Characterizing the variability and meteorological drivers of wind power and solar power generation over Africa

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RESEARCH ARTICLE

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Characterizing the variability and meteorological drivers of wind power and solar power generation over Africa

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Abstract
Sub-Saharan Africa (SSA) has the lowest energy access rates in the world, which poses a key barrier to power system development. Deployment of renewables, including wind and solar power, will play a key role in expanding electricity supply across SSA: distributed generation (enabling access for remote communities), cost-effectiveness and low emissions are key advantages. However, renewable generation is weather dependent; therefore, including more renewables increases the amount of meteorologically driven variability in the power system. Two countries in SSA are chosen for detailed investigation of this meteorologically driven variability: Senegal in West Africa and Kenya in East Africa. These are chosen due to being areas of dense population, where there is operational wind and solar power, and plans for regional expansion. In Senegal, solar generation is fairly consistent throughout the year, while wind generation exhibits strong seasonality, with a peak in the boreal spring. Low wind and solar power generation days during the boreal summer are found to be related to the passage of African Easterly Waves. Over Kenya, both wind and solar generation exhibit seasonal variability, with wind generation peaking during boreal autumn, and solar generation at a minimum during boreal summer. Inter-annual variability in generation is greater over Kenya than over Senegal; the El Nino Southern Oscillation is found to impact wind and solar generation over Kenya. El Nino phases are associated with lower wind and solar generation in October–December over Kenya, but higher generation in July–September. This improved understanding of variability will assist system planners in designing reliable future energy systems.

KEYWORDS
Africa, climate variability, grid management, renewable energy, solar power, wind power

1 | INTRODUCTION

The seventh Sustainable Development Goal expresses the aim to *ensure universal access to affordable, reliable and modern energy services* by 2030 and also *increase substantially the share of renewable energy in the global energy mix* (UN General Assembly, 2015). Currently, sub-Saharan Africa (SSA) has extremely low energy access rates, with around 580 million people lacking access to electricity in 2019 (IEA, 2021). This includes approximately half of the people in West Africa and three quarters of people in East Africa (IRENA, 2015). This lack of energy access limits economic growth and development (World Bank, 2017). Deployment of renewables (e.g., wind, solar and hydropower) is a key factor in expanding electricity supply across SSA; not only does this allow countries to meet emission targets outlined in the Paris Agreement, it enables generation to be distributed across countries, including remote communities where energy access is currently particularly low. Renewable Energy has also become a cost-effective method of meeting emission goals with the costs of installing wind and solar power now falling below those of fossil fuel generation (see figure SPM.4. of Lecocq et al., 2020). The International Renewable Energy Agency's (IRENA's) global Renewable Energy map 2030 analysis identifies modern renewable technology options for African countries, which collectively could supply 22% of Africa's total final energy consumption by 2030, compared with just 5% in 2013 (IRENA, 2015).

Before renewable energy generation can be deployed, an initial resource assessment is required to confirm the site is appropriate, and that the project will be cost-effective. These types of assessments have been ongoing for multiple years: initial investigations over Africa by Archer and Jacobson (2005) suggested that wind power potential over Africa is low compared with other parts of the world, with only a few suitable regions (e.g., the Turkana Channel region of Kenya, and a few offshore locations around the African coast). However, with the development of more sophisticated global and local-scale modelling tools, the potential has started to look more promising. More recent studies have looked at wind power potential over the whole of Africa, showing that in many regions there are favourable sites for development, including the Horn of Africa, South Africa and parts of North-West Africa (Elsner, 2019; Fant et al., 2016; GWA, 2018; Hafner et al., 2018; Mentis et al., 2015). Particularly high wind resource potential was again found over parts of Kenya (Fant et al., 2016).

SSA has excellent solar power potential with East Africa highlighted as having the highest combined solar photovoltaic (PV) and wind power potential of all of the African regions (Hermann et al., 2014). A high number of annual sunshine hours are present across the continent, with areas of the Sahara Desert, the Sahel, the south-west tip of the continent and the Horn of Africa experiencing high levels of solar irradiance (Hafner et al., 2018; Huld et al., 2012; Soares et al., 2019). Incorporating siting information from Geographic Information Systems (e.g., land-use type and elevation) suggests Senegal as a particularly favourable region of West Africa (Yushchenko et al., 2018), although Ramdé et al. (2013) highlight the importance of thoroughly accounting for land-use constraints. Sterl et al. (2018) highlighted the potential for exploiting hybrid solar and wind power over West Africa. When thinking about both wind and solar together, their assessment found more sites of high population density, with close proximity to existing grid structures than suggested by previous resource availability assessments.

The inclusion of renewable energy technologies results in a number of extra weather-dependent decisions to be made for reliable power system operation (Bruno Soares & Dessai, 2016; White et al., 2017). This requires a thorough understanding of the meteorological drivers that may cause these fluctuations in renewable generation (Bloomfield et al., 2018). These meteorological drivers will be timescale dependent. Local weather conditions will impact short-term power system operation (e.g., hourly wind power ramping, or sudden drops in solar PV output). Whereas, on seasonal-annual timescales, power system operation will be related to modes of large-scale climate variability (e.g., in Europe, colder, stiller, winters have higher demand and lower wind power generation than milder windy winters). This behaviour can be related to the phase of the North Atlantic Oscillation (Bloomfield et al., 2018). Understanding the role of meteorological variability in wind power and solar PV production is key for balancing supply and demand and providing a reliable electricity supply. The impact of meteorologically driven variability on wind and solar electricity generation has been investigated across multiple regions including Europe (Bloomfield et al., 2020; Zeyringer et al., 2018), North America (Kumler et al., 2019) and parts of Asia (Dunning et al., 2015). While some studies have investigated both the resource potential and variability of wind and solar generation over Southern Africa (Fant et al., 2016), fewer studies have examined potential and weather-driven variability in SSA.

In this study, two countries are chosen for a detailed investigation of this meteorologically driven variability: Senegal in West Africa and Kenya in East Africa. These are chosen due to being areas of dense population, where there is currently operational wind and solar power, and plans for regional expansion (Hafner et al., 2018). For example, Senegal has ambitious renewable deployment goals (aiming for 30% of energy from renewables by 2030; Niane, 2022). Senegal has a 158 MW wind farm currently operational in Taiba N'Diaye, and Kenya is one of the top five countries for wind energy investment due to the 310 MW Lake Turkana project (Hafner et al., 2018). Kenya aims to have 80% of energy production from renewable sources by 2030 (Kiva et al., 2022).

The aims of this study are therefore:

1. To quantify the historical variability and complementarity of wind power and solar PV generation in the case study regions on timescales of hours to years.
2. To explore the meteorological drivers of wind and solar PV variability in the study regions on both weather and climate timescales.

2 | DATA AND METHODS

2.1 | The ERA5 reanalysis

The meteorological data used for this study are from the ERA5 reanalysis (Hersbach et al., 2020), available from Copernicus Climate Data Store (CDS, 2020). A reanalysis is a reconstruction of recent atmospheric conditions, which is created by running a numerical weather prediction model, with data assimilation to ingest all available observations for a given period. In this study, hourly data from 1979 to 2019 are used to give a 41-year analysis period, at approximately 0.3° spatial resolution. Gridded 2 m temperature, surface solar shortwave radiation and 100 m wind speed data are used to create the energy variables discussed in this study. Surface rainfall data are also used to complement the analysis for Senegal. For all analyses, the data are downloaded at hourly resolution, transformed into renewable generation and then aggregated to the relevant timescale. This is important due to the non-linear relationships between wind speed and wind power (Section 2.2) and between surface irradiance, surface temperature and solar PV generation (Section 2.3).

We note that it is common for bias correction to be applied to ERA5, before calculating wind power generation, as it has a known low wind speed bias (Bloomfield et al., 2020; Ramon et al., 2019). In previous studies the data have been mean-bias corrected to either wind mast observations (Thomas et al., 2020) or to the Global Wind Atlas data set (Bloomfield et al., 2020; GWA, 2018; Lledó et al., 2019). The wind speeds have, however, not been bias corrected for this study due to computational limitations and a lack of observational data. We note that Gleixner et al. (2020) and Quagraine et al. (2020) show that ERA5 performs better over East and West Africa than its predecessor ERA-Interim (Dee et al., 2011), when considering precipitation. Sterl et al. (2018) also shows ERA5 near-surface wind speeds compare well to observations over West Africa. Nefabas et al. (2021) found high correlation between measured wind power and modelled wind power at two sites in Ethiopia, where the modelled wind power was produced using ERA5 reanalysis winds (although statistical down-scaling was applied). These studies give us confidence that ERA5 represents the wind climate over Africa reasonably well, but it should be noted this is a challenging region for accurate observations.

2.2 | Wind power model

A physical model is used to produce estimates of wind power capacity factor (CF) in each grid box of the ERA5 reanalysis. Gridded 100 m wind speeds are converted into wind power CFs using the power curve from the Enercon E70 2.3 MW wind turbine (class 1 wind turbine used in Bloomfield et al., 2020). The CF can be defined as the ratio of the present output compared with the maximum possible output of the wind farm when operating at rated power (ranging between 0 and 1). The CFs at particular locations can be calculated by bi-linearly interpolating the ERA5 data onto the known wind farm locations (as in Cannon et al., 2017). Information regarding the spatial distribution and installed capacity of operational wind turbines is taken from various online resources, shown in Table 1. Validation of this methodology has not been possible, as data from wind farms at the sites of interest are not available. Any wind power CFs shown in this study should therefore be thought of as wind power potential, and the method does not include local effects such as grid-induced curtailment, or wake effects of surrounding turbines.

2.3 | Solar PV model

The solar PV model follows the empirical formulation of Evans and Florschuetz (1977), but with adaptation to newer solar PV technologies using methods from the study by Bett and Thornton (2016). The meteorological inputs are gridded 2 m temperature and incoming surface shortwave irradiance, from the ERA5 reanalysis. The capacity factor in each grid box is calculated using the equations below:

$$\mathrm{CF}(t) = \frac{\mathrm{power}}{\mathrm{power}_{\mathrm{STC}}} = \eta(G,T)\frac{G(t)}{G_{\mathrm{STC}}(t)}, \quad (1)$$

where G is the incoming surface solar radiation and T is the grid box 2 m temperature, and t is the time step (hours). STC stands for standard test conditions ($T = 25°\mathrm{C}$, $G = 1000\ \mathrm{Wm}^{-2}$) and η is the relative efficiency of the panel following:

$$\eta(G,T) = \eta_r[1 - \beta_r(T_c - T_r)], \quad (2)$$

where η_r is the PV cell efficiency evaluated at the reference temperature T_r, β_r is the fractional decrease of cell

TABLE 1 Details of the installed wind and solar capacities used at sites in this study.

Region	Site name	Wind or solar PV	Installed (MW)	Data source
Senegal	Taiba N'Diaye	Wind	158	wikipedia.org/wiki/Taiba_N%27Diaye_Wind_Power_Station[a]
Senegal	Senergy	Solar PV	30[a]	wikipedia.org/wiki/Energy_in_Senegal[a]
Senegal	Ten Merina	Solar PV	30	wikipedia.org/wiki/Energy_in_Senegal[a]
Senegal	Malicounda	Solar PV	22	wikipedia.org/wiki/Energy_in_Senegal[a]
Kenya	Ngong Hills	Wind	26	thewindpower.net
Kenya	Turkana	Wind	310	thewindpower.net
Kenya	Garissa	Solar PV	55	thewindpower.net
Kenya	Rumuruti	Solar PV	40	thewindpower.net

[a]Locations/names found on web-page listed, exact locations found by checking on satellite imagery for wind turbines/solar panels.

efficiency per unit temperature increase and T_c is the cell temperature (assumed to be identical to the grid box temperature). Similarly to wind power generation, since the output from solar PV farms across Africa is not available, the model cannot be validated. The solar PV capacity factors should therefore be thought of as solar PV potential.

2.4 | Sites of interest

In this study, we decided to focus upon two regions: Senegal in West Africa and Kenya in East Africa. These are areas that have relatively good wind power and solar PV potential in regions of high population density (see Figure 1), have operational wind power and solar PV (see Table 1), and large nearby hydropower installations (for which there is competition with neighbouring countries, Falchetta et al., 2019; Naibei, 2017) which could be complemented by an expanded wind and solar portfolio (Sterl et al., 2020).

Wind power and solar PV capacity factors of operational wind and solar PV farms are calculated by bilinearly interpolating the meteorological variables onto the farm locations, and then calculating generation (see Table 1 for site locations). Both regions have more wind power generation than solar PV generation, although we note that this study only accounts for large-scale solar farms, and there may also be rooftop solar PV present in cities. The comparison of production at these sites is intended to give indications of potential challenges for large-scale grid balancing within the countries.

2.5 | Meteorological drivers

We have examined meteorological drivers that may impact the day-to-day operations of wind and solar PV capacity factors (hereafter termed weather drivers) and that may be more relevant on monthly seasonal timescales (hereafter termed climate drivers). Knowledge of the weather and climate conditions, which impact wind and solar PV generation in each study region, is relevant for both short-term decision-making and longer-term system planning. For example, knowledge of the meteorological drivers of a power system can be used when planning the amount of capacity required to meet a peak demand, or on longer timescales identifying meteorological conditions that could cause the largest energy storage requirements (Bloomfield et al., 2018).

Information on the meteorological drivers of power system behaviour is particularly useful if the meteorological drivers are predictable. The weather drivers may be predictable at short lead times (e.g., the passage of weather systems such as African Easterly Waves (AEWs), which have periods of 2–6 days; Bain et al., 2014; Cornforth et al., 2017; Elless & Torn, 2018), whereas the climate drivers may be predictable months–seasons in advance (e.g., the El Niño Southern Oscillation, ENSO, Barnston et al., 2012; Tang et al., 2018).

2.5.1 | Weather drivers

To identify the weather drivers in Senegal and Kenya, the 1st and 99th percentiles of aggregate wind and solar PV generation were analysed (weighted by the installed capacities given in Table 1). Following this, meteorological phenomena known to act at relevant times were investigated. Meteorological composites are created for high and low production days, which highlight meteorological features of interest. In Senegal, the majority (72.7%) of low production days (first percentile of country-weighted wind and solar PV generation) occur during August and September, during the peak of the

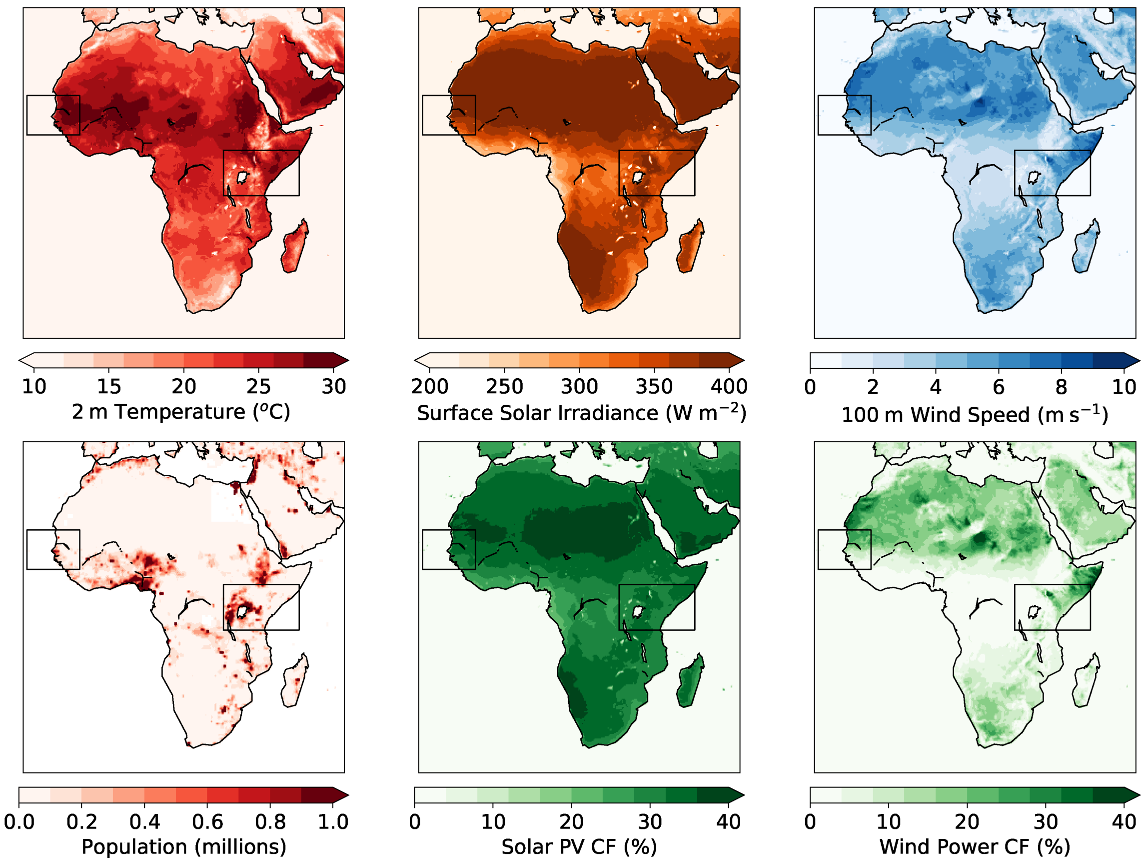

FIGURE 1 Climatologies of 1979–2019 mean fields for (top) 2 m temperature, surface solar irradiance and 100 m wind (bottom) 2020 population density (taken from Doxsey-Whitfield et al., 2015), solar PV capacity factor (CF) and wind power CF. See Figure S1 for ocean data.

West African Monsoon (WAM). AEWs are the dominant synoptic-scale weather phenomena within the WAM (Cornforth et al., 2017), and hence are chosen as the main weather-driver of interest for Senegal.

The African Easterly Jet (AEJ) is characterized by a peak in the zonal easterly wind at 600–700 hPa over West Africa, in approximate thermal wind balance with the lower tropospheric temperature gradient from the Gulf of Guinea to the Sahara Desert (Cornforth et al., 2017). AEWs are synoptic-scale disturbances that form over central or eastern Africa, and propagate westward on the AEJ, across West Africa and into the tropical Atlantic (for more details on the AEJ and AEWs see; Cornforth et al., 2017). Their passage is marked by a peak in convection (located ahead of the AEW trough in early stages and behind the trough by the time they reach the ocean) and low-level wind anomalies (Cornforth et al., 2017). Hence the passage of such systems may impact wind and solar generation over West Africa. AEWs occur throughout the WAM season, and peak in intensity during August and September.

In this study, AEWs were identified by tracking local vorticity maxima in 700 hPa relative vorticity field from ERA5 reanalysis data (Thorncroft & Hodges, 2001; Yang et al., 2018), where vorticity is a measure of local rotation in a fluid flow. The vorticity field used is spectrally filtered and the field is truncated to T63. The tracks of positive vorticity centres at 700 hPa with amplitude larger than $0.5 \times 10^{-5}\ s^{-1}$ are used to represent the phase propagation of AEWs. Tracks were considered that start between 1 August and 31 September, last for at least 2 days, travel at least 500 km, and pass through the region $12-17^{\circ}$N, $15-19^{\circ}$W. Days in August and September when vorticity tracks pass through $12-17^{\circ}$N, $15-19^{\circ}$W are defined as AEW days.

A weather-driver of interest in Kenya, which has previously been highlighted, is the behaviour of the Turkana Jet (Fant et al., 2016). This is a southeasterly low-level jet located in the Turkana Channel in northern Kenya. The shape of the channel and surrounding topography results in a southeasterly jet throughout the year, regardless of the low-level winds to the southeast of the channel (King et al., 2021). The jet is present throughout the calendar year, strongest in boreal spring and boreal autumn/winter, and weakest in boreal summer (King et al., 2021; Nicholson, 2016). The flow in the jet is divergent from the entrance to the exit region of the jet, hence the Turkana Channel experiences little rainfall (Nicholson, 2016), and the presence of the jet has been linked to the aridity of the region as a whole, with a weaker jet linked to more rainfall over Kenya (King et al., 2021; Nicholson, 2016). The jet exhibits a strong diurnal cycle; in all months, the jet is distinct from 06:00 PM to 06:00 AM, and weaker during the day, thus is it primarily a nocturnal feature (Nicholson, 2016).

2.5.2 | Climate drivers

The ENSO is a major mode of inter-annual meteorological variability, with significant impacts on the African climate (Ficchi et al., 2021; Joly & Voldoire, 2009; Nicholson, 2017). The positive and negative phases of ENSO, El Niño and La Niña respectively, describe changes in the ocean and atmosphere over the tropical Pacific Ocean. During El Niño (positive/warm) phases, a reduction in the easterly trade winds allows sea surface temperatures (SSTs) to warm over the central and eastern Pacific, while during La Niña (negative/cold) phases, stronger easterly trade winds lead to warmer SSTs in the western Pacific, and cooler SSTs, associated with enhanced upwelling, in the eastern Pacific. The associated changes in atmospheric circulation over the Pacific occurring as a result of these oceanic changes have global influence, impacting temperatures and precipitation across the tropics.

Over East Africa, El Niño events are associated with wet conditions (Indeje et al., 2000), particularly during the October–December short rains, while La Niña events are associated with dry conditions over East Africa (MacLeod et al., 2020; Nicholson, 2017). Generally, El Niño events are associated with depressed June–September (JAS) rainfall over West Africa (Rowell, 2001). Over West Africa, the interaction between ENSO events and the WAM is complex; ENSO events peak in late boreal autumn, while the WAM occurs during boreal summer. Joly & Voldoire, 2009 found that impacts of ENSO on the WAM can be detected during the developing phase of ENSO or during the decaying phase of some long lasting La Nina events.

Although the impact of ENSO on precipitation variability over Africa has been widely studied (Indeje et al., 2000; Joly & Voldoire, 2009; Rowell, 2001), the impact of ENSO on wind power and solar PV potential has not previously been investigated over Africa.

The ENSO index used in this study was taken from https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php. It is defined as a 3-month running mean of SST anomalies in the Niño 3.4 region (5° N–5° S, 120°–170° W). The relationship between ENSO and wind and solar PV over the whole of Africa is first investigated, followed by the impact of ENSO on the sites of interest. In this study, years were selected with an ENSO signal of at least $\pm 0.5^\circ$C in July–September (a time where ENSO has been shown to strongly influence rainfall over West Africa (Joly & Voldoire, 2009; Rowell, 2001), which then persists for the rest of the calendar year. Thus, the El Niño years used are 1982, 1987, 1991, 1997, 2002, 2004 and 2015, and the La Niña years used are 1988, 1998, 1999, 2007, 2010, 2011 and 2016. Composites of wind and solar PV CF are calculated for these years, and compared with the 42-year climatology.

3 | RESULTS

3.1 | Variability of existing wind and solar PV generation in Senegal

Figure 2 shows the mean diurnal and seasonal cycles of wind and solar generation over the four sites in Senegal. Solar generation has a strong diurnal cycle, peaking in the middle of the day, but exhibits consistent generation throughout the year (also found in Newton et al., 2014; Sterl et al., 2018); there is a slight dip in August, presumably due to enhanced cloudiness at the peak of the monsoon season. Wind power generation, however, is variable on both seasonal and diurnal timescales. On diurnal timescales, wind power generation peaks overnight and is lower during daytime hours—this is particularly pronounced during boreal spring. On seasonal timescales, wind power generation peaks during the boreal spring months, decreases during the boreal summer and increases again during boreal autumn—minimum wind generation is found during September. The combined wind and solar diurnal and seasonal cycles are weighted more heavily towards wind power, as there is 158 MW of installed wind capacity, while only 80 MW of installed solar capacity. However, because the solar is focused in daylight hours the combination of wind and solar leads to a fairly flat diurnal cycle, with a peak during the daytime. The combined seasonal cycle exhibits a dip during boreal summer, driven by the dip in wind power production during the boreal summer.

Figure S2 shows that high production days (top 1% of generation over the full reanalysis period) happen exclusively in the dry season, which could complement potentially depleting reservoir supplies. High production events are driven by anomalously high wind speeds off the coast of Senegal. Conversely, low production days (bottom 1% of generation) happen near to exclusively in

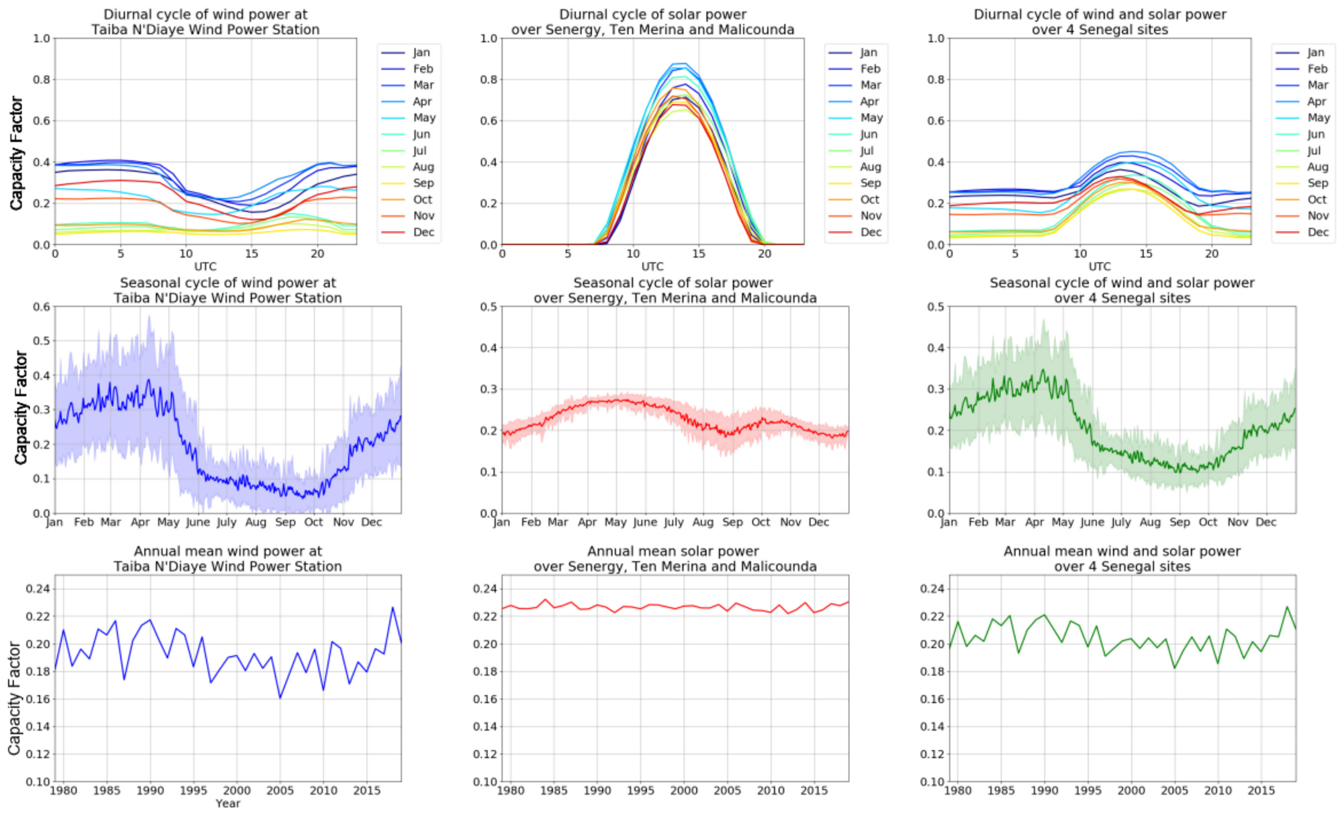

FIGURE 2 Diurnal (top) seasonal (middle) and inter-annual (bottom) cycles of wind (left), solar (middle) and combined wind and solar (right) capacity factor (CF) over the four sites in Senegal (see Table 1). The mean diurnal and seasonal cycle at each point was weighted by the installed capacity at each site.

the monsoon season and are driven by anomalously low solar power generation, with some contribution from low wind speeds (see bottom panels of Figure S2). The drivers of low production days can be explained by the seasonal cycles in Figure 2. Wind power generation is at its seasonal minimum during the wet season, solar is responsible for the bulk of renewable generation.

The bottom row of Figure 2 shows the inter-annual variability in wind, solar and combined power; this shows that inter-annual variability is fairly low, with larger variations in wind power than solar power. Figure 2 emphasizes the complementarity of wind and solar generation within Senegal, demonstrating that a combined portfolio of renewables acts to reduce variability on multiple timescales. Adeoye & Spataru, 2019 has shown that electricity demand peaks from July to October, and during the middle of the day. Comparing this to Figure 2 suggests that the periods of lowest wind generation (boreal summer and during the daytime) coincide with periods of highest electricity demand. This further emphasizes the need for a blend of wind and solar generation over Senegal. In this section, we have confirmed the results from Sterl et al., 2018 using an extended period of 40 years of data. The following section will examine the meteorological drivers of this behaviour.

3.2 | Meteorological drivers of renewable generation in Senegal

Drivers of daily variability in generation were examined, with a particular focus on the boreal summer. As detailed in Section 2.5.1, low production days in country-weighted wind and solar PV generation were identified, and were found predominantly to occur during the peak months of the WAM over Senegal, from August to September (see Figure S2). AEWs are the dominant synoptic-scale weather phenomena within the WAM, and peak during August and September (Cornforth et al., 2017). Furthermore, analysis of 'Weather Types' during the monsoon over Senegal reveals weather types associated with westward moving disturbances and AEWs (Moron et al., 2008; Rust et al., 2013). Thus, we examined the impact of AEWs on wind and solar production over Senegal.

Figure 3 shows the locations of the AEW tracks, and the distribution of wind power production, solar power

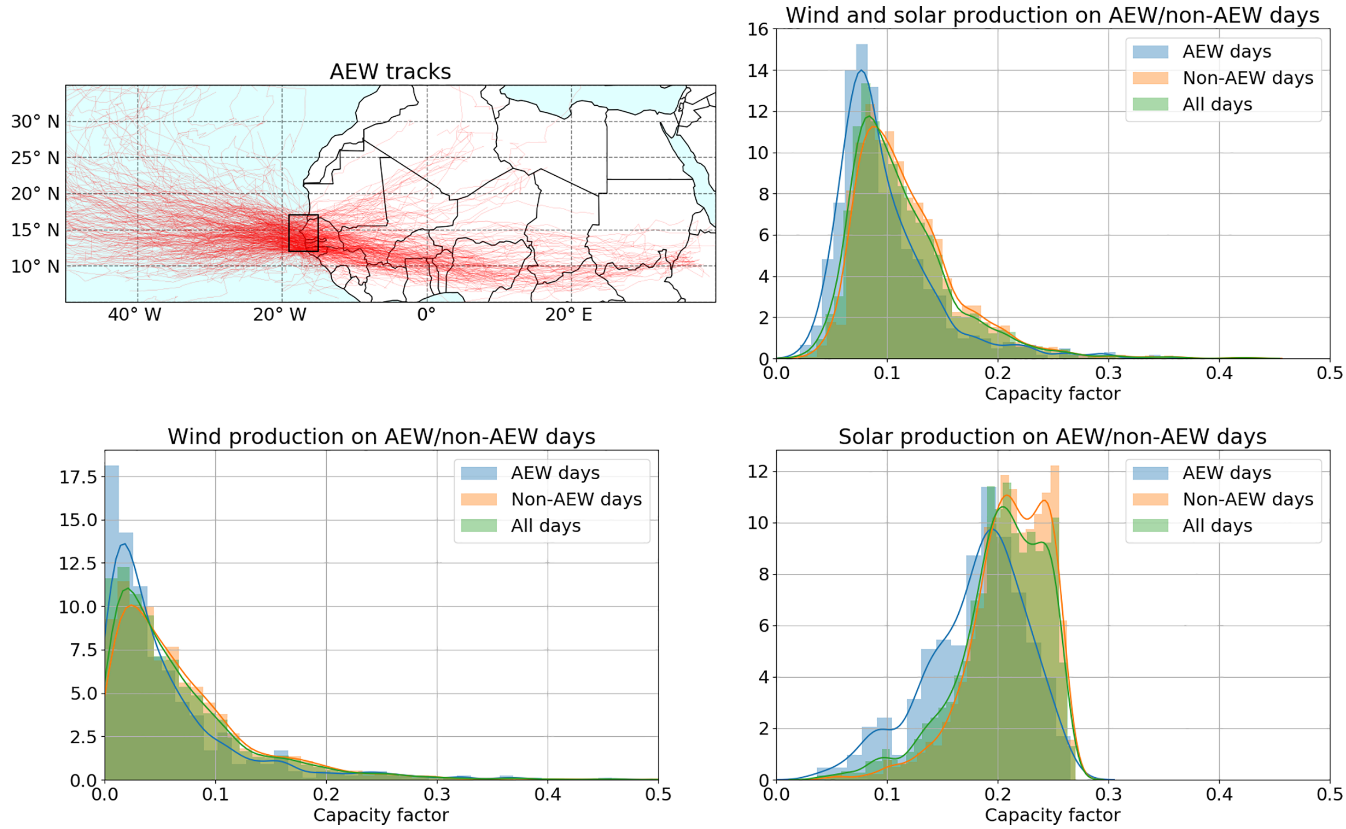

FIGURE 3 Influence of African Easterly Waves (AEWs) on wind and solar energy production over Senegal. (Top left) Map showing the tracks of AEWs from 1979 to 2018 where the box indicates the region used to define active AEW days. Histogram plots show the distribution of wind power (bottom left), solar power (bottom right) and combined production (top right) on active AEW days (blue) non-AEW days (orange) and all days (green) in August and September.

production and combined wind and solar production on days where an AEW passes through the black box in Figure 3 (AEW days), non-AEW days and all days during August and September (the peak of the monsoon season). The histograms in Figure 3 show both wind and solar CFs are generally lower on an AEW-day, with a clearer response seen for solar power.

The meteorological drivers of the reduced solar and wind power CFs are unpacked in Figure 4. A large positive precipitation anomaly is seen around Dakar and off the coast of Senegal during AEW days. This is associated with a reduction in shortwave radiation (due to cloud cover) and therefore reduced solar power CFs in the region of the Senegal coastline. Conversely, on non-AEW days, precipitation is lower and hence surface shortwave radiation and solar PV generation are higher (see Figure 3).

The most notable reduction is in solar power generation—but wind power generation is also reduced, and is generally low (CF less than 0.1) at this time of year. The Harmattan winds, which lead to high dry-season wind power potential, are not present over Senegal during the wet season. AEW days are associated with a southerly wind speed anomaly over the Senegal/Mauritania coastline. While the anomaly is more pronounced to the north, it partly impacts the winds over Senegal, explaining the marginally lower wind power generation shown in Figure 3 on AEW days. Sensitivity analysis showed that these results were consistent when the region of interest (black box in Figure 3) was modified (not shown).

This highlights the importance of accurate forecasts and tracking of AEWs for the renewable energy sector, as knowledge of the timing of their arrival can prepare system operators for likely periods of reduced renewable generation.

Although this analysis has focused on the meteorological drivers of low renewable generation in the wet season, we note that there are a few interesting days of extremely low renewable generation happening in the dry season (see Figure S2). These are January 15, 1980, February 4, 1981, January 15, 1992, and January 7, 2003. Examining past weather records does not show any notable behaviour on these days except 'dust and haze', but they provide interesting case studies for future analysis.

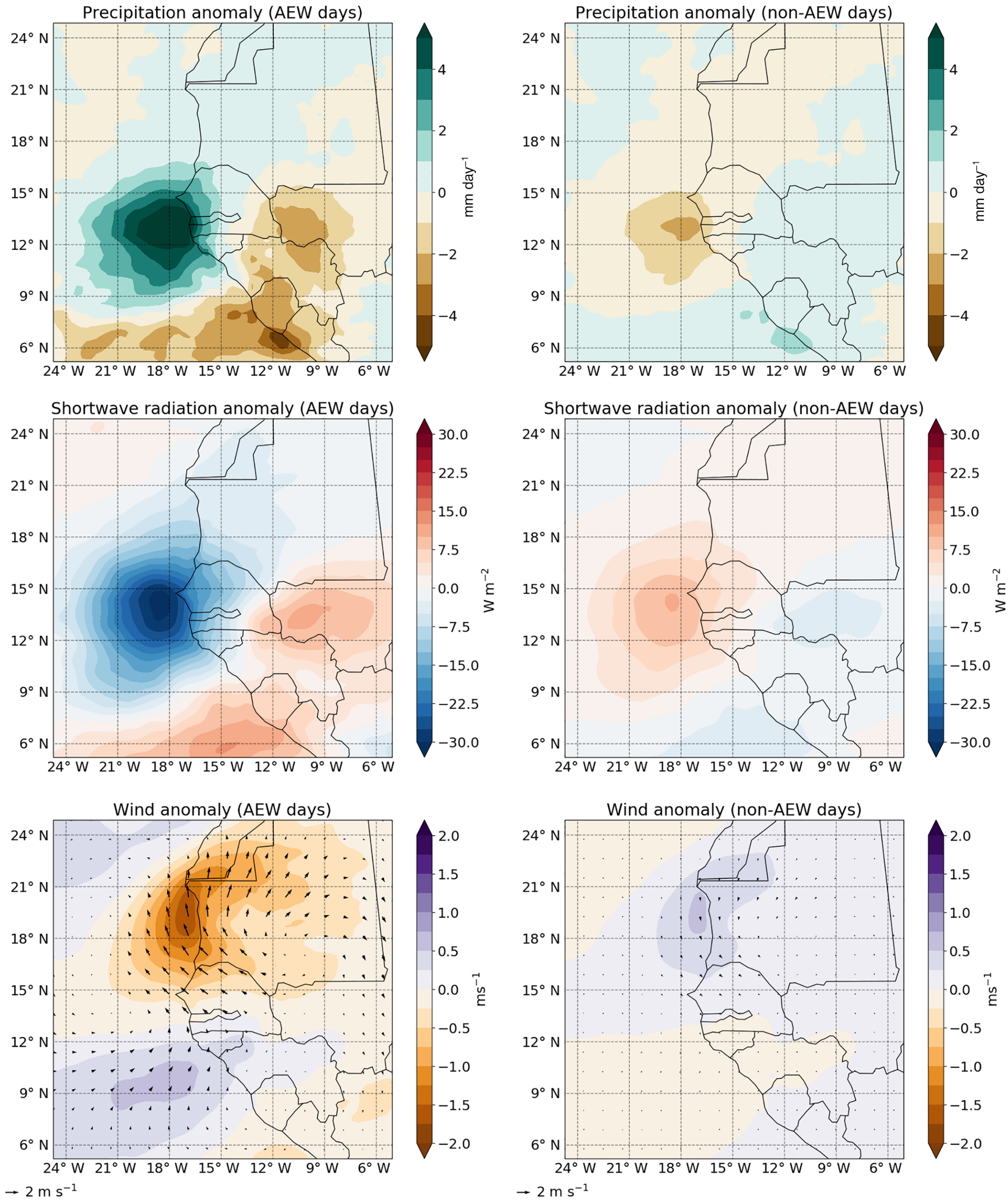

FIGURE 4 Anomaly in precipitation (top), surface shortwave radiation (middle) and 100 m wind speed and direction (bottom) on days with an active African Easterly Wave (AEW) in the vicinity of the Senegal coastline (left) and days without an active AEW in the vicinity of the Senegal coastline (right). Only days in August and September were included.

3.3 | Variability of existing wind and solar PV generation in Kenya

The top panels of Figure 5 show the monthly mean diurnal cycles for operational wind and solar farms over Kenya (see Table 1 for details of their locations). The diurnal cycles of solar power CF are similar throughout the year, with a peak at approximately 10:00 AM (1:00 PM local time). Generation peaks in boreal winter, within a minimum in boreal summer and an average difference in peak capacity factor of 20%. In contrast to this, the monthly mean diurnal cycles of wind power capacity factor show contrasting behaviour throughout the year. Generally, capacity factors are much lower for wind power than for solar power, although we note that in reality these farms record capacity factors of over 50%,

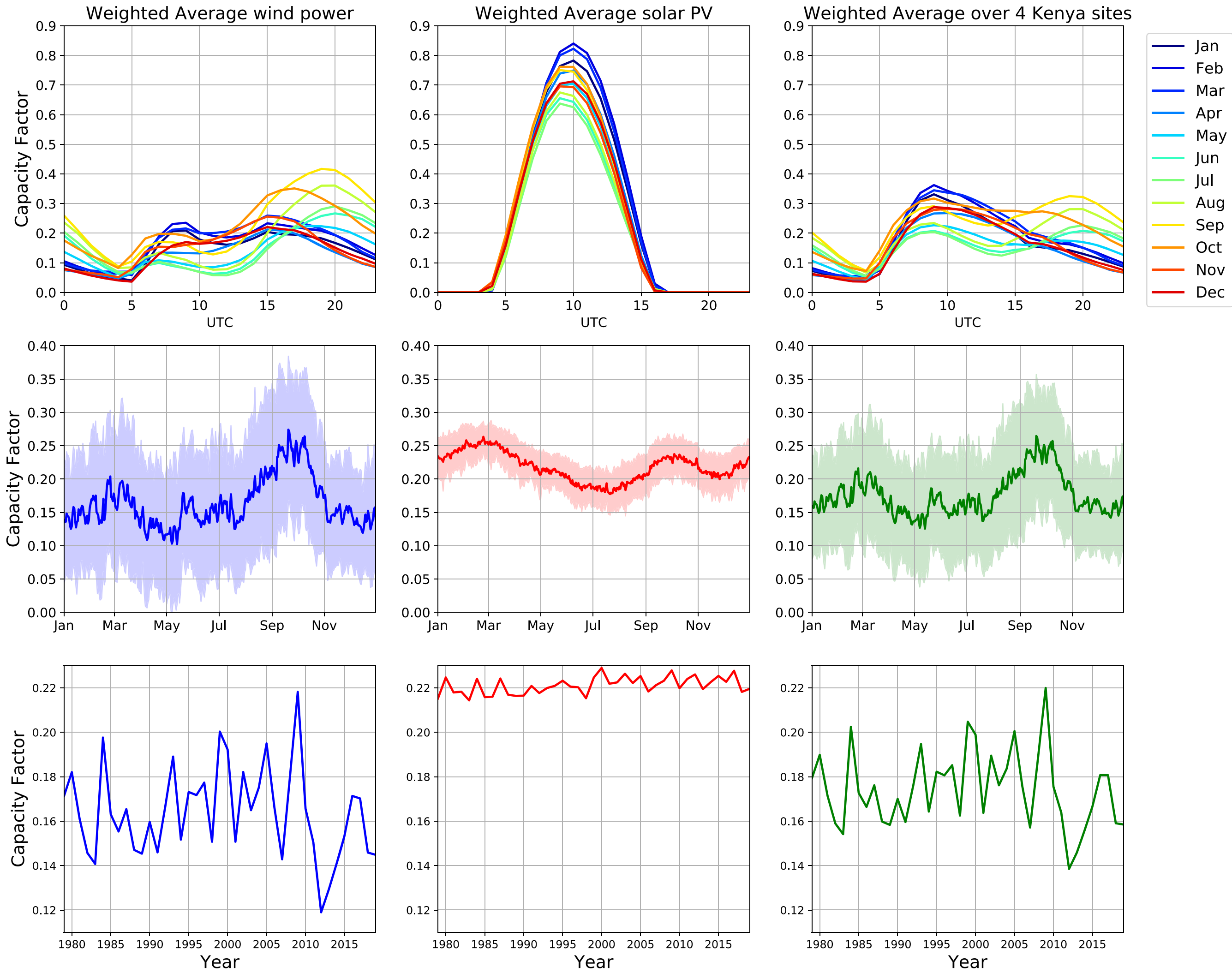

FIGURE 5 Diurnal (top) seasonal (middle) and inter-annual (bottom) cycles of wind power (left), solar power (middle) and combined wind and solar power (right) capacity factor (CF) over the four sites in Kenya (see Table 1). The mean CF at each point was weighted by the installed capacity at each site.

suggesting some deficiencies in ERA5 wind speeds in the region. It is beyond the scope of this work to correct these deficiencies as this is a region with a particularly limited observation network (King et al., 2021).

In boreal winter, peak wind capacity factors are found during the daylight hours with peaks of 20%, whereas diurnal peaks of 40% are found in September evenings. This change in seasonal variability could be related to the seasonal cycle of the Turkana Jet, as this is the region where the largest Kenyan wind farm is located.

A weighted average of wind and solar PV capacity factors is also provided in Figure 5. This highlights the complementary characteristics of solar and wind power in Kenya, as wind generation is present during hours of darkness throughout the year, and solar power can support the relatively low daytime wind power generation in boreal winter. The time of highest combined generation is from 08:00 AM to 10:00 AM in January. This is a time of minimum daytime demand in other African nations where data are available (Adeoye & Spataru, 2019). Therefore, further deployment of renewables in this region may require advancement of grid infrastructure to include short-term energy storage.

The seasonal cycle of wind power capacity factors over Kenya is less pronounced than that previously discussed for Senegal (compare Figures 5 with 3). Wind power capacity factor peaks in September with a minimum from May to July. We note that this minimum still provides a much higher generation level than that seen in Senegal, confirming previous resource assessments that this region can provide reliable generation throughout the year (Fant et al., 2016). Solar capacity factors peak in March, although there is very little variability in the

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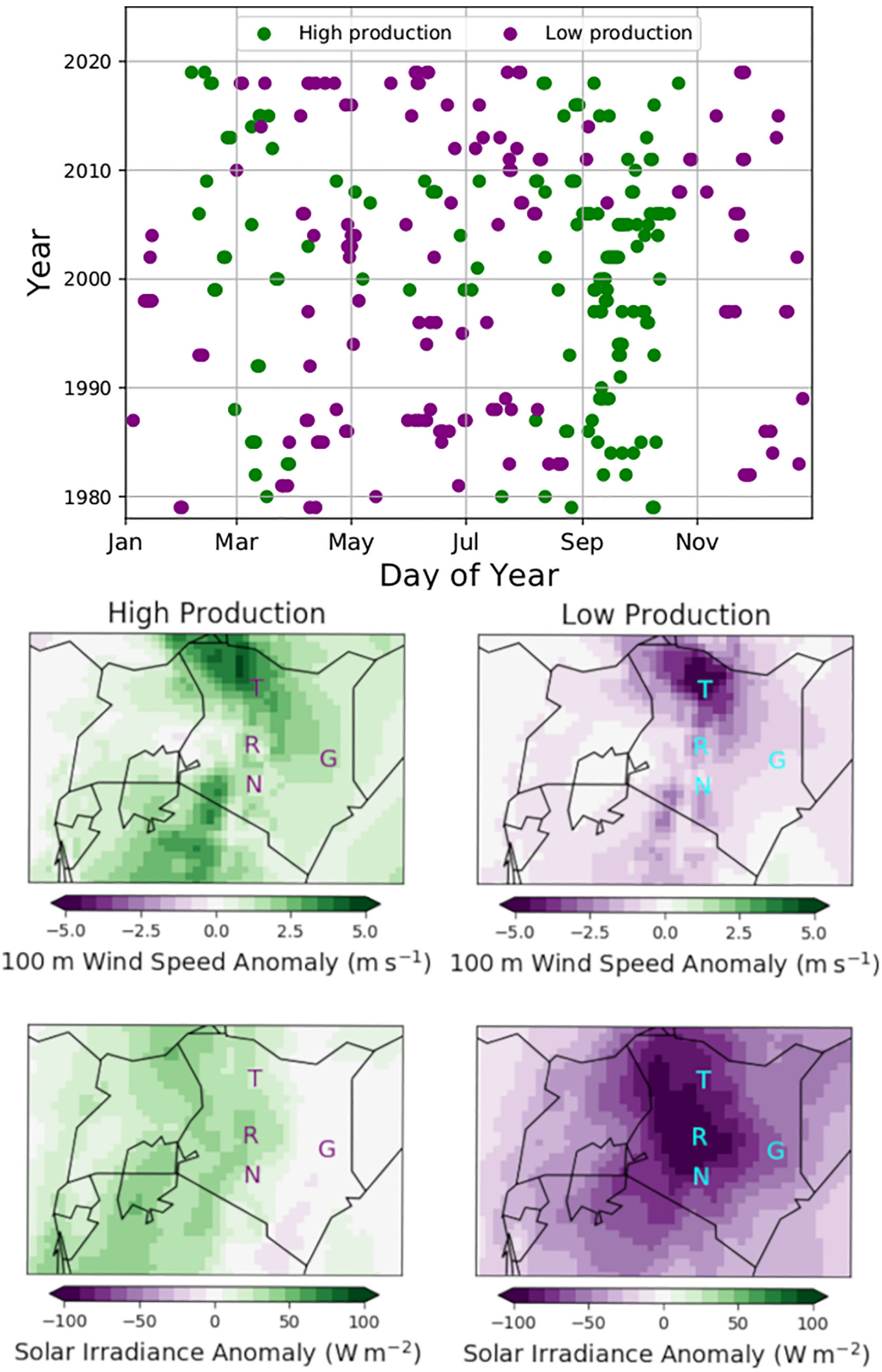

FIGURE 6 Top: Details of the high production (green; top 1%) and low production (purple; bottom 1%) of weighted wind and solar power generation in Kenya. Bottom: Wind speed and surface solar radiation anomalies during the high and low production events with letters marking the four sites from Table 1.

output throughout the year. The combination of wind and solar power capacity factors acts to moderately reduce the variability seen in the wind power generation, although we note that this result is influenced by the proportionally greater amount of wind than solar power generation.

Figure 5 shows considerable inter-annual variability in the wind power capacity factors over Kenya. The most marked differences are seen between 2008 (average CF of 22%) and 2011 (average CF of 12%). These large year-to-year variations could severely impact the profits of Kenyan wind farm developers, and the ability to provide a reliable power supply. We note however that the solar power generation exhibits very low inter-annual variability, and again, the combination of wind and solar power acts to reduce the inter-annual variability. The low CF year of 2011 has previously been identified as a strong La Nina year (see Section 2.5.2). Potential meteorological drivers of this inter-annual variability are discussed in Section 3.5.

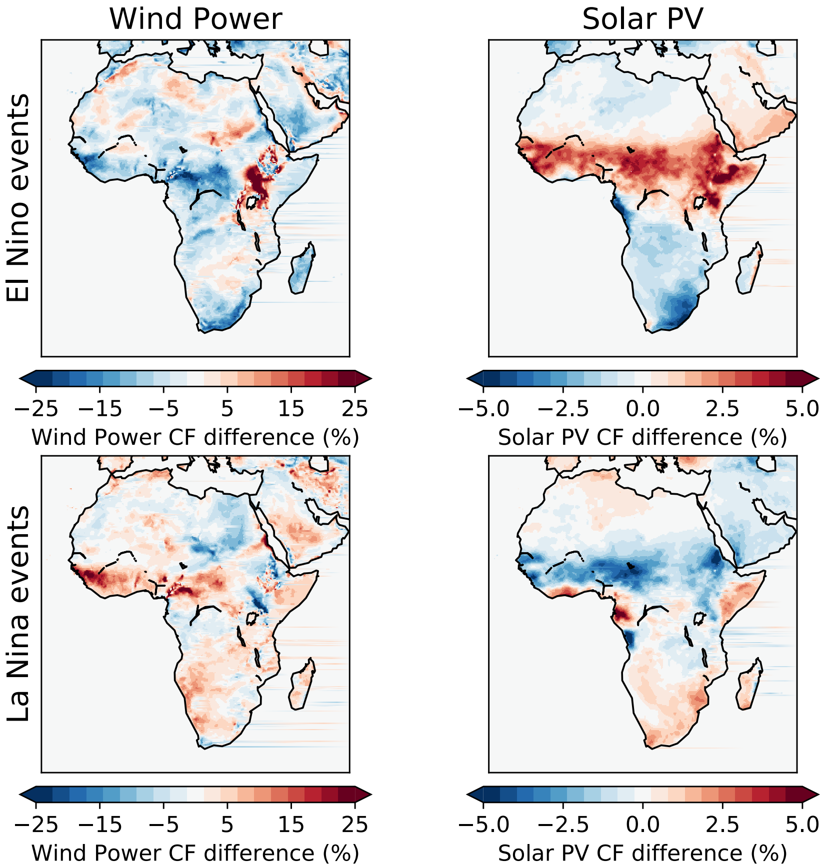

FIGURE 7 July–September anomaly composites of wind power (left) and solar power (right) generation in the seven largest El Nino events (top) and La Nina events (bottom). See Section 2.5.2 for details of the years. See Figure S3 for ocean data.

3.4 | Meteorological drivers of renewable generation in Kenya

In this section, meteorological drivers of the highest (top 1%) and lowest (bottom 1%) of weighted wind and solar generation over Kenya (see Table 1 for the sites used) are considered. Figure 6 shows that the majority of high production days occur in September, when there is a peak in the seasonal cycle of wind power and solar power CF (see Figure 5). High production events are also seen in early March when secondary peaks are present in wind and solar CF. Conversely, low production events are present throughout the year. Both high and low production events are well spread throughout the study period (1979–2019).

Figure 6 shows that the high production events are associated with very large positive 100 m wind speed anomalies over the Turkana Jet region, particularly over the Lake Turkana wind farm (labelled 'T' on Figure 6). Interestingly, these are also days of anomalously high solar irradiance at two of the three solar sites. The low production events are at times of anomalously low wind speeds in the Lake Turkana region. During these times, the solar anomalies are anomalously low and widespread over Kenya and neighbouring countries. The timing of high production events in September and March is consistent with the Turkana Jet, peaking in boreal spring and autumn (King et al., 2021; Nicholson, 2016). King et al. (2021) also found a negative correlation between Turkana Jet strength and rainfall over western Kenya, consistent with the finding here of high wind speeds in the Turkana Jet region and higher solar generation (implying greater irradiance and hence less cloudiness and less rain).

These results suggest at times of highest production resource curtailment could be required as both wind and solar capacity factors are high, whereas at times of low production there is widespread stillness and cloudiness across the whole of Kenya, suggesting alternative solutions (such as hydropower) may be in high demand. With the current operational renewable portfolio, the behaviour of the Turkana Jet dominates the amount of renewable generation available. The predictability of the behaviour of this phenomenon is therefore very important for understanding potential renewable generation in the region.

3.5 | Climate drivers of renewable generation

Section 3.3 has previously shown large inter-annual variability in wind power CF over Kenya; the possible

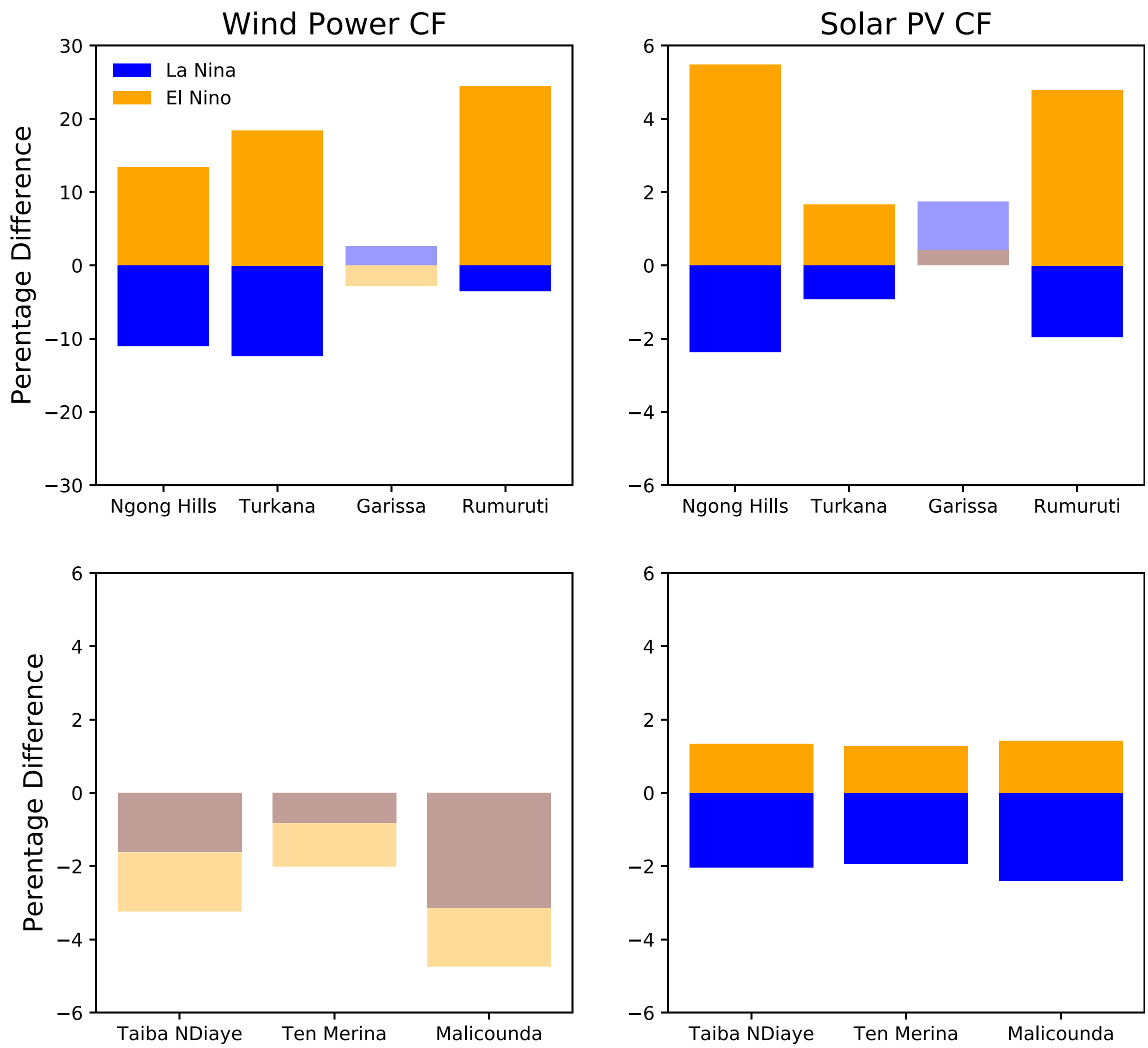

FIGURE 8 Percentage difference in July–September wind power capacity factor (CF) (left) and solar PV CF (right) for the four sites in Kenya (top) and Senegal (bottom) averaged over the seven largest La Nina (blue) and El Nino (yellow) events, compared with the long-term seasonal mean. See Section 2.5.2 for details of the years. Light shading indicates that the sites did not exhibit significant correlation between ENSO index and wind/solar generation.

relationship of this variability with ENSO is now investigated. Two seasons are considered; July–September (JAS) when ENSO has been shown to influence WAM rainfall (Joly & Voldoire, 2009; Rowell, 2001) and October–December (OND) when ENSO influences East Africa rainfall (Indeje et al., 2000).

Figure 7 shows boreal summer (JAS) composites of wind power CF and solar power CF over the African continent during El Niño and La Niña years. Generally wind power CF is below average during El Niño years, although there are regions such as the Turkana Channel and off the coast of Senegal, (see Figure S3 for coastal regions) with positive CF anomalies. During La Niña, this pattern is reversed and low wind power CFs are seen over northwest Kenya, with the opposite dipole of CF seen off the Senegalese coast. We note from Figure 1 that these are regions where on average wind power CF is highest.

These results are interesting when combined with the boreal summer solar CF El Niño/La Niña anomalies. During El Niño years, anomalously high solar CFs are seen across the Sahel, with anomalously low CFs in La Niña years (Figure 7). This is consistent with lower WAM rainfall (hence higher solar generation) during El Niño years (Rowell, 2001).

Figure 7 suggests that during El Niño years, when there is a reduction in boreal summer WAM rainfall, over both of our study regions there would be anomalously high wind and solar CF, which, in the case of Senegal, would compensate for lower hydropower generation. While there are no hydropower plants in Senegal, Senegal obtains some electricity from the Manantali Dam in Mali, which receives rainfall during the boreal summer WAM. Conversely, during La Niña years, wind and solar CF may be below average and there may be heavier competition for hydropower resources.

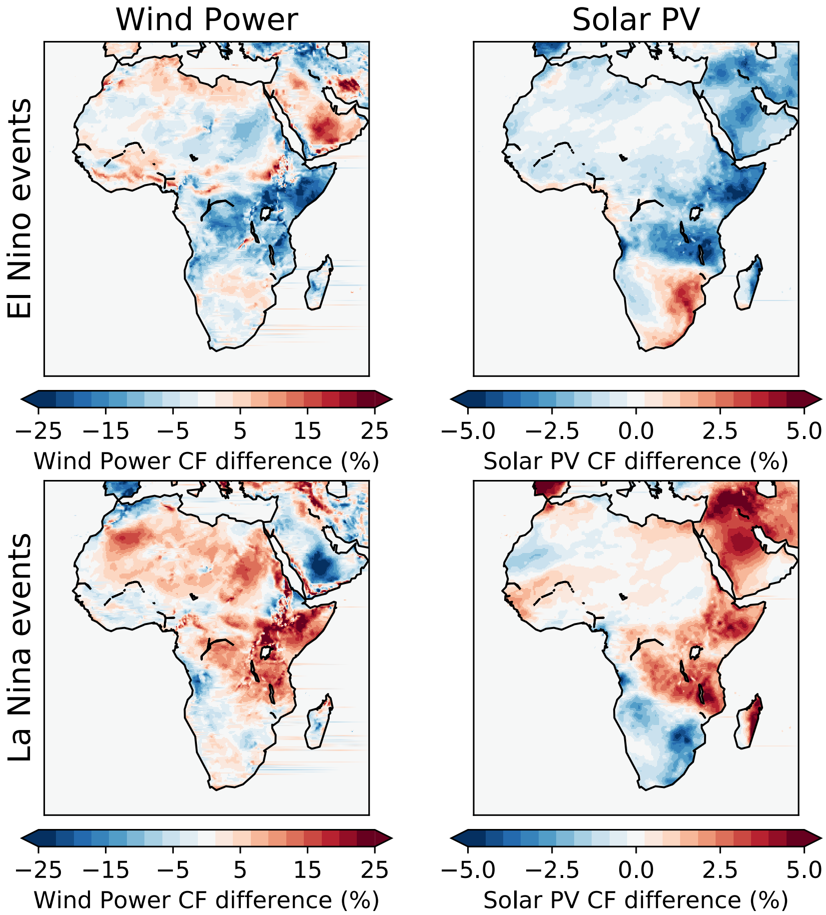

FIGURE 9 October–December anomaly composites of wind power (left) and solar power (right) generation in the seven largest July–September El Nino events (top) and La Nina events (bottom). See Section 2.5.2 for details of the years. See Figure S4 for ocean data.

Figure 8 shows the percentage difference in JAS wind and solar CF at the sites of interest. Over the Senegal locations, we see no significant relationship between the wind power CF and ENSO, whereas for solar, we see a significant relationship where generation is on average 1% higher during El Niño. This relationship is much stronger in Kenya where approximately 20% (10%) more (less) wind power generation would be seen during JAS in an El Niño (La Niña) year, which would be particularly significant at sites like the large Lake Turkana wind farm (see Table 1). The anomalies are much smaller for solar CF over Kenya with approximately 5% (1%) more (less) solar power generation during El Niño (La Niña). We note here that wind power generation is generally more variable on seasonal timescales (see Figures 2 and 6) so it is not surprising they are seeing a larger ENSO influence.

Figure 9 shows spatial anomaly composites of wind and solar CF from OND (for the same set of El Niño/La Niña years). The spatial patterns of wind and solar CFs are quite different from those seen in Figure 7 with the largest responses over East Africa. In these periods, El Niño (La Niña) events are associated with anomalously low (high) wind and solar CF over Kenya. Lower solar generation during El Niño years is consistent with wet OND anomalies over East Africa during El Niño years (Indeje et al., 2000). Given this is the opposite response to that seen in JAS (the preceding season), it suggests that over this region investment in seasonal storage (such as large batteries or solar thermal storage) could provide a long-term solution to excess/lack of renewable generation.

Figure 10 shows that at our sites of interest in Senegal there is no significant relationship between OND wind and solar CFs and ENSO. Significant results are seen in Kenya, with El Niño (La Niña) resulting in 15% (10%) less (more) wind power CF (Figure 10). Again smaller anomalies are seen for the less variable solar power CF, and a significant response is not seen at the solar farm location (Garissa) only at the Lake Turkana wind farm. This significant relationship suggests that accurate seasonal forecasts of ENSO would be particularly useful in anticipating times of anomalously high/low wind power generation over Kenya, with some small benefits to anticipating solar PV generation over Senegal.

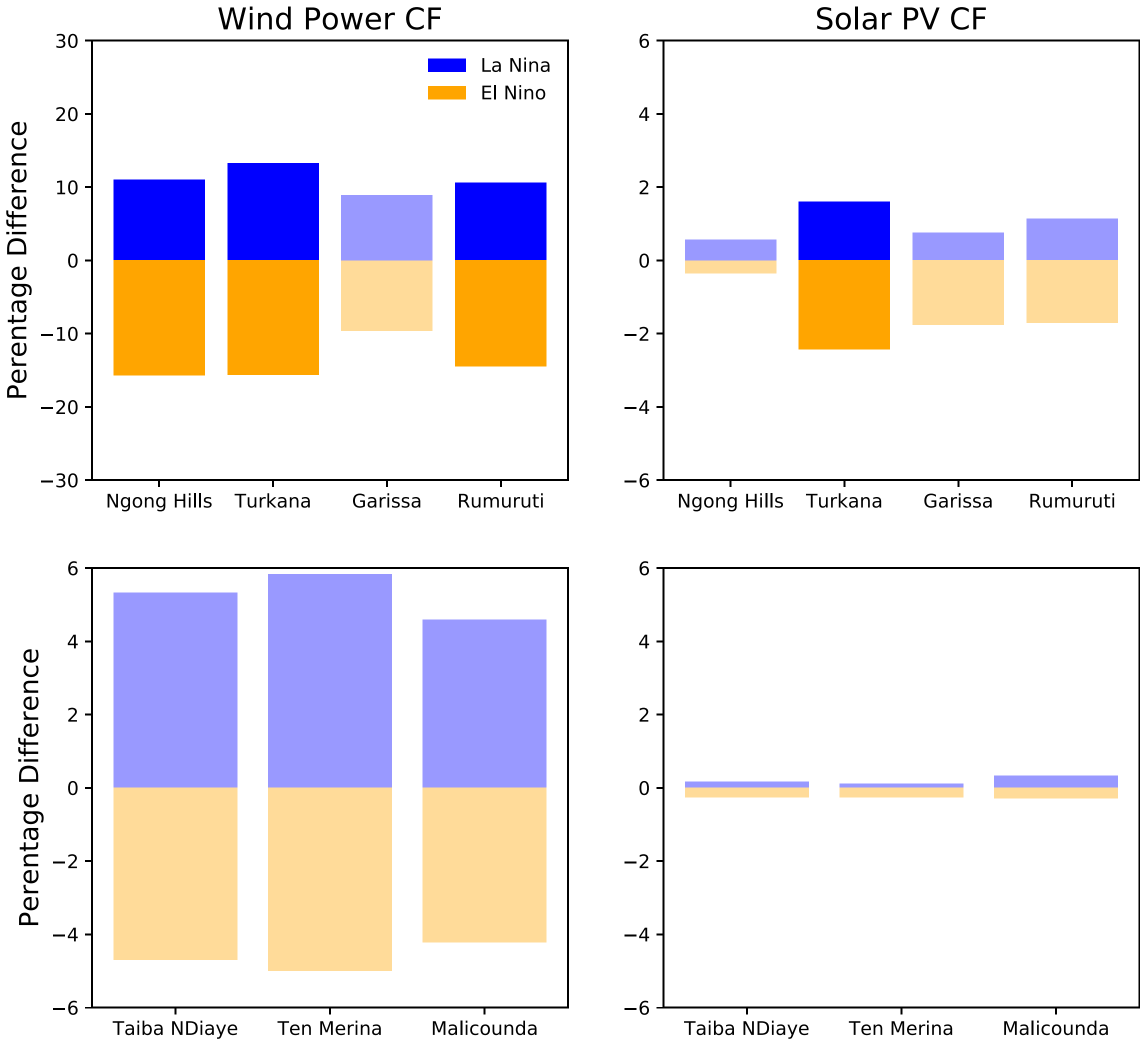

FIGURE 10 Percentage difference in October–December wind power capacity factor (CF) (left) and solar PV CF (right) for the four sites in Kenya (top) and Senegal (bottom) averaged over the seven largest La Nina (blue) and El Nino (yellow) events, compared with the long-term seasonal mean. See Section 2.5.2 for details of the years. Light shading indicates that the sites did not exhibit significant correlation between ENSO index and wind/solar generation.

4 | DISCUSSION AND CONCLUSIONS

This article has shown the variability of wind and solar PV generation on diurnal, seasonal and inter-annual timescales across two case study regions of high population density and large proposed renewable growth: Senegal (Figure 2) and Kenya (Figure 5). At both sites, the diurnal cycles of existing wind and solar generators were found to be complimentary, with wind helping to balance out the lack of solar generation provided at night (supporting the previous work of Sterl et al., 2018). In Kenya, the peak in the diurnal cycle of wind and solar CF occurs at a time of low demand (Adeoye & Spataru, 2019). This supports the conclusions of (Moner-Girona et al., 2016), suggesting that short-term storage or demand-side management (e.g., load shifting from day to night) could be useful if more wind and solar generation is installed.

In Senegal, the seasonal cycles of wind and solar CF are relatively correlated, with both peaking in April–May. Solar provides more stable levels of generation throughout the year, which helps compensate for the variability of the wind power generation (Figure 2). In Senegal, the seasonal minimum in wind power CF is aligned with the time of highest demand (Adeoye & Spataru, 2019), suggesting the need for a blend of wind and solar in the region. In both regions, the inter-annual variability of solar power CF is much lower than wind power CF at existing sites. The wind power CF has particularly large inter-annual variability at the Kenyan wind farm locations, which could result in problems for providing reliable supply, and for wind farm developers repaying loans.

The meteorological drivers of wind and solar CF have been investigated for both regions. In Senegal, the passing of an AEW results in reduced wind and solar CF (Figure 3). However, it is noted that during AEW days high precipitation anomalies are found towards the West coast of Senegal, and in general wet years over West Africa tend to have longer and more active AEW seasons (Grist, 2002). This suggests that summers with more AEW activity, and hence lower wind and solar potential, may receive more rainfall and hence higher potential for productive hydropower generation (Figure 4). Furthermore, El Niño events have been found to occur in conjunction with seasons with suppressed AEW activity (Ruti & Dell'Aquila, 2010). Currently, all wind power developments in Africa are onshore due to the relatively higher costs associated with offshore generation (Hafner et al., 2018). However, here we see that there are some good potential offshore wind generation sites off the North coast of Senegal and Mauritania during non-AEW days (see Figure 4) that could complement existing generation sites. We note that our meteorological driver analysis was predominantly focused around the wet season, as this is the season in which the majority of African climate impacts research is focused. Understanding the drivers of wind power variability in the dry season is a key topic requiring future research.

Over Kenya, the times of highest existing wind and solar CF are found in September–October where the strength of the winds in the Turkana Jet is maximized (Figure 6). Low production events are found throughout the year, and are associated with widespread regions of anomalously low solar irradiance, and low wind speeds in the Turkana Jet region. These large regions of low wind speed and solar irradiance suggest times when there will be a strong need for hydropower in Kenya, and likely heavy competition for the resource, with neighbouring countries also experiencing poor generating conditions (Figure 6). This will be particularly problematic when times of low wind and solar CF combine with dry seasons and drought years (Naibei, 2017).

On seasonal timescales, ENSO has been shown to have a strong relationship with wind power generation over Kenya, with anomalously high wind power CFs (and to a lesser extent solar CFs) in July–September during El Niño with the opposite for La Niña (Figure 7). Interestingly, we find that the opposite conditions are seen in the October–December periods, which follow these JAS seasons (Figure 9). So, although a boreal summer El Niño event may result in anomalously high wind and solar generation over Kenya, it is likely that the October–December period will have anomalously low wind and solar generation. This promotes consideration of seasonal storage options when developing African energy grids, and highlights how seasonal forecasts of ENSO could be useful for anticipating times of high/low renewable generation over Africa.

In this study, just one reanalysis dataset (ERA5) was used to provide meteorological variables for calculating wind and solar power CFs. This may have some limitations, especially for wind power generation, as previous studies have highlighted potential issues with ERA5 (Bloomfield et al., 2020; Ramon et al., 2019). Using observed data of the Turkana Jet Munday et al., 2022 found that ERA5 underestimates low-level wind speeds in the Turkana Jet region by around 30%. King et al. (2021) shows three different reanalysis products perform quite differently over Kenya; however, the lack of available observational wind data makes it difficult to determine which is most accurate. Further studies, if possible using observational data, should examine this.

This study focuses on the present climate (1979–2019), and climate change may also play a role in the development of renewable generation over the two regions. Except for a few regions in eastern central Africa, there is a low probability of significant changes in wind and solar potential over Africa under future climate change, with the majority of changes favouring the implementation of renewable generation (Fant et al., 2016; Sawadogo et al., 2020; Soares et al., 2019). Climate change could, however, lead to changes in the diurnal cycle of wind power potential (Célestin et al., 2019) and reductions in solar PV potential over West Africa (Danso et al., 2022).

This study has demonstrated the complementarity of wind and solar power generation over Senegal and Kenya and explored weather and climate conditions, which can lead to particularly anomalous wind and solar capacity factors. With this knowledge, the ability of future wind and solar sites to compliment existing generation can be assessed. More widely this work supports the global journey to ensure universal access to affordable, reliable and low-carbon energy services.

AUTHOR CONTRIBUTIONS

Hannah C. Bloomfield: Conceptualization (equal); data curation (equal); formal analysis (equal); funding acquisition (equal); methodology (equal); project administration (equal); supervision (equal); writing – original draft (equal); writing – review and editing (equal). **Caroline M. Wainwright:** Conceptualization (equal); formal analysis (equal); funding acquisition (equal); project administration (equal); supervision (equal); writing – original draft (equal); writing – review and editing (equal). **Nick Mitchell:** Formal analysis (equal); investigation (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST

The authors declare no conflict of interests in this study.

DATA AVAILABILITY STATEMENT

The ERA5 dataset used in this study is available from the Climate Data store: https://confluence.ecmwf.int/display/CKB/How+to+download+ERA5. The ENSO index data are taken from: https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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