function. Therefore, it can be used anywhere with necessary modifications.

2. DATA SOURCE

2.1. National Solar Radiation Resource Assessment Station, Chittagong

The Sustainable and Renewable Energy Development Authority (SREDA), the nodal agency of Bangladesh, installed eight solar irradiance resource measurement stations in different locations of Bangladesh under a Global Environment Facility (GEF) funded project 'Sustainable Renewable Energy Power Generation (SREPGen)' to promote Renewable Energy in the country. Locations of the solar resource monitoring sites were Rangpur (BRUR), Rajshahi (RUET), Mymensingh (BAU), Sylhet (SUST), Kushtia (KPL), Khulna (KU), Patuakhali (PSTU), and Chittagong (CUET). Out of these eight solar radiation resource measurement stations, the Chittagong division's site (CUET) was selected for this analysis. 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 in the resource monitoring station. The solar irradiance data were recorded using pyranometers and a datalogger. The data sampling frequency was 10 seconds and averaging frequency was 4 minutes. The maximum, minimum, and standard deviation data of global horizontal irradiance also were present with the average global horizontal irradiance, which shows the more precise scenario of solar irradiance variation. The location of the selected site is shown below in Fig. **1** from the geographical map of Bangladesh.

Fig. 1. Location of the data source

3. MATERIALS AND METHODS

3.1. Block diagram of a utility-scale SPV power plant

The utility-scale SPV plant consists of one or multiple blocks and each block is connected to a central substation. There should be one or more, central or string inverters in each block where each inverter has one or more input terminals with a Maximum Power Point Tracking (MPPT) unit. The number of PV modules will be connected in series and create a sting according to the voltage of the input terminal of the inverter. Similarly, the number of the string will be connected in parallel and creates an array to achieve the input current and power of each MPPT input terminal of the grid-tied solar inverter. Synchronization and power quality will be ensured in each inverter of the SPV plant by following international standards where the output voltage of an inverter is normally less than 1kV. Alternating Current (AC) terminals of each inverter of a block are connected to a low-voltage busbar. The voltage level will be stepped up to 11kV or 33kV level through a power transformer and it will be connected to a central substation of the SPV plant. A central substation may have step-up transformers according to the voltage level of the integration point of the utility network. At least one energy meter will be placed to measure the power, energy and related parameters that will be used for billing and other purposes. A Power Plant Controller (PPC) may be installed in the control room with the necessary data communication infrastructure which will be connected to each inverter of the SPV plant. There should be at least one solar irradiance measurement station in a utility-scale SPV plant. A block diagram of a utility-scale SPV plant is shown in Fig. 2.

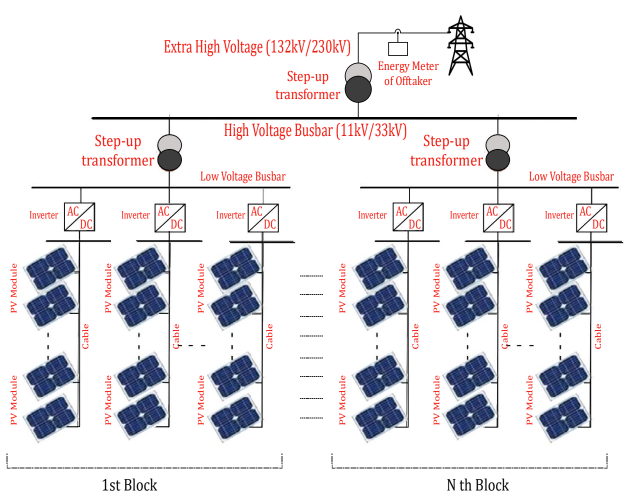

Fig. 2. Block diagram of a utility-scale solar power plant

The output power of an inverter depends on the input solar irradiance on solar modules that are connected to this inverter. Similarly, the combined output of all inverters will represent the output power of the SPV plant. In this study, variation of input solar irradiance has been identified to determine the variation of output power and develop necessary recommendations to reduce the variation for safe grid integration of SPV plant. A case study site, mentioned in the data source section, has been selected for this study.

3.2. Fuzzy Logic Approach

The solar irradiance data, mentioned in the data source section, were used to determine the variation analysis. The dataset was checked by the MATLAB program to find out the out-of-range and unexpected values. The ramp rate is the change rate of PV output per unit of time. As it is a feasibility study before installing the SPV plant, the solar irradiance dataset is the foundation, precise per unit time series solar irradiance data is not available in Bangladesh; a study has been conducted considering the existing resources to present the current scenarios. A fuzzy logic-based model was used to determine the energy and power support amount by minimizing the output power variation of a proposed 20 MWp CUET solar power plant in Bangladesh. This solar power variation minimization support could be delivered from the Energy Storage System (ESS) but the only tentative requirement was assessed to reduce the solar ramping. The required support power and energy amount were calculated on a daily basis to understand the case study. Detailed working procedures of the fuzzy model and its calculation are discussed below.

3.3. Fuzzy Model

Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multivalued logic. However, in a wider sense, Fuzzy Logic (FL) is almost synonymous with the theory of fuzzy sets, a theory that relates to classes of objects with unsharp boundaries in which membership is a matter of degree. Fuzzy logic differs both in concept and substance from traditional multivalued logical systems.

The collected solar irradiance dataset mentioned above was utilized to create a model using a fuzzy logic approach to obtain the optimum charging and discharging rate of storage considering the minimization of output power variation of the solar power plants. MATLAB R2018a was used to develop the fuzzy model and calculate the power and energy support analysis to reduce the solar ramp. A triangular membership function was selected to develop this fuzzy model. Using the developed model based on the solar resource variation and its patterns, the required battery storage capacity was suggested to optimize the output power variation of the solar power plant by solar ramp management. The required investment amount was identified from the suggested battery storage capacity. This will optimize the variability of the output power of the solar power plant at the grid interconnection point.

3.4. Input and output selection

The daily solar irradiance data and supporting storage capacity were the inputs of the fuzzy model. The output was the marginal stable equivalent of solar irradiance data after ramp management support. Sometimes surplus energy is needed to be stored in the ESS for smoothing. Similarly, sometimes energy support will be needed from ESS to manage the deficit solar irradiation. Energy calculations were done by the MATLAB program. ESS is considered a full charge during the initial study whereas it will be reduced gradually with its discharge. Input and Output of the model including levels are given below:

INPUT: Solar Radiation Data (W/m^2)

INPUT: Battery Storage Capacity (MWh)

OUTPUT: Output Power Equivalent Solar Radiation Data (W/m^2)

Radiation Difference = Input Solar Radiation Data - Output Power Equivalent Solar Irradiance Data

Where,

VL [1] = Very Low

LOW [2] = Low

MID [3] = Medium

HIGH [4] = High

VH [5] = Very High

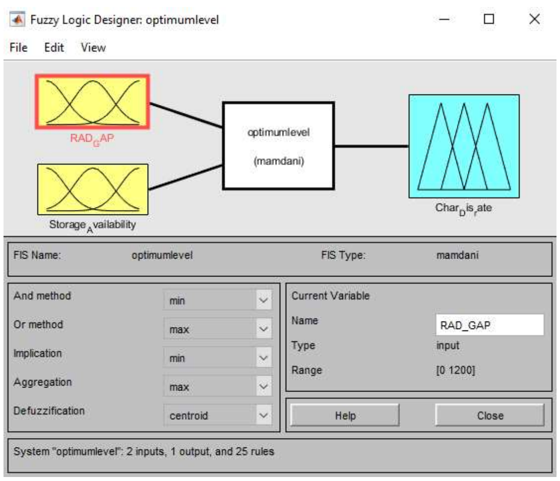

Fig. 3. GUI of Input and Output of the Fuzzy model

Fig. **3**, a Graphical User Interface (GUI) of fuzzy logic, represents the Mamdani-type Fuzzy Logic Designer which is used to design the fuzzy model. Two inputs, the irradiance gap (difference between the previous level and present level) and storage availability are shown on the left. The charging/discharging rate is displayed on the right side of the Mamdani block. Each input and output block containing the membership functions can be displayed by clicking on the block of MATLAB Fuzzy Toolbox as displayed in Fig. **3**.

3.5. Membership functions

A membership function for a fuzzy set-A on the universe of discourse X is defined as $\mu A:X \rightarrow [0,1]$, where each element of X is mapped to a value between 0 and 1 for the membership function μA. This value, called membership value or degree of membership, quantifies the grade of membership of the element in X to the fuzzy set A.

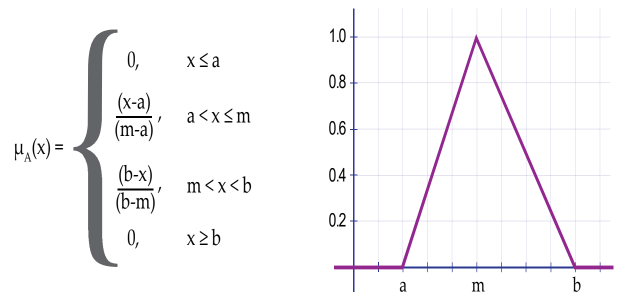

Fig. 4. Triangular membership function

Membership functions allow us to graphically represent a fuzzy set. The x-axis represents the universe of discourse, whereas the y-axis represents the degrees of membership in the [0,1] interval. The triangular membership function is described below as it was used in the developed fuzzy model.

Triangular membership function: defined by a lower limit 'a', an upper limit 'b', and a value 'm' as mentioned in Fig. **4**, where a < m < b. Each position of the x-axis gives a membership value defined in the y-axis.

3.6. Rules of the fuzzy model

To develop the rules, the following Table 1 was developed according to the two input projections.

Table 1. Fuzzy Rule Development

		ESS CAP				
		VL [1]	**LOW [2]**	**MID [3]**	**HIGH [4]**	**VH [5]**
IRR DIF	**VL [1]**	**VQC**	VQC	QC	QC	MID
	LOW [2]	VQC	**QC**	QC	MID	MID
	MID [3]	QC	QC	**MID**	MID	FLC
	HIGH [4]	QC	MID	MID	**FLC**	FLC
	VH [5]	MID	MID	FLC	FLC	**VFLC**

Based on Table 1, 25 rules were developed considering the relation between the irradiance difference and ESS conditions. Irradiance difference has been classified into five groups, starting from Very Low (VL) to Very High (VH). Similarly, ESS capacity has been classified into five groups, starting from VL to VH. Based on the condition of 2 inputs, 25 situations have been identified like Very Quick Change (VQC), Quick Change (QC), Medium (MID), Flexible Change (FLC), Very Flexible Change (VFLC), etc. A GUI image of the MATLAB Fuzzy Rule Editor is shown in Fig. **5**.

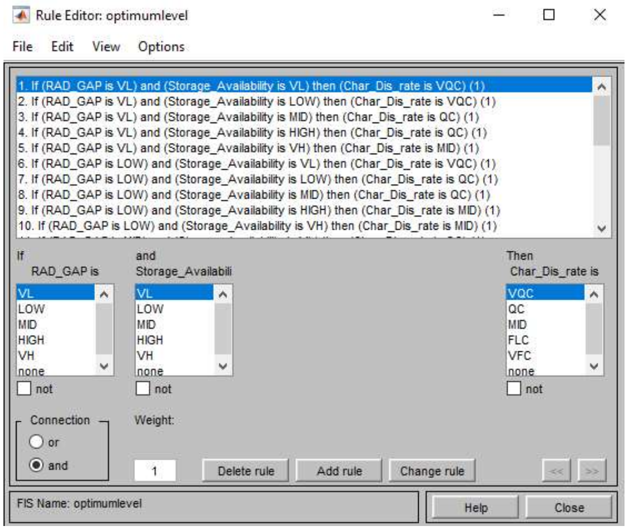

Fig. 5. GUI of Fuzzy Rule Editor

3.7. Calculation and Model Development using MATLAB

The function evalfis() was used to execute the fuzzy model in MATLAB. Based on the result of the fuzzy model, an estimated output level was identified. Energy deficit and surplus were calculated using the MATLAB program. Maximum deficit power and maximum surplus power were also recorded to identify the required maximum discharge/storage rate. Finally, a summarized record table was generated to get the evaluated results. A block diagram of the calculation process is shown below.

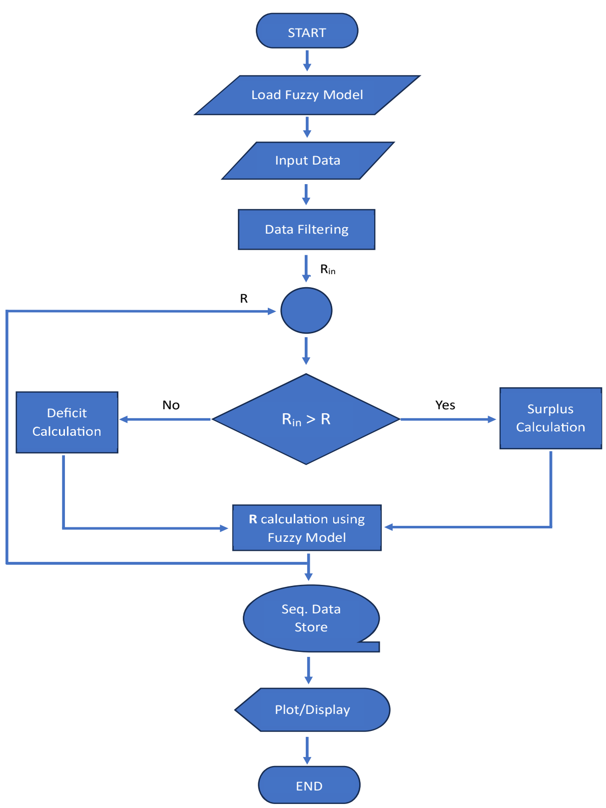

Fig. 6. Block diagram of the data analysis process

In Fig. **6**, 'R_{in}' is the input time series solar irradiance data and 'R' is the modified output power equivalent solar irradiance level after giving support according to the fuzzy model.

4. RESULTS AND DISCUSSIONS

Solar irradiance is variable in nature as the weather conditions may be different in each place. Therefore, a whole-year assessment is essential to understand the actual output including seasonal variations. According to a yearly solar irradiance assessment of two sites in Bangladesh, more than 50% of days in a year contain high solar irradiance variation, a few days have washout days and only 25-30% of days in a year were clear weather days. The result of the case study site is shown in Fig. **7** and more details can be found in [8].

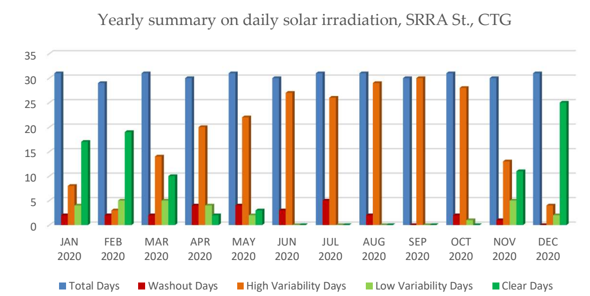

Fig. 7. Yearly summary on daily solar irradiation, SRRA St., CTG

4.1. Assessment of Solar Irradiance

The variation of solar irradiance creates an effect on the output power of the SPV plant as well as the effect of load flow in the interconnection point of the utility network. The cloud enhancement effect is partly reflected in the solar irradiance data but the geographical dispersion effect is not included in the recorded solar irradiance data. Although considering the geographical dispersion effect, the variation is still present in the output of solar power plants in a significant amount. The amount of additional energy support is essential to decrease the sharp power variations that are calculated from the solar irradiance data set. A daily solar irradiance data reflecting a high solar irradiance variable scenario is shown in Fig. **8**.

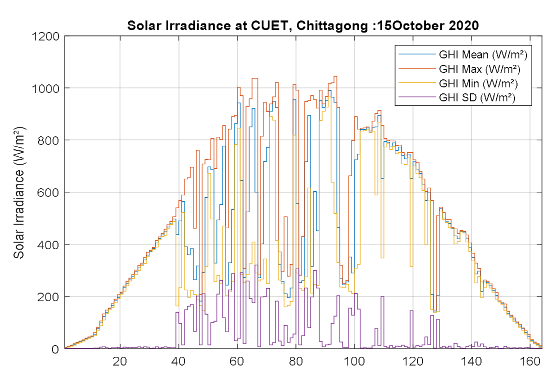

Fig. 8. A daily solar irradiance variation data

Fig. **8** is a representation of the daily solar irradiance curve of the case study site. The data sampling frequency of that site was 10 seconds and the averaging frequency was 4 minutes. There are some data other than mean solar irradiance which are very helpful to understanding the precise variation. Those are the maximum value, minimum value and standard deviation of solar irradiance within a data averaging period. The blue colour represents the mean value of GHI. It was a high solar irradiance variability day as the short-term variation of solar irradiance level is very high, almost 200 W/m^2 to 1000 W/m^2. Also, the irradiance change rate is very sharp and the change number per day is more. The maximum value, minimum value and standard deviation of GHI give a clearer understanding of the variation with a precise time scale. The very sharp decrease or increase of solar irradiance, several times a day is not a safe grid integration for large utility-scale solar power plants. Additional support could reduce the effect of those solar irradiance variations where the necessary technical arrangement is essential.

A fuzzy model using fuzzy logic approach was used to minimize the solar ramping using the energy support from the ESS. Details are described in the methodology section. MATLAB R2018a version was used to develop the fuzzy model and data analysis was completed by the MATLAB program. The data analysis procedure is shown in Fig. **6** and some significant analysed figures are described below.

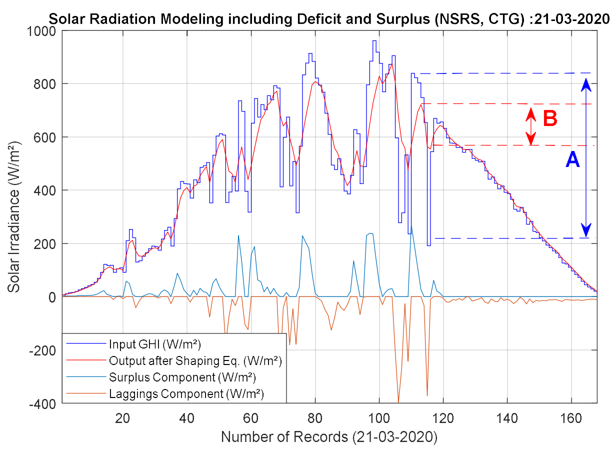

Fig. 9. Reducing the sharp variation by additional support or surplus component

The deep blue line of Fig. **9** indicates the daily solar irradiance status of the day whereas the red line represents the marginal stable output after providing the power and energy support according to the developed fuzzy model. The light blue line represents the surplus electricity according to the ramp management and the brown line represents the deficit electricity which will be supported by the ESS. After calculation using the MATLAB program with fuzzy model, the result shows that the total deficit electricity was approximately 4.91 MWh on that day whereas the surplus electricity amount was approximately 5.14 MWh for a 20 MWp solar power plant. The maximum deficit power was approximately 6.6 MW and the maximum surplus power was approximately 4.5 MW. It was a medium solar irradiance variability day. Based on solar irradiance, the total power generation capability of the 20MWp plant was approximately 81.2 MWh on that day. Therefore, the support or surplus energy on that day was approximately 6% of the total generation although support energy and surplus energy are close to each other. The equivalent irradiance change level per second has been decreased by a good amount. The power ramp-rate control (PRRC) strategy is employed to limit the fluctuation rate in the PV output power under dynamically changing irradiance conditions (e.g., passing clouds) [7]. The ramp level, very much related to the PRRC, decreased significantly in Fig. **9** as indicated by the mark ‘A’ and ‘B’, where mark ‘A’ is the ramp level without support from ESS and mark ‘B’ is the reduced ramp level to be obtained after providing support from ESS. Due to the reduction of the ramp level to a significant level with the proposed ESS support, the output power of the solar photovoltaic power plant will be more stable and its fluctuation level will be reduced. Category wise some results have been described below.

4.2 Solar Irradiance in high variability days

The number of ramps and the ramp level are high on high solar irradiance variability days which represents the short-term variation especially due to the cloud movement. An example scenario is discussed below.

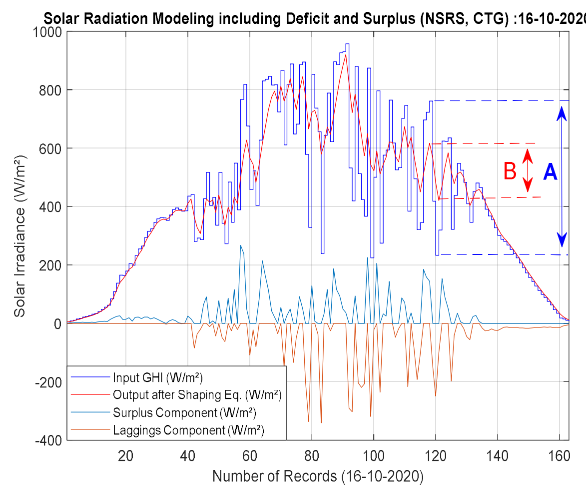

Fig. 10. Example-1 of high solar irradiance variability day

Fig. **10** represents a high solar variability day where solar ramping is very high and frequent. The lower irradiance level of ramps was around 250 W/m^2 and the higher irradiance level was around 950 W/m^2. After providing support from ESS according to the developed model, the ramping level reduces significantly and is reduced to approximately one-third in sample ramp levels as shown by ‘A’ & ‘B’ in Fig. **10**. Equivalent irradiance change slopes decrease as well. Similar another example is displayed in Fig. **11**.

In Fig. **11**, the ramp rate, i.e., dy/dt is found to be decreased where the y-axis represents the irradiance level and the x-axis represents the number of records with a fixed time interval. The comparative power falling time has been highlighted in Fig. **11** between before and after providing support from ESS. The equivalent power falling time has been increased compared with the before providing support and hence power falling occurs gradually instead of sharply. The ramp level also decreases similarly as indicated in Fig. **10**.

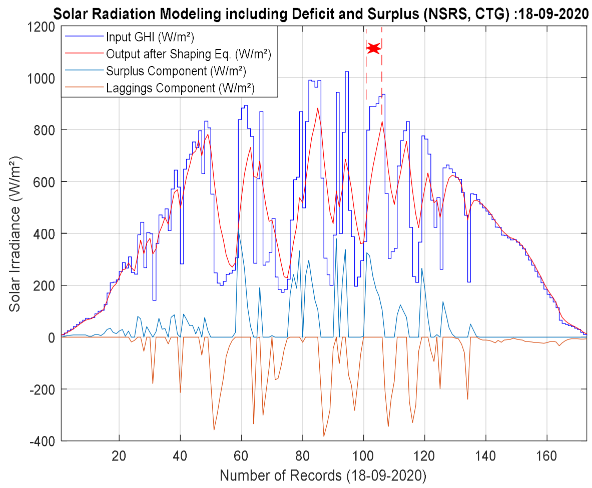

Fig. 11. Example-2 of high solar irradiance variability day

4.3. Solar Irradiance in small variability days

The small short-term solar irradiance variability days are close to the clear weather days but little solar ramping is present. The ramp number and level are not that much like high solar irradiance variability days. An example is shown below.

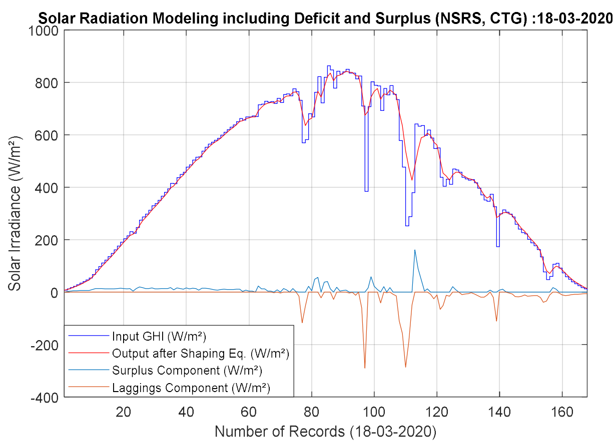

Fig. 12. Examples of a small irradiance variability day

Fig. **12** represents a small variability day. Most of the time of the day, it is like clear weather but variability occurs sometimes. Due to this sudden change in weather and solar irradiance, the output of the SPV plant also changed. Therefore, this change is a cause of load flow direction change in the interconnection area of the utility network. After providing the necessary power and energy support from ESS, this variation can be reduced to a significant level.

4.4. Solar Irradiance on washout days

The washout day is cloud-covered and receives very little solar irradiance in a day. In most cases, partly diffuse irradiation is received on that day and variation may be also less as indicated in the sample figure given below.

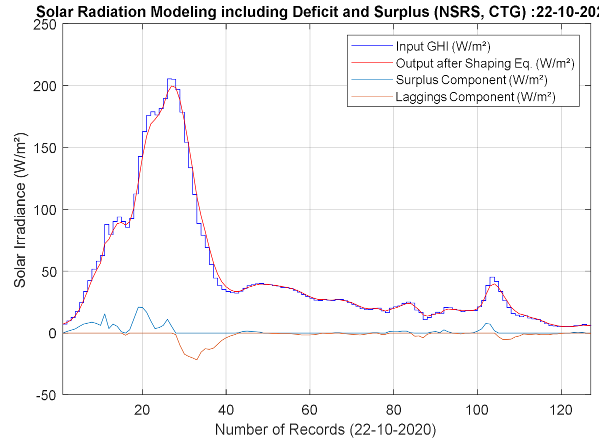

Fig. 13. Example of a washout day

Fig. **13** is a representation of a washout day where the total solar irradiation received on that day is 8.16 MWh according to the recorded data. The maximum solar irradiance received on that day is 200 W/m^2 only for a few hours and for the rest of the hours, it is within 50 W/m^2. Although it is a full cloud-covered day, the short-term solar irradiance variation is very less. According to the calculation, the deficit and surplus of both energies on that day is 0.33 MWh, which is much less compared with other days.

4.5. Solar Irradiance on clear weather days

Clear weather days are cloud-free days where solar modules receive maximum solar irradiance from the sun. In most of the cases, short-term variation of solar irradiance was absent or may present very little. An example is shown in Fig. **14**.

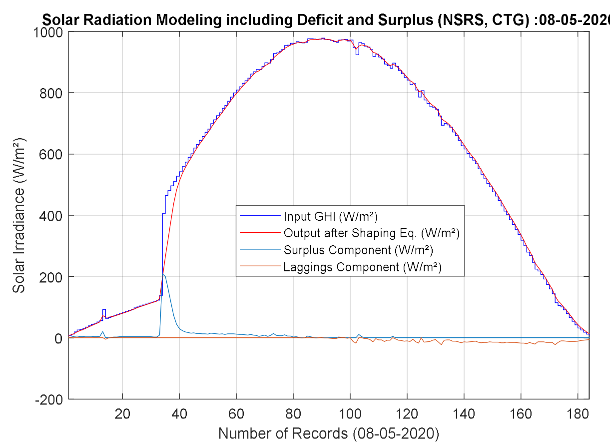

Fig. 14. Example of a clear weather day

Fig. **14** is an example of a clear weather day where the short-term variation of solar irradiance is close to zero. Also, the daily maximum solar irradiance is close to 1000 W/m^2 and the total energy of that day is 143 MWh according to the recorded data. Solar energy generation on this day is more than 17 times higher than the energy on washout day mentioned in Fig. **13**.

4.6. Full-year assessment results

A one-year daily solar irradiance pattern was analysed with the developed fuzzy model. Daily maximum power support from ESS depends on the irradiance change level. Daily energy support from ESS depends on the irradiance change level and the number of ramps. Using the MATLAB program, daily energy support from ESS, Surplus energy amount for ramp management, and maximum power for deficit or surplus energy were calculated. Based on the calculation, a full-year daily ramp management result has been analysed and a summary is shown in Table 2.

Table 2. A sample of the daily variation status of the output power of a 20MWp Solar Power Plant using CUET irradiance data

1	2	3	4	5	6	7	8	9	10	11
DATE	**Plant Capacity (MWp)**	**Irradiation (kWh/m2/day)**	**Irradiation after RM (kWh/m2/day)**	**Plant Expected Output (MWh)**	**RMO (MWh)**	**PEO-SURE (MWh)**	**Deficit Energy (MWh)**	**Surplus Energy (MWh)**	**Max Deficit Power (MW)**	**Max Surplus Power (MW)**
01-01-2020	20	3.04	3.00	60.82	59.92	57.00	2.92	3.82	3.71	4.22
02-01-2020	20	1.98	1.95	39.55	38.95	36.83	2.12	2.72	2.27	4.79
03-01-2020	20	1.48	1.46	29.67	29.13	27.35	1.78	2.32	1.56	3.35
~ ~	~ ~	~ ~	~ ~	~ ~	~ ~	~ ~	~ ~	~ ~	~ ~	~ ~
29-12-2020	20	4.53	4.53	90.62	90.61	89.60	1.00	1.01	0.33	0.62
30-12-2020	20	4.67	4.67	93.44	93.43	92.41	1.02	1.02	0.32	0.66
31-12-2020	20	4.64	4.64	92.75	92.74	91.74	0.99	1.01	0.33	0.82
Average		**4.51**	**4.52**	**90.25**	**90.43**	**86.19**	**4.24**	**4.06**	**4.60**	**4.59**
Maximum		**7.18**	**7.16**	**143.66**	**143.29**	**141.52**	**12.14**	**11.51**	**11.65**	**12.73**
Minimum		**0.41**	**0.41**	**8.16**	**8.16**	**7.83**	**0.33**	**0.33**	**0.28**	**0.27**
Sum(352d)		**1588**	**1592**	**31769**	**31831**	**30339**	**1491**	**1430**	**-**	**-**
Eq.Sum(365d)		**1647**	**1650**	**32943**	**33006**	**31460**	**1546**	**1483**	**-**	**-**

In Table 2, column 1 represents the date and column 2 represents the capacity of the SPV plant that has been considered for the case study. Column 3 represents the actual GHI solar irradiation received in the case study site in kWh/m^2/day measured by the pyranometer. Column 4 indicates the modified output equivalent input GHI solar irradiance data in kWh/m^2/day after using the fuzzy model. Columns 5 & 6 indicate the energy output of that day's before and after ramp management support respectively. Column 7 is the difference between column 5 and column 9 which represents the expected energy output of the SPV plant other than surplus energy. Columns 8 & 9 are the daily deficit/support energy and surplus energy for ramp management arrangement calculated according to the fuzzy model mentioned in the methodology section. Columns 10 & 11 are the calculated maximum deficit and surplus power respectively according to the ramp management support. A full one-year assessment has been conducted where the first 3 days and last 3 days are mentioned in the table and the rest of the days (dotted) are hidden to make it simple. However, all data should be reflected in the figures shown below. Finally, the average, maximum, minimum, and summation records of the year have been calculated in the few last rows.

The daily deficit energy values mentioned in column 8 of Table 2 are plotted and shown in Fig. **15**.

Fig. **15**, it is shows that the first few months and the last few months of the year have required a small amount of ramp management support energy and it is less than 2 MWh/day except on some days. This support requirement is increasing in the summer season and goes up to 12 MWh/day energy support requirements. Similarly, to avoid the sharp rise of the SPV plant's output and minimize the ramp rate, some surplus energies have been identified. It is mentioned in column 9 of Table 2.

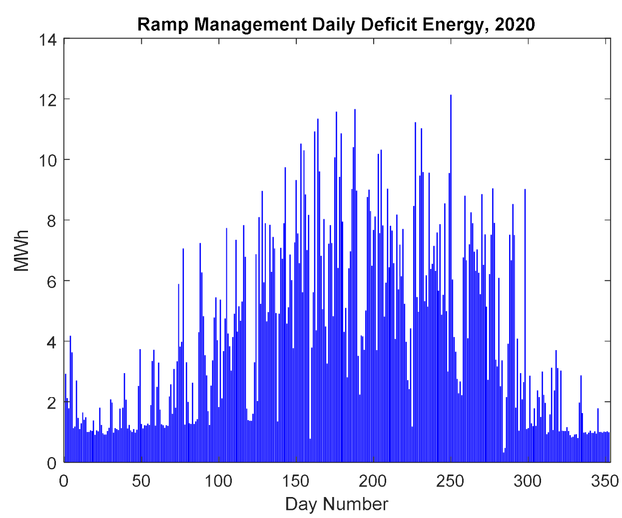

Fig. 15. Daily deficit energy for Ramp management, 2020

The plotted values of this result are shown in Fig. **16**.

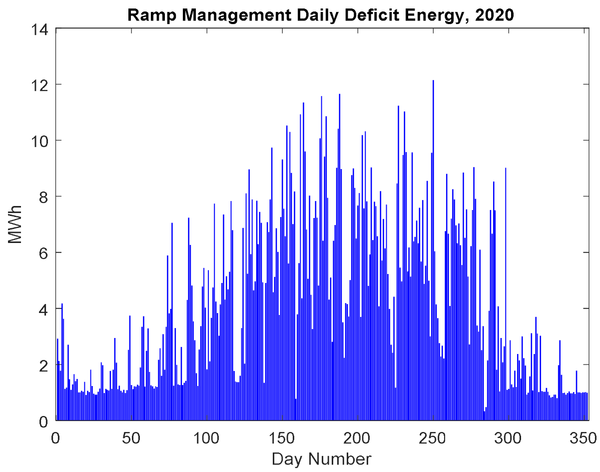

Fig. 16. Daily surplus energy from Ramp management, 2020

Fig. **16** looks similar to Fig. **15**. It is shown that the first few months and last few months of the year have required small ramp management surplus energy and it is less than 2 MWh/day except for some days. This surplus energy is increasing in the summer season and goes up to 12 MWh/day. The comparison analysis of ramp management deficit energy versus surplus energy on a daily basis has been analysed and shown in Fig. **17** below.

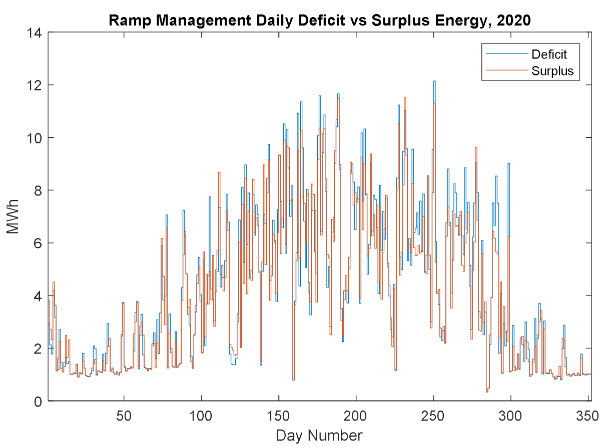

Fig. 17. Comparing the daily deficit energy versus surplus energy

It can be observed from Fig. **17** that the daily deficit energy and surplus energy for ramp management are almost close to each other with a small difference. Also, it is observed that all days of the summer season are not similar. Some days require high ramp management support whereas the next day's requirement is not that much. It depends on the weather condition of that area, especially cloud pattern and movement; and it's a location-specific issue.

The energy and power are proportional to each other but a high-power requirement could be involved with more power electronic equipment where the cost will be significantly involved. The maximum deficit and surplus power have been analysed daily and shown in columns 10 and 11 of Table 2. The plotted figure of those values is shown in Fig. **18**.

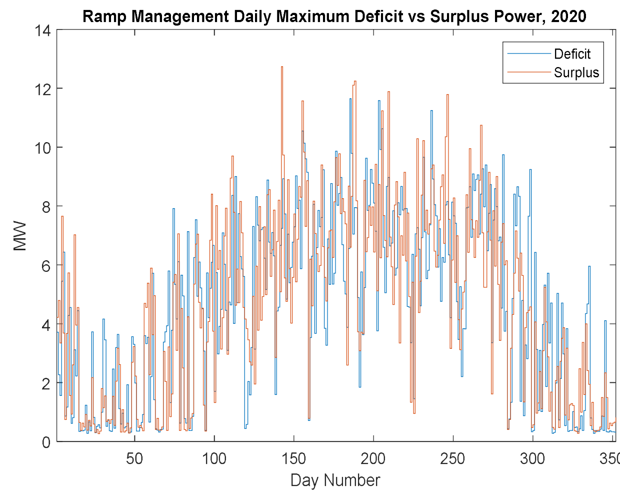

Fig. 18. Comparing the daily maximum deficit power versus surplus power

The power requirement according to Fig. **18** is limited to 12 MW of which 4 – 8 MW is the common scenario for most days. There is some difference between the daily maximum deficit and surplus power although the maximum one needs to be counted. Finally, the deficit and surplus power and energy scenario calculated by the model is presented in

Table **3**.

In

Table **3**, the ITEM/RANGE row is the range of Power (MW) or Energy (MWh). The rest of the values represent the number of days on which the power or energy amount was within this range. It is noted that it could be varied with the support instruction provided by the model and final output shaping will change accordingly. More support will provide more stable output and less support will provide less stable output, but the cost is associated with it accordingly. The summarized results are shown in Fig. **19** and Fig. **20** for the power and energy scenarios separately.

Table 3. Summary of Power Variation and Energy Variation of a Solar Power Plant, in number of days in a year (352d)

ITEM/RANGE (MW/ MWh)		0-2	2-4	4-6	6-8	8-10	>10
Maximum Surplus Power	**Number of days**	99	55	71	75	41	11
Max Deficit Power		103	49	67	79	48	6
Surplus Energy		112	79	71	54	27	9
Deficit Energy		120	69	54	66	29	14

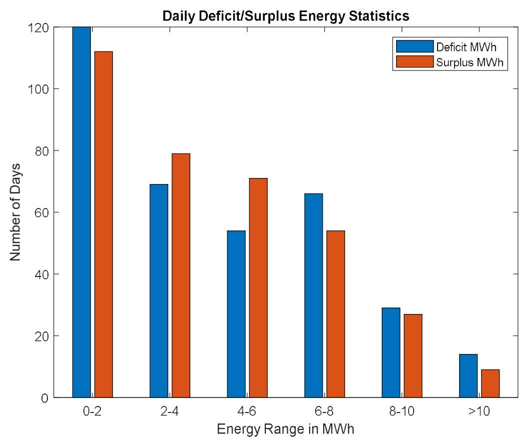

Fig. 19. Energy deficit and surplus statistics in a year

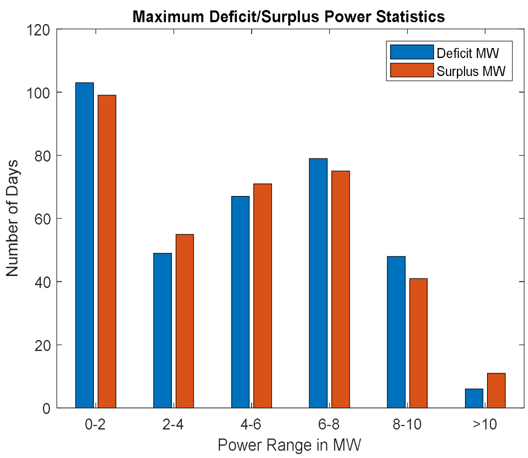

Fig. 20. Maximum deficit and surplus power statistics in a year

From the above Fig. **19** and Fig. **20**, a minimum 8 MWh ESS with 8 MW charging/discharging capacity can be considered for solar ramp management support. Also, we observed that the deficit and surplus energy and power are nearly close to each other. Therefore, around 50% of the storage can be charging state, and the remaining half can be discharging state up to the safe discharging level, then it could be swapped. The battery type must be capable of dynamic charging and discharging for solar ramp management. The lithium-ion battery technology is the most popular grid-scale stationary energy storage technology as it has a fast response capacity and high specific energy [20]. Small energy storage units close to the source of power quality disturbance are cost-effective and offer excellent potential for widespread implementation in the low-voltage distribution grid [33]. The effect on the cycle life of energy storage needs to be analysed for ramp management support purposes that could be discussed in a separate paper.

4.7. Cost Scenarios

Gravity energy storage, a novel energy storage system, compares its performance with alternative energy storage systems used in large-scale applications such as Pumped-hydro energy storage (PHES), Compressed air energy storage (CAES), Sodium Sulfur (NaS), and Li-ion batteries (Li-ion). The GES is the most cost-effective large-scale energy storage technology for storage capacities of more than 1 GWh. In addition, for a 1 GW power capacity and 125 MWh energy capacity system, gravity energy storage (GES) has an attractive LCOS of 202 \$/MWh [34]. The Liner Electric Machine-based GESS is about 26% more cost-effective than the currently competitive flywheel energy storage technology whereas this technology is more sensitive in terms of capital expenditure, efficiency, discount rate and discharge duration [35].

The comprehensive review of the paper [36] shows that the lithium-ion battery fits both low and medium-size applications with high power and energy density requirements in the electrochemical storage category. According to the report [37] of National Renewable Energy Laboratory (NREL) of the USA, the fixed-Tilt utility-scale PV benchmark cost was \$0.89/W_{DC} and the one-axis tracker utility-scale PV benchmark cost was \$0.96/W_{DC} in the first quarter of 2020. Similarly, the fixed-Tilt utility-scale PV benchmark cost was \$0.83/W_{DC} and the one-axis tracker utility-scale PV benchmark cost was \$0.89/W_{DC} in the first quarter of 2021 where the assessment was conducted considering 100 MW_{DC} plant capacity [38].

Li-Ion Utility-Scale Storage and PV-Plus-Storage Model have been calculated by NREL in the report [39]. In this model, the cost of a Stand-alone 100-MW_{DC} PV system with one-axis tracking was \$89 million. The cost of a Stand-alone 60-MW_{DC} /240-MWh Usable, 4-hour-duration energy storage system was \$90 million. For DC-coupled PV (100-MW_{DC}) plus storage (60-$MW_{D/AC}$/240-MWh_{Usable}, 4-hour-duration) system, the cost was \$168 million, whereas AC-coupled PV (100-MW_{DC}) plus storage (60-$MW_{D/AC}$/240-MWh_{Usable}, 4-hour-duration) system, the cost was \$167 million. In those cases, the cost difference between DC-coupled and AC-coupled utility-scale energy storage systems were not a significant amount. Finally, the investment cost of PV (100-MW_{DC}) and storage (60-$MW_{D/AC}$/240-MWh_{Usable}, 4-hour-duration) systems sited in different locations was \$179 million. The Li-ion battery cabinet cost is approximately 59% of the total storage cost (4hr) whereas it will be approximately 44% for a 1hr duration with similar storage capacity. A storage cost scenario from this report is shown below.

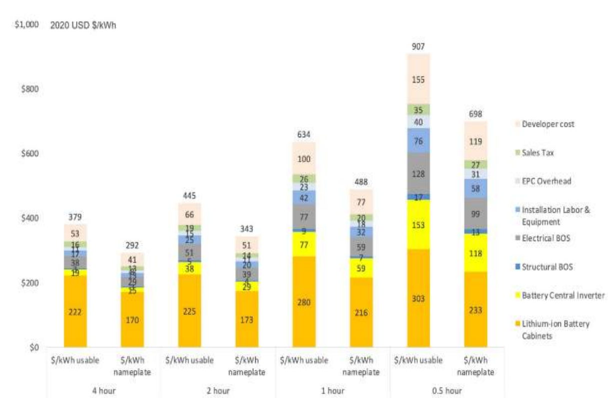

Fig. 21. U.S. utility-scale Li-ion battery stand-alone storage costs for durations of 0.5–4.0 hours (60 MWDC), Q1 2021 [39]

In Fig. **21**, $/kWh$_{usable}$ and $/kWh$_{nameplate}$ data are presented for 0.5-hour, 1-hour, 2-hour, and 4-hour conditions. Here, a Lithium-ion battery cabinet holds the maximum percentage of cost in each category. However, due to the increasing charging and discharging power capacity, lower hour scenarios have more battery central inverter and similar other costs, known as power electronic cost. According to the approximate cost projection of our proposed capacity, the 20 MW_{DC} solar project's cost should be around $18 million. Whereas Li-ion energy storage cost of 8 MWh with 8 MW power capacity (1 hour) should be around $5 million, which is 28% of the solar project cost.

However, the volume-weighted price of lithium-ion battery packs across all sectors averaged $152/kWh according to the assessment of BloombergNEF in 2022 [40]. The energy storage systems whose total costs are dominated by power component costs ($/kW) are better suited for longer-term energy storage and those dominated by energy (storage) component costs ($/kWh) should be used for shorter-term energy storage [41]. For the promotion of wide-scale Li-ion energy storage, the key challenges are fire safety and recycling, instead of capital cost, battery cycle life, or mining/manufacturing challenges [42]. Round-trip efficiency, the ratio of useful energy output to useful energy input, is identified as 86% and the 2022 Annual Technology Baseline (ATB) adopts this value [43]. The cost and performance of the battery systems are based on an assumption of approximately one cycle per day. The fixed operation and maintenance costs include battery replacement costs, based on assumed battery degradation rates that drive the need for 20% capacity augmentations after 10 and 20 years to return the system to its nameplate capacity [39].

5. CONCLUSION

Global warming is a challenge considering sustainable development and it is essential to move from the dependency on fossil fuels to renewable energy sources, where Solar PV is a suitable one. The intermittent nature of Solar PV energy is one of the main challenges for the promotion of large-scale power plants, especially for grid connected systems. For a high share of such VRE in grid should have some auxiliary support system to reduce this short-term variation of the output power of the Solar PV power plant that is generated due to the short-term variation of Solar irradiance. Additionally, the effects associated with the utility system will be reduced which will be helpful including frequency regulation and supply-demand management by the transmission system operator. Therefore, before the establishment of a large-scale Solar PV plant in a location, grid integration effects of short-term power variation should be conducted for the proposed interconnection point.

In this paper, a feasibility study of SPV power smoothing has been conducted using the Fuzzy Logic approach. This analysis is conducted for a 20 MWp SPV plant based on the 1-year's time series solar irradiance dataset at the case study site. A fuzzy model has been used to determine the smoothing amount in terms of power and energy. The smoothing level may be adjusted by changing the degree of membership function. According to the assessment of the whole year's data, a minimum 8 MWh ESS with 8 MW charging/discharging capacity has been calculated for the ramp management support, which will increase approximately 28% of the solar project cost. The daily requirement of support amount and surplus amount in terms of energy and power were found identical. The actual scenarios may be slightly different due to the geographical dispersion, cloud enhancement, and similar other effects. It may be relaxed for low VRE penetration, but essential for high VRE penetration into the grid. This is a site-specific feasibility study of Solar photovoltaic power smoothing using the Fuzzy Logic approach that represents a scenario of Bangladesh. It is recommended to analyse with real-time output power and energy data of a solar power plant with a precise timescale.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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