Collective Ramp Event Analysis for Four Solar Farms in China's Dali Yunnan Province

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This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of the author's knowledge, it contains no material previously published or written by another person, except where due reference is made in the text.

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ABSTRACT

The total capacity of solar PV systems in China was 35 GW at the end of 2015 and is expected to grow to 100GW by 2020 in line with national energy targets (Jiahai Yuan, 2016). This aggressive uptake of solar PV within China is leading to uncertainty in Chinese electricity markets/networks, and demonstrating the need for an integrated solar forecasting system within its operations. This work is intended to demonstrate the types of variability events which require the most accurate forecasts, so as to advise the development of future Chinese solar forecasting systems.

Researchers at The Australian National University recently demonstrated a strong relationship between certain meteorological phenomena, and broad-scale, rapid changes in the collective PV power output for a given region (Wellby and Engerer, 2016). Such events occur when all of the PV generators in a given region experience a similar step change in available solar radiation (Andu Nguyen, 2015). These “critical collective ramp events” arguably pose the greatest risk to electricity utilities and markets in China, where hundreds of 10-1000MW scale solar farms are now in operation. To assess the risk of such events more fully, the ANU has partnered with North China Electric Power University (NCEPU) to analyse the power output from 4 medium scale (30-50MW) solar farms in the Dali, Yunnan province of China. This study will identify and characterise the ‘critical collective ramp events’ experienced over the 2014-2015 period, and establish the maximum ramp rates experienced by a distributed network of solar farms within a 25km x 35km region. It will also present basic algorithms for quality controlling the provided data.

CONTENTS

List of Figures

List of Tables

Chapter 1 INTRODUCTION

1.1 CONTEXT

The installation of solar photovoltaic (PV) systems has increased rapidly over the past decade. This global trend is expected to continue, with estimates that solar PV installations in china will grow to 100GW by 2020 in line with national energy targets (Jiahai Yuan, 2016). However, the integration of high penetrations of solar PV systems into electricity grids presents complex challenges. The performance of distributed solar PV systems is highly dependent on environmental conditions – specifically, cloud cover, meaning that solar PV power generation is largely dependent on cloud movements. The result is power output that can rapidly increase or decrease over various timescales while also varying intensity through the day according to the sun's position. This intermittency of solar power generation complicates the integration of solar PV systems, as it greatly affects the quality and quantity of electricity that is generated. This is of concern to grid operators, particularly when groups of solar PV systems experience collective solar PV power output variability (both a sudden decrease and increase in power) meaning collective variability. Electricity grid operators are required to balance the supply and demand through other means. To realize this, a secondary power source that can ramp up or down at high frequencies is suggested and it may also help to monitor demand management and energy storage. However, the operation of such services are often costly, so it is important to fully understand the characteristics of collective power output variability, particularly collective changes in geographically distributed PV systems. To date, collective ramping events have not been characterized for China. The motivation for this research is to address this lack, by analyzing and interpreting local data. It will examine the categories of ramp events, depending on the time-steps and thresholds of events, thereby characterizing collective ramp events for the city of Dali.

1.2 LITERATURE REVIEW

There is an inherent relationship between the power output of the solar PV system and the cloud movements. A PV system power output fluctuates over short time period resulting from irregular cloud motion. ‘Ramp events’ describe these unexpected changes in PV system power output as a result of external conditions. A positive ramp event is characterized by a rapid increase in power output. Conversely, a negative ramp event describes a rapid decrease in power output (Florita et al., 2013). A collective ramp event describes a scenario where the majority of solar PV systems in a given region concurrently experience a positive or negative ramp event within a given time-step (Wellby and Engerer, 2015). The analysis of these events in distributed PV system power output is a relatively new field of research, and a specific analysis of collective ramp events in China have not yet been conducted.

When attempting to characterize collective ramp events in a given region, it is important to understand PV array output behavior for distributed PV sites. Several studies have investigated aggregate solar power output variability for geographically dispersed systems. Wiemken et al. (2001) analyzed combined power generation of 100 PV systems across Germany and compared to the characteristics of an individual system. The study showed that the standard deviation curve of an average daily power generation profile of 1 month is significantly decreased for the ensemble and corresponds to predictions based on cross-correlation characteristics of the radiation field. Otani et al. (1997) explored the overall behavior of nine sites located within a $16km^2$ region in Japan. The study compared the average output from all nine sites with the instantaneous output and hourly average for the nine sites independently. By utilizing the root mean square of the difference, the authors found that the variability decreased significantly when the collective output was compared to each independent site. Further analysis by Kawasaki et al. (2006) led to definition of the ‘smoothing effect’ and verified the smoothing effect using frequency analysis. The study confirms that the more irradiance fluctuates, the more the smoothing effect.

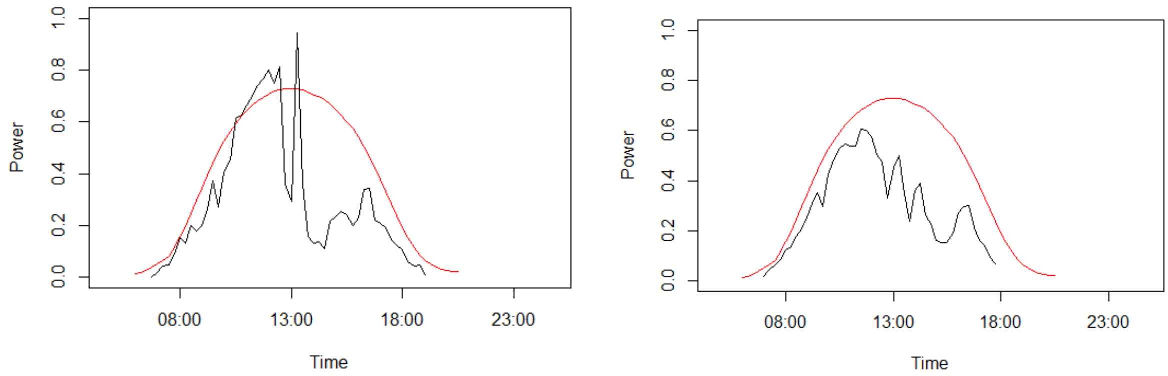

Figure 1.1 Single site power output VS Multi site power output

Subsequent studies have further investigated PV power output variability for distributed PV systems. Hoff and Perez (2010) introduced the 'dispersion factor', which is a new variable that captures the relationship between PV fleet configuration, cloud transit speed, and the time interval over which variability is evaluated. This paper presented an approach to rigorously quantify the variability in power output from a fleet of PV systems, ranging from a single central station to a set of distributed PV systems. Results indicated that Relative Output Variability for widely-spaced PV systems equals the inverse of the square root of the number of systems. Results also indicated that optimally-spaced PV systems can minimize Relative Output Variability. Murata et. al. (2009) performed a related analysis using a 1999 data set composed of 52 PV systems. They analysed the correlation between two systems' short-term change. They found that the experimentally derived correlation increased with the inverse of the sites' distance and the length of the considered fluctuation time intervals (see Figs. 8 and 9 in that paper). An empirical model was derived based on this experimental evidence but the relationship was not fully explained on a mathematical basis and did not result in a general model that could be applicable for any number of PV systems for deployments ranging from central station to distributed generation. Furthermore, for sites that were located more than 50 km apart, it found that the change in power output between these sites were not correlated.

Despite none of these studies specifically examined ‘collective ramp events’, the importance of such events has been emphasized. Since geographic smoothing reduces the overall output variability for distributed PV sites, independent ramp events at single sites can be considered unproblematic for grid stability. In other words, the power output variability at one site can be balanced relatively easily due to the effects of geographic smoothing. However, when all individual sites in a given region experience the same scale of ramping – a collective ramp event- this puts significant pressure on grid operators, as the effects of geographic smoothing is eliminated.

Clear-sky models are often used for various purposes such as HVAC design, meteorological modelling and solar energy system design. Within solar energy, the clear-sky model represents a PV array’s expected power output on a cloudless day. This is important for the in-depth analyses of output collective ramp events, as shown by the use of the clear-sky index when analyzing high-frequency irradiance fluctuations (Lave et al., 2012), and the analysis of output variability for a fleet of identical PV systems (Hoff and Perez, 2010). Many other contemporary analyses of solar variability utilize the clear sky estimate as a fundamental basis for analysis (Woyte et al., 2007; Kleissl et. al., 2010).

It is worth noting that there is a range of methods for generating clear-sky models. A study by Engerer and Mills (2015) showed that the Bird (Bird, 1981) and ESRA (Rigollier et al., 2000) models perform the best when compared to models by Ineichen, Ineichen and Perez Molineaux, and MAC. Clear-sky models are essential to the accurate characterization of the China collective ramp events since they are the basis for quantifying the scale and implication of solar power output fluctuations. The purpose of this study is to use the clear sky method to accurately describe the distinctive nature or features of collective ramp events occurring in China, despite the effects of geographical smoothing, which have been discussed in detail in some previous studies.

1.3 MOTIVATIONS

Grid operators pay much attention to the operation and stability of the solar PV system and therefore collective ramp events are of their concern since these events can severely affect the output. In the past, grid operators have successfully balanced the collective power output fluctuations, but with the continued growth of PV array installations, the ability to seamlessly manage these fluctuations is weakening. From the grid operator's perspective, it is desirable to gain a better understanding of the overall collective ramping behaviour and the movements' cycle of collective ramping events.

Limited number of studies have so far been carried out relating to this critical research, focusing particularly on the characterization of collective ramp events in a given region. Such events occur when all of the PV generators in a given region experience a similar step change in available solar radiation (Andu Nguyen, 2015). More recently, a study on the meteorological origins of critical ramp events in collective photovoltaic array output has been conducted by Wellby and Engerer (2015). This study identifies citywide collective ramp events, which occur when a 60% change in collective PV power output is experienced within 60 minutes occurring in Canberra, Australia and they are termed critical collective ramp events. The study examined the collective ramp events in a given region and focused on the meteorological origin of collective ramp events, classifying collective ramp events with specific weather patterns. Through analysis, the study highlights the importance of local climatology and collective ramp activities. This further emphasizes the importance of characterizing collective ramp events in Dali. Another recent study by Engerer (2015) quantifies power fluctuations and impacts on the grid during collective slope events using a municipal PV simulation system. This study further validates the K_{PV} method but only characterizes the collective ramp events in Canberra. While these are important contributions to the overall study of collective ramp events, the region-specific characteristics of collective ramp events remain to be fully understood.

As discussed in the literature review, recent research and analysis of distributed PV system power output is limited to the assessments of measured performance against expected performance. Whilst geographic smoothing is validated through a number of studies, collective ramp events have not been investigated in detail (with the exception of Wellby and Engerer (2015); Engerer (2015)). Since all of the PV generators in a given region will experience a similar step change in available solar radiation, the relationship between certain solar PV systems is critical. The efforts of this research aim to address this lack. The present study focuses on characterizing collective ramp events and developing an automated detection algorithm for collective ramp events. By doing so, it is hoped that collective ramp events are accurately characterized for Dali, and the assessment goes beyond comparing performances. Further, through the development of an automated algorithm that will detect ramp events for a given threshold and timescale. This study will identify and characterize the 'critical collective ramp events' experienced over the 2014-2015 period, and establish the maximum ramp rates experienced by a distributed network of solar farms within a 25km x 35km region. It will also present basic algorithms for quality controlling the provided data. The most important part is proving the correlation between four solar PV systems in Dali will be quantified and analyzed.

1.4 PROJECT SCOPE

The research in this thesis will specifically focus on characterizing collective ramp events of distributed PV system power output in Dali, China. It will analyze the dataset for the study period, and seek to characterize collective ramping events. The behavior of each solar farm will be analyzed, correlation of collective ramping events between those sites is the main target of this project. The implementation and usage of the findings from this research in areas such as energy market operation and policy development will be beyond the scope of this project. It is, however, hoped that this study will provide a foundation for the subsequent research in these areas.

1.5 THESIS STRUCTURE

In this thesis, it has a linear structure. First, the Theoretical Background part provide the basic theory that will be applied in the later thesis. And it will also help readers to understand the topic easily. Next section is Data, it presented the data provider and how to control the quality of data source. The third section is Methodology, in that section, all models and methods which will be used to get the result are explained. In the Case study section, it contains result of clear day, high variability day and clear sky day, also the observations in the result will be analysed and discussed.

Chapter 2 THEORETICAL BACKGROUND

2.1 CLEAR SKY MODEL

On the purpose of obtain the accurate and useful result, the real power data should be subjected to a comparative analysis. To compared the real measured data and the estimated data from a clear sky day. To do so, a model which reliant on geometric and atmospheric factors need to be generated.

That model is simulated with two primary inputs. Firstly, a performance model for the Solar system and a clear sky irradiation model. The most notable PV system performance model which will be relied on in this thesis is the Photovoltaic Performance Modelling Collaborative(PVPMC) at sandia National Laboratories (Klise, Stein 2009). Here performance models for solar panels, inverters and related components are developed and tested (Engerer & Mills 2014; Stein 2012). The Sandia Performance Model is well established as the industry standard.

For the purposes of this research the ESRA (European Solar Radiation Atlas) clear sky model has been implemented. This model has been established as one of the most accurate and the simplest to compute model in a recent review of clear sky models in Australia (Engerer & Mills 2015). The ESRA produces estimates of clear sky beam and diffuse solar radiation. For these calculations one primary input is required; the Linke turbidity. Calculation of the ESRA model is detailed in Appendix

2.2 K_{PV}

K_{PV} value is the clear sky index. It has been defined in the following equation. It is used for distributed solar generation and estimating the performance of solar system within the vicinity of PV systems for which there are data (Engerer, Mills 2014)

$$K_{PV} = \frac{PV_{MEAS}}{PV_{CLR}}$$ Equation 1

In Equation 1, the PV_{MEAS} means the measured data from our data providers and the PV_{CLR} is the result which generated by the clear sky model.

2.3 RAMP EVENT

The variability of solar power can be attributed to meteorological phenomena, most commonly as clouding. The relationship between PV generation and these events was first investigated by Jewell and Ramakumar (Jewell & Ramakumar 1987). Events where the PV generation undergoes a significant change over a short period of time are referred to as ramp events.

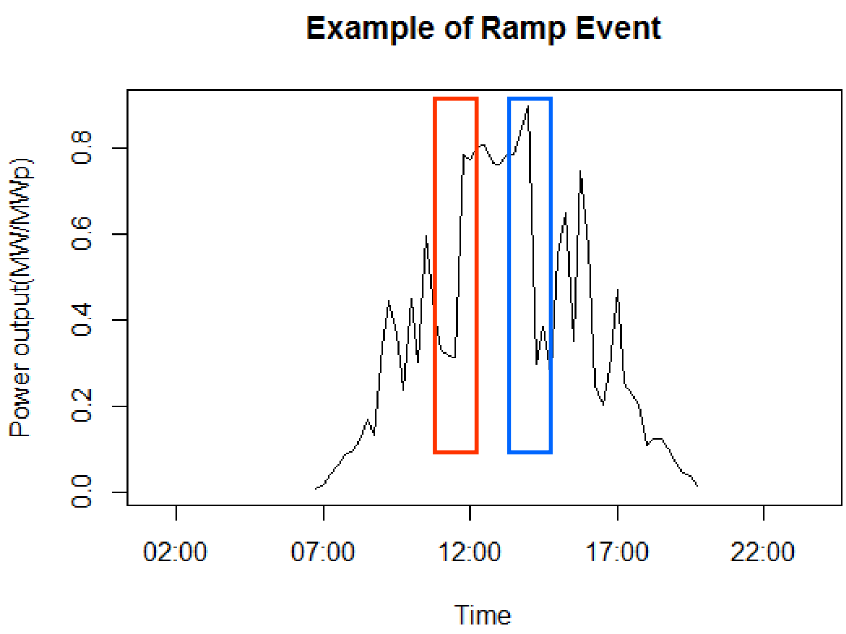

Figure 2.1 Example of Ramp Event

From Figure 2.1, an example of ramp even shows in the figure. A positive ramp event (in red mark) happened around 11:00am, the power output from 0.4 jump to 0.8 in about 10mins, at 2:00pm, a negative ramp event (in blue mark) happened, the power output drop back to 0,4.

Ramp events can also occur at widely varying geographic scales, however as Jewell and Ramakumar (1987) noted, the greater the geographical diversity amongst PV generation systems, the less their outputs correlate. The implication of this is that the effects of any given ramp events will be mitigated by averaging PV generation over a larger area, with their frequencies and ramp rates decreasing as the geographic scale is increased (Florita et al. 2013; Lave et al. 2012). This effect is known as geographic smoothing and occurs when the PV network is larger than the meteorological events affecting PV generation.

2.4 CRITICAL COLLECTIVE RAMP EVENT

Critical collective ramp event is a special ramp event. It demonstrates 1% ramp change in 1 minute with respect to the clear sky curve. The detection of critical collective ramp event is based on time-step, percentage threshold and critical event. The critical ramp event is different as normal ramp event. Critical ramp events result is categorized according to a 1 % change over 1 minute and result in ramp events of significant magnitude. As for normal ramp event, it's not following the threshold which is 1% rate change in 1 minute, and it may not necessary to have a high impact.

Chapter 3 DATA

The project is cooperated with North China Electric Power University (NCEPU) to analyse the power output from 4 medium scale (30-50MW) solar farms in the Dali, Yunnan province of China. A team from NCEPU travelled to Dali, and collected raw data from 5 solar farms, only data from 4 solar farms are accept in this project, reason of that is explained later. The following section details the PV dataset used for analysis, as well as the methods used for data quality control.

3.1 DATA PROVIDER

Dali, a beautiful city located South-West China, based on the special location and elevation, it has huge penitential of solar energy. 5 medium scale(30-50MW) solar farms which are the data provider of the project located around the city. The name of those solar farms are marked as A, B, C, D, E in this thesis. Following map shows location of solar farms.

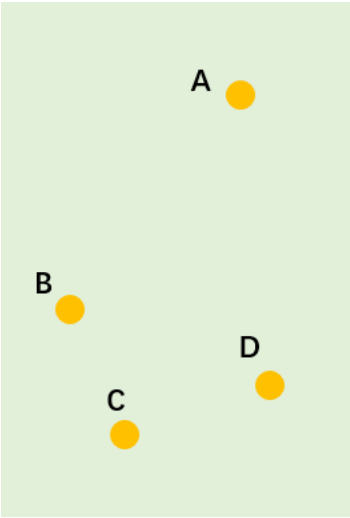

Figure 3.1 Simulated Locations of Data Providers

The accuracy of the dataset is of critical importance. Due to the short producing period of site E, the power output is not stable and the important variables such as the tilt and orientation of the PV array, which are utilized for calculating the theoretical clear-sky power output, lack consistent accuracy. It is important to ensure that the chosen dataset is well characterized by users, with a reliable power output reporting history. All 3 sites have been ensured for accuracy from March 2015 to March 2016.

From the map, Solar farm A,B,C,D are located in an rectangular area which is 20km in length and 40km in width. That area is acceptable to analysis the correlation between those sites, in this case those 4 sites became good target to analysis. As for site E, two reasons make it as poor data provider, the first reason is that the distance between site E and another site is large. Like the distance between E and A is 45km, distance between E and D is 75km, large distance makes it hard to analysis the correlation, details will be explained in Chapter 4. The second reason will be the quality of data from solar farm E, details will be explained in quality control.

Solar Farms	Altitude/m	Capacity/MW	Grid voltage/KV
A	1980	20	110
D	1600	30	35
B	2090	60	110
C	2370	100	110
E	2220	30	35

Table 3.2 Information of Data Providers

The core data for analysis has been obtained solar farms. The power outputs of a solar farm can be compared in a variety of time intervals. These include live readings (5 to 15 minutes) as well as daily, weekly, monthly and yearly data.

Solar Farms	Location data	Power	Irradiance	Ambient Temperature	Module Temperature	Humidity	Wind Speed	Air Pressure
A	Yes	Yes	No	No	No	No	No	No
D	Yes	Yes	Yes	No	No	No	Yes	Yes
B	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
C	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
E	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes

Table 3.3 Data Elements

3.2 QUALITY CONTROL

Following the initial data from the data provider, it is of paramount importance to review and sanity-check the power output data, ensuring the accurate analysis of collective ramp events of the target solar farms. The original data provided directly from the solar farms, but we still not sure if the power data is consecutive in constant time period which is problematic for consistent ramp rate calculations. Both of these inconsistencies have been addressed to ensure the accurate estimation of power outputs across all sites.

In order to accurately model collective ramp events, the time intervals used for analysis must remain consistent across all sites. While the majority of sites have reported 5-minute power output recordings everyday, others have only recorded 15-minute time intervals. As a result, there is a need for 5-minute power outputs to be estimated for sites that have only reported at 15-minute time intervals.

To achieve that, Rstudio which is a powerful data analysis platform is used.

To make sure the time interval is consistent, one long time period will be applied to cover all sites, even there is an independent recording period. Data period applied in this thesis is from 1st March 2015 to 23th March 2016, which covered each recording from all sites. Applying 5 mins interval to the whole time period will produce a long time period with constant interval.

Time	Power	Time	Power
2015/3/1 0:00	0	2015/3/1 0:00	0.251
2015/3/1 0:05	0	2015/3/1 0:15	0.251
2015/3/1 0:10	0	2015/3/1 0:30	0.251
2015/3/1 0:15	0	2015/3/1 0:45	0.251
2015/3/1 0:20	-0.18	2015/3/1 1:00	0.251
2015/3/1 0:25	-0.18	2015/3/1 1:15	0.251
2015/3/1 0:30	-0.18	2015/3/1 1:30	0.251
2015/3/1 0:35	0	2015/3/1 1:45	0.251
2015/3/1 0:40	0	2015/3/1 2:00	0.251
2015/3/1 0:45	0	2015/3/1 2:15	0.251
2015/3/1 0:50	0	2015/3/1 2:30	0.251
2015/3/1 0:55	-0.18	2015/3/1 2:45	0.251
2015/3/1 1:00	-0.18	2015/3/1 3:00	0.251
2015/3/1 1:05	0	2015/3/1 3:15	0.251
2015/3/1 1:10	-0.18	2015/3/1 3:30	0.251
2015/3/1 1:15	-0.18	2015/3/1 3:45	0.251
2015/3/1 1:20	0	2015/3/1 4:00	0.251
		2015/3/1 4:15	0.251

	ltms	gtms	power.DFS	power.GHZ	power.GTZ	power.LYY	power.XC
1000	2015-03-04 11:15:00	2015-03-04 03:15:00	NA	4.21	25.41	21.451	42.06
1001	2015-03-04 11:20:00	2015-03-04 03:20:00	NA	NA	25.69	NA	41.36
1002	2015-03-04 11:25:00	2015-03-04 03:25:00	NA	NA	26.09	NA	44.18
1003	2015-03-04 11:30:00	2015-03-04 03:30:00	NA	3.58	26.04	22.062	42.94
1004	2015-03-04 11:35:00	2015-03-04 03:35:00	NA	NA	26.26	NA	28.86
1005	2015-03-04 11:40:00	2015-03-04 03:40:00	NA	NA	26.72	NA	23.76
1006	2015-03-04 11:45:00	2015-03-04 03:45:00	NA	2.53	5.74	22.827	40.83
1007	2015-03-04 11:50:00	2015-03-04 03:50:00	NA	NA	28.14	NA	44.00
1008	2015-03-04 11:55:00	2015-03-04 03:55:00	NA	NA	27.34	NA	44.00
1009	2015-03-04 12:00:00	2015-03-04 04:00:00	NA	4.18	27.06	23.437	44.88
1010	2015-03-04 12:05:00	2015-03-04 04:05:00	NA	NA	26.66	NA	13.55
1011	2015-03-04 12:10:00	2015-03-04 04:10:00	NA	NA	27.46	NA	47.52
1012	2015-03-04 12:15:00	2015-03-04 04:15:00	NA	4.70	27.40	24.653	36.78
1013	2015-03-04 12:20:00	2015-03-04 04:20:00	NA	NA	28.31	NA	24.82
1014	2015-03-04 12:25:00	2015-03-04 04:25:00	NA	NA	27.74	NA	17.95
1015	2015-03-04 12:30:00	2015-03-04 04:30:00	NA	3.07	28.71	25.114	33.09
1016	2015-03-04 12:35:00	2015-03-04 04:35:00	NA	NA	27.74	NA	47.52
1017	2015-03-04 12:40:00	2015-03-04 04:40:00	NA	NA	28.42	NA	51.92
1018	2015-03-04 12:45:00	2015-03-04 04:45:00	NA	4.87	28.88	25.420	49.46
1019	2015-03-04 12:50:00	2015-03-04 04:50:00	NA	NA	0.00	NA	44.00
1020	2015-03-04 12:55:00	2015-03-04 04:55:00	NA	NA	28.25	NA	12.32
1021	2015-03-04 13:00:00	2015-03-04 05:00:00	NA	4.91	27.63	25.752	21.65
1022	2015-03-04 13:05:00	2015-03-04 05:05:00	NA	NA	29.50	NA	39.60
1023	2015-03-04 13:10:00	2015-03-04 05:10:00	NA	NA	12.68	NA	34.50
1024	2015-03-04 13:15:00	2015-03-04 05:15:00	NA	4.99	30.64	26.058	41.18
1025	2015-03-04 13:20:00	2015-03-04 05:20:00	NA	NA	8.41	NA	12.14

Table 3.4 Constant time interval

Figure 2.2.1.1 shows power output with different time interval and constant interval. After modified the original data, only the data we need shows up, any other duplicated data, missed data, wrong data have been removed, that will increase the accuracy of data analysis and prepare to get the perfect clear sky curve.

And the following figure shows clearly that the power generated from site E is not stable, there are a lot unusual power output in quite long time period. It is because the solar farm E is the last one built, there are a lot of power are generated for testing, only 1440 hours are scheduled to produce power in its first year, that is also reported by China CNE News.

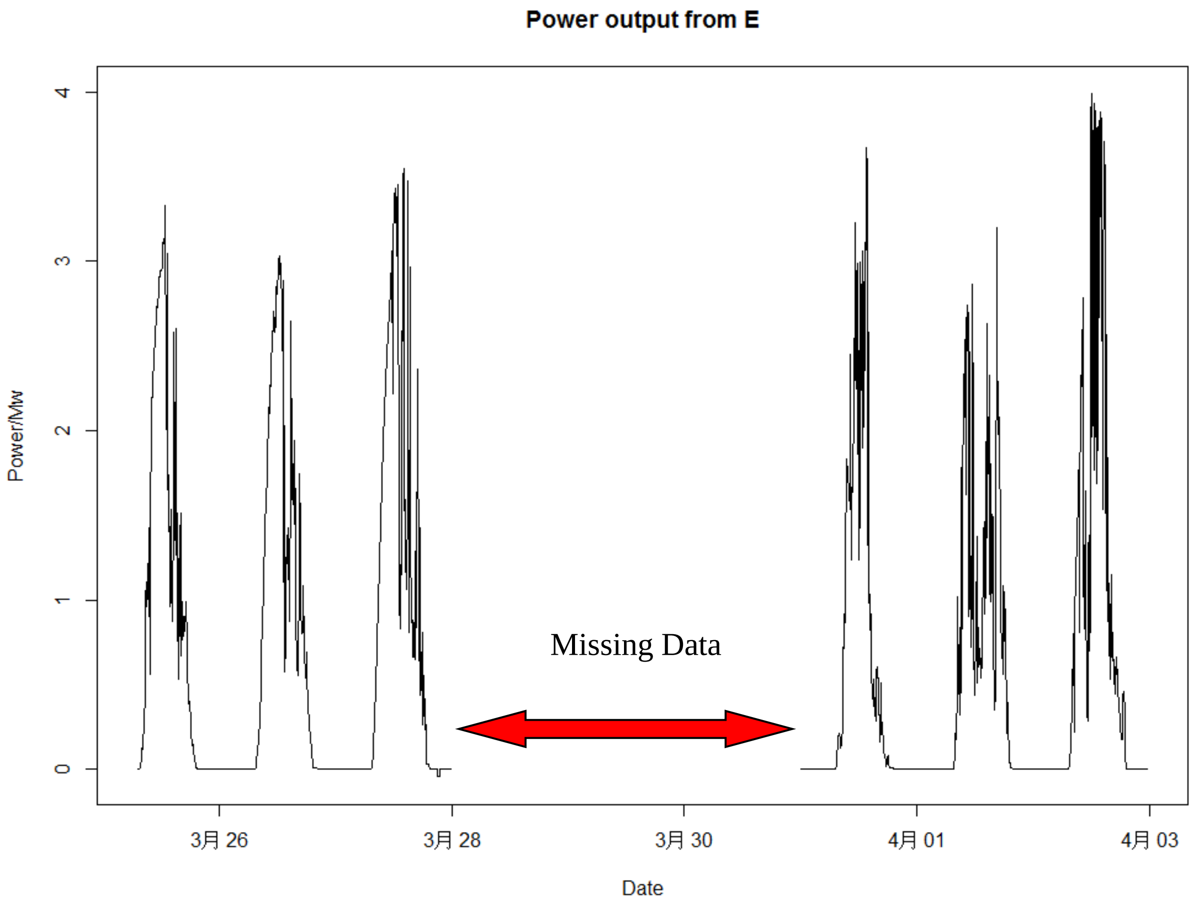

Figure 3.5 Discontinued Power Output from site E

Above figure shows that the data from Site E is not continued, the power system may shut down in some time period which is caused by its self-testing program. Missing data leads to the decreasing of mean power generation and it is not reliable to estimate the clear sky curve. In this case, the power data from site E won’t be used in this thesis, data analysis is based on data from site A,B,C,D. Power output from one site showing as figure 3.6. it is the qualitied data which used to find the result.

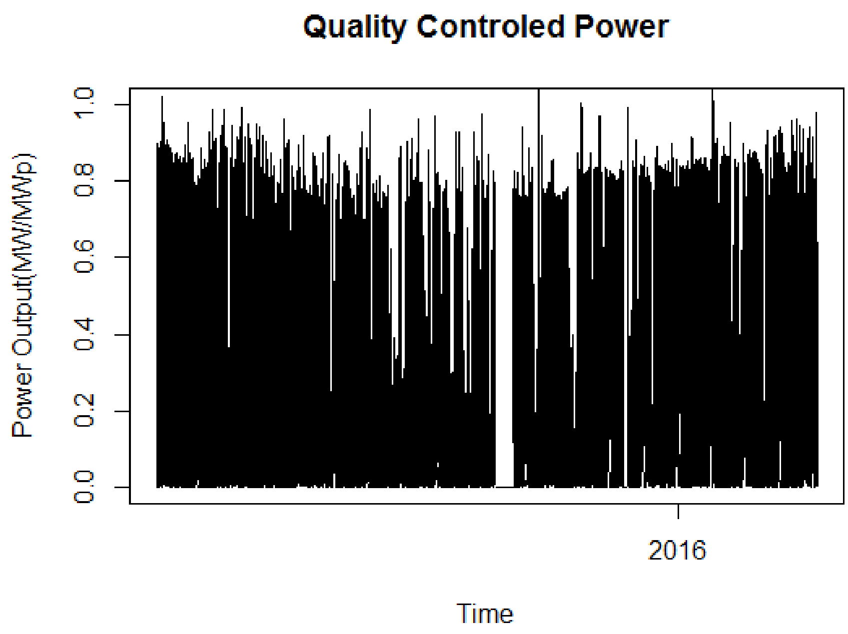

Figure 3.6 Data source used in later analysis

Chapter 4 METHODS

In this thesis, at first we need is to identify the critical collective ramp event behavior by using four key variables – time-step, collective ramp event threshold, collective ramp rate, and the solar zenith angle (SZA), the most important part is find the relationship between solar farms and prove that in a 25km*35km range, the behavior of 4 solar farms is correlated. That will base on the correlation test based on modified ramp rate.

4.1 RAMP RATE

A ramp rate (RR) is defined as the change in measured power output compared to the clear-sky estimation over a given timescale. Equation 1 shows the formula used for RR calculation (Lave and Kleissl 2010).

$$RR = \frac{(PV_{meas_t} - PV_{clr_t}) - (PV_{meas_{\Delta t}} - PV_{clr_{\Delta t}})}{\Delta t}$$

Equation 2

From Equation 2, the PV_{meas} is the real power measured from solar farms, and PV_{clr} is the clear sky model result. Δt is the timescales.Figure 4.1 shows how does the equation works.

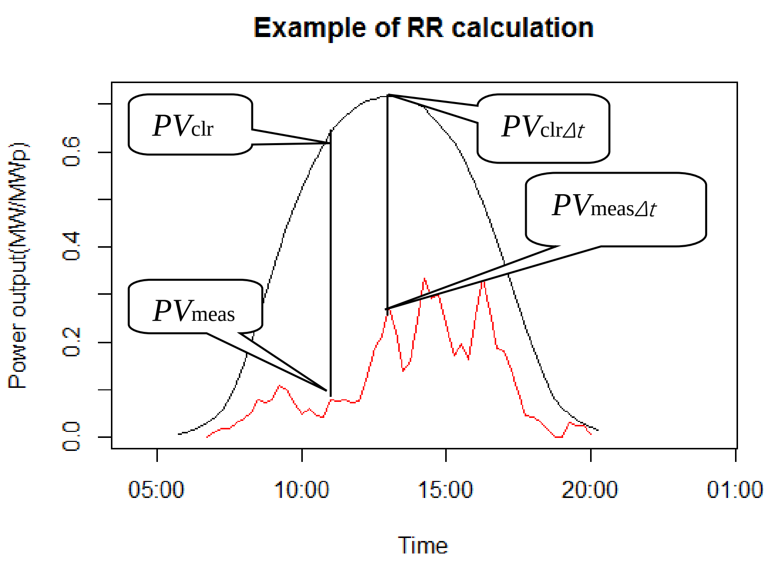

Figure 4.1 Example of RR calculation

Ramp rate in this thesis is an very basic data for analyzing the critical collective events. It shows how fast the power output changes. Further calculation based on ramp rate and threshold value will be set.

4.2 COLLECTIVE RAMP EVENT

The collective ramp events happen when most of the PV sites are experiencing a same ramp rate concurrently at the same time step. As the sun follows its path, it is possible for geographically dispersed PV sites to experience both positive ramp events and negative ramp events. To understand better of the collective ramp event, absolute ramp event (ARE) are defined in the following equation.

$$ARE = \left| \frac{(PV_{meas_t} - PV_{meas_{\Delta t}})}{(PV_{clr_t} + PV_{clr_{\Delta t}})/2} \right| > TD$$

Equation 3

TD in equation 3 is the threshold value which limit the size and impact for the ramp event. The TD value will be use to identify the critical ramp event. When the collective ramp event exceed the threshold value about 60% of the clear sky potential in 1 hour, it is considered as critical collective event. In this thesis, the time shift will be set to 60 mins to identify the critical collective event. Equation 3 is applied as a filter to delete the ramp rate which is less than 60%.

Chapter 5 ANALYSIS DATA FROM SITES

On the purpose of enhance the accuracy of analyzing ramp event. It's necessary to analyse and understand the relationship between ramp events, ramp rates, time-steps and the solar zenith angle. In the thesis, the critical ramp event defined as the ramp rate changed over 60% in 60mins. And the time period for analyzing is from 1 March 2015 to 23 March 2016.

5.1 RAMP RATE

In the following table this part, statistic ramp rate is provided.

	Mean RR	Max RR	Std RR
Site A	0.1149461	0.96	0.1337842
Site B	0.1310984	0.92	0.1613704
Site C	0.167335	0.99	0.2432533
Site D	0.1102478	0.9	0.1322949

Table 5.1 Statistic Ramp Rate

The average and maxima of the magnitude of RRs for each site are shown in Table 5.1. With an average RR magnitude of 0.167. Site C had the largest, while Site D had the smallest at 0.11. that means the average range of ramp event at site C are larger than that of the other sites. The maximum RRs are very similar for all sites. Means all of those sites experienced large ramp rate during the test period. And also Site C goes through the largest ramp rate event over the test period. Since the mean absolute value of the RR is already a measure of the RR variability, the standard deviation of the RR is expected to give qualitatively similar results as is confirmed in the table. Site C has the largest standard deviation; it also shows that the variability of that site is the highest of all those sites.

5.2 CLEAR SKY DAY

A clear-sky day provides a suitable reference point for developing a RR boundary.

Theoretically, on a clear-sky day the curve of a collective power output will perfectly align on top of the estimated clear-sky curve, resulting in a RR of zero. But it is not going to happened. Because when the clear sky curve was estimated, it is not perfect, means incorrect data may uploaded, that lead to inaccuracy clear sky curve. And under the large zenith angles, the mismatch between estimated power output and real power output may happened, and PV systems are subject to shading due to the surrounding environment. Because of these limitations, the algorithm will always calculate a difference between the clear-sky estimation and observed collective power output, resulting in a calculated RR, even though no actual collective ramp event occurs.

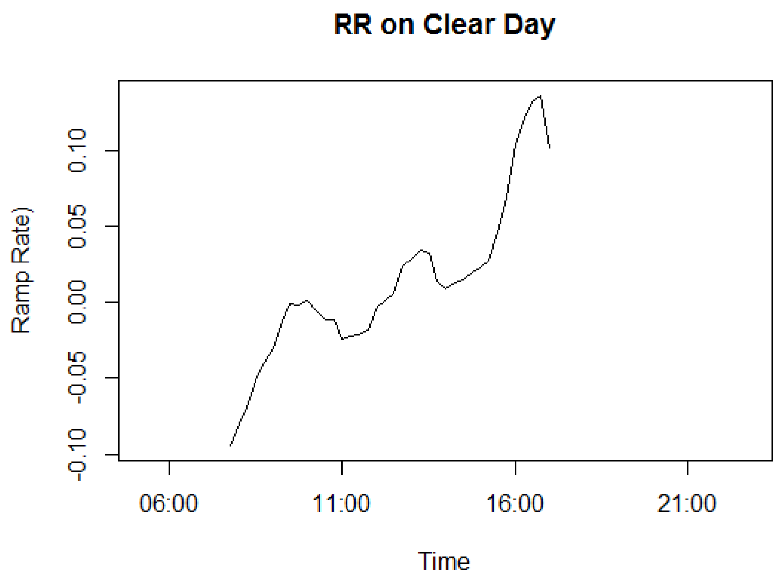

Figure 5.2 Average Ramp Rate on Clear Sky Day

For graph 5.2, it shows the ramp rate on a clear sky day which on 9 Nov 2015. The range of ramp rate is located between -0.1 to 0.1. it is considered at small ramp rate. That means the real power output is almost close to the estimated clear sky curve, that proved the assumption before.

Figure 5.3 shows the observe power output and the estimated clear sky curve on 9 Nov 2015. Each site located differently, but their behavior looked similar on clear sky day.

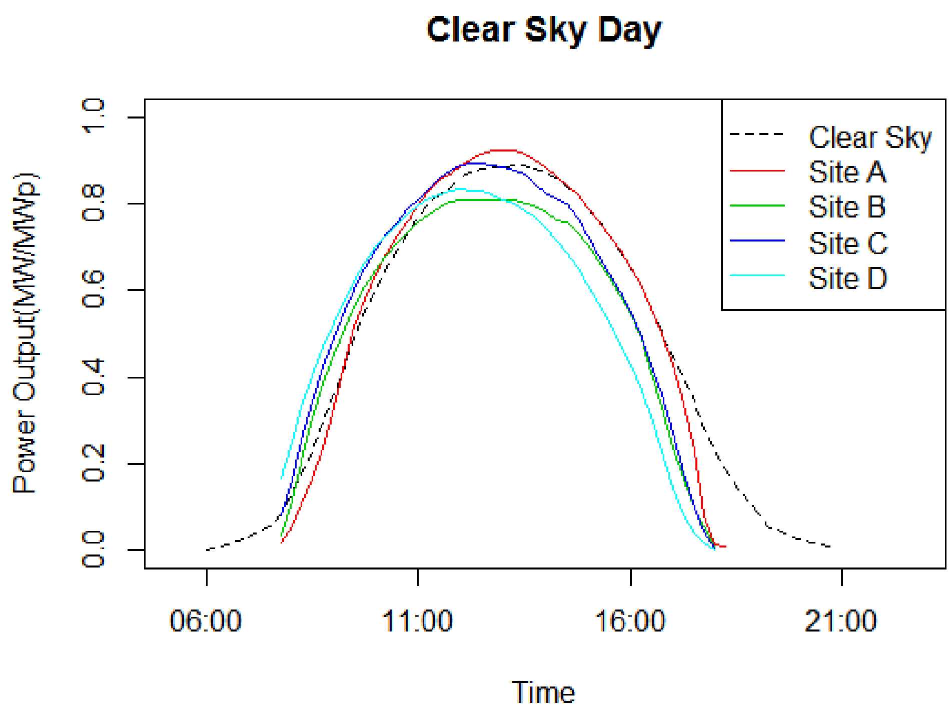

Figure 5.3 Real Behaviour over 4 sites on clear sky day

Correlation coefficient is a number that used to quantify the type of correlation or dependence. It means the statistical relationship between two or more observed data. The range of correlation coefficient is from -1 to 1, result is 0 means it's dependence for those tested data, the result close to 1 means it has strong positive correlations, on the opposite, it close to -1 means it has strong negative correlations. P-value is probability value present if the variable is correlated, p-value less than 0.05 is defined that the two variables are correlated. During this tes, relationship between sites is proved by mathematical method. Table 5.4 shows the correlation coefficient over 5 sites.

Site Pairs	A-B	A-C	A-D	B-C	B-D	C-D
Corelation Coefficier	0.590297	0.74083	0.511937	0.906494	0.951464	0.862271
P-Value (<0.05)	9.58E-05	1.05E-07	0.001018	4.79E-15	2.20E-16	3.50E-12

Table 5.4 Correlation Coefficient between 4 sites

Above table shows that the correlation coefficient value of every two sites over 5 sites. Table shows the Correlation Coefficient between site by site. P-Value is the threshold, P<0.05 means Sites are correlated. Obviously, 4 Sites correlated to each other on clear sky day. And P less than 0.01 means the correlation is quite strong. That proves that the behaviour over 4 sites on clear day is correlated.

5.3 HIGH VARIABILITY DAY

In a high variability day, the power output from sites is not stable, radiation from sun to solar panel keeps in high variability, because of the media change like cloud. In these days, the correlation between sites is not easy to identify. Also, the RR graph looked more randomly. It has been confirmed that averaging geographically separated sites will lead to a smoother output. RR analysis of the average site confirms this effect. (Lave, Kleissl 2010) AVE curve is defined as the average power output based on 4 sites. In the AVE curve, there is a decrease in mean magnitude, maximum magnitude and standard deviation compared with other single sites. And that will indicating a lower probability of extreme RR.

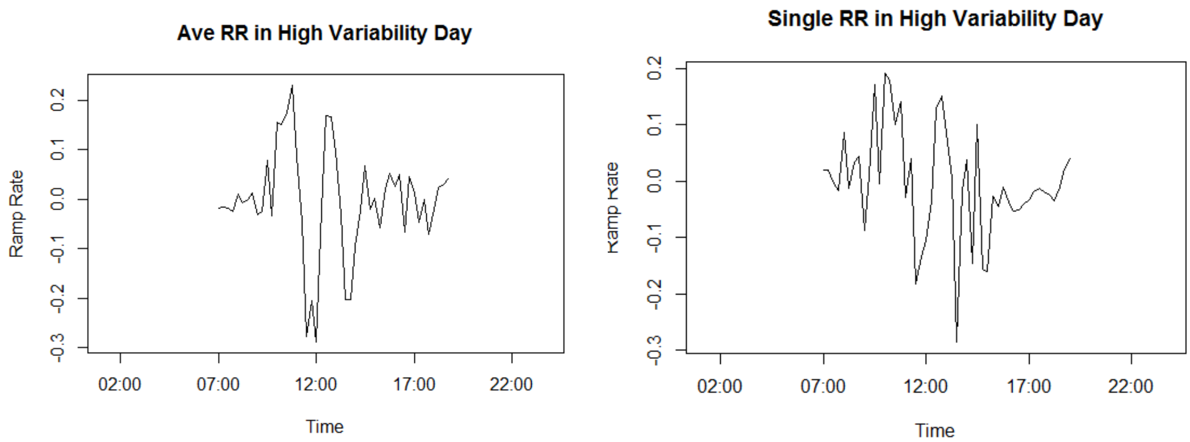

Figure 5.5 Average Ramp rate on a High Variability Day

Figure 5.5 shows the average ramp rate on a high variability day which is 3 July 2015. Within that day, the ramp rata also has high variability, it located at a range from -0.3 to 0.2 and there is a few high impact at 11am to 1pm on that day. Compared with the AVE Ramp rate and single site Ramp rate, it's clear to see that the average ramp rate present a 'smoother' output than RR from single site.

Power performance also can be seen directly through the power curve on a high variability day.

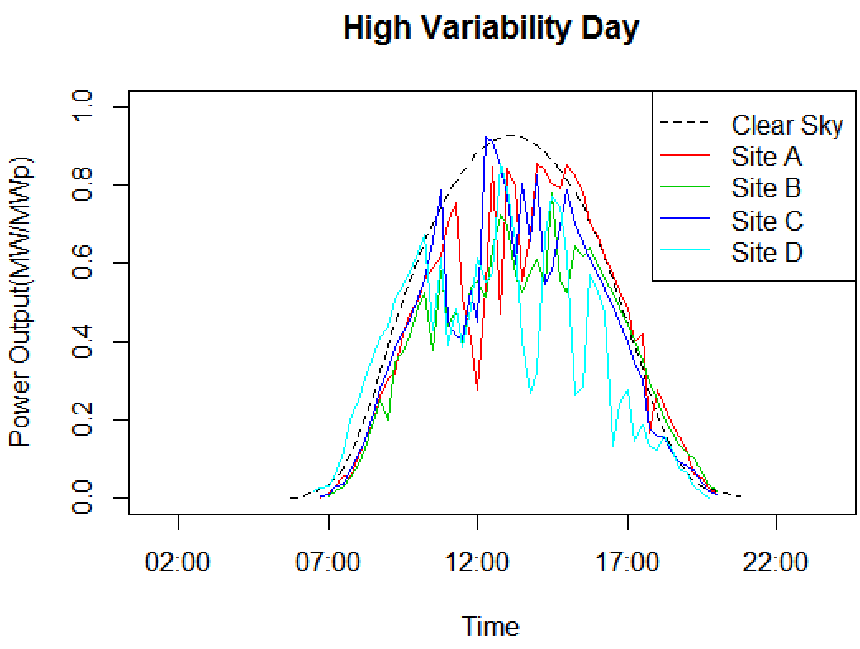

Figure 5.6 Power output through High variability Day

The real power performance is messy and that is not easy to see any correlated behaviour by figure directly due to the complex weather condition on that day.

Site Pairs	A-B	A-C	A-D	B-C	B-D	C-D
Corelation Coefficier	0.253405	0.247096	0.297156	0.646842	0.211677	0.415862
P-Value (<0.05)	0.07894	0.08696	0.04026	3.87E-07	0.1443	0.003286

Table 5.7 Correlation Coefficient over all sites.

Site Pairs	AVE-A	AVE-B	AVE-C	AVE-D
Corelation Coefficier	0.481029	0.355898	0.300704	0.501556
P-Value (<0.05)	0.000538	0.01304	0.03782	0.000329

Table 5.8 Correlation Coefficient between average site and single site

Table 5.7 shows that the correlation coefficient value of every two sites over 5 sites. In that table, the correlation coefficient between site pairs is not strong. It has the highest correlation coefficient between B and C which is 0.65, as for the rest, it is not good enough to prove that the sites are correlated. To find the correlation on high variability day, average value is used as the reference element. In the AVE data, it has less extreme ramp rate and more smooth than single site. From table 5.8, each single site is correlated with the smoothed value, which means it still have similar trend on high variability day and also correlated with each other.

5.4 CRITICAL RAMP EVENT DAY

Critical Collective ramp event day is that during the day, the ramp rate of the power performance change 60% in 1 hour. The total frequency of critical collective ramp events for the study period has been recorded for a time-step 60 minutes in 15-minute intervals. Following the implementation of a SZA and ramp rate threshold, the frequency are calculated as a reasonable number. For example, 20 critical collective ramp events which include 8 positive critical collective ramp events and 12 negative critical collective ramp event. These critical ramp events have been plotted against their corresponding SZA and ramp rates in Figure 5.9. The distribution of events according to the SZA indicates that critical ramp events for a 60-minute time-step are more likely to occur at a SZA between 20 degree to 30 degree.

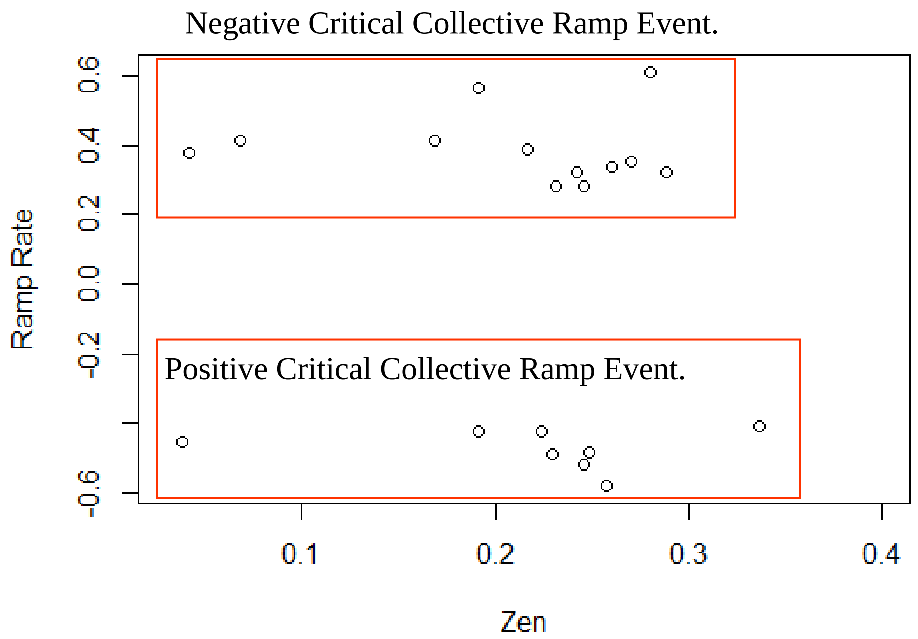

Figure 5.9 Critical Collective Ramp Events

Detected Critical ramp event shows in figure 5.9. for the ramp rate larger than zero, it's negative critical collective ramp event and on the other side, it's positive critical collective ramp event. There are a lot of normal ramp event but critical ramp event has large impact and short time period, that's why in only happened 20 times in the test period.

As for figure 5.10, it is obvious that there is a large ramp rate change around 1:30pm to 2:30pm, the ramp rate change from -0.2 to 0.4. it is considered as large ramp rate change.

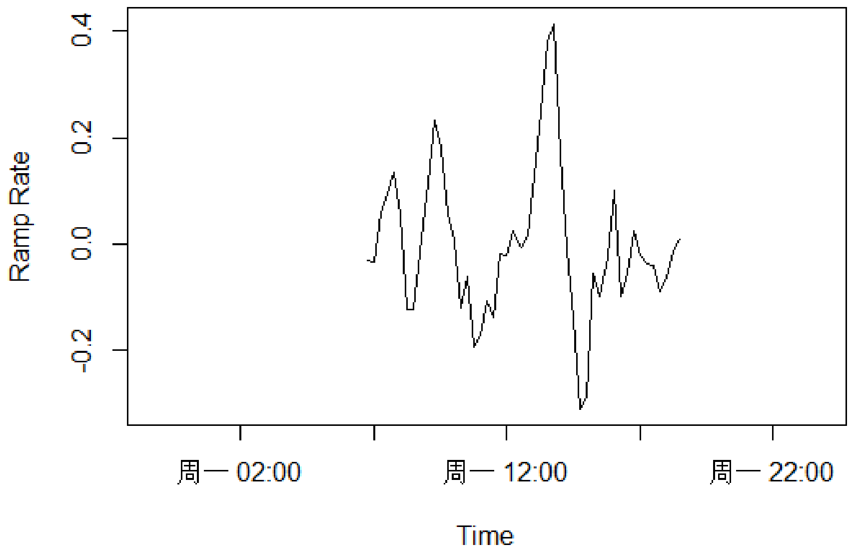

Figure 5.10 Ramp Rate on collective ramp day

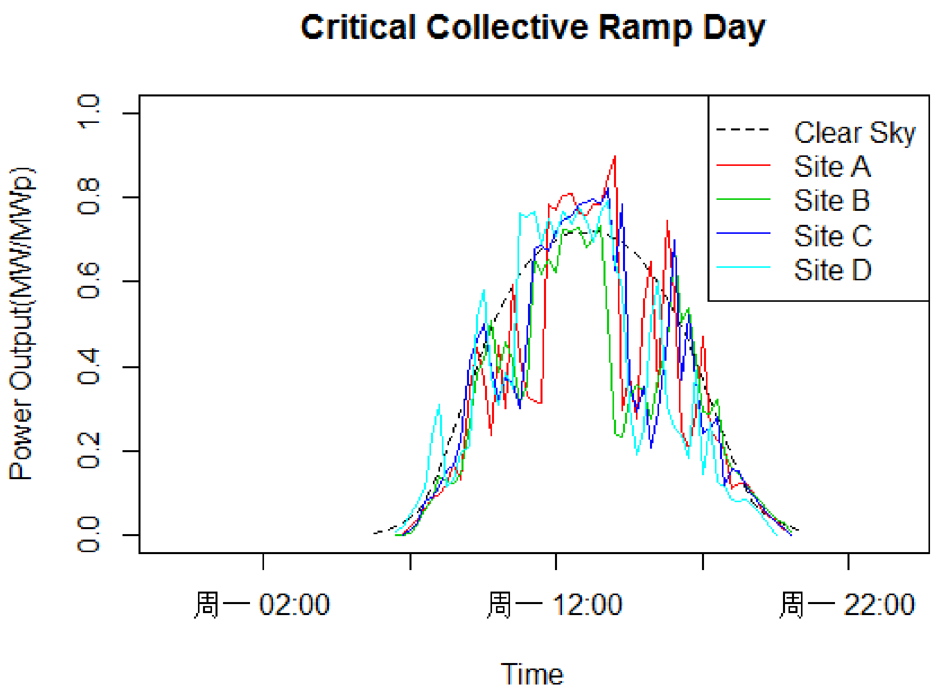

Figure 5.11 Power performance on collective ramp day

A critical collective ramp event happened between 1:30pm to 2:30pm. Figure 5.11 shows that power from 4 sites in similar trend during that time but the ramp has delay by different site. Assumption was made that its correlated over 4 sites. Overall the curve of each site looks similar. But from the table 5.12, not much correlation found. The highest correlation coefficient still in site B and site C, which is 0.64. For site pairs A-B, A-C and B-D, it is not even correlated. That is different with the previous assumption on figure 5.11.

Site Pairs	A-B	A-C	A-D	B-C	B-D	C-D
Corelation Coefficier	0.253405	0.247096	0.297156	0.646842	0.211677	0.415862
P-Value (<0.05)	0.07894	0.08696	0.04026	3.87E-07	0.1443	0.003286

Table 5.12 Correlation coefficient on collective ramp day

Site Pairs	A-B	A-C	A-D	B-C	B-D	C-D
Corelation Coefficier	0.424655	0.438313	0.478123	0.646842	0.327634	0.516285
P-Value (<0.05)	0.002627	0.001632	0.000676	3.87E-07	0.02156	0.000146

Table 5.13 Correlation coefficient over shifted sites

By looking through the critical ramp rate in figure 5.11, it happened on site B first, then followed by site A and Site C, D happened at last in 15 mins interval. That means the critical ramp event not happens simultaneously cross those 4 sites. That's why the correlation test can't base on a same time. Table 5.13 shows correlation coefficient over shifted sites. Shifted sites means test the correlation based on different time, in other words, put 4 sites in order based on the time line. After shifting the sites data, it can be seen from table 5.13 that the correlation coefficient is high enough to prove that the critical ramp event are correlated on that day.

From Figure 5.13, it shows the zoom in figure about the critical collective ramp event that happened on 8 June 2015. It can be seen clearly that the ramp event happened from 1:30pm to 2:30pm. In 1 hour period, the Site B happened first at 1:30 and followed by site A, the Site C and Site D happened almost same time at last. The starting interval is 15 mins for each ramp event. Combined with the location map, we can imagine that the clouds are moving from bottom left towards top right. That's may be a further topic to analysis in the fulture.

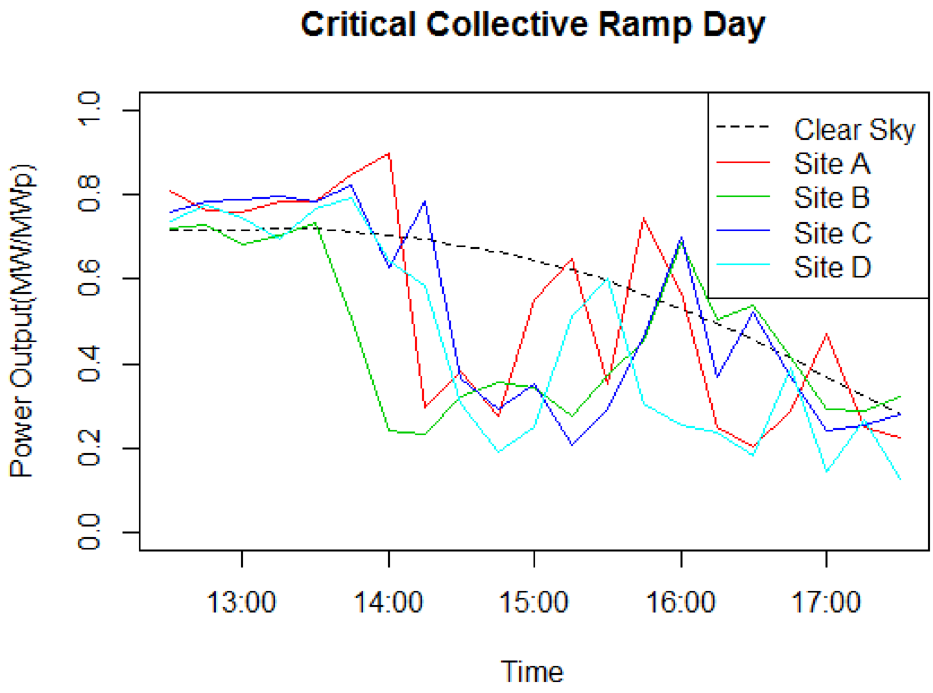

Figure 5.13 Critical Collective Ramp Event Zoom in

Chapter 6 CONCLUSION

Overall, Critical Collective Ramp Event of 4 Solar farms which located in Dali, China is identified during the test period. Totally 20 critical collective ramp events are identified which includes 12 negative critical ramp events and 8 positive critical ramp event. The large ramp rate change easily happened when the solar zenith angle located in 20 to 30 degrees. The largest Ramp rate are found which is 0.99 and the critical ramp event also cause large impact to the grid network. Finally, this thesis proved that the 4 solar farms are correlated with each other based on different dates. On clear day, the power performances are strong correlated and matched the clear sky model; on high variability day, the power performances are hard to predicable but it’s still correlated with the average site which has lower variability, as for the date that the critical collective ramp events happened, 4 sites have similar performance and it has strong correlation between site pairs. Based on the movement of clouds and the sites location, the critical ramp event may happen at different times. That will be an interesting topic to analysis in the future, it will help us to simulate the power performance over 4 sites in the future.

Appendix A

ESRA MODEL

The ESRA model requires one major input; the Linke turbidity at Air Mass (AM) = 2. This turbidity is then used to calculate the Linke transmittances (TL) and Rayleigh optical thickness (δR). Estimates of the clear sky beam and diffuse solar radiation are obtained in equations (4) and (5) respectively.

$$Ebnc = Eextn \times e{-}0.8662 \times TL \times AM \times \delta R \ [J] \qquad (4)$$

$$Edhc = Eextn \times TRd(TL) \times Fd(\theta z, TL)[J] \qquad (5)$$

Where TRd models the diffusion of air molecules, Fd is the diffuse angular function accommodating for the extra diffusion encountered at higher air masses and solar zenith angles (θz). Further details on the ESRA model can found in its seminal paper (Rigollier et al. 2000).

Bibliography

Andu Nguyen, Maxime Velay, Jens Schoene, Vadim Zheglov, Ben Kurtz, Keenan Murray, Bill Torre, Jan Kleissl, 2015. High PV penetration impacts on five local distribution networks using high resolution solar resource assessment with sky imager and quasi-steady state distribution system simulations. Solar Energy, Volume 132, July 2016, pp. 221-235.

Rigollier, C., Bauer, O. & Wald, L., 2000. On the clear sky model of the ESRA — European Solar Radiation Atlas — with respect to the heliosat method. *Solar Energy*, 68(1), pp.33–48. Available at: http://www.sciencedirect.com/science/article/pii/S0038092X99000559.

Commencement of on-grid connection and generation of the Dafoshan solar power plant, 2nd March, 2015, [Available online at: http://www.chinawindpower.com.hk/CN/News/3271.html]

Engerer, N.A., Mills, F. 2014: KPV: A clear-sky index for photovoltaics, *Solar Energy*, 105, 679-693.

Engerer, N.A., 2015: City-wide simulations of distributed photovoltaic array power output. PhD Thesis, The Australian National University, Canberra.

Engerer, N.A., Mills F. 2015: Validating Nine Clear-sky Radiation Models in Australia., The Australian National University, Canberra.

Florita, A., Hodge, B-M., Orwig, K. 2013: Identifying wind and solar ramping events,

Hoff, T. Perez, R., 2010: Quantifying PV power output variability, Solar Energy, 84, 1782-1793.

IEEE 5th Green Technologies Conference, Denver, CO, U.S.A., IEEE 147-152.

Jiahai Yuan, Chunning Na, Zheng Hu, and Ping Li, 2016. Energy Conservation and Emissions Reduction in China’s Power Sector: Alternative Scenarios Up to 2020. Energies, Volume 9, Issue 4, p 266.

Kawasaki, N., Oozeki, T., Otani, K., Kurokawa, K., 2006: An evaluation method of the fluctuation characteristics of photovoltaic systems by using frequency analysis. Solarn Energy Materials and Solar Cells, 90, (18-19). 3356-3363.

Lave, M., Kleissl, J., 2010: Solar variability of four sites across the state of Colorado, Renewable Energy, 35, 2867-2873.

M. Lave, J. Stein, A. Ellis, 2012. Analyzing and Simulating the Reduction in PV Power plant Variability due to Geographic Smoothing in Ota City, Japan and Alamos, CO, Photovoltaics Specialists Conference (PVSC), Austin, TX, USA, 3–8 Jun, volume 2, p38.

Murata, A., Yamaguchi, H., Otani, K. 2009: A method of estimating the output fluctuation of many photovoltaic power generation systems dispersed in a wide area. Electrical Engineering in Japan, 166, 9-19.

Otani, K., J. Minowa, and K. Kurokawa (1997): Study on area solar irradiance for analysing areally-totalized PV systems. Solar Energy Materials and Solar Cells, Volume 47, pp. 281-288

Sonya J. Wellby and Nicholas A. Engerer, 2016. Categorizing the Meteorological Origins of Critical Ramp Events in Collective Photovoltaic Array Output. Journal of Applied Meteorology and Climatology, Volume 55, Issue 6, June 2016, pp. 1323-1344.

Wellby, S. Engerer, N.A., 2015: Categorizing the meteorological origins of critical ramp events in collective photovoltaic array output. The Australian National University, Canberra.

Wiemken, E., Beyer, H. G., Heydenreich, W., Kiefer, K., 2001: Power characteristics of PV ensembles: experiences from the combined power production of 100 grid connected PV systems over the area of Germany, Solar Energy, 70, 513-518.