23rd International Conference on Renewable Energies and Power Quality (ICREPQ'25)
Tenerife (Spain), 25th to 27th June 20245
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.23, September 2025

Long-term stability of a low-cost sensor for aerosol measurements: insights for the development of air-quality monitoring networks in solar power plants

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Abstract. With a view to improve the warning and forecast systems of solar power plants, in this work we examine the feasibility of using low-cost sensors for measuring mass concentrations of suspended particulate matter of natural origin, such as that caused by African dust outbreaks. In Spain, these events especially affect the Canary Islands, and South and Mediterranean coast of the mainland, and they have been shown to have a large effect on solar photovoltaic power production. Extending our previous work on a low-cost sensor operating in a suburban location in the Canary Islands, here we examine 5 years of data – the longest study of a dataset of this type to our knowledge. The comparison of the low-cost sensor measurements with the data of a scientific-grade monitoring system shows a high correlation of 0.8 and a remarkable stability: during these 5 years of almost continuous and semi-autonomous operation, only a minor shift in the data, following a large African dust event, is observed. Although often overlooked, stability is a particularly important variable to assess the cost-effectiveness of a low-cost monitoring system, so we have further checked our results performing another comparison with satellite data – in this second analysis, we find confirmation of our first stability results. All this suggests that, in environments with low anthropogenic pollution, such as a suburban location or a solar power plant, these low-cost sensors can operate reliably for extended periods with little maintenance, providing useful data to monitor natural dust pollution and its impact on solar energy production at very little cost.

Keywords. African dust, particulate matter, air quality, low-cost sensors, solar energy

1. Introduction

Air pollution caused by suspended particulate matter can affect energy production, particularly in solar photovoltaic (PV) plants [1, 2]. Besides the effect of the interaction between the airborne material and the incoming solar radiation, this type of pollution can also have an impact on the formation of clouds, and it can also result in the deposition of material on top of the solar panels [3, 4].

In the case of Spain, the South and Mediterranean areas of the mainland, and the Canary Islands are specially affected by African dust outbreaks [5]. Such events can have a large effect on solar energy production: for example, it has been estimated that an extreme dust storm on March 2022 halved the PV capacity factor in Spain for more than 2 weeks [6]. Extensive air-quality monitoring networks can help to offset the effects of such events, by providing real-time data to warning and forecast systems, thus allowing, for example, to balance the energy production of conventional and solar power plants, or to determine the optimal schedule for cleaning PV solar panels, this being particularly important to maximise energy production [7].

In recent years, many types of low-cost sensors (LCS) have been made available in the market at prices much lower than those of scientific-grade instruments. Although the accuracy and operational life of these LCS is expected to be reduced compared to the more expensive instruments, their low price allows, for example, to deploy multiple sensors at the same place, thus providing redundant measurements which improve the quality of the data, or to create large networks of inexpensive instruments. Some of these LCS can measure mass concentrations of particulate matter (PM, usually expressed in $\mu g/m^3$), usually for particles with diameters between 1 and 10 μm [8]. The integration of these sensors in Internet of Things (IOT) devices to monitor PV solar production is currently a particularly active topic, see e.g. [9, 10].

We have recently shown that a Nova Fitness SDS011 LCS operating in a suburban location in the Canary Islands can provide reliable mass-concentration PM data for particles with diameters up to 2.5 and 10 μm (PM2.5 and PM10, respectively) [11]. Note that the low anthropogenic pollution conditions of this suburban environment are analogue to those that would be found in a solar power plant. Besides its low acquisition price and low power requirements, this sensor was found to be very reliable, requiring almost no maintenance. All this makes this LCS an attractive instrument for building extensive air-pollution monitoring networks. The main open question is for how long the LCS can operate reliably – this is an often-overlooked topic, despite its importance to determine the cost-effectiveness of this type of solutions.

In this paper, we extend our previous analysis to include an additional 1.5 years of data from an SDS011 LCS operating in a suburban environment in the Canary Islands. It should be noted that, to our knowledge, this 5-

year study of an LCS dataset is the longest one up to this date. With a view to analyse the long-term stability of this LCS, we compare these data with both a nearby ground-based air monitoring system belonging to the air quality monitoring network of the Gobierno de Canarias (the Canary Islands' government), and with satellite data provided by the NASA Moderate-Resolution Imaging Spectroradiometer (MODIS) instrument on board of the Terra spacecraft. This paper is structured as follows: in Section 2 we provide an overview of the LCS monitoring instrument and its emplacement, as well as of the two reference datasets used for comparison. In Section 3 we present the results of our long-term stability analysis and further provide insights on how these LCS instruments could be deployed in solar power plants. Finally, in Section 4 we provide some closing remarks.

2. Methods and Data

A. The SDS011 LCS

We provide here a short overview of our SDS011 LCS-based monitoring system and its emplacement, see [11] for further details.

The SDS011 is a laser-scattering sensor capable of measuring both PM2.5 and PM10 concentrations. The manufacturer, Nova Fitness Co. Ltd. (Jinan, China) does not provide a detailed description of the sensor's operational method but lists an accuracy of ±15% (with a minimum of ±10 $\mu g/m^3$), and a measurement range up to 1000 $\mu g/m^3$ [8]. The sensor can operate in the range from −10°C to 50°C, and from 0 to 70% relative humidity. The price of this sensor is in the range of 20 US dollars. Relative humidity can have a large effect in measurements of this kind, because it produces an "optical enlargement" of the dust particles. We have thus deployed a DHT22 relative humidity and temperature sensor next to our SDS011. As mentioned in [11], the DHT22 sensor had to be replaced twice during the experiment, and thus there are periods without relative humidity and temperature data – in particular, there is a large data gap from January to October 2022. Another sensor, a BMP180 capable of measuring temperature and ambient pressure, is also installed next to the SDS011, but its data has not been used in this work. The whole system is controlled by a NODE MCU, ESP8266-based microcontroller, running the firmware released by Sensor.Community [12]. Power is provided by a 25,000 mAh power bank with a solar panel which partially recharges the battery during daylight hours. The NODE MCU is Wi-Fi capable, and data of the SDS011 and DHT22 sensors are acquired in near real time by a Raspberry Pi microcomputer which produces plots and checks the status of this low-cost air-monitoring system, issuing a warning when the Wi-Fi connection fails, usually due to a power outage.

As mentioned, the system is placed in a suburban location in the Canary Islands, in the outskirts of the city of San Cristóbal de La Laguna, in the island of Tenerife. To be more specific, it is located in a window on the third floor of a residential building, with other buildings of similar heights to the sides and lower ones in front, thus allowing for good wind circulation. Road traffic is fairly low in the area, so the main source of air pollution corresponds to African dust outbreaks.

B. Ground-based PM monitoring system

An MP101M beta monitor, part of the air-quality network of the Gobierno de Canarias, operates some ~5 km away from our LCS monitor, at the site of Vuelta de los Pájaros (VP). Although the two instruments are not collocated and the environment of the VP monitor is much more affected by anthropogenic pollution, in [11] we found that the PM2.5 and PM10 measurements of both instruments compare favourably, with a Spearman's rank correlation value close to 0.8. VP data is available online [13], although as of January 2025, only the measurements up to October 2024 are available to download.

C. AOD satellite data

Daily aerosol optical depth (AOD) level 3 data from the MODIS instrument onboard of the NASA Terra satellite has been downloaded from the NASA Giovanni portal [14]. Although AOD and particulate matter concentrations are expected to be related, their exact relationship based on physicochemical considerations is quite complex [15]. However, simple statistical models, based in a multilinear relationship between AOD, particulate matter, and other meteorological variables, have also been proposed in the literature, see e.g. [16].

In this work, we perform an ordinary least squares multivariate fit of the AOD satellite data to the PM2.5, PM10, temperature, and relative humidity measurements of our low-cost air-quality monitor taken from October 2020 to December 2021 – this is the first period in which we have all the necessary LCS data (PM concentrations, relative humidity, and temperature) to perform the fit, and should correspond to the LCS instrument running without any degradation. Adding further meteorological variables could result in an improved model, but this is outside the scope of this contribution. The coefficients resulting from the fit have then been used to calculate the AOD of the LCS for the whole period considered in the present study, from October 2020 to January 2025. Spearman's rank correlation between the two AOD datasets – NASA MODIS and our LCS – is 0.5, much lower than the correlation between the LCS and VP PM datasets already mentioned. However, we are not interested in obtaining precise AOD data from our LCS, but just in checking the stability of the instrument, so we believe this simple approximate model can provide reasonable results. It should also be noted that, given the abrupt orography of the Canary Islands and the spatial resolution of the MODIS data, the satellite AOD measurements can indeed be expected to have a higher spread than the LCS data.

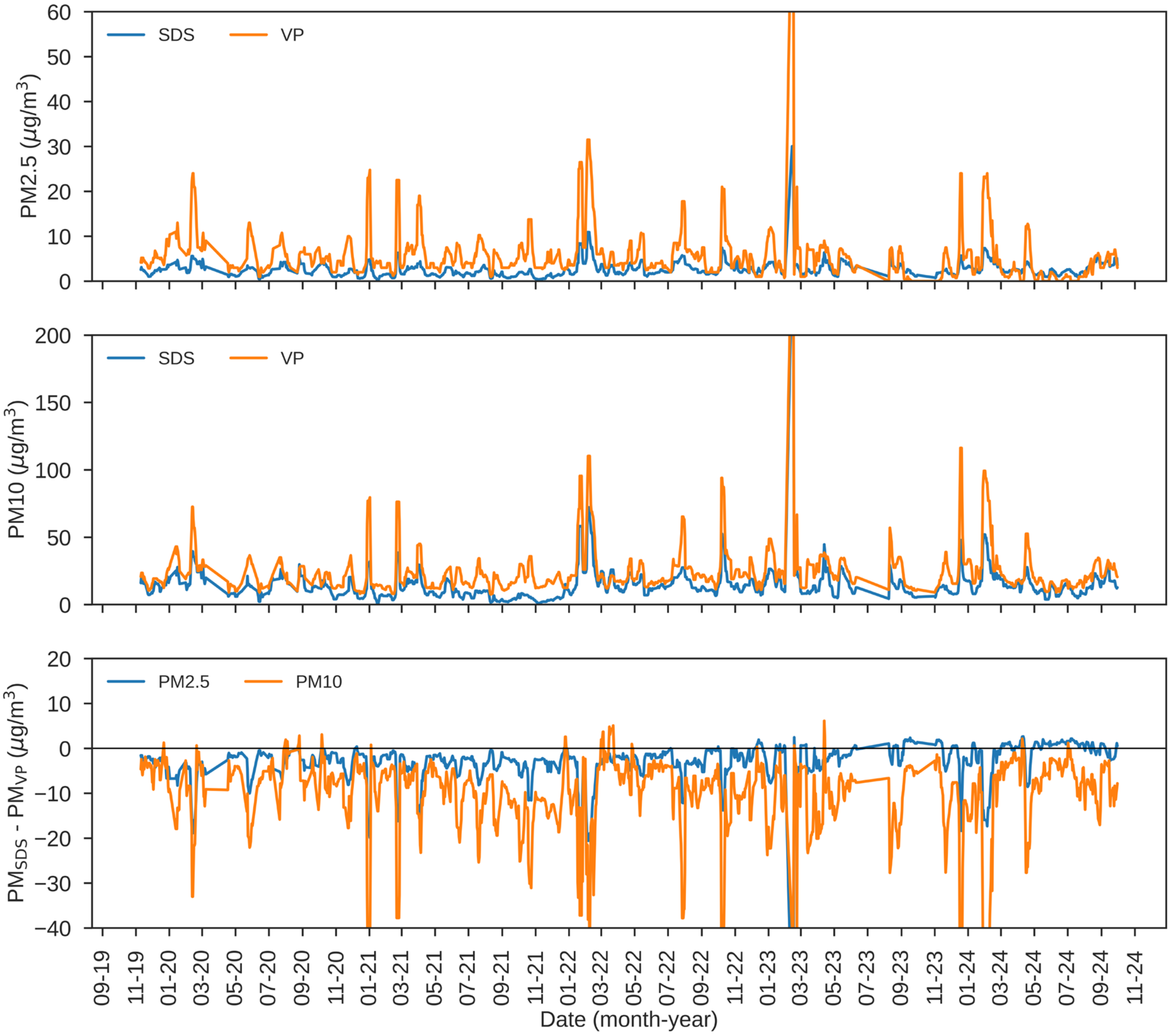

Fig. 1. PM2.5 (top) and PM10 (mid) concentrations from the SDS and VP datasets. The difference between these measurements is shown in the bottom panel.

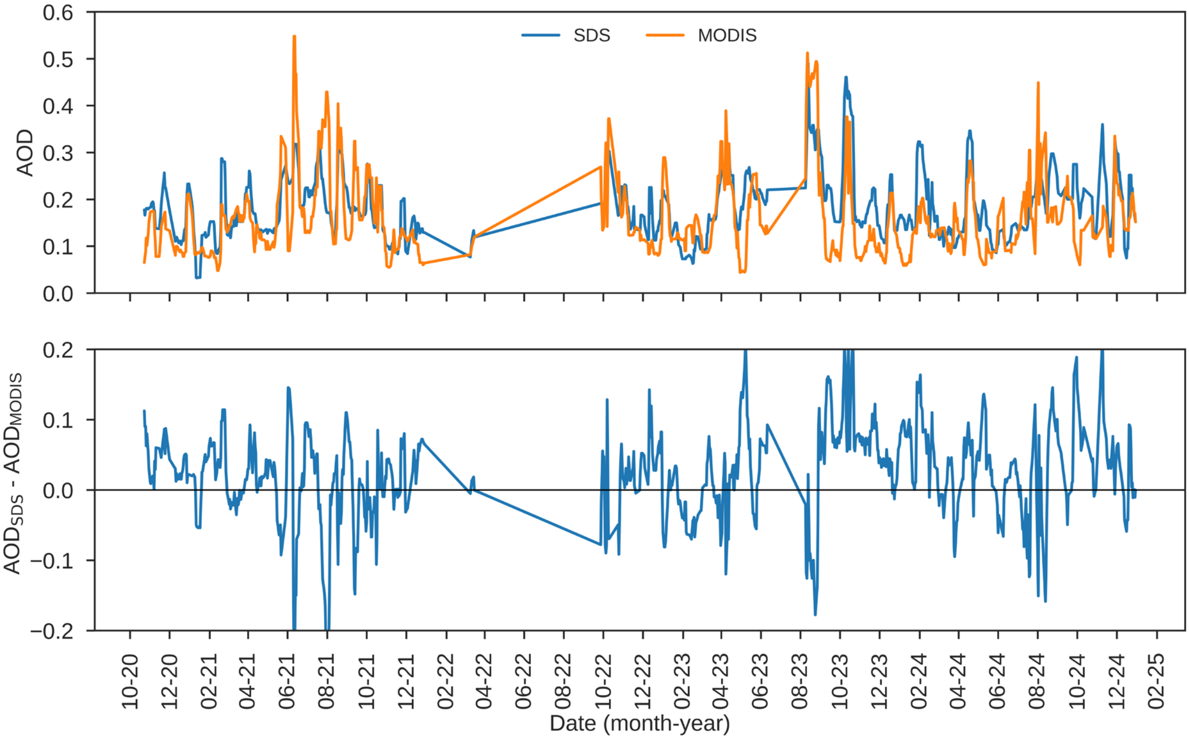

Fig. 2. AOD from the NASA MODIS instrument and the SDS low-cost air-quality monitor (top), and their difference (bottom)

3. Results and Discussion

A. VP and MODIS comparison

Figure 1 shows a comparison of the SDS and VP data for the PM2.5 and PM10 concentrations. As already mentioned, in [11] we found that data from both instruments presented a high correlation of approx. 0.8, with a difference of approx. 15 $\mu g/m^3$ between the VP and SDS PM10 concentrations, the SDS measurements being consistently lower. A small shift in the SDS data was observed in February 2022, after an intense African dust outbreak, resulting in an average increase of approx. 1.2 $\mu g/m^3$ in the SDS PM10 measurements.

Compared to our previous study, in which we analysed a period of 3.5 years, Fig. 1 shows almost 5 years of data. With a calculated value of approx. 0.8, Spearman's correlation remains the same for the extended dataset analysed in this work. Besides the already-discussed shift in February 2022, no further changes are observed in the 5-years dataset, and there is no clear evidence of a deterioration of the LCS-based air quality monitor. This is quite a surprising result, since the expected operational life of the SDS011 sensor is estimated in 8000 hours [8] – roughly one year of continuous operation. It should also be noted that our LCS air quality monitoring system has received minimal maintenance in this 5-year period. We believe that this longer-than-expected operational life can be attributed to the low anthropogenic pollution in our suburban emplacement, but this unexpected result deserves further validation.

We have thus further compared our SDS data with that from the MODIS satellite instrument. As explained in Section 2.*C*, we calculate AOD values from our SDS011 and DHT22 data, after performing an ordinary least square fit to the MODIS AOD data of approx. the first year of operation of the LCS monitor. The resulting dataset is represented in Fig. 2, together with the satellite data.

As mentioned, the correlation between the two AOD datasets in the top panel of Fig. 2 is just 0.5. Such a low value can be expected given the simple AOD determination method used in this work. Despite that, we believe Fig. 2 can be used to check the stability of the LCS. In this regard, Fig. 2 indeed seems to confirm our conclusions from Fig. 1, with just one noticeable but small upward shift of the data after the February 2022 dust outbreak. No further sign of deterioration of the LCS air quality monitor is evident from the comparison with the satellite data.

B. Insights for the development of LCS monitoring networks

Having confirmed both the quality and the stability of the LCS data, we can suggest the application of this type of sensors for monitoring networks in locations with low anthropogenic pollution, such as solar power plants. Next we provide some insights based on our experience with this type of sensors.

We will first discuss the monitoring of the quality of the LCS data and the operational status of these instruments. Given the low price of this type of sensors and their capability to operate with little maintenance, we propose to deploy multiple instruments in close proximity from each other. Thus for example, tracking the evolution of triads of LCS instruments it would be possible to easily determine if one instrument is going astray, triggering maintenance, a calibration, or a complete replacement. Given the Wi-Fi capabilities of the LCS instruments discussed here, a fully automated warning system could be easily implemented, with a computer running near-real-time comparisons of the data of multiple instruments. The same computer could be used to store the LCS data, so that it can be used for forecasting and further scientific analysis.

It can be expected that some dust outbreaks will affect at least some of the instruments, as observed in our data in February 2022. The deployment of multiple instruments might help to identify such issues, assuming that some instruments remain unaffected. Further checks against instruments designed as references, and stored protected from the dust outbreaks, should be run periodically. Again, the low price of the LCS facilitate having multiple instruments reserved to be used as references. In case a shift is observed in the measurements of an LCS instrument, it should be easy to calibrate it by applying a correction to its data by comparing with these reference instruments. Indeed, the LCS instruments should be periodically calibrated, either against the LCS references or to some other devices – the results presented in the previous section show it's not necessary to have collocated scientific-grade instruments, and it might be even possible to use satellite data. In the case that some LCS instrument is deemed as completely malfunctioning, it should also be noted that a dust outbreak will likely only affect the SDS011 sensor, so that all the remaining parts of the instrument could be repurposed.

Regarding the deployment of the monitoring network, it should be noted that the power required to run this kind of LCS air-monitoring systems is fairly low, to the extent that they could be possibly made completely autonomous by using a suitable (but small) solar panel and a battery for overnight operation. This makes the location of the instruments only dependent on other operational needs, such as the Wi-Fi cover, or just purely on considerations based on the desired coverage of the monitoring network. The later will also depend on the prevalent wind directions and the topography of the emplacement, but it should be noted that in a suburban location with multiple nearby 3-story buildings, the LCS monitor was able to provide reliable data. Again, using such inexpensive instruments allows for dense and redundant networks, where the main factor for deployment could be just the initial work required for setting up the instruments – the need for maintenance, in our experience, being rather low.

4. Conclusions

With a view to implement large and inexpensive air quality monitoring networks, in this work we examine the quality and stability of measurements produced by a low-cost instrument based on the Nova Fitness SDS011 sensor. These networks can complement existing scientific-grade instruments, usually much more expensive, thus providing more data to improve warning and forecast systems. In areas affected by sudden and intense African dust outbreaks, such monitoring systems can provide information to adjust the balance between conventional and solar energy production, to schedule the cleaning and maintenance of solar panels, or to implement health-risk mitigation strategies for the power plant operators exposed to the air pollution.

Our analysis of approx. 5 years of LCS data shows just one major change in the instrument. We believe this was caused by an intense African dust event, but it should be noted that events with comparable and even higher concentrations have taken place during this period, without any noticeable effect on the LCS. Regardless, the effect of this event was rather harmless, resulting in just a small shift in the PM measurements – this could be corrected applying a constant correction factor to the LCS data. Furthermore, no clear trend can be observed in our data, so we believe our SDS011 sensor is still in good conditions after almost 5 years of continuous operation with very little maintenance.

This somewhat surprising result points to the SDS011 having quite a robust design, perhaps because the sensor was developed for deployment in areas with heavy anthropogenic pollution. In the case of emplacements mostly affected by infrequent natural events, such as a suburban environment or a solar power plant, these low-cost sensors can be expected to operate reliably for long periods of time with minimal maintenance. Besides measuring PM, temperature and humidity are also important meteorological variables to acquire, and their sensors are also inexpensive, although in our experience they are not very reliable – our DHT22 sensor had to be replaced twice in 5 years. Measurements of other variables, such as ambient pressure or wind speed, should also be considered, because these data could be used to build improved forecast systems.

Acknowledgements

We gratefully acknowledge the Gobierno de Canarias for maintaining and providing the data of the air quality monitor at Vuelta de Los Pájaros. We also acknowledge Sensor.Community for making available on-line the firmware of the ESP8226 microcontroller.

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