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On the impact of haze on the yield of photovoltaic systems in Singapore

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A B S T R A C T

Anthropogenic haze, caused at least in parts by forest and agricultural land clearing fires in Sumatra (Indonesia), is occasionally causing air quality issues in Singapore, located 150–300 km east of the majority of these “hot spots”. The resulting air pollution partially blocks sunlight from reaching the ground, and consequently affects the electric power generation of solar photovoltaic (PV) systems in Singapore. In this work, a methodology is presented to estimate the haze-induced reduction of the light intensity reaching PV panels and the corresponding loss in the electric energy yield. An assessment of a major haze event in June 2013 is the basis for the loss analysis, which takes into account data filtering techniques in order to isolate cloudless conditions for inter-comparison between clear and hazy days. Data from previous years in non-hazy conditions serve as baseline for the determination of the clear sky conditions for Singapore. The novel method is further applied to investigate the power output of ten PV systems in Singapore during the June 2013 haze event. It is found that poor air quality levels during this event caused yield losses of PV systems in Singapore in the range of 15–25%.

1. Introduction

Anthropogenic haze in Southeast Asia has become a problem in recent decades [1–4]. The clearing of forest vegetation and land for agricultural purposes has sparked continuous political debate among nations as the resulting air pollution covers skies above vast land areas [5,6]. Fires often originate from within Indonesian borders, with the wind transporting smoke clouds to neighboring countries such as Singapore and Malaysia [7,8]. In Singapore, located 150–300 km east of most forest/land fire “hot spots” in Sumatra, Indonesia, a so-called “haze season” is an annual event, causing reduced air quality which, in turn, trigger population and government outcry [9,10]. Depending on the prevailing wind direction, some of the fires might also originate from Borneo, ~600 km east of Singapore [7].

Most haze periods take place between August and October, which coincides with the dry monsoon season (Southwest monsoon) for the region [11]. Haze events are further accentuated through the absence of rain showers, as air pollution clouds take longer to dissipate. Fig. 1 shows two images of the Marina Bay area in downtown Singapore under moderate and unhealthy aerosol concentrations during the haze crisis in June 2013.

It is only natural that the first major concern when haze occurs is linked to health implications in terms of the detrimental influence air pollution has on individuals with heart or respiratory illnesses [12–14]. Haze could also affect other aspects of life, such as the ecosystem and climate change, but those effects are still being researched on [7]. In this work, we investigate the impact of haze on the power output of solar photovoltaic (PV) systems in Singapore. Quantifying the impact of haze on the output of PV systems poses some challenges. Although diminishing levels of illumination on the ground are obvious when air pollution is high,

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a)

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Fig. 1. Photograph of the Marina Bay area in downtown Singapore on (a) a day with air quality in the moderate range (Pollutant Standards Index PSI of 51–100) and (b) on a day with PSI values in the very unhealthy range (PSI = 201–300). Photo courtesy of Monika Bieri-Gmuer.

one must be able to differentiate between the reduction in irradiance caused by haze and that caused by clouds, or by a combination of both. Furthermore, haze not only has an impact on the light intensity (which affects the electric current), but also on the PV module temperature (which affects the voltage). In this investigation, we propose a novel filtering technique to eliminate cloud effects and hence can gauge the full impact of the haze alone. We also determine a clear sky day as a baseline for Singapore and compare it against increasing haze conditions. An analysis of ten existing PV systems in Singapore and their operational behavior during a strong haze day is presented. This paper aims at addressing the haze issues specifically for PV applications, without relying on more complex physical models. It serves as an indicative tool to the alteration of PV system performance, both on yield as well as on performance ratio levels, which serve the purpose of advising system owners, investors and stakeholders alike in the field of photovoltaic technology.

Section 2 discusses the atmospheric conditions in Singapore and the motivation for this work. Section 3 explains how the filtering method was created. Section 4 presents the results and a discussion of the proposed analysis, as well as future implications haze might have on the PV power generation in Singapore. Section 5 presents the conclusions drawn from this work.

2. Atmospheric conditions in Singapore

Singapore is a city-state and island country in Southeast Asia located at the southern of the Malay Peninsula, one degree north of the equator, and is separated from Peninsular Malaysia by the Straits of Johor to the north and from Indonesia's Riau Islands by the Singapore Strait to the south. Singapore has a tropical rainforest climate (Köppen: Af) with no distinctive seasons, uniform temperature and high humidity, and abundant rainfall. Temperatures usually range from 22 to 35 °C with the hottest months occurring between April and May. Precipitation is larger along the wetter monsoon season from November to January achieving values around 250 mm and 18 rain days per month. During the drier monsoon season, the number of rain days are around 14 and the monthly precipitation varies from 150 mm till 180 mm [15]. From July to October, there is often haze caused by bush fires in neighboring Indonesia, usually from the island of Sumatra.

The National Environment Agency of Singapore (NEA) established the Pollutant Standards Index (PSI, from now) in 1997 aiming to provide the stakeholders and the general public with information on daily air quality [7]. The PSI is derived taking into consideration the atmospheric particulate and four pollutant gas concentrations in atmosphere. Table 1 presents the PSI indexing, with the relationship between the particulate matter (PM) concentration in the atmosphere and the air quality descriptor. The fine particulate concentration $PM_{2.5}$ (for particulate size < 2.5 microns) was not used before 2014. The PM_{10} concentration (for particulate size < 10 microns) was part of PSI determination since 2010. Only PSI data from 2010 till 2013 were used for the analysis proposed in this study.