Joule
CellPress

Report

The Impact of COVID-19-Related Measures on the Solar Resource in Areas with High Levels of Air Pollution

Following restrictions to counter the spread of COVID-19, reports about unusually clear skies appeared in many regions of the world. In this study, we explore how air pollution in Delhi has developed following the lockdown on March 24th and how this reduction has affected how much sunlight the city received. Until early April, pollution levels had dropped to half of their usual levels. The cleaner air allowed more sunlight to pass, increasing insolation by more than 8%.

Ian Marius Peters, Christoph Brabec, Tonio Buonassisi, Jens Hauch, André M. Nobre

im.peters@fz-juelich.de

HIGHLIGHTS

Unusually high insolation levels appeared in Delhi after COVID-19 lockdown

The increase in insolation coincides with an ~50% reduction in air pollution

In late March, 8.3% more sunlight reached the city than in previous years

Elevated insolation is consistent with expectations from reduced pollution

Peters et al., Joule 4, 1–7
August 19, 2020
https://doi.org/10.1016/j.joule.2020.06.009

Joule

CellPress

Report

The Impact of COVID-19-Related Measures on the Solar Resource in Areas with High Levels of Air Pollution

Ian Marius Peters,[1,5,*] Christoph Brabec,[1,3] Tonio Buonassisi,[2] Jens Hauch,[1,3] and André M. Nobre[4]

SUMMARY

Restrictions enacted to reduce the spreading of COVID-19 have resulted in notably clearer skies around the world. In this study, we confirm that reduced levels of air pollution correlate with unusually high levels of clear-sky insolation in Delhi, India. Restrictions here were announced on March 19th, with the nation going into lockdown on March 24th. Comparing insolation data before and after these dates with insolation from previous years (2017 to 2019), we observe an 8.3% ± 1.7% higher irradiance than usual in late March and a 5.9% ± 1.6% higher one in April, while we find no significant differences in values from previous years in February or early March. Using results from a previous study, we calculated the expected increase in insolation based on measured PM2.5 concentration levels. Measurements and calculations agree within confidence intervals, suggesting that reduced pollution levels are a major cause for the observed increase in insolation.

Context & Scale

A broadly noticed consequence of the restrictions enacted to counter the spreading of COVID-19 was unusually clear skies in many regions of the world. Better air quality has an impact on solar power generation, as fewer pollution particles in the air means that more sunlight will reach solar panels on the ground. In this study, we explore how air pollution in Delhi has developed following the lockdown on March 24th and how this reduction has affected how much sunlight the city received. First, we looked at measured particle concentration levels and noticed that after lockdown, levels dropped to about half of where they had been in previous years. Then, we looked at how much sunlight was received by solar panels. Before lockdown, insolation was similar to previous years. Yet, after lockdown, there was a clear and significant increase. In late March, insolation was up by 8.3% compared with levels in previous years. This is comparable to moving a solar panel from Toronto to Houston.

INTRODUCTION

A very noticeable effect of the restrictions enacted to counter COVID-19 are clearer skies. Satellite data showed a reduction in air pollution levels in many areas of the world. On March 19th, the European Space Agency (ESA) reported a decline in nitrogen dioxide levels over China.[1] On April 9th 2020, NASA reported a 30% drop in air pollution over the Northeastern US.[2] On April 26th, ESA reported pollution levels fell by 45%–50% compared with those in the same period last year in some European cities.[3] In previous reports, we discussed the impact of haze[4,5] and air pollution[6] on the performance of photovoltaic (PV) systems and provided a quantitative relation between PM2.5 (particle matter) concentrations and solar resource in India and Singapore. Given the recent low levels of air pollution, we set out to explore whether there wass a noticeable impact on the available solar resource that could have lead to unusually high electricity generation from PV installations. An article in Green Tech Media (GTM) from April 22nd already mentioned that "reduced air pollution from the lockdown has contributed to new records (in PV electricity generation) in Germany and the UK."[7]

To quantify a possible impact on solar resource, we used recent air quality and weather data from Delhi, one of the most polluted cities on the planet,[8] for the years 2017 to 2020. We follow the approach described in Peters et al.[6] to quantify clear-sky insolation. Comparing air pollution and insolation characteristics from 2020 with those of previous years, we identified and quantified anomalies for the periods before and after measures were taken in India.

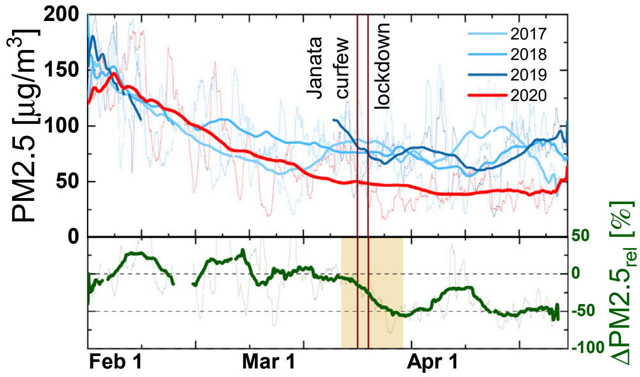

Figure 1. Timeline of PM2.5 Concentration in Delhi

PM2.5 particle concentration measured at the US Embassy in Delhi between February 1st and April 30th for the years 2017 to 2020. The graph on the bottom shows the relative deviation of 2020 values from those of previous years (2017 to 2019). Solid lines are running averages over 1 week.

RESULTS

COVID-19-Related Measures in Delhi

The first case of COVID-19 in India was confirmed on January 30th, 2020. As in other countries, confirmed case numbers only rose slowly, initially, yet on March 19th, more than 500 cases were confirmed, and further measures were decided by the government. The same day, Prime Minister Modi asked all citizens to observe a Janata curfew (people's curfew) on Sunday, March 22nd.[9] The curfew lasted for 14 h and affected everyone not pursuing an ''essential'' profession. At the end of the curfew, a lockdown was announced beginning midnight, March 24th, for a duration of 21 days.[10] On April 14th, the lockdown was extended until May 3rd, with relaxations in little-affected areas being possible after April 20th.[11] As this article is written, the lockdown has been further extended through May 17th[12] with additional relaxations being in place.

Timeline of PM2.5 Particle Concentration

PM2.5 particle concentration measured at the US embassy in Delhi[13] once every hour for the months of February to April and years 2016 to 2020 is shown in Figure 1. Note that no air pollution data were available between February 11th and March 14th, 2020. While a reduction in air pollution is visible for all years as winter gives way to spring, concentrations in March and April in 2020 reach lower levels than usual. This reduction becomes especially clear when looking at relative concentration deviations, defined here as the 2020 value divided by the average value from the previous years minus one, shown in the lower part of Figure 1. Before the Janata curfew, 2020 showed a particle concentration signature that is similar to that of previous years, i.e., values around 0%. Just before the Janata curfew, a notable reduction in particle concentration begins with levels decreasing to −50% of those in previous years at the end of March—these findings are similar to those shown by the European Space Agency[3] for other cities. Low PM2.5 concentration levels are maintained, mostly, throughout April.

Measured Clear-Sky Irradiance before and after Lockdown

To explore a potential impact on solar resource, we analyzed irradiance data captured with a pyranometer close to a commercial PV installation in Paschim Vihar, a residential area in Delhi. Data were analyzed for four time periods: (1) the month of February; (2) the period between March 1st and March 20th, which marks the period

[1]FZ Jülich, Helmholtz-Institut Erlangen-Nürnberg for Renewable Energies, Immerwahrstraße 2, Erlangen 91058, Germany

[2]Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

[3]Institute of Materials for Electronics and Energy Technology (i-MEET), Department of Materials Science and Engineering, Friedrich-Alexander University Erlangen-Nürnberg, Erlangen 91058, Germany

[4]Cleantech Solar, 25 Church Street #03-04 Capital Square Three, Singapore 049482, Singapore

[5]Lead Contact

*Correspondence: im.peters@fz-juelich.de

https://doi.org/10.1016/j.joule.2020.06.009

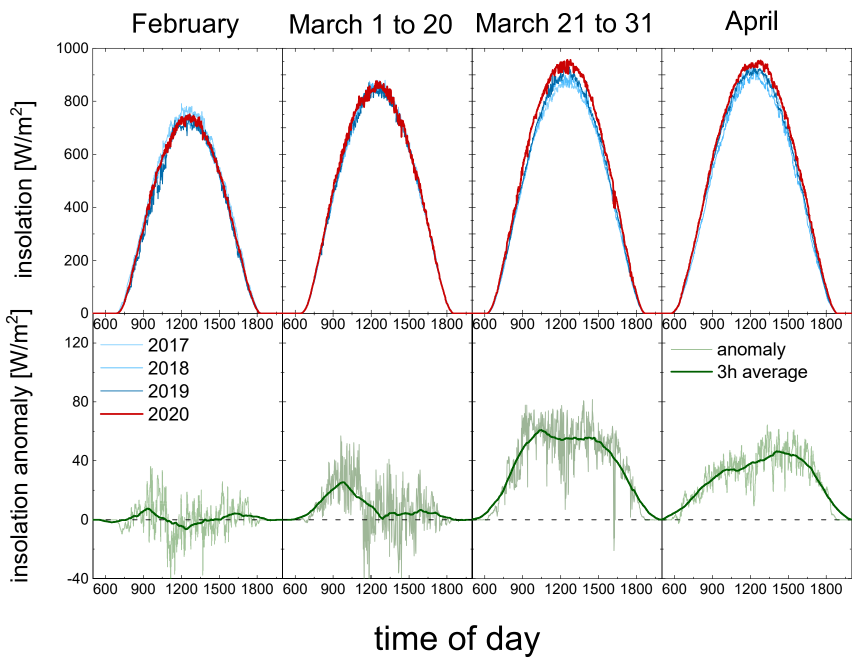

Figure 2. Reconstructed Clear-Sky Insolation and Insolation Anomaly
Upper half shows reconstructed clear-sky insolation curves for four investigated periods in the years 2017 to 2020. The value for 2020 is plotted in red, pervious years in different shades of blue. Lower half shows insolation anomaly. Here, the difference between the 2020 value and the average value of previous years is shown above. The dark green line is a guide to the eye, showing the 3 h adjacent average.

before the curfew in 2020; (3) March 21st to March 31st; and (4) the month of April. To reconstruct clear-sky conditions, we used the approach published in Peters et al.,[6] and for each time stamp, the 75% percentile value of all available data was calculated and plotted. The resulting clear-sky insolation curves are shown in the upper half of Figure 2. Curves for 2017 to 2019 are shown in blue, the curve for 2020 in red. Before March 20th (periods 1 and 2), there was no visible difference in insolation between 2020 and the previous years; after March 20th (periods 3 and 4), the insolation curve for 2020 had a notably greater amplitude than those of previous years.

In addition to the reconstructed clear-sky insolation curve, we also show the insolation anomaly in the lower half of Figure 2. Insolation anomaly was calculated as the difference between the 2020 clear-sky insolation and the average of previous years for each time stamp. Before March 20th, we observed little to no deviation to the behavior of previous years. After March 20th, and especially in period 3, insolation levels were higher than normal. To test whether these deviations were significant, we compared the insolation anomaly with typical insolation variations from previous years over the entire observed period (February 1st to April 30th). Typical insolation variations were calculated as the weighted average of the standard deviation of clear-sky insolation values for 2017 to 2019 (blue curves in Figure 2) for the four considered periods. The obtained value was 4.6 W/m^2. Results are summarized in Table 1. Comparing the average anomalies with typical variations, represented by the uncertainties, shows that high insolation values after March 20th, 2020, are statistically significantly abnormal, whereas calculated anomalies before March 20th are within typical fluctuations.

Table 1. Average Insolation Anomaly Values

Period/Quantity	February	March 1–20	March 21–30	April
Average Anomaly	0.3 ± 4.6 W/m^2	4.6 ± 4.6 W/m^2	22.6 ± 4.6 W/m^2	16.9 ± 4.6 W/m^2
Relative Average Anomaly	0.14 ± 2.3%	1.8 ± 1.8%	8.3 ± 1.7%	5.9 ± 1.6%

PM2.5 Concentration as Indicator for Insolation

In Peters et al.,[6] we presented an analysis of the correlation between PM2.5 concentration and solar resource in Delhi. We showed that insolation could be predicted using the exponential relation $\frac{I}{I_0} = Exp\left[-\frac{PM2.5}{750 \pm 90}\right]$. The assumption behind this relation is that the PM2.5 concentration measured on the ground can be used as an indicator for the overall atmospheric optical depth. We used this relation to calculate the expected insolation anomaly at noon during the four considered periods. A perfect quantification should not be expected as the relation used describes average behavior over multiple years. The results of these calculations together with the average measured relative anomaly are shown in Figure 3. We observe that calculated and measured results generally agree, with measured values in late March being especially high compared to expectations. This behavior suggests that the drop in air pollution levels is the main cause for the observed increase in insolation. It also suggests that the composition and optical characteristics of the air pollution in Delhi in 2020 is not profoundly different from that in previous years. In addition to reduced ground-level air pollution, reduced air pollution in higher atmospheric levels can be expected, due to reductions in pollutant emission from industry or air traffic. The corresponding change in atmospheric optical depth could be an additional contributor to the observed anomaly.

DISCUSSION

Following the outbreak of COVID-19, first a curfew on March 22nd and then a lockdown were in effect all over India. Following these measures, unusually clear skies were observed in Delhi.[14,15] When looking at particle concentration data recorded at the US embassy in Delhi, we found that air pollution levels were indeed lower than usual—in late March and April, values dropped to about half of what they had been in previous years over longer periods of time. It should be noted, though, that the air quality in Delhi in April, even with lockdown, was still worse than the typical air quality in other cities. Looking at histograms in Peters et al.,[6] the closest resemblance we found was Hanoi 2017. Places like London, Los Angeles, or Jakarta, all had better air quality in 2017 overall than Delhi did in April 2020.

Given the unusually low levels of air pollution and the allegedly good visibility in Delhi, we set out to explore if the conditions for solar energy production were impacted by the COVID-19-related measures. For this purpose, we analyzed measured insolation data from a PV installation in Paschim Vihar, about 10 km from Delhi center. For more details about the implications of this distance, please refer to Peters et al.[6] Reconstructing clear-sky data for this installation, we found that insolation levels after March 20th were notably and significantly above those from previous years: 8.3% ± 1.7% in late March and 5.9% ± 1.6% on average in April. When looking at data from earlier in March or February, we observed no significant deviations from previous years. We also compared the measured insolation anomaly to predictions using the method outlined in Peters et al.[6] Agreement between simulations and measurements indicate that the drop in air pollution is the

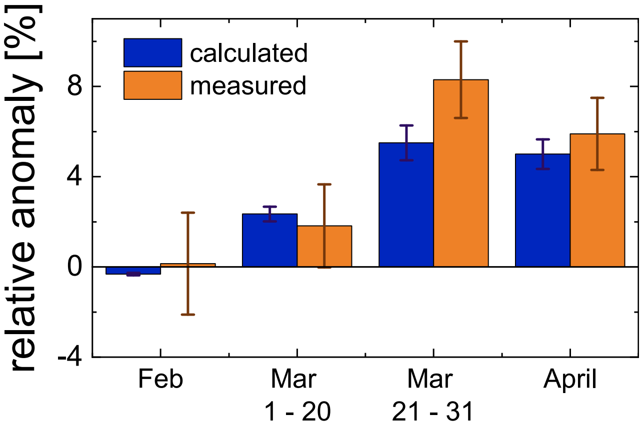

Figure 3. Comparison of Measured and Calculated Anomaly

Measured (orange) and calculated (blue) relative insolation anomaly at noon for the four considered periods. Error bars mark uncertainties for the calculations and typical variations in irradiance for the measured values. Calculations were done using the method presented in Peters et al.[6]

root cause for the observed increase in insolation and that the optical characteristics of the air above Delhi are consistent with that of previous instances of low air pollution. We conclude: COVID-19-related measures have improved air quality, which has increased solar insolation in Delhi.

What Does This Mean for PV?

Results shown here paint a plausible picture: air pollution levels drop notably, and this drop results in clearer air that allows more sunlight to pass through the atmosphere, which increases the yield of PV installations. For Delhi, our analysis supports this picture. PV installations in March and April received more than 6% more light in total than in previous years and will continue to generate record amounts of electricity as long as air pollution levels stay low. We expect the same to be true for urban PV installations in other cities with high air pollution levels and COVID-19-related restrictions. Examples for such cities are Kolkata, Wuhan, Mumbai, Dhaka, Los Angeles, or London.

In many other cities and rural areas, however, the anthropogenic contribution to aerosols is much smaller. We performed a similar analysis, as shown in Figure 1, for data from an air-quality measurement station and a nearby PV plant in Northern Italy, the first European country to enact severe restrictions. We could not find any statistically significant effects here. Anthropogenic air pollution levels in this area are so low that the current reductions could only have a minute impact on PV power generation. Currently, we have no indications to confirm statements, like the one found in a recent GTM article,[7] that "Reduced air pollution from the lockdown has contributed to new records in Germany and the U.K." Cleaner air may have had a tiny influence, yet we attribute the high solar energy production, for the most part, to the very sunny weather in March and April. In both Germany and the UK, April 2020 was the sunniest April in recorded history.[16,17]

Afterthought

Air pollution and solar energy interact in a self-reinforcing network. High levels of air pollution block sunlight and cause greater levels of soiling,[18,19] either of which reduce solar panel performance. Replacing the sources of air pollution by solar-powered technology will result in cleaner air, which, in turn, will benefit solar-powered devices. Much greater benefits from cleaner air can be expected for human health.[20] One relevant aspect of this study is that air pollution may factor into the vulnerability of people to the current coronavirus.[21,22] Reduced levels of air pollution triggered by restrictions to counteract the spreading of the virus could have a positive network effect and reduce harm from the disease.

Yet again, results here, like many others, only point in one direction: it is vitally important that we improve air quality, especially in urban areas with high pollution levels. Hopefully, solar energy can contribute to this goal.

ACKNOWLEDGMENTS

The authors thank Tobias Pickel for support with data for PV installations in Italy. This work was supported by the Bavarian State Government (project "PV-Tera—Reliable and cost-efficient photovoltaic power generation on the Terawatt scale," no. 44-6521a/20/5).

AUTHOR CONTRIBUTIONS

Conceptualization, I.M.P. and A.M.N.; Methodology, I.M.P., T.B., and A.M.N.; Validation, I.M.P., C.B., J.H., T.B., and A.M.N.; Investigation and Resources, I.M.P. and A.M.N.; Writing – Original Draft, I.M.P.; Writing – Review and Editing, I.M.P., C.B., J.H., T.B., and A.M.N.; Visualization, I.M.P.; Supervision, I.M.P. and A.M.N. All authors reviewed and approved the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: May 15, 2020
Revised: June 6, 2020
Accepted: June 15, 2020
Published: June 19, 2020

REFERENCES

1. European Space Agency (2020). COVID-19: nitrogen dioxide over China. https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-5P/COVID-19_nitrogen_dioxide_over_China.

2. NASA (2020). NASA satellite data show 30 percent drop in air pollution over northeast U.S.. https://www.nasa.gov/feature/goddard/2020/drop-in-air-pollution-over-northeast.

3. European Space Agency (2020). Air pollution remains low as Europeans stay at home. https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-5P/Air_pollution_remains_low_as_Europeans_stay_at_home.

4. Liu, H., Nobre, A.M., Yang, D., Ye, J.Y., Martins, F.R., Rüther, R., Reindl, T., Aberle, A.G., and Peters, I.M. (2014). The impact of haze on performance ratio and short-circuit current of PV systems in Singapore. IEEE J. Photovoltaics *4*, 1585–1592.

5. Nobre, A.M., Karthik, S., Liu, H., Yang, D., Martins, F.R., Pereira, E.B., Rüther, R., Reindl, T., and Peters, I.M. (2016). On the impact of haze on the yield of photovoltaic systems in Singapore. Renew. Energy *89*, 389–400.

6. Peters, I.M., Karthik, S., Liu, H., Buonassisi, T., and Nobre, A. (2018). Urban haze and photovoltaics. Energy Environ. Sci. *11*, 3043–3054.

7. Parnell, J. (2020). Clean air, clear skies and fresh megawatts cause europe's solar records to tumble. Greentech Media, April 22, 2020. https://www.greentechmedia.com/articles/read/clean-air-clear-skies-and-fresh-megawatts-see-europes-solar-records-tumble.

8. IQAir. (2020). World's most polluted cities 2019 (PM2.5). https://www.iqair.com/world-most-polluted-cities.

9. Bureau Business Line. (2020). PM Modi calls for 'Janata curfew' on March 22 from 7 AM-9 PM. Bussiness line, March 20, 2020. https://www.thehindubusinessline.com/news/pm-modi-calls-for-janta-curfew-on-march-22-from-7-am-9-pm/article31110155.ece.

10. Staff, F.P. (2020). Coronavirus outbreak updates: npr to be deferred amid covid-19 lockdown, say reports; positive cases rise to 536 in india. First Post, March 25, 2020. https://www.firstpost.com/health/narendra-modi-on-coronavirus-speech-live-updates-streaming-watch-india-pm-address-to-nation-on-covid-19-today-latest-news-lockdown-janata-curfew-8182241.html.

11. Bhaskar, U. (2020). India to remain closed till 3 May, economy to open up gradually in lockdown 2.0. Live Mint, April 14, 2020. https://www.livemint.com/news/india/pm-modi-announces-extension-of-lockdown-till-3-may-11586839412073.html.

12. India TV News Desk (2020). Lockdown extended till May 17. Relaxations in green and orange zones. India TV, May 01, 2020. https://www.indiatvnews.com/news/india/breaking-coronavirus-lockdown-extended-by-two-weeks-till-may-17-613204.

13. Information about the Air Quality data measured by the U.S. Embassy and Consulates in India is provided here. https://www.airnow.gov/international/us-embassies-and-consulates/.

14. Johnson, R., and Beurer, L. (2020). Corona ensures clean blue sky in Asia's cities! Daswetter, April 16, 2020. https://www.daswetter.com/nachrichten/wissenschaft/corona-sorgt-fue-sauberen-blauen-himmel-in-asiens-staedten.html.

15. Eco-Business. (2020). Delhi, Mumbai, Seoul and Wuhan see record-breaking clear skies as Covid-19 lockdowns subdue air pollution. https://www.eco-business.com/news/delhi-mumbai-seoul-and-wuhan-see-record-breaking-clear-skies-as-covid-19-lockdowns-subdue-air-pollution/.

16. Deutscher Wetterdienst (2020). Selected services for the climate monitoring Germany. https://www.dwd.de/EN/climate_environment/climatemonitoring/germany/germany_node.html.

17. Met Office (2020). Climate summaries: overview of weather across the UK for previous months, seasons and years. https://www.metoffice.gov.uk/research/climate/maps-and-data/summaries/index.

18. Ilse, K., Micheli, L., Figgis, B.W., Lange, K., Daßler, D., Hanifi, H., Wolfertstetter, F., Naumann, V., Hagendorf, C., Gottschalg, R., and Bagdahn, J. (2019). Techno-economic assessment of soiling losses and mitigation strategies for solar power generation. Joule *3*, 2303–2321.

19. Bergin, M.H., Ghoroi, C., Dixit, D., Schauer, J.J., and Shindell, D.T. (2017). Large reductions in solar energy production due to dust and particulate air pollution. Environ. Sci. Technol. Lett. *4*, 339–344.

20. Butt, E.W., Turnock, S.T., Rigby, R., Reddington, C.L., Yoshioka, M., Johnson, J.S., Regayre, L.A., Pringle, K.J., Mann, G.W., and Spracklen, D.V. (2017). Global and regional trends in particulate air pollution and attributable health burden over the past 50 years. Environ. Res. Lett. *12*, 104017.

21. Ogen, Y. (2020). Assessing nitrogen dioxide (NO2) levels as a contributing factor to coronavirus (COVID-19) fatality. Sci. Total Environ. *726*, 138605.

22. Cao, Y., Chen, M., Dong, D., Xie, S., and Liu, M. (2020). Environmental pollutants damage airway epithelial cell cilia: implications for the prevention of obstructive lung diseases. Thorac. Cancer *11*, 505–510.