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ELEVATED LIGHTNING ACTIVITY AT LARGE PV PLANT ENVIRONMENTS – A HYPOTHESIS AND PRELIMINARY FINDINGS

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Synopsis: Investigations related to lightning activity and problems experienced at large photovoltaic (PV) plants in South Africa, yielded higher lightning activity following the construction of the plant compared to at the design stage of the plant. Even though the latest lightning data may be used at the design stage, the actual lightning activity that affects the plant, is likely to only be revealed following the construction of the plant. This has serious implications in terms of the lightning risk assessment: i) now under estimated, because it was done during the design stage using lightning flash density data with the lightning protection system to be implemented; ii) Particularly in South Africa, large PV plant may typically be introduced in parts of the country that appears to have lower lightning flash densities. The dilemma is the design requirements faced by the design engineer and the adjustment that need to be made to accommodate for this increase in lightning flash density. An aspect likely to have significant cost implications. Without engaging in lightning physics, the hypothesis of elevated lightning activity following construction of and at large PV plants in arid regions, is presented. The latter is based on observations, actual lightning data collected and analysed, with preliminary findings presented in the context of some PV plant in South Africa. The anticipated mechanism of how the plant may contribute to the elevated lightning activity to create a “micro-climate” is addressed.

Keywords: Elevated, Lightning, Photovoltaic Plant, Hypothesis

1. INTRODUCTION

1.1 Background

Specific investigations that focused on equipment damage, caused by lightning at large photovoltaic (PV) plants in the Northern Cape in South Africa, spawned information that suggested higher lightning activity following the construction of the plant compared to at the design stage of the plant. In other words, lightning activity, elevated from that noted on the lightning flash density map of the region, was observed at the operational plant.

With the lightning risk of any installation directly proportional to the lightning flash density in the area of the installation [1], this elevated lightning activity presents significant implications in terms of the lightning risk assessment:

- Now under estimated, because it was done during the design stage of the plant based on lightning flash density data;

- Particularly in South Africa, large free field PV plant may typically be introduced in parts of the country that appears to have lower lightning flash densities.

- The risk assessment process promulgated by IEC 62305-2 is limited [2], particularly when equipment is accompanied and supported by large electrodes, such as that applied in open field photovoltaic plants. The reason for this is, lightning ground potential rise (GPR) causes significant potential differences that may exist between interconnected structures and equipment (using wire-line technology), when the electrode is embedded in high soil resistivity soil, as reported by Pretorius (2017) [3, 5].

The dilemma now is the design requirements faced by the design engineer in terms of how the risk assessment should be dealt with. An aspect that is likely to have significant cost implications.

This paper offers a hypothesis for the elevated lightning activity without engaging in the physics of lightning. Specific observations, from actual lightning data collected and analysed are presented as preliminary findings of two PV plants in South Africa. Finally, the anticipated mechanism, of how the plant may act as a “heat island” to contribute to the elevated lightning activity to create a “micro-climate” at the plant, is addressed.

1.2 Approach

The preliminary study involved two photovoltaic (PV) plants, A and B, in the Northern Cape in South Africa. Specific dates, when lightning activity was recorded at the plants, were used in the analysis. The dates of lightning activity were reported by plant personnel as a result of equipment damage that occurred at the plant/s.

In addition, lightning data for the following periods were considered for comparison:

i) A period well before construction of the plant (2007 to 2012 – 5 years);
ii) A period that included and followed on construction and commissioning of the plant (2012 to 2017 – 5 years) and
iii) The complete, available data period (2006 to 2017 – 11 years) [4].

The preliminary analysis was then completed as a desk-top exercise. Future work will include the specific aspects noted in this paper.

1.3 Definitions

Before embarking on the discussion and details of the paper, it is necessary to reflect on the following definitions, as per IEC 62305 [1]:

Lightning flash to earth – an electrical discharge of atmospheric origin between cloud and earth consisting of one or more strokes;

Lightning stroke – a single electrical discharge in a lightning flash to earth;

Multiple strokes – a lightning flash consisting, on average, of 3 to 4 strokes with typical time interval between them of about 50 ms (**Note:** Events having up to a few dozen strokes with intervals between them ranging from 10 ms to 250 ms have been reported). (***Note:*** *In the* *context of this discussion, the term lightning activity is loosely used and distinguishes between a single flash with multiple strokes (see Figure 1 (a) for an example) or a single flash, branched with multiple strokes (see Figure 1 (b) for an example*).

(a) (b)

Figure 1: Lightning activity examples: (a) Single flash with multiple strokes; (b) Single flash, branched with multiple strokes.

Risk – the value of probable average annual loss (humans and goods) due to lightning, relative to the total value (humans and goods) of the structure to be protected.

The risk is the relative value of a probable average annual loss**.** For each type of loss (risk of loss of a human life (including permanent injury); risk of loss of service to the public; risk of loss of cultural heritage and risk of loss of economic value) which may be associated with a structure, the relevant risk shall be evaluated.

Each risk component (Related to injury to living beings caused by electric shock due to touch and step voltages inside the structure and outside; Related to physical damage caused by dangerous sparking inside the Structure; Related to failure of internal systems caused by lightning electromagnetic pulse; Related to injury to living beings caused by electric shock due to touch voltage inside the structure; Related to physical damage and related to failure of internal systems caused by overvoltages induced on incoming lines) may be expressed by the following general equation [1]:

$$R_X = N_X \text{ x } P_X \text{ x } L_X \quad (1)$$

where

- N_X is the number of dangerous events per annum;
- P_X is the probability of damage to a structure and
- L_X is the consequent loss.

The number N_X of dangerous events is affected by the lightning ground flash density (N_G) and by the physical characteristics of the structure to be protected, its surroundings, connected lines and the soil [1]. (***Note:*** *IEC 6235-2 only considers ground flash density and not ground stroke density. Further, the standard does not elaborate further on the importance of, specifically, high soil resistivity that, in the context of this paper, is viewed as a limitation*).

The probability of damage P_X is affected by characteristics of the structure to be protected, the connected lines and the protection measures provided [1].

The consequent loss L_X is affected by the use to which the structure is assigned, the attendance of persons, the type of service provided to public, the value of goods affected by the damage and the measures provided to limit the amount of loss [1].

The average annual number N of dangerous events due to lightning flashes influencing a structure to be protected depends on the thunderstorm activity of the region where the structure is located and on the structure's physical characteristics [1].

To calculate the number *N*, one should multiply the lightning ground flash density N_G by an equivalent collection area of the structure, taking into account correction factors for the structure's physical characteristics [1]. The lightning ground flash density N_G is the number of lightning flashes per km^2 per year [1]. (***Note:*** *The fact that ground flash density is employed in the calculation of the annual number of dangerous events, is a limitation of IEC 62305-2 in the context of large free field PV plant, as pointed out by this paper*).

Tolerable risk - maximum value of the risk which can be tolerated for the structure to be protected.

2. LARGE FREE FIELD PHOTOVOLTAIC PLANT

Two large, free-field photovoltaic (PV) plants (Plant A and Plant B) were considered in this preliminary study and discussion. The two PV plants were established in the Northern Cape in South Africa and are located close to each other (closest border points are 1,2 km apart as illustrated in Figure 2), with the following details (Table 1):

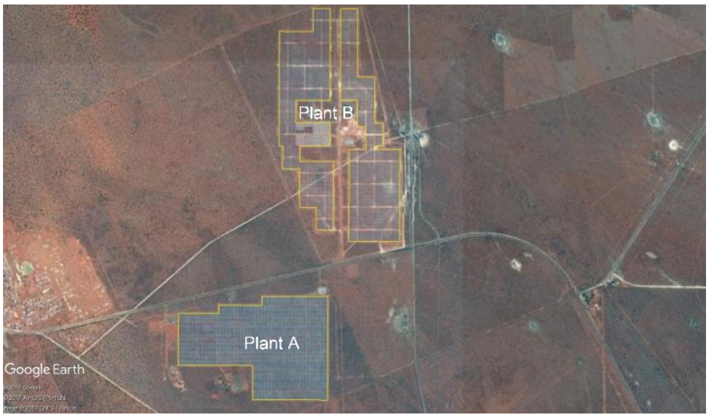


Figure 2: Two large free, field photovoltaic (PV) plants (Plant A and Plant B) considered.

Table 1: Technical Description of Plant A and Plant B.

No	Description / Parameter	Plant A	Plant B
1	Technology	Solar PV	Solar PV
2	Tracking	Hydraulic drive serving several rows.	Single drive motor with mechanical interlink between several rows.
3	Tracking Mechanism	352 107	319 600
4	Number of PV modules	352 107	319 600
4	Area covered by PV modules	1,82 km^2 (182 ha)	2,33 km^2 (233 ha)
5	Nominal Power	81 MW	74 MW
6	Commissioning / Operational	Aug 2014	Dec 2014
7	Telecommunication	Wire-Line	Optic Fibre

3. LIGHTNING

3.1 Lightning Activity in South Africa

Figure 3 and 4 respectively illustrate the most recent [4] ground flash density and ground stroke (positive and negative stroke) density maps for South Africa.

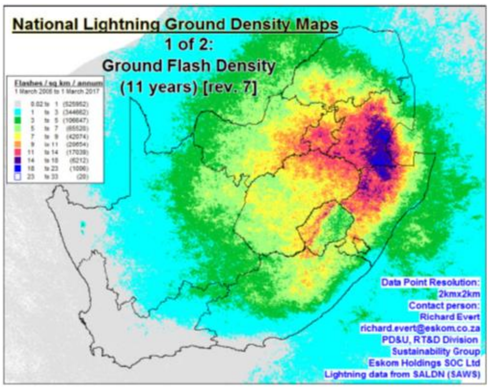


Figure 3: Lightning Ground Flash Density map of South Africa (11-year data) [4]

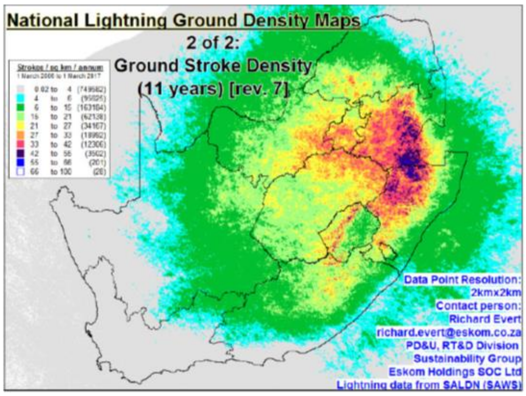


Figure 4: Lightning Ground Stroke Density map of South Africa (11-year data) [4]

On face value, based on the lighting flash density indicated in Figure 3, it appears as if the lightning risk for structures towards the western / south western parts of the country are diminishing because of lower ground flash density. But it must be remembered, as noted earlier in Section 1.3, that lightning risk is a function of N_X - the number of dangerous events per annum; P_X - the probability of damage to a structure and L_X - the consequent loss. Further, the number of dangerous events is not only a function of lightning ground flash density but also the physical characteristics of the structure to be protected, its surroundings, connected lines and, perhaps most importantly, the soil conditions.

The above, in essence, means that a structure (with poor protection) located in the western parts of the country, such as the Northern Cape, may have a similar, high lightning risk compared to a structure located in the eastern parts of the country where the lightning flash density is higher (but with better structure protection).

These arguments illustrate the importance of and need to do a lightning risk assessment in order to identify the required mitigation level for a new structure to be designed and constructed.

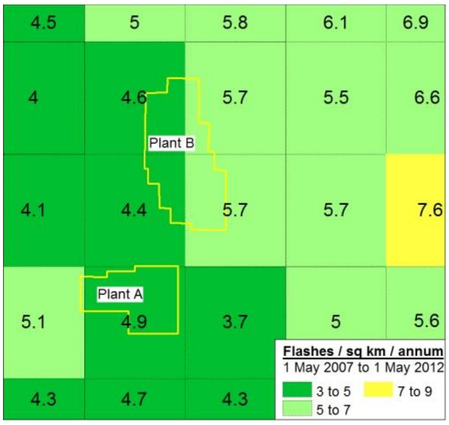
3.2 Lightning Activity at the PV Plants (LDN Based Data)

To ensure that lightning data was captured well before the construction and commissioning date of the two PV plants, lightning data was considered up to and including 2012 for the first part of the analysis. The lightning detection network (LDN) of the South African Weather Services was commissioned at end of 2005 with the collection of reliable lightning data that started from March 2006. For these reasons, lightning data before the commissioning of the PV plants was considered for the 5 year period from 2007 to 2012.

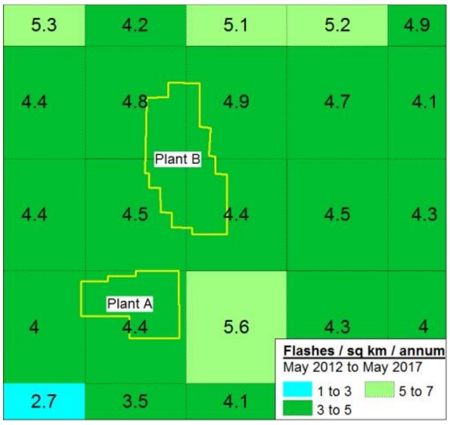
Figure 5(a) and (c) respectively illustrate the Ground Flash Density (GFD) and Ground Stroke Density (GSD) for the period 2007 to 2012, at the locations of Plant A and Plant B, a period well before the construction and commissioning of the two plants. Figure 5 (b) and (d) illustrates the GFD and GSD for the period 2012 to 2017 (the 5 year period that included any construction period, the commissioning and the period following commissioning of the plant).

The limitation in the short periods (5 years) of data considered in the preliminary study is realised. Longer periods will be considered for future studies and as more data become available. For this reason, all lightning data available for the 11 year period [4] was also considered.

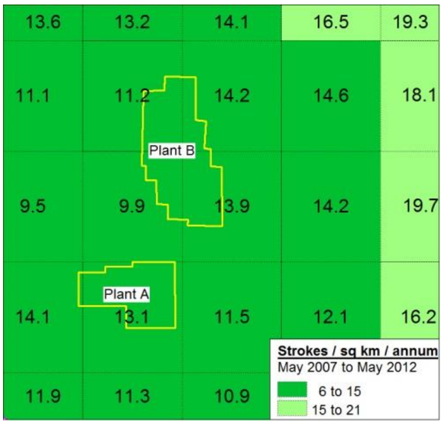
Figure 6(a) and (b) respectively illustrate the Ground Flash Density and Ground Stroke Density for the period 2006 to 2017 at the locations of Plant A and Plant B. A summary of the maximum GFD and GSD, associated with each plant based on Figures 5 and 6, is presented in Table 2.



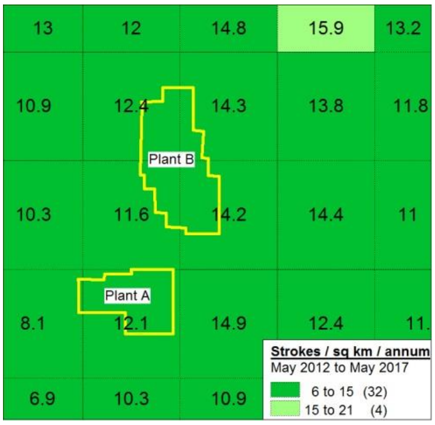
(a) GFD - 5 years before.



(b) GFD - 5 years during and following.

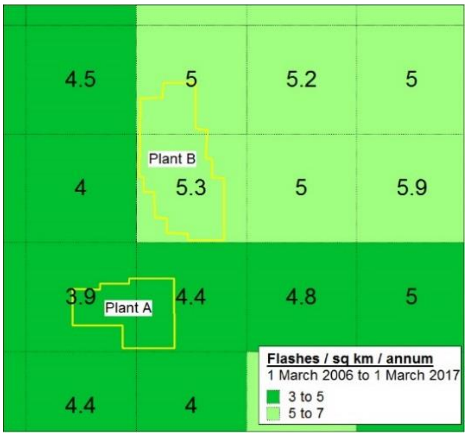


(c) GSD - 5 years before.



(d) GSD - 5 years during and following.

Figure 5: Lightning density for the <u>5 year</u> period before, as well as during and following construction and commissioning.



(a) GFD.

(b) GSD.

Figure 6: Lightning Density for <u>11 year</u> period (2006 to 2017) at Plant A and Plant B.

Table 2: Summary of Maximum Ground Flash Density and Ground Stroke Density at Plants A and B.

Max Ground Flash Density (flashes/ km^2 / year)						Max Ground Stroke Density (strokes/km^2 /year)					
Plant A			Plant B			Plant A			Plant B		
5 years 2007 to 2012	5 years 2012 to 2017	11 years 2006 to 2017	5 years 2007 to 2012	5 years 2012 to 2017	11 years 2006 to 2017	5 years 2007 to 2012	5 years 2012 to 2017	11 years 2006 to 2017	5 years 2007 to 2012	5 years 2012 to 2017	11 years 2006 to 2017
5,1	4,4	4,4	5,7	4,9	5,3	14,1	12,1	12,4	14,2	14,3	14,0

It is clear from Table 2 that the stroke density is significantly higher than the flash density (as expected). The lower lightning activity for the period 2012 to 2017 (compared to the 2006 to 2012 period) may be related to the significant drought period experienced in South Africa the last few years.

3.3 Lightning Activity at the PV Plants (Direct Stroke Data Based on Field Reports)

In this section, only data related to direct strokes to the plants were considered. The lightning event dates were obtained from field reports from the plant operators (see Table 3). The 19 x lightning events span a period of 128,5 weeks or 2,5 years (20 Aug 2014 to 8 Feb 2017)].

Table 3: Summary of lightning event dates considered.

No	Date	No	Date
1	20-Aug-2014	11	11 Jan2016
2	3 - 4 Nov 2014	12	15 Jan2016
3	12 - 13 Nov 2014	13	3 Feb 2016
4	11 - 12 Dec 2014	14	10 Feb 2016
5	17 Dec 2014	15	28 - 29 Feb 2016
6	26 - 27 Dec 2014	16	13 May 2016
7	23 - 24 February 2015	17	15 Dec 2016
8	9 - 10 May 2015	18	30 Dec 2016
9	20 Oct 2015	19	8 Feb 2017
10	19 Dec2015		

Figure 7 indicates the number of direct strokes to the plant based on the data received from the South African Weather Service for the dates noted in Table 3. Only where the black square inside the white circle of the icon indicating the stroke coordinates, touched the plant or was located inside the plant, was that stroke taken as a direct stroke. Some icons may appear to be on top of each other, but these were in fact separated from each other (reflecting actual spatial and temporal diversity) and should be seen as individual direct strokes to the plant as per Figure 1 (a) and (b). The location data of each stroke, as received from the South African Weather Services and applied in Figure 7, was based on a typical request for such data by the design engineer. This excluded any detailed analysis of the accuracy of the location (probability ellipse) of each stroke.

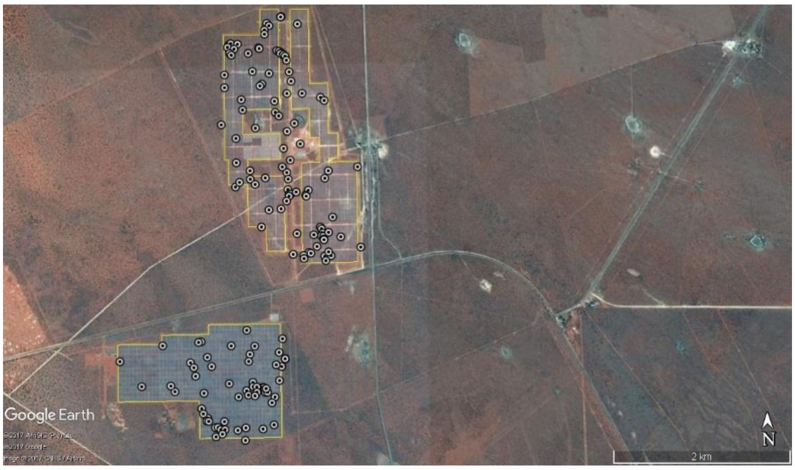


Figure 7: Number of strokes to the plant based on the dates from Table 3.

Figure 7 yields 57 direct strokes to Plant A, 65 direct strokes to Plant B and a total of 122 direct strokes to Plant A and B.

3.4 Analysis of Data

Table 4 presents a summary of the analysis of the direct stroke data presented in Figure 6.

Table 4: Summary of the analysis of the direct strokes to the PV plants.

Plant	No of Events	Data Period (Years)	No of Direct Strokes	PV Area (km^2)	Stroke Density (Strokes / km^2 / year)
A	19	2,5	57	1,82	13
B	19	2,5	65	2,33	12
A + B	19	2,5	122	4,15	12

The above stroke densities from Table 4 agree well with the data presented in Figure 6(b): 12,4 strokes / km^2 / year (Plant A) and 14 strokes / km^2 / year (Plant B) based on the 11-year lightning data (as expected because the data is from the same source / LDN).

This is considered a very important finding, showing that the direct strokes to the plant agrees better with the lightning stroke density data compared to the lightning flash density data. This finding strongly suggests that a risk assessment for large free field PV plant (in arid regions) should be done on stroke density rather than flash density. (***Note:*** *The latter supports the notion of the limitation of IEC 62305-2 to base the risk assessment on ground flash density as pointed out in Section 1.3*).

From Figure 6(a), the Flash Density of Plant A is 4,4 flashes / km^2 / year and for Plant B is 5,3 flashes / km^2 / year. From a risk perspective [5] and actual strokes to the plant (that caused the damage), it means that the risk is 13,0 ÷ 4,4 = 2,9 x higher for Plant A and 12,0 ÷ 5,3 = 2,3 x higher for Plant B compared to when the risk is assessed on Flash Density. (This is conservatively estimated because indirect strokes (off-plant strokes that fall within the effective collection area of the plant) can also cause damage and were ignored in this analysis). In essence, the above finding suggests that, based on direct lightning strokes to the plant, the risk is 2 to 3 times higher than when estimated and based on flash density.

The question of “Why this elevation in lightning activity (a better match to stroke density compared to flash density)?” is then raised. Could this elevated lightning activity be linked to a so-called “heat island” phenomenon, as presented in the next section?

4. HEAT-ISLAND

In accordance with the US Environmental Protection Agency (EPA) [6], the “term "heat island" describes built-up areas that are hotter than nearby rural areas”. Heat islands are frequently studied in the context of large cities where “the annual mean air temperature of a city, with 1 million people or more, can be 1 to 3°C warmer than its surroundings” [6]. “In the evening, the difference can be as high as 12°C. Heat islands can affect communities by increasing summertime peak energy demand, air conditioning costs, air pollution and greenhouse gas emissions, heat-related illness and mortality, and water quality” [6].

Salamanca, *et al*, (2015), have shown through “an assessment of mitigation strategies that combat global warming, urban heat islands and urban energy demands is crucial for urban planners and energy providers, especially for semi-arid urban environments where summertime cooling demands are excessive” [7]. Here, the semi-arid areas attracted attention because of similarity to the Norther Cape area. (A semi-arid area is defined as an area with very little rainfall. Usually between 250 to 500 mm per annum. The area in the Northern Cape where the two PV plants are located, typically receives 240 mm rain per year and during the summertime. From this perspective, the area where the PV plants are located can be considered slightly dryer than semi-arid).

Sato, *et al*, (2009) [8], have shown an interesting and unexpected outcome, namely, the cooling effect from PV modules, which was noted during off-sunshine hours. They recorded temperatures of PV modules to be 2 – 4 °C less than the ambient temperature when direct sun light is not falling on the modules [8]. From experimental investigations and the physics of photovoltaic systems, it was shown that during off-sunshine hours (absence of direct beam radiation), even if diffused sunlight is adequately available, module temperature will be always below atmospheric temperature [8]. Sato, *et al*, (2009), suggested that this phenomenon is likely to reduce “heat island” effects from very large scale solar photovoltaic systems if installed in major deserts.

Because earlier work only focused on a single biome, the work from Barron-Gafford, *et al*, (2016) [9], attracted further attention. Barron-Gafford, *et al*, (2016) studied the "heat island" effect of solar energy installations that spanned three different desert ecosystems in Arizona: i) a natural desert ecosystem; ii) the traditional built-environment of a parking lot surrounded by buildings and iii) a photovoltaic plant [9].

In this case, Barron-Gafford, *et al*, (2016), defined the “heat island” effect as “the difference in ambient air temperature around the solar power plant compared to that of the surrounding wild desert landscape”. The findings of the study indicated that temperatures around a solar power plant were 3 - 4 °C warmer than the nearby areas.

In the discussion and context of this paper, the heat island phenomenon attracted attention because of the elevated lightning activity at the plant, from a risk perspective and from flash density to stroke density, as suggested and discussed in Section 3 above. Without analysing the physics, it is thought that, the elevated temperature created by the “PV plant heat island” may contribute to actions, such as, a rising column of warmer air above the plant; with the rising air, dust and particles may be drawn from the surrounding cooler air; the drawn-in dust across the PV panels may create additional electrically charged conditions that may contribute to a micro-climate providing the necessary ingredients in support of the elevated lightning activity. The “heat island” is then specifically considered to contribute to branched flashes, such as, that indicated as example in Figure 1 (b).

Figure 8 illustrates a typical infra-red image of a photovoltaic plant (typically used to point out hot-spots on the PV panels). From this image, the elevated temperature (yellow areas) of the PV panels compared to the environment can be seen. The image also supports, visually at least, the findings by Barron-Gafford, *et al*, (2016) [9].

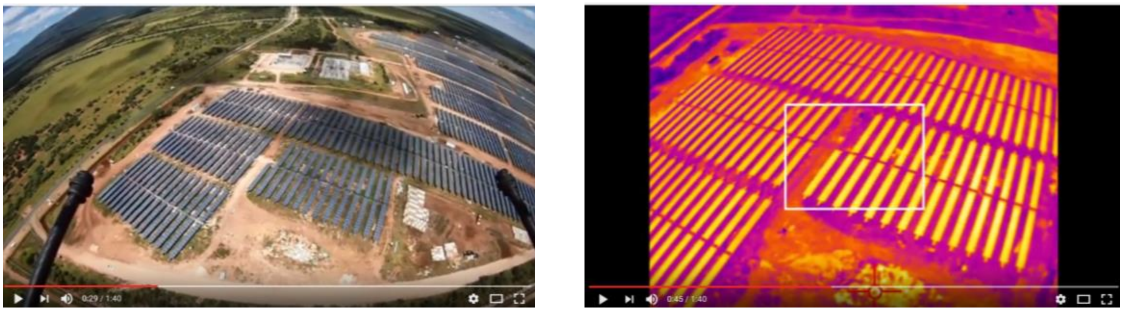


Figure 8: Typical infra-red image of a photovoltaic plant with the PV panels at an elevated temperature (yellow areas): (a) Daylight image; (b) Infra-red image.

From the above, the following hypothesis was developed: *The heat island effect at large free field photovoltaic plant contributes to the development of a micro-climate forcing the use of lightning stroke density rather than lightning flash density of the plant area for lightning risk assessment.*

In addition to the noted hypothesis, more detailed analysis of spatial accuracy of the lightning strokes form part of future work.

5. CONCLUDING REMARKS

The lightning activity associated with two PV plants located in a semi-arid part of South Africa was discussed in this paper. Specific observations from lightning data collected over an 11-

year period and also actual direct lightning strokes to the PV plants were discussed. Analysis and preliminary findings of the lightning data led to the following conclusions:

- Elevated lightning activity, that is, activity higher that that indicated by a most recent lightning flash density map have been observed at two PV plants in the Northern Cape in South Africa.

- The lightning stroke density at the plants aligns better with reported lightning activity at the plants compared to the lightning flash density. This strongly suggests that risk assessment for large free field PV plant should be done and based on lightning stroke density rather than lightning flash density of the particular area of interest.

- From a risk perspective, the risk appears to be at least, 2 to 3 x higher when based on stroke density compared to when the risk is assessed on flash density. (This was conservatively estimated because indirect strokes (off-plant strokes that fall within the effective collection area of the plant) can also cause damage and were ignored in this analysis). The latter will be incorporated in future studies.

- The "heat island" effect from the PV plant may be linked to the elevated lightning and the following hypothesis was developed for further study: *The heat island effect at large free field photovoltaic plant contributes to the development of a micro-climate forcing the use of lightning stroke density rather than lightning flash density of the plant area for lightning risk assessment*.

Testing of the noted hypothesis, the evaluation of the accuracy of reported lightning data and the inclusion of other PV plants in South Africa, form part of future investigations.

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