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Characterizing solar PV grid overvoltages by data blending advanced metering infrastructure with meteorology

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ABSTRACT

If rooftop-installed solar energy systems generate more energy than locally consumed, the excess is fed into the electricity grid, increasing the voltage. Rising penetration levels of solar photovoltaic (PV) systems increase voltage levels, thereby threatening power quality. The extent to which solar PV cause grid issues in actual, nation-wide distribution grids, and how these issues correlate with cloud conditions and irradiance variability has yet to be quantified. This work provides a spatial and temporal characterization of overvoltage events linked to solar PV, using novel data sources. The analysis is based on over 200,000 events from advanced metering infrastructure (AMI) spanning 1/3rd of the Netherlands, combined with satellite observations and 1-minute irradiance measurements. As a result, we find that the typical duration of overvoltage events is in the order of 5 min, and frequently-reporting meters are geographically dispersed. While overvoltages are driven by high PV generation, we do not find evidence that local, short-term irradiance peaks result in additional events as compared to clear sky conditions. However, we do find that median overvoltage event occurrence on Sundays is more than 2.1 times that of weekdays, which can be related to low energy consumption. Our findings indicate PV hosting capacity to be reached throughout the service area simultaneously, and surprisingly show no reduction in event duration by inverter- or grid control. Notably, while a sharp increase in occurrence is observed, overvoltage events are still scarce in absolute terms, with only 0.1% of the AMI reporting more than 10 events in spring-summer 2020.

1. Introduction

The penetration level of household photovoltaics (PV) is increasing. This in turn increases the occurrence of overvoltages, when photovoltaic (PV) feed-in minus local energy consumption exceeds grid constraints. Such overvoltages can lead to unsafe situations and failure or destruction of appliances for customers within the residential and commercial fields (David, Elphick, & Crawford, 2017). The effect of overvoltage has been described from a general power system point of view (Bollen & Hassan, Integration of Distributed Generation in the Power System, 2011) (Jenkins, Allan, Crossley, & Strbac, 2000), considered for radial low-voltage grids specifically (Haque & Wolfs, 2016) and mitigating control strategies have been proposed (Vergara, Salazar, Mai, Nguyen, & Slootweg, 2020). Such control strategies include curtailment of PV energy feed-in, which directly result in financial losses for the owner of the PV system. Studying and understanding the dynamics of these grid issues require two major challenges to be tackled. Up to recently, distribution system operators (DSO's) have few to no measurements available in the low-voltage network for assessing the power quality (Abur & Expósito, 2004) (Zarco & Exposito, 2000) and are only informed of issues when end-users file a complaint with their grid operator. This lack of measurements from actual grids poses a challenge to the academic community as well, frequently limiting the scope of research to idealized, lab-condition grids, or labor-intensive small-scale case studies (Cobben, Gaiddon, & Laukamp, 2008). The large-scale deployment of advanced metering infrastructure (AMI, or 'smart meters') provides detailed data at an unprecedented scale (U.S. International Trade Commission, 2014), thereby creating opportunities to study and understand low voltage grid issues assiduously. Secondly, PV related power quality issues are driven by regional meteorology (i.e. clouds) of which observations at high spatial and temporal resolution are scarce (Driemel, et al., 2018).

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Extensive research has been performed on several aspects related to PV grid integration challenges (Alboaouh & Mohagheghi, 2020). However, those works focus on each aspect independently. For instance, studies on the variability of irradiance (Lave and Kleissl, 2013; Lohmann, 2018) and events of overirradiance due to cloud enhancement (Gueymard, 2017) provide insights in the relevant temporal and spatial resolution of high irradiance events and under what weather conditions those can occur. Importantly, highest values of irradiance are found under broken-cloud conditions. Subsequently, fluctuations of generated solar PV energy for household PV systems (Kreuwel, et al., 2020) as well as utility scale PV plants (Haaren, Morjaria, & Fthenakis, 2014) (Marcos, Marroyo, Lorenzo, D. Alvira, & Izco, 2011) have been studied in great detail for several cases. These indicate that the largest peaks in PV generation also occur on timescales in the order of seconds to minutes, depending on the spatial extent of the PV system. Finally, work has been performed to assess the impact of those fluctuations on grid quality, using small scale case studies of feeder lines (Sharma, Aziz, Haque, & Kauschke, 2020) and simulated distribution grids (Cohen & Callaway, 2016) (Luo & Shi, 2020). Investigation on the interdisciplinary relation between highly local weather conditions and grid issues in actual grids on a large scale has yet to be performed.

The rise of distributed renewable energy causes low voltage grid dynamics to become strongly impacted by highly local meteorological conditions, in particular rapid perturbation due to the passage of clouds, openings in cloud decks and variations in the cloud optical depth. As such, it intertwines the fields of grid management and meteorology. Unlocking the full potential of large-scale smart-meter data has the potential to bridge the gap between these domains, thereby playing a key role in the energy transition. Our approach is to analyze widespread AMI overvoltage events using satellite observations as well as local, high frequency irradiance measurements. This combination allows for unprecedented analysis of distribution grid dynamics due to highly local radiation disturbances. Due to strict privacy regulations (General Data Protection Regulation (European Union, 2016)), large scale collection of AMI data is limited to anonymized overvoltage events, not allowing retrieval of more detailed time series of voltages or net power exchange at the end user connection.

In this work, the characteristics of overvoltage events originating from AMI spanning approximately a third of the Netherlands are studied in relation to meteorological conditions. We examine the typical duration of overvoltage events and compare this to that of high-irradiance events. Secondly, we investigate the distribution of overvoltage events per day and its diurnal evolution. Thirdly we examine the distribution of correlated clusters of overvoltage events in combination with satellite images. Lastly, we analyze in detail at overvoltage events in the vicinity of high-resolution irradiance measurements, quantifying the relation between cloud conditions and occurrence of overvoltage events. Since high frequency irradiance measurements are highly local, statistical parameters relating to variability and cloudiness are derived which are suitable for analysis outside the direct vicinity of the sensor (Stein, Hansen, & Reno, 2012).

We anticipate our study to be a starting point for more detailed studies on grid issues caused by the spatial and temporal variability of solar PV energy. For example, to link event occurrence to specific grid topology and asset specifications. The scope of this work is to analyze and describe the overvoltage issues which can currently be observed and how these relate to irradiance and cloudiness. We will not define a statistical model for these events since the occurrence of a single overvoltage event is driven by many highly local factors for which data is, at least at present, not available at the national scale. For a detailed study on the effect of cloud enhancement on peaks in solar PV generation, the reader is referred to previous work (Kreuwel, et al., 2020).

The rest of this paper is organized as follows. Section 2 describes the data sources and definitions used throughout this work. In Section 3, characteristics of overvoltage events are analyzed and their relation to local weather conditions is assessed. As a conclusion, the impact of the findings presented in this work is discussed in Section 4.

2. Data and methods

This work combines several distinct data sources, which are described in Section 2.1. Fig. 1 provides an overview of the spatial extent and relative location of each data source.

2.1. Data

2.1.1. Overvoltage events

DSO Liander provided overvoltages events generated by their AMI consisting of approximately 2.5 million smart meters, of which the service area is approximately 1/3rd of the Netherlands (Alliander, N.V., 2020). These meters are connected to residential and small commercial customers. The exact definition of an *overvoltage event* differs between countries due to national requirements on voltage quality that deviate from EN 50160 (EN, BS, 2010). In this study, the definition applicable to the Netherlands is used (Bollen, et al., 2012). Here, the start of an overvoltage event is defined by the voltage at the connection point of the end user exceeding the nominal voltage by at least 10% for at least 1 min. For the area of study, the nominal voltage is 230 V. The event ends when the voltage is again within 10% of the nominal voltage for at least 1 min. The minimal duration of an overvoltage event is therefore 1 min. A schematic representation of an overvoltage event is depicted in Fig. 2.

In the period between the 3rd of February 2020 up to and including the 2nd of August 2020, a total of 203,866 overvoltage events, originating from 3645 individual low voltage meters was received, representing approximately 0.1% of the smart meter population. The period of observations covers the general increase in solar energy production during spring, warm temperatures in summer which decrease PV efficiency and an almost complete variety of weather and specifically cloud conditions. Since strict privacy regulations govern the use of AMI-data, each meter was anonymized to a unique but non-traceable id and location information was stored at a postal code level. Since the fraction of meters reporting events is very low, it is important to note that the quality of the meters is strictly ensured by national and European directives (Directive 2004/22/EC), (Netbeheer Nederland, 2021) ruling out that overvoltage events are significantly impacted by faulty observations.

2.1.2. Irradiance

Global horizontal irradiance (GHI) was measured on a 1-minute time

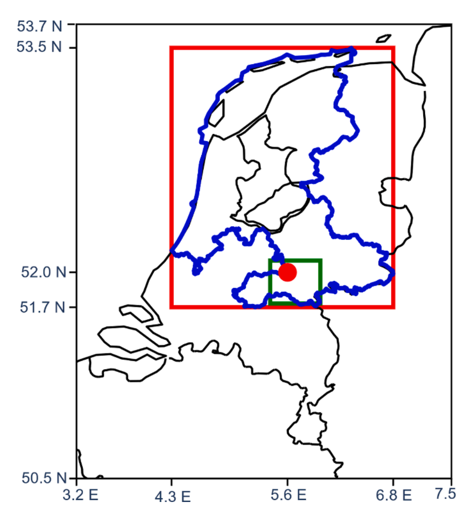

Fig. 1. Overview of the spatial extent and position of each data source in relation to the other. Outer box (red): Terra and EUMETSAT coverage; curved outline (blue): region with overvoltage event monitoring; inner box (green): local case study; marker (red): irradiance observations.

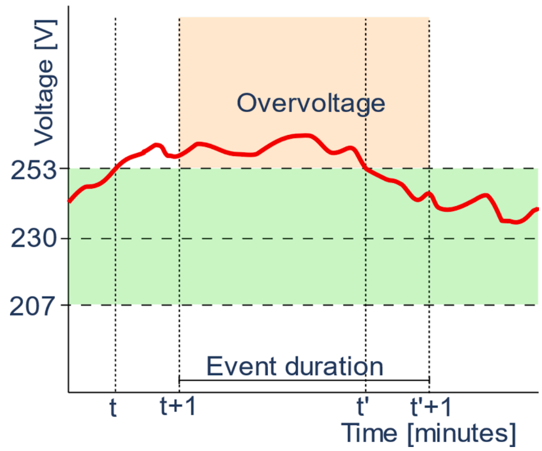

Fig. 2. Schematical representation of an overvoltage event, defined as the period in which the voltage at the end user exceeds 253 V for at least 60 s.

resolution at an automated weather station near Veenkampen, the Netherlands (51.98°N, 5.62°E), using a CMP11 Kipp & Zonen pyranometer, conforming to ISO 9060 spectrally flat Class A. The fine temporal resolution enables accurate assessment of high-irradiance event duration, which allows for a comparison to overvoltage event duration.

Irradiance measurements are relevant only up to a limited distance from the observation site. Moreover, irradiance observations at 1-minute resolution are scarce for the area for which overvoltages are available, while previous work has shown that such high temporal resolution is required to capture peaks relevant for PV integration (Kreuwel, et al., 2020). Therefore, generalizable statistics of irradiance observations are used for the entire overvoltage dataset (Section 3.1) while timeseries of irradiance observations will only be used to analyze a local-scale case study (Section 3.4). The authors note that a high-quality observation site participating in the Baseline Surface Radiation Network exists at approximately 50 km from the weather station used in this work (Knap, 2015). However, for that region no AMI data was available since it was outside of the DSO service area. Additionally, the authors note the existence of 1-min, satellite-based irradiance products by the Copernicus Atmosphere Monitoring Service (CAMS). These were not used in this study since these products are an interpolation of 15-min observations and as such do not sufficiently capture the variability of irradiance (Copernicus Atmosphere Monitoring Service, 2017).

2.1.3. Satellite observations

Remote sensing is used to asses cloud cover and cloud dynamics for locations of interest further away from the irradiance observations site. The MODIS instrument aboard the Terra satellite (Barnes, Xiong, & Salomonson, 2003) is used to observe cloud cover. The orbit of this satellite is timed so it passes the equator from north to south around noon, viewing the entire Earth's surface every 1 to 2 days. This allows for high resolution, static images of cloudiness.

Derived cloud products of EUMETSAT using the cloud physical properties algorithm (Roebeling, Feijt, & Stammes, 2006) are used to derive cloud dynamics for locations of interest. Cloud cover was extracted at a temporal resolution of 15 min, based on distance-weighted average of cloud mask. This geostationary satellite operates with an effective spatial resolution of 3x3km.

2.1.4. Net grid load

Due to GDPR restrictions, no load measurements at end user connection can be retrieved from AMI. However, at the substation level, measurements are available of the net grid load for the city of Wageningen (NL), representing approximately 18,000 residential and 3000 small commercial end-users. Active power measurements of the 50/10 kV transformer at a 5 min resolution are retrieved through the supervisory control and data acqusition (SCADA) system of the DSO. While no direct measurements of the net load at the local, low-voltage level is available, the measurements at the substation give an indication of the load on lower grid levels.

2.2. Methodology

2.2.1. AMI preprocessing

In addition to solar PV, other types of electricity generation, such as wind or combined heat power, can increase the voltage levels of the grid, potentially leading to overvoltages. However, for the distribution grid in scope of this research, these types of generation are seldomly connected to the grid at the household-level. There are household-size wind generation installations installed at the low-voltage grid. The installed capacity of solar PV connected at the low-voltage grid, however, greatly exceeds that of wind power. We will therefore disregard wind power as a significant source of overvoltages in this study.

To remove events not linked to PV feed-in, the following filtering was applied, where the number of events removed per step is included in parenthesis. First, overvoltage events with a duration of over 2 h were removed (1199). In section 3.1 we show that periods of high irradiance persist in the order of minutes, therefore we consider these extremely long events to not be primarily caused by PV feed-in. Second, the number of events per 5-minute interval was counted. 4 Periods were found with a suspiciously high number of overvoltage events. These are considered to be caused by large-scale grid issues, such as failing control logic of a substation voltage transformer and are therefore removed from the analysis (3067). As a last filtering step, events originating from meters with 10 or fewer events in total were excluded (6189) since observations from these locations fail to carry statistical importance. As a result, 193,411 events originating from 1409 m were used in the study. We do not filter on weather conditions or time of day, as to give an indication of overvoltage events that remain in the dataset after filtering which are not linked to solar PV.

2.2.2. Characterization of event duration

To help understand to what extent overvoltages are directly related to high values of solar energy production, we compare the distribution of the duration of overvoltage events to the duration of global horizontal irradiance exceeding certain thresholds. In this a linear relation between global horizontal irradiance and PV energy production is assumed. This assumption is valid since on the one hand the timescales of overvoltage events are much greater than the response time of inverters, which is in the order of 25 ms (Matsukawa, et al., 2003). On the other hand, effects due thermal response of PV panels or change in angle of incidence of solar radiation can be neglected on these timescales. We examine the cumulative fraction of events as a function of event duration.

2.2.3. Spatial extent of linked events

To analyze the spatial extent of a cluster of overvoltage events, events are aggregated per numerical postal code level. This level corresponds to approximately 10 km^2 and 3500 households (Centraal Bureau voor de Statistiek, 2018). We find that a large fraction of events is reported by a small fraction of meters, which we will distinguish as 'frequently reporting meters' versus 'commonly reporting meters'. Secondly, we analyze at the spatial distribution of both the frequently and commonly reporting meters, to assess if certain domains of the service area of the DSO are overrepresented. This would be an indication of particularly weak grid segments. To investigate this further, we perform a case study on three selected days within a one-week period, where the total event count ranges from low to high and assess geospatial differences in the occurrence of event-clusters.

2.2.4. Local case study on variability

To quantify the relationship between irradiance variability and cloud-conditions on the occurrence of overvoltage events, a detailed study is performed on a smaller region, of approximately 30 × 30 km. Since irradiance conditions are highly local, a selection is made on overvoltage events originating from smart meters near the site of irradiance observations (Section 2.1.2). This area is indicated by the green inner box in Fig. 1.

In total, 62 smart meters were available from postal codes close that of the irradiance observation site which generated 4575 overvoltage events. First, a case study is performed on a 10-day period of different meteorological conditions to assess in detail the effect of cloudy, mixed-clouds and clear sky conditions on the occurrence of overvoltage events. Secondly, to determine if variability of irradiance has a statistically significant effect on the number of overvoltage events, a quantitative analysis is performed on the entire time-domain. For this analysis, each day is classified based on its Daily Clearness Index (DCI) and Variability Index (VI) as described in previous work (Stein, Hansen, & Reno, 2012). The original, 1-minute resolution of the irradiance measurements is used to quantify DCI and VI.

3. Results

3.1. Event duration

The distribution of overvoltage event duration is examined. We find that 67% of the events last at most 5 min, and 92% last at most 15 min. The fractional cumulative sum of events as a function of event duration is compared to that of high irradiance events, as depicted in Fig. 3.

There is a strong correlation between the distributions of both overvoltage events and high irradiance events, with the overvoltage distribution matching closely the irradiance events for thresholds of 900 W/m^2, slightly flattening off to that of 850 W/m^2. The resemblance of the distributions is quite surprising. We had expected the duration of overvoltage events to be typically shorter than that of high irradiance events, due to overvoltage events being terminated by feedback loops of grid-control or active power curtailment by the inverter. However, the observed similarity suggests that these potential limiters of overvoltage event duration are not in effect, at least not at timescales between 1 and 15 min. We will elaborate on the implications of this result in the discussion. Notably, a similar distribution has been found for cloud size density, which is well-described by a power law for smaller cloud sizes (Neggers, Jonker, & Siebesma, 2003), even though the relation between cloud size, high irradiance and overvoltage events is far from linear. In the next section we will investigate the geographical spread of overvoltage events, and how their number increases from spring to summer.

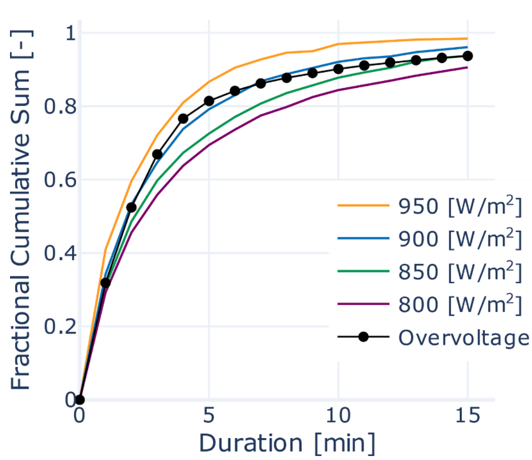

Fig. 3. Distribution of event duration of overvoltage events (black, dotted) and events of high irradiance. The legend shows the threshold used for the irradiance events.

3.2. Temporal distribution

An analysis is performed on the temporal distribution of overvoltage events. Events are grouped to a total per 15-minute interval based on the event start-time, where we denote that the typical event duration is smaller than this time resolution. Fig. 4 shows the increasing trend since the start of the year (x-axis) and the distribution of events during a diurnal cycle (y-axis). The distribution of overvoltage events follows that of the seasonal and daily solar cycle, as one would expect assuming solar PV energy being the main driver of overvoltage events. On a weekly basis, we find a strong increase, starting from approximately 1500 overvoltage events per week in spring, towards a more-or-less steady level of 9000 weekly events in summer. At the time-per-day level we see a close resemblance to a typical irradiance profile.

For some time-periods, especially during the first weeks of study, overvoltage events can be observed during night times. We conjecture that these events are not caused by solar PV, but by other sources. These events were not removed by the filtering process described under Section 2.1, as to give an indication of non-PV related overvoltage events remaining in the dataset.

We investigate the distribution of total events registered per smart meter. The number of events per smart meter, and the geographical spread of events is depicted in Fig. 5. We find that 61% of the events originate from 16% of the smart meters included in this work. This over-representation could be caused by a particular weak section of the grid. However, Fig. 5 shows that frequent-reporting meters and not-frequent-reporting meters are evenly distributed throughout the DSO service area.

3.3. Spatial distribution

To assess the possible correlation of neighboring cluster of events, a case study is performed on three days within the same week with few, moderate and many overvoltage events. Fig. 6 shows the distribution of event clusters for each day, on top of observations from the Terra Modis satellite (Barnes, Xiong, & Salomonson, 2003). The selected days are 19th (left, 693 events), 17th (middle, 2242 events) and 23rd (right, 4016 events) of May 2020. These days feature commonly occurring meteorological conditions for this time of year in the Netherlands. Moist maritime air is transported inland, where the late-spring sun heats the

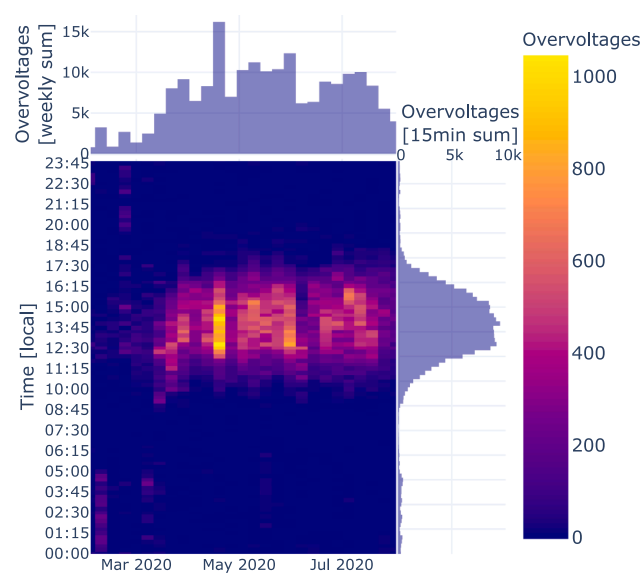

Fig. 4. Temporal distribution of overvoltage events depicted as a density heatmap. The x-axis and marginal are grouped per week, while the y-axis is grouped per 15 min. The color of the heatmap indicates the total number of events.

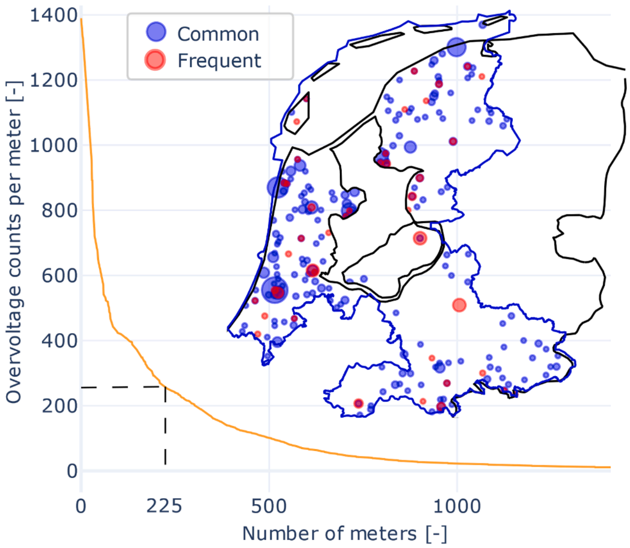

Fig. 5. The distribution of overvoltage events per meter is skewed. The dotted line indicates the threshold where 16% of the smart meters account for 61% of the total overvoltage events. The map (inset) shows that both frequently reporting meters (red) and commonly reporting meters (blue) are distributed throughout the DSO service area. The size of the markers gives an indication of the number of smart meters per postal code.

surface enough to cause shallow convection and the formation of low clouds, which develops further downwind into cloud streets (Etling & Brown, 1993). This can evolve into stratocumulus due to a capping inversion associated with a high-pressure system, as visible for May 17th. The prevailing wind direction for the respective days was WNW, W, WSW going left to right, as reported by the KNMI for location 'de Bilt', near the center of the Netherlands (KNMI, 2009).

The condition, strength and PV hosting capacity of the electricity grid differs throughout the network. Before starting the analysis, we hypothesized that on days with few overvoltage events, the events would originate from the weakest sections of the grid, where impedance of feeder lines and the number of end customers is relatively high. On days with a higher number of overvoltage events, we would expect that in addition to the weakest sections, less weak sections of the grid would report overvoltage events as well. The circles in Fig. 6 denote some areas of specific interest, where clusters only appear on some days, but not on others. Interestingly, the circle on the left indicates a cluster which only occurs on the day with the smallest total number of events. The occurrence of this cluster cannot be explained based on distinct cloud conditions derived from static satellite imagery. Similarly, for days with moderate and high number of events, clusters are visible which only occur on that one specific day. These findings indicate that local effects, e.g. in energy consumption or production, strongly influence the occurrence of overvoltage events, and that it is not necessarily the case that specific weak grid sections experience overvoltage first.

While the Terra Modis satellite provides information on cloud cover at a very high spatial resolution, the single observation in time is unable to capture cloud dynamics. A complementary analysis is given by the derived cloud products of EUMETSAT using the cloud physical properties algorithm (Roebeling, Feijt, & Stammes, 2006). Cloud cover was extracted for the three areas of interest at a temporal resolution of 15 min, based on distance-weighted average of cloud mask. Fig. 7 shows the cloud dynamics for May 17th, as well as the overvoltage events of the southern area of interest. For comparison, the overvoltage events are grouped as a total per 15 min. The other areas of interest reported no overvoltage events, even though the cloud cover was constantly low. While the cloud cover shows a large evolvement during the day, moving from almost completely clouded to near clear sky, these dynamics are not reflected in the reported overvoltage events.

3.4. Impact of variability

To further quantify the impact of highly local effects, overvoltage events are selected which originate from AMI near the irradiance measurement site, as described in Section 2.2.4. Fig. 8 shows the diurnal cycle of irradiance at 1-minute resolution and overvoltage events at 15-minute resolution for a period of 11 consecutive days spanning 19th −29th of March. This period features a wide variety of cloud conditions within a short time span, such as clouds (March 19th and 20th), broken clouds (29th) and clear sky (21st to 28th). For context, Terra Modis satellite observations are included at the top. The bottom part of the figure depicts the net grid load of a substation in the case study region, as described in section 2.1.4. The load of the substation is an indication of the net grid load on lower voltage levels. As expected, almost no overvoltage events are measured under clouded conditions. However, even though the irradiance observations are nearly indistinguishable under clear sky conditions, there is a large spread in total overvoltage events per day, with the 23rd to the 27th of March showing a substantially smaller number of overvoltage events. Coincidentally, the four days with many overvoltage events are all weekend-days (March 21, 22, 28, 29), indicated in Fig. 8 in grey.

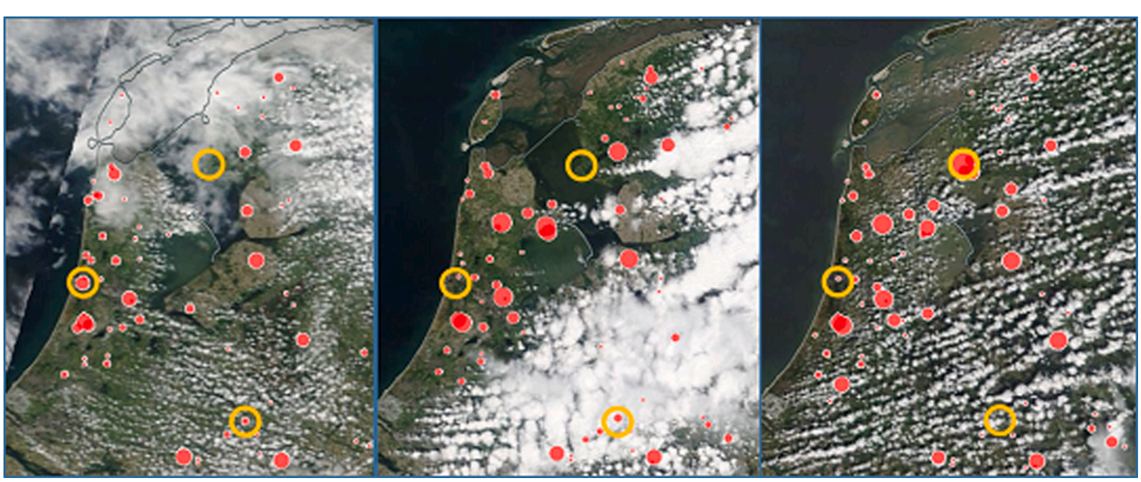

Fig. 6. Clusters of overvoltage events are shown for three days, on which the total number of events range from few (left, 693 events, 19-05-2020) to medium (middle, 2242 events, 17-05-2020) to many (right, 4016 events, 23-05-2020). The circles indicate regions where clusters occur only on specific days. The cloud observations originate from the Terra Modis satellite.

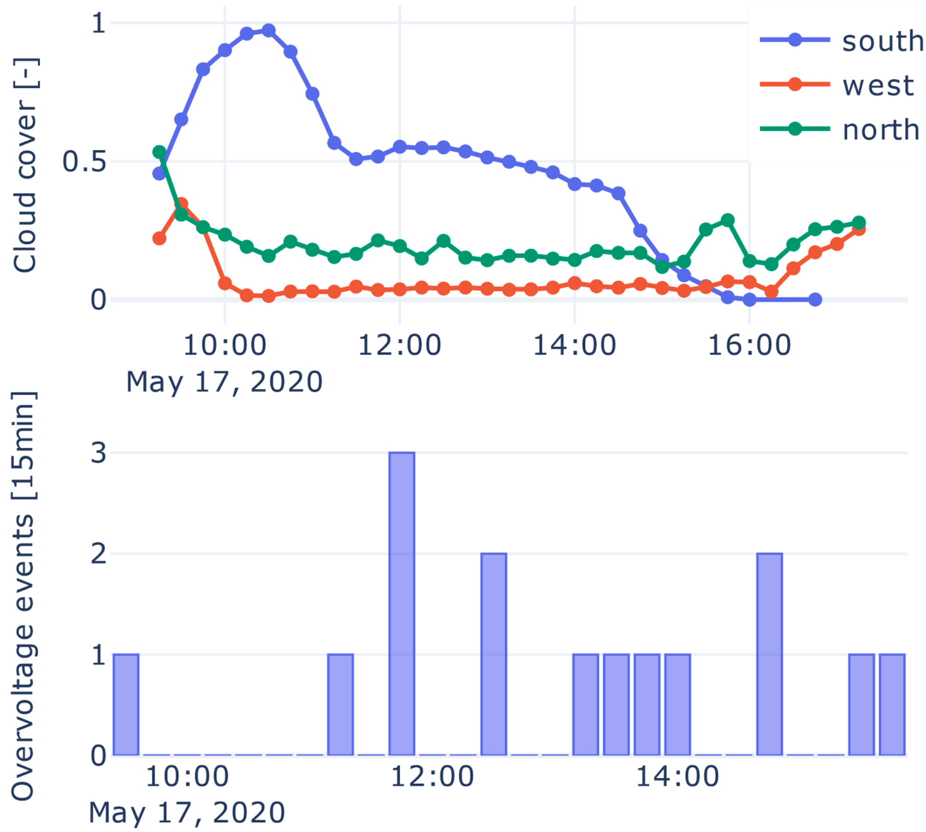

Fig. 7. Evolution of cloud cover (top) for the three areas of specific interest and total overvoltage events per 15 min for the southern area of interest (bottom), for 2020-05-17. Derived cloud cover originates from EUMETSAT observations.

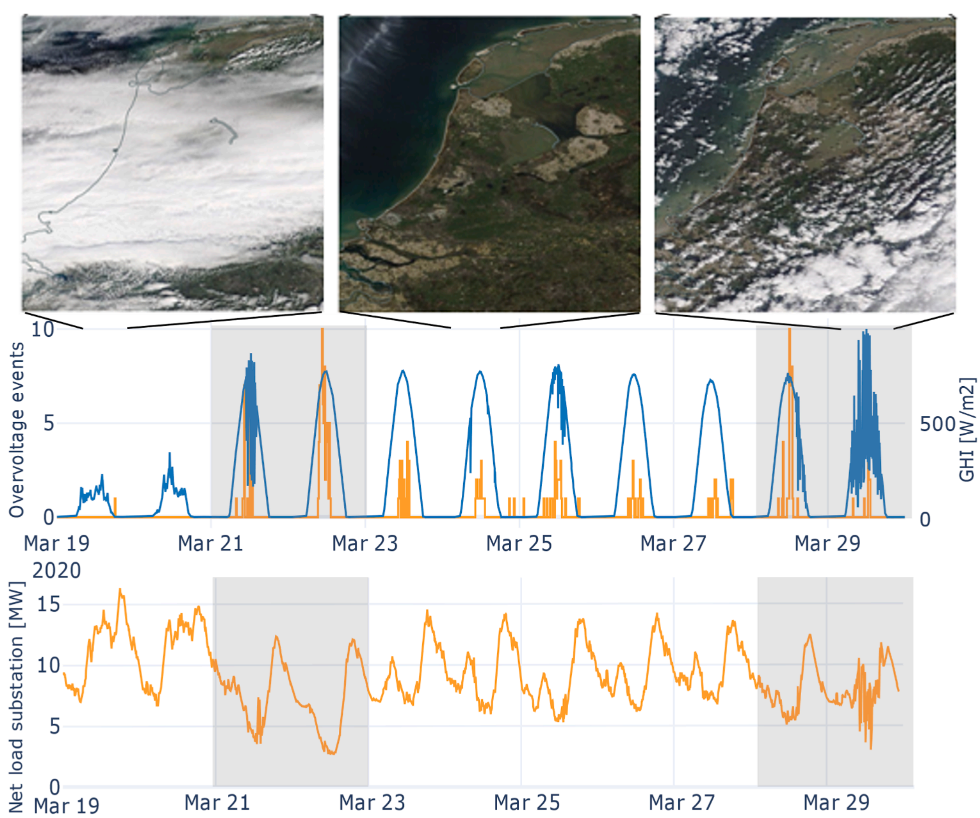

Fig. 8. Depiction of 11 days of the local case study on overvoltage events. Top: Terra Modis satellite observations indicate cloud conditions for three selected days, corresponding to overcast (left), clear sky (center), and broken-cloud conditions (right). Middle: overvoltage occurrence (orange, left y-axis, 15-minute bins) in relation to global horizontal irradiance (blue, right y-axis) at 1-minute resolution. Weekends are shaded grey. Bottom: Net load on the level of a substation in the local case study region.

A statistical analysis is performed on smart meters near Veenkampen for the entire data acquisition period to test significance of irradiance variability on the one hand, and day of the week on the other. Effects of cloud enhancement, where partial cloud cover leads to irradiance exceeding clear sky irradiance, can be observed on 21st and 29th of March in Fig. 8. Using the methodology referenced in section 2.2.4, each day of the entire dataset is categorized as 'clouded', 'variable', 'clear', or 'mixed' according to their DCI and VI, based on the irradiance observations at a 1-minute resolution. Fig. 9 shows the distribution of daily aggregated overvoltage events per type of irradiance, where the number of events increases as the total irradiance per day increases. We note that the spread in events per day is considerable. Additionally, we calculate the median overvoltage events as a function of day of the week, for which the result is shown in Fig. 10. Notably, the median overvoltage event count on Sundays is 2.1 times that of weekdays. From Fig. 8 it is clear that on weekend-days around noon, the net load at the substation level reaches its minimum. This corresponds to a combination of high PV generation and low energy consumption. At this aggregation, the load is positive, indicating net energy consumption. However, on the local, low-voltage level, this can correspond to high amounts of net feed-in of PV energy.

Using Student's *t*-test (Student, 1908), we study if the difference in the mean overvoltage events per day for each category, given the event distribution, is statistically significant. We find that the distributions on 'variable' versus 'clear' days do not differ with statistical significance. However, for the difference between overvoltage events on Sundays compared to weekdays, we find a *p*-value of 0.016, indicating statistical significance.

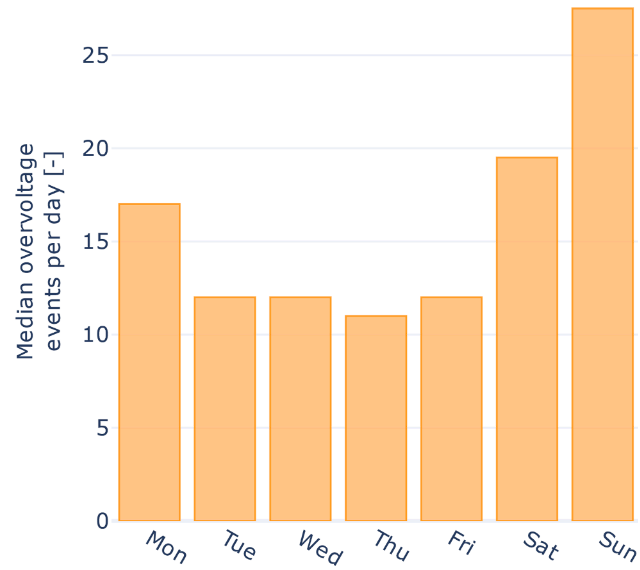

Fig. 10. Median of daily overvoltage events per day of week. On Sunday a significantly higher number of overvoltage events is observed.

4. Discussion and outlook

4.1. Discussion

This study presents a characterization of solar PV induced overvoltage events reported by AMI, in relation to clouds and irradiance variability. Previous work showed the dominant timescales for peaks in PV generation to be in the order of seconds to minutes, for household PV systems (Kreuwel, et al., 2020) as well as utility-scale PV parks (Haaren, Morjaria, & Fthenakis, 2014) (Marcos, Marroyo, Lorenzo, D. Alvira, & Izco, 2011). In this work, we showed the dominant timescales for overvoltage events to also be in the order of minutes. Surprisingly, we did not observe a decrease in overvoltage event duration due to voltage control, such as active power control by droop curves in end-user inverters (Vasquez, Mastromauro, Guerrero, & Liserre, 2009) (De Brabandere, Woyte, Belmans, & Nijs, 2004) or onload tap changers at substation transformers. We would like to point out that this is only investigated under the condition that an overvoltage event occurs in the first place. In all likelihood, many potential events in the making are either already mitigated within the 1-minute duration threshold, or some form of voltage control has acted before the voltage threshold at the end user is exceeded.

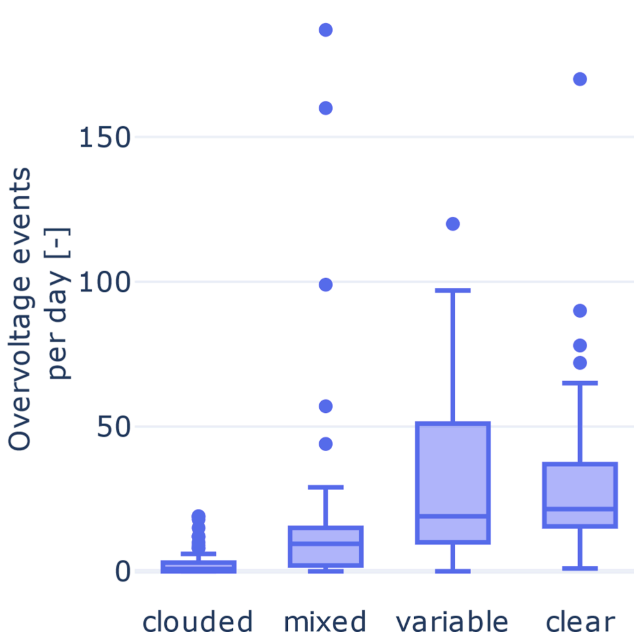

Fig. 9. Distribution of overvoltage events aggregated per day, as a function of irradiance category. Whiskers mark the closest points to points within 1.5 times the interquartile range, while the vertical line in the box indicates the median.

Our results show that, while high irradiance is required for an overvoltage event to occur, the variability or height of irradiance peaks do not significantly influence event occurrence. The impact of 'Sunday versus weekday' exceeds that of 'clear sky versus broken clouds', as described in section 3.4. Based on open-data standard consumption profiles provided by the Dutch energy sector (NEDU, 2020), we find that mainly industrial energy consumption diminishes on Sundays, whereas household energy consumption only slightly decreases. As discussed in the introduction, previous work shows that broken clouds lead to the largest peaks in irradiance (Gueymard, 2017) and PV energy generation (Kreuwel, et al., 2020). However, we find the impact of low energy consumption exceeds that of irradiance peaks in causing overvoltage events, at least for the area considered in this study and current penetration level of household solar PV systems. Our conjecture is that when the number of PV systems increases and the hosting capacity of the grid is reached, the impact of irradiance variability on overvoltage incidence could surpass that of low energy consumption.

The scope of this work does not include a detailed analysis into the context and origin of individual overvoltage events, such as grid topology, asset information and end-user energy consumption. The reason for this decision are the strict conditions under which AMI data can be used, specifically in relation to the GDPR (European Union, 2016). While many novel and important results have been presented based in this work, a lower level of aggregation of overvoltage events would allow for more detailed studies, for instance into the impact of end-user behavior and specific grid parameters on overvoltage event incidence. In particular, the large-scale analysis of overvoltage events in relation to clouds and cloud dynamics presented in this work could greatly benefit from the addition of such specific information. Potentially, this would allow definitive explanation of the occurrence and absence of clusters of overvoltage events on particular days, thereby aiding in the challenge of integrating high levels of solar PV into the grid. Despite the good intentions of the GDPR, its current interpretation limits scientific and societal progress.

While the number of events shows a strongly increasing trend, the fraction of smart meters reporting overvoltages is still well below 0.1%. Additionally, many other processes apart from solar PV can trigger an overvoltage event, such as other types of decentralized energy generation, failing control-logics or non-compliancy of end-users. However, the relation with irradiance is strong to such an extent that a detailed statistical characterization is already possible, as shown in this work.

4.2. Outlook

The framework provided in this work can help to assess overvoltage events on both a large and a local scale. Information on typical event duration and spatial extent can aid grid operators in improving their AMI data acquisition routines. For example, at present events are only triggered when voltages are exceeded beyond regulatory levels. After interviewing subject matter experts at DSO Liander, we recommend including additional triggers at lower voltage levels, e.g. 6–8% of the nominal voltage. This would make it possible to identify grid section where PV penetration levels start to reach the hosting capacity even before end users experience any issues. This enables data driven preventive maintenance and grid reinforcements, resulting in an increased hosting capacity of the grid. Additionally, we recommend repeating the analysis discussed in this work with an updated dataset next year to further investigate the relation between irradiance, PV penetration levels, and overvoltage event occurrence.

Interviews with subject matter experts at the DSO indicate that when a power quality issue is reported by a customer, voltage profiles from neighboring smart meters of a limited duration are requested, which differ from overvoltage events. This work gives a starting point on how overvoltage events can help to understand and pro-actively mitigate PV related issues.

5. Conclusion

This work provides a thorough characterization of overvoltage events in the distribution grid due to solar PV on a nation-wide scale, using novel data sources. Using high resolution irradiance observations in a local case study, we find that median overvoltage event incidence on Sundays compared to weekdays is 2.1 times higher, while no distinction could be found between highly variable irradiance during broken clouds or constant irradiance during clear sky conditions. This suggests that, while overvoltages are caused by high PV generation, overvoltage event incidence is increased more strongly by low energy consumption than by short peaks of high feed-in. We find that a small number of smart meters is responsible for many events, but that these do not indicate any particular weak grid segments. This indicates that the PV hosting capacity of the electricity grid is reached simultaneously throughout the service area of the DSO. When grouping events into clusters at a postal-code level, we find no clear relation in event incidence between separate clusters, not even in conjunction with static or dynamic satellite observations. On weekly to monthly timescales, a strong increase in overvoltage events is found during spring which flattens out towards the summer, from approximately 1.500 weekly events up to 9.000 with a peak exceeding 16.000, on an AMI population of 2.5 million.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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