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A new approach for assessing synergies of solar and wind power: implications for West Africa

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A new approach for assessing synergies of solar and wind power: implications for West Africa

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**Keywords:** renewable energy, power mix, West Africa, energy policy, reanalysis data, climate servicesSupplementary material for this article is available [online](#)**Abstract**

West African countries' energy and climate policies show a pronounced focus on decarbonising power supply through renewable electricity (RE) generation. In particular, most West African states explicitly focus on hybrid mixes of variable renewable power sources—solar, wind and hydropower—in their targets for the electricity sector. Hydropower, the main current RE resource in West Africa, is strongly sensitive to monsoon rainfall variability, which has led to power crises in the past. Therefore, solar and wind power could play a stronger role in the future as countries move to power systems with high shares of RE. Considering the policy focus on diversified RE portfolios, there is a strong need to provide climate services for assessing how these resources could function together in a power mix. In this study, climate data from the state-of-the-art ERA5 reanalysis is used to assess the synergies of solar photovoltaic (PV) and wind power potential in West Africa at hourly resolution. A new metric, the stability coefficient C_{stab} , is developed to quantify the synergies of solar PV and wind power for achieving a balanced power output and limiting storage needs. Using this metric, it is demonstrated that there is potential for exploiting hybrid solar/wind power in a larger area of West Africa, covering more important centers of population and closer to existing grid structures, than would be suggested by average maps of solar and wind resource availability or capacity factor for the region. The results of this study highlight why multi-scale temporal synergies of power mixes should be considered in RE system planning from the start.

1. Introduction

Electricity demand in West Africa (WA) may increase fivefold by 2030 compared to 2013 [1]. To meet this rising demand while contributing to the objectives of the Paris Agreement [2], nearly all WA countries' energy policy targets envision a mix of renewable electricity (RE) sources in the future—typically solar, wind and hydropower. Most WA countries have targets for the RE share in power production and/or installed RE capacity in the near future [3–16]. The region-wide forecast in the ECOWAS (Economic Community Of West African States) Renewable Energy Policy (EREP) also foresees strong growth in

solar, wind and hydropower capacity up to 2030 [17]. These power sources are all weather- and climate-dependent; therefore, if they are to be part of future power systems, their potential synergies must be estimated such that they can be optimally combined [18].

Solar, wind and hydropower potential in WA is governed by the monsoon, which causes the seasonal variability of solar potential due to changing monsoon cloud cover; that of wind potential due to the switch from Harmattan (strong) to monsoon (weak) conditions around the monsoon trough [19]; and that of water availability for rivers and reservoirs due to the seasonality of precipitation. Currently, most RE

generation in WA is hydropower; for some countries it is even the main power source [20].

Clearly, other sources would have to be added to a future power mix to ensure reliable power supply, since the overdependence of some countries on rainfall for hydropower has been highlighted as principal reason behind past power crises [21–23]. The role of other sources in future power systems with substantial RE shares would thus be to mitigate this dependence, reducing power variability and shock risk. The 100%-RE scenarios for sub-Saharan Africa in [24], in fact, see only a limited future role for hydropower in WA.

Solar photovoltaic (PV) power has excellent technical potential in WA [25], but heavy reliance on solar PV causes balancing problems on diurnal timescales [26]. Across WA, wind power potential on its own is not estimated as particularly high [27, 28]; wind speed is quite variable temporally and geographically, with the highest potential found towards the north/north-west [25, 27, 29, 30]. However, wind speed has a pronounced diurnal cycle in many places in WA: pressure gradients drive nocturnal low-level jets (NLLJ) whose signatures are already discernible between 100–200 m [31, 32], and which disappear during daytime due to thermal turbulence [19, 31–34]. Thus, electric power production from large wind turbines could have an opposite diurnal cycle to solar power production, complementing it in a hybrid power system [34]. The potential for concentrated solar power (CSP) in combination with thermal storage is also promising [35], although it has not yet been deployed anywhere in WA [25]; it is currently still deemed less economic than solar PV for the short-term future according to the EREP [17], but this is poised to change as costs of CSP have recently decreased strongly [36].

Therefore, under the right circumstances, a mix of solar PV, CSP, wind and hydropower could be a good candidate for WA power systems, if (i) solar PV and wind power synergise well on diurnal scales, limiting the need for storage and other flexibility options; (ii) hydropower (e.g. conventional, pumped-storage, run-of-river) and CSP with storage can bring additional (e.g. seasonal, peak-shaving) stability; and (iii) the day-to-day and interannual variability of such a system remains small. Literature attempting to quantify RE resource synergies for WA is scarce; currently available data on RE potential in WA remains limited to annual average resource availabilities [1, 25, 27, 29, 30, 37]. This study is aimed at going beyond these averages by proposing a new metric for quantifying the synergies between solar PV and wind power potential for hybrid systems on diurnal and seasonal scales, and demonstrating its implications for the West African context. Solar/wind power mixes have received substantial attention recently [38–49], but assessments for WA, such as [50], are rare.

This paper is organised as follows. Section 2 focuses on methodological aspects concerning the assessment of hybrid power mixes and describes the new

metric proposed in this study. Section 3 presents the main results. Section 4 brings forth several discussion points, and section 5 ends with conclusions. Methodological details are given in the supplementary material available online at stacks.iop.org/ERL/13/094009/mmedia.

2. Methodology and approach

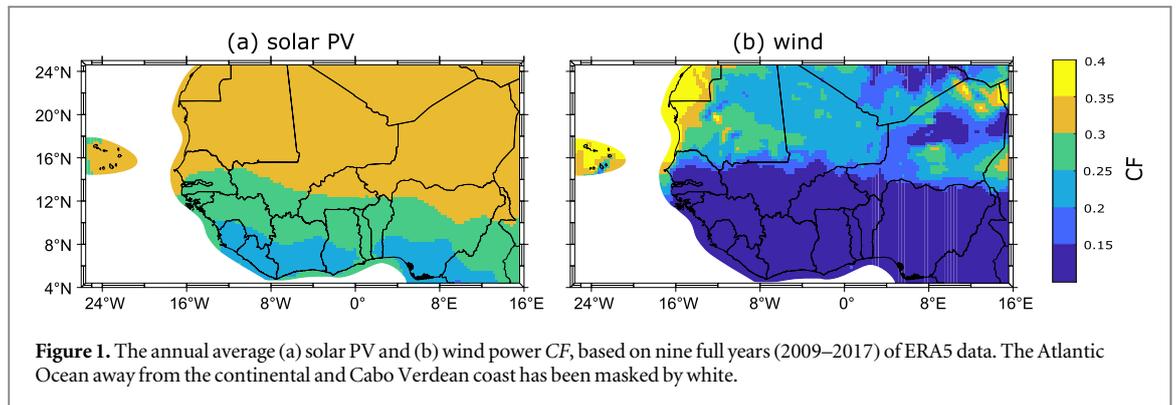
2.1. Calculation of capacity factors (CFs)

In this study, the CF of solar PV cells is modeled based on monocrystalline silicon cell efficiency as function of global horizontal irradiation (GHI) G and air temperature T , following [51]. The wind turbine CF is modeled following [52] as function of hub-height wind speed V , based on Vestas V126-3.3 turbines with 117 m hub-height and 3.3 MW rated power, the type currently used for one of WA's largest wind power projects, in Taïba Ndiaye, Senegal [53]. (See supplementary material A for details.) The state-of-the-art European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis is used to obtain G , T and V at 31 km spatial and hourly temporal resolution (see supplementary material B). Using ERA5 data allows following best-practice recommendations on estimating hub-height wind speed [54] (see supplementary material C).

Our domain covers [4°N–25°N; 26°W–16°E], covering all 15 ECOWAS member countries. Figure 1 shows solar and wind CF across the domain, using $CF = 0.15$ as lower threshold (stricter than [55, 56]). Solar potential is high on average, with CF generally increasing northward (due to diminishing monsoon influence) and reaching 0.30 over large parts of the territory. Wind power potential is weaker and concentrated in the north, with Mali, Niger and Senegal the only ECOWAS countries having substantial areas with $CF \geq 0.15$.

A prerequisite for using ERA5 data is an evaluation of the relevant reanalysis parameters by comparison to observations from the region. Irradiance, near-surface temperature, and near-surface wind speed measured by 15 meteorological stations, covering up to three years of data with sub-hourly resolution, spread across four WA countries, have been compared to hourly data from the corresponding ERA5 grid cells. An evaluation has been undertaken of (i) whether biases exist in ERA5, through the criterion that the Perkins skill score (S_{score}), reflecting the common area of probability density functions (PDFs) from reanalysis and observations, is larger than 70% as skill indicator [57, 58], and (ii) whether ERA5 reproduces diurnal wind cycles, using the correlation coefficient C_{corr} between reanalysis and observations.

This evaluation indicates that the median S_{score} is higher than 70% for 12 (GHI), 15 (temperature) and 11 (wind speed) out of 15 stations (see supplementary material D). For those stations, therefore, more than 70% of observed PDFs is captured by ERA5



in a majority of recorded months. C_{corr} is found to be very high, between 80% and 90% on average, also in individual cases where $S_{\text{score}} < 70\%$ for wind speed, indicating that deviations are mostly mean value biases, not misrepresentations of diurnal wind cycles. In conclusion, we find no objections to using ERA5 for understanding solar-wind synergies across WA.

2.2. Power mixes

Several criteria exist for how mixing different RE sources can positively impact power systems, such as through smoothing (reducing variability) of power output [43, 44, 47, 49] or supply-demand balance [41, 42, 45, 48, 59], or lowering system costs [50, 60–62]. These are usually interlinked: e.g. smoothing of electric power output implies lower variability and fewer shocks, thus less need for storage and lower balancing costs [63]. In this study, smoothness of power output is used as criterion, i.e. without explicitly considering demand profiles; see section 4 for a discussion.

To quantify hybrid power output smoothness, many studies use statistical measures, such as (anti) correlation coefficients between power production from different resources [40, 43, 44, 47, 59], or variabilities of energy balance shapes, assuming (multi)-annual average power production is equal to average demand [41–43, 48]. Such approaches have been valuable in exploring synergies between renewable resources in various regions. However, when applied on diurnal timescales, they can cause the following issues:

1. Locations where resources are complementary (one is high when the other is low, and vice versa) will ‘score high’ even if actual resource strength is too low for practical exploitation, because using correlation coefficients between potential generation time series fails to put realistic constraints on the implied installed capacity. For instance, if a wind power potential cycle is complementary to solar PV potential—i.e. more wind at nighttime than during daytime—but the wind is weak, diurnal anticorrelation coefficients are high, but one would need to install large amounts of generating capacity running at very low efficiency to have a chance of using the wind resource for balancing.

2. Locations where resources are not complementary, but strong enough to still be useful, are undervalued. For instance, if wind does not vary diurnally, but is strong enough to result in high wind turbine CF , wind power could still replace solar PV power during nighttime, simply by virtue of the wind being strong, not by virtue of high anticorrelation coefficients.

Several studies have addressed (1) by considering the CF of individual resources *before* calculating correlation coefficients [45, 47, 48]. A realistic constraint is then put on the amount of installed capacity *a priori*, removing locations where CF falls below a certain threshold, before assessing complementarities. This, however, also entails limitations:

3. It removes locations where resource synergy may result in good balancing but that fall just outside the individual resource CF threshold, for example if wind is strong at night, but too weak during daytime to move the average CF above the threshold. Such locations may be similarly suitable for hybrid systems as others where both resources are strong but less complementary.

Here, we attempt to address these issues by introducing a new metric, the *stability coefficient* C_{stab} , which represents the reduction in the coefficient of variance (c_v) [43–45, 49] on diurnal timescales of the CF of a hybrid solar/wind system with equal capacity for solar and wind (1:1 capacity ratio), as compared to a solar-only system. It is thus a measure of the added value of wind power to balance daily electric power production from solar PV. In our view, using a solar-only system as reference is instructive for WA, as it has the most widespread potential in WA of modern RE sources. Mathematically, C_{stab} is defined as follows:

$$\begin{aligned}
 C_{\text{stab}} &= 1 - \frac{c_{v,\text{mix}}}{c_{v,s}} \\
 &= 1 - \frac{\sqrt{\sum_{\text{day}} (CF_{\text{mix}}(t) - \overline{CF_{\text{mix}}})^2} \overline{CF_s}}{\sqrt{\sum_{\text{day}} (CF_s(t) - \overline{CF_s})^2} \overline{CF_{\text{mix}}}}.
 \end{aligned} \tag{1}$$

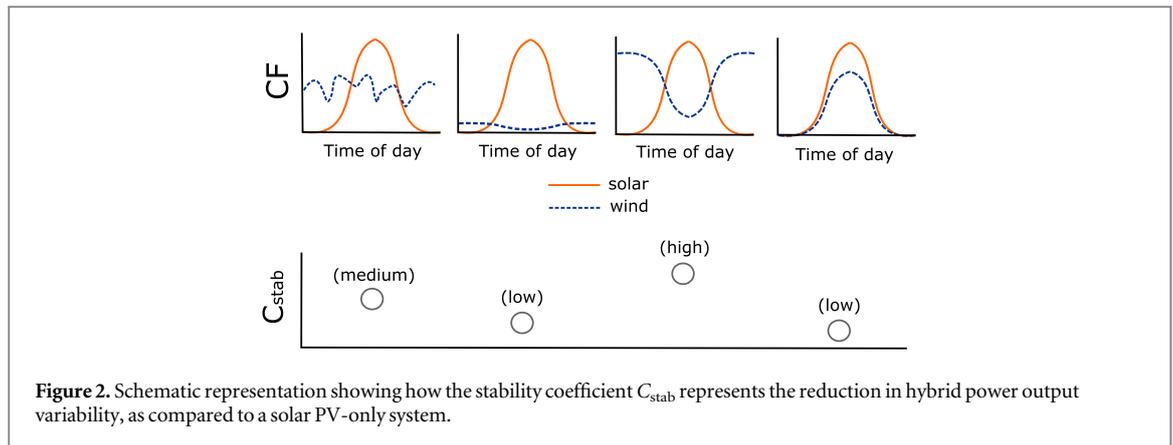


Figure 2. Schematic representation showing how the stability coefficient C_{stab} represents the reduction in hybrid power output variability, as compared to a solar PV-only system.

Here, $CF_{mix} = (CF_s + CF_w)/2$, an overlined \overline{CF} denotes a daily average, t is the time step (sub-daily), and subscripts s , w , mix denote solar, wind and hybrid mix, respectively. By definition, $C_{stab} \leq 1$, with $C_{stab} = 0$ meaning that a hybrid solar/wind system does not improve balancing relative to solar-only (wind and solar output having the same relative shape) and $C_{stab} = 1$ meaning the sum of solar and wind power output is constant over time (perfect synergy). We note that, for a more general solar-wind capacity ratio of $n:m$, one should use the expression $CF_{mix} = (nCF_s + mCF_w)/(n + m)$.

C_{stab} addresses the limitations of correlations-based approaches, because it takes the CF of hypothetically installed solar panels and wind turbines into account. This is not the case when calculating solar-wind correlation coefficients, which can give similar values for solar with strong wind as for solar with weak wind, i.e. independent of CF, as long as the strong and weak wind have similar normalised cycles. In contrast, high complementarity only results in high values of C_{stab} when the average resource strength is reasonable, while low complementarity does not necessarily result in low values of C_{stab} if the resource strength is high enough. This is shown schematically in figure 2: low complementarity does not preclude usefulness in a hybrid system (first panel from the left); high complementarity does not automatically mean usefulness in a hybrid system (second panel), but only if resource strength is sufficient (third panel); the latter, however, does not imply usefulness if complementarity is low (fourth panel).

To our knowledge, this study is the first time a hybrid metric like C_{stab} , combining information on complementarity and on CF, has been benchmarked against using average CF maps. The coefficient of variation itself [43–45, 49], on which C_{stab} is based, or alternative fluctuation indices [64] have been used before to quantify resource complementarities, but none of these works studied the implications of combining such metrics with information on CFs. The mathematical hybrid index for synergies presented by [65] goes in this direction, but it works optimally only if power output shapes are sinusoids, and its

implications for RE potential estimation vis-à-vis using average CF maps were not studied. The latter topic, however, has been touched upon by [66], who noted that compromises in solar PV CF may be beneficial for synergies with other power sources.

Criteria like C_{stab} can also be used on seasonal scales to assess the stability of a hybrid solar/wind/hydropower mix [49]; the only difference may then be choosing a different baseline than solar power variability, since this may be smaller on seasonal timescales (e.g. in WA, see figure 3(b)) than that of wind and hydropower potential; in WA it is the latter two that would necessitate seasonal balancing. However, since large-scale hydropower is dispatchable, and solar and wind could conceivably be used during the dry season for e.g. water pumping to fill reservoirs [24, 67], this is not only a question of weather and climate, but also of system operation.

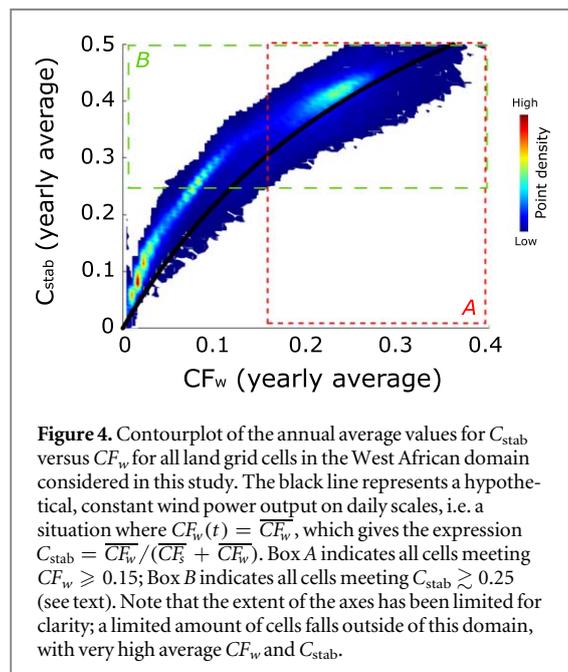
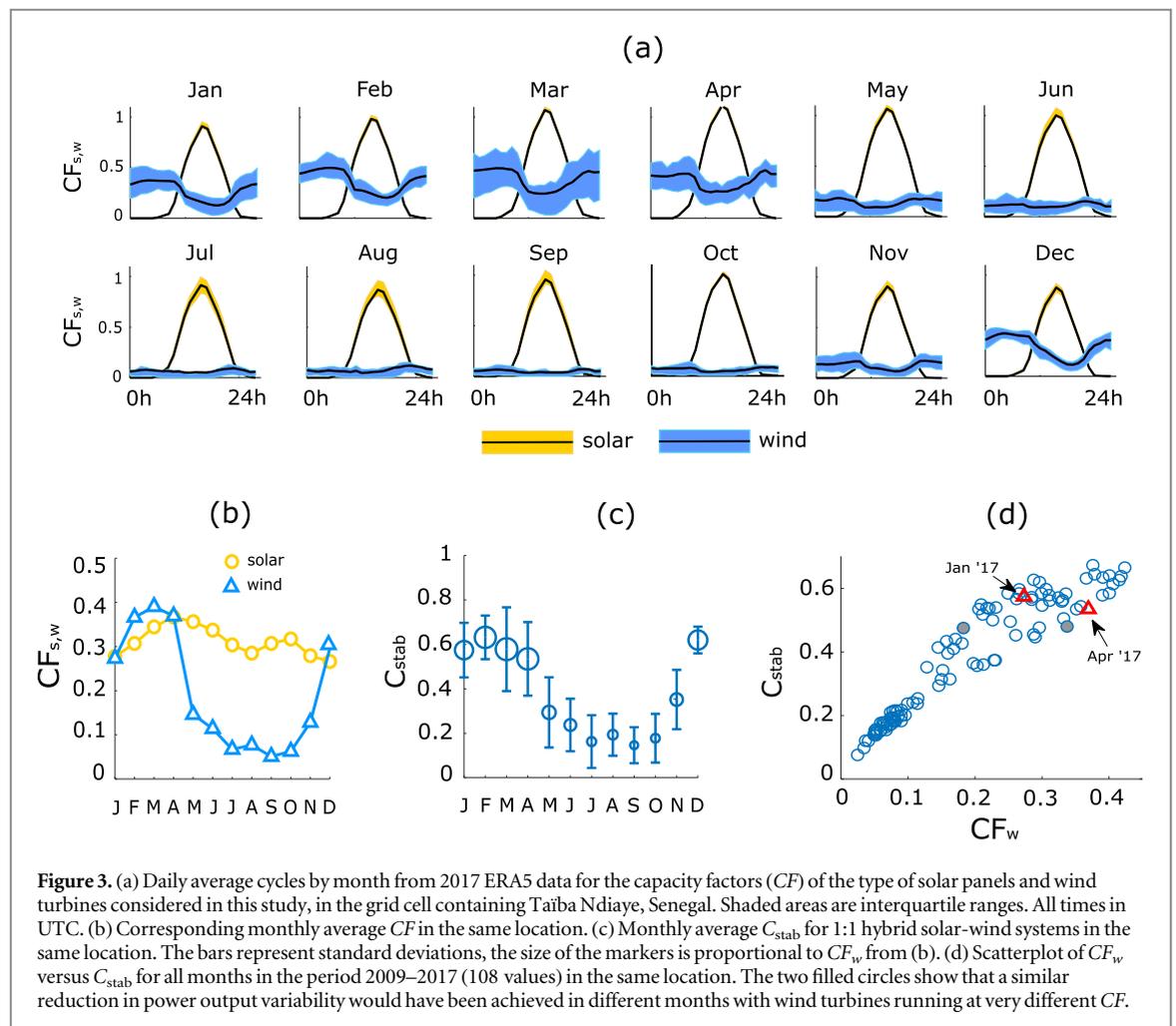
In this study, we calculate C_{stab} for solar and wind capacity installed in the same spatial location, but it could also be applied to analyse synergies between spatially separated power stations if transmission is taken into account; see section 4 for a discussion.

3. Results

Here, we first discuss hybrid solar/wind systems for one example location (Taïba Ndiaye, Senegal; see supplementary material figure 4), before scaling up the analysis across WA.

3.1. Case study: Taïba Ndiaye

Figure 3(a) shows hourly solar and wind CF by month for 2017 in (the ERA5 grid cell containing) Taïba Ndiaye. Figure 3(b) visualises the corresponding monthly average CF. These plots reveal that (i) the impact of the monsoon on solar power production is reflected mostly by changing power output variability (larger interquartile range), not so much its average; (ii) the impact of the monsoon on wind power production is pronounced, with the strongest wind resources in and after the Harmattan period (November/December–April), and a substantial drop in



resources during the monsoon from May–October/November; and (iii) the potential wind power production may indeed have an opposite diurnal cycle as compared to the solar cycle in many months.

To further investigate the possible solar-wind interplay in a hybrid system in Taïba Ndiaye, the monthly average C_{stab} is plotted in figure 3(c). In this figure, the marker size is proportional to the monthly CF_w . Overall, C_{stab} broadly follows the pattern of CF_w , which is as expected: since CF_s varies much less by season than CF_w , it is the latter that controls the seasonal shape of C_{stab} . A stronger wind resource results in better hybrid output balancing, especially when the strongest winds blow during the night.

The figure also reveals the added value of the parameter C_{stab} to the individual $CF_{s,w}$. Compare, for instance, the values in January and April: these months have nearly the same C_{stab} , but figure 3(b) shows that the difference in wind power production between them would be nearly ten percentage points. Thus, despite a substantially stronger wind resource in April than in January, the potential of this extra wind for balancing solar power production is limited. Figure 3(a) reveals why: the difference between wind power output in January and April consists mainly of the *daytime* wind resource being weaker in January than in April. For a hybrid system, in which solar power would be the main power source during daytime, this is no substantial disadvantage.

This can be more clearly visualised with a scatter-plot of C_{stab} versus CF_w , as in figure 3(d), revealing different regimes of influence of the wind resource on hybrid power balance. This plot includes all monthly average CF_w and C_{stab} values from the years 2009–2017. For $CF_w \lesssim 0.12$, C_{stab} scales more or less linearly with CF_w , so in a hybrid system, the shape of the wind cycle matters little if CF_w is very low, and the only contribution of the wind is then to (sometimes) provide (low) power during nighttime. However, as $CF_w \gtrsim 0.15$, the points scatter, i.e. beyond a certain threshold, the wind cycle plays a more significant role in the added value of using wind in a hybrid solar/wind system than the CF itself. The points representing January and April 2017 have been highlighted for clarity. There are more extreme examples (filled circles in figure 3(d)): in one of the months, wind turbines running at $CF_w = 0.34$ would have led to an average reduction of nearly 50% in daily power output variability in a 1:1 solar/wind system, but in another month, the same would already have been possible with wind turbines running at a much lower $CF_w = 0.18$.

3.2. Scaling up to regional level

We now turn from temporal to spatial scales. Figure 4 shows a contourplot of the annual average C_{stab} versus annual average CF_w for all land grid cells in our domain, from the ERA5 years 2009–2017 (the plot thus contains nine points for each land grid cell in the domain). This is the ‘spatial’ analogue of figure 3(d), which showed C_{stab} against CF_w for different *months* in a single location. The black line represents ‘constant wind power’: the hypothetical situation where CF_w (not V , since CF_w does not scale linearly with V) has the same diurnal average, but no diurnal cycle, e.g. $CF_w(t) = \overline{CF_w}$. One can then analytically derive the expression $C_{\text{stab}} = \overline{CF_w} / (\overline{CF_s} + \overline{CF_w})$ from equation (1). Since $\overline{CF_w}$ and $\overline{CF_s}$ differ by day and location, the black line is this expression’s spatio-temporal average across all days and land grid cells. (One could instead also construct another contourplot from values of annual averages per grid cell, which would be clustered very close to the black line.) It is clear that C_{stab} values are mainly concentrated above this line. In practical terms, this means that the added value of wind in balancing power output in tandem with solar PV power is ‘better than its average’ in WA: the diurnal wind power potential cycle is, on average, complementary to the solar cycle.

Figure 4 can highlight the consequences of considering only average values of $CF_{s,w}$ (figure 1) in selecting locations for RE production. The plot contains two dashed squares, denoted A and B. Square A represents $CF_w \geq 0.15$. A map indicating suitability of locations for wind power on the basis of $CF_w \geq 0.15$ would sample all cells within that square—essentially, all cells in the north of the region in figure 1(b). However, since the scatter cloud is concave, sampling

square A leaves out many cells where comparable balancing would be achieved, despite not meeting $CF_w \geq 0.15$. Sampling all cells whose C_{stab} falls within the same range as that of the cells meeting $CF_w \geq 0.15$ corresponds to square B, representing $C_{\text{stab}} \gtrsim 0.25$. Thus, if *usefulness of wind in reducing hybrid power output variability* were the criterion, instead of *usefulness of wind as standalone*, one could find substantially (here, 30%) more cells meeting this criterion. It is also to be noted that nearly all cells sampled additionally by square B lie *above* the constant wind power line (many more, relatively, than in square A), which confirms what was referenced in section 2.2: with high solar-wind synergies, there are many locations that may be interesting for hybrid systems even if wind as standalone source would not be classified as viable there.

Figure 5 shows a map indicating (i) which locations would be ‘suitable’ for standalone wind power with the criterion $CF_w \geq 0.15$ (in gray), and (ii) all *additional* locations that would be ‘suitable’ for hybrid solar/wind power with the criterion $C_{\text{stab}} \gtrsim 0.25$ (in colours). For the latter, the blue to red shades indicate for how many years the criterion is met in the period 2009–2017 (signal robustness). Blue colours indicate that this location is (i) instead classified as marginally suitable for standalone wind in some years (near $CF_w = 0.15$ in square A), or (ii) instead classified as unsuitable for hybrid systems in some years (near $C_{\text{stab}} = 0.25$ in square B).

The main ‘hotspots’ of additional locations are a band stretching across the Soudano-Sahelian zone [68] and covering large parts of Senegal, The Gambia, southern Mali, Burkina Faso, southern Niger, northern Nigeria, the Benue basin, and small areas in the very northeast of Guiné-Bissau, northwest of Guinée-Conakry and north of Benin; plus offshore locations close to Ghana, Togo, Benin and Nigeria. (Note that offshore cells were not included in figure 4 for purposes of clarity—these locations tend to have much higher average CF_w than onshore cells and would have basically added a separate ‘cluster’ in that figure.) These zones are much closer to hotspots of population density, and much closer to existing transmission grid lines [25], than the northern areas where the criterion $CF_w \geq 0.15$ is met. Despite not appearing on typical wind power suitability maps [1, 25, 27, 28, 30, 69], they may thus be important to consider for energy policy-makers, power system planners and other stakeholders, especially since most countries containing such zones have included wind power targets in their NDCs or energy policies (see table 1). While such an approach can be applied anywhere worldwide, it may be particularly relevant for WA, since it is not known as a region of particularly high wind resources, and by looking at wind power as standalone, one would indeed tend to conclude that its potential in the region is rather limited.

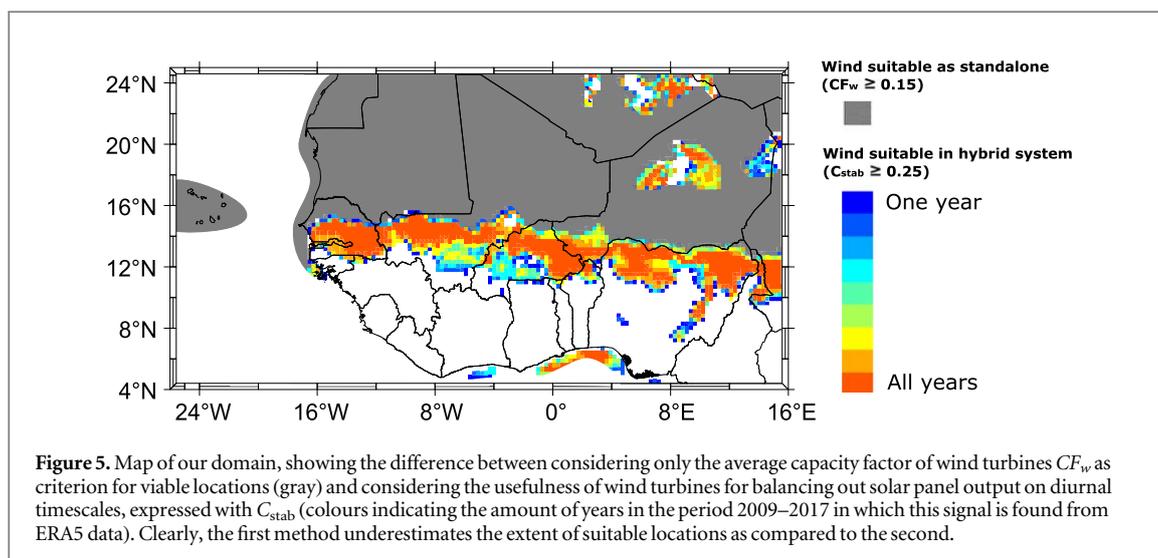


Table 1. List of countries in WA containing (parts of) the coloured area in figure 5 with policy targets pertaining to renewable energy (mixes) including solar, wind and hydropower.

Country	Energy policy targets for solar/wind/hydro	Source
Niger	250 MW RE by 2030, of which 130 MW hydro and 20 MW wind	[3]
Mali	More than 100 MW of renewable power capacity installed by 2020, mainly solar, wind, small hydro and biomass, to attain a 10% share of RE in the ‘electricity mix’	[4]
Nigeria	Ensure 10% of hydro in power production by 2030 and 6% of solar; no quantified wind power target, but ‘developing wind energy as an alternative renewable energy resource’ to ‘integrate this with other energy resources into a balanced energy and electricity mix’ is mentioned as key objective.	[5]
Gambia	44 MW hydro, 50 MW solar, 20 MW wind installed capacity by 2030	[6]
Guinée-Bissau	72 MW of RE capacity installed by 2030, of which 53 MW hydro, 15 MW solar and 2 MW wind power	[7]
Guinée-Conakry	30% of electricity production from renewable sources by 2030 (excl. biomass); 50 MW installed capacity of wind and solar and 1650 MW of hydropower	[8]
Ghana	RE penetration of 10% by 2030, with 150–250 MW utility-scale solar power, 50–150 MW utility-scale wind power, 150–300 MW small/medium hydropower	[11]
Togo	67.5 MW of solar, 24 MW of wind, 115 MW of medium/large hydro, and 70 MW of small hydropower capacity by 2030	[12]
Senegal	Achieve rate of energy independence of at least 15% by 2025 from using renewable sources (without biomass); solar, wind and hydropower all mentioned as candidates	[15]
Burkina Faso	50% of RE in ‘energy mix’ by 2025; wind energy potential ‘worthwhile to evaluate’	[16]

4. Discussion

Here we highlight several notes of caution and provide recommendations for future studies. First, focusing on smoothing power output does *not* imply that a flat power output is the desired outcome. This is (i) practically impossible with fluctuating renewables, and (ii) unnecessary, since demand profiles are not flat either. We use a hypothetical solar/wind hybrid system with equal capacity for solar PV and wind (1:1 capacity ratio) for demonstration; this ratio could be ‘tuned’ to better match demand. For instance, if demand has a strong diurnal shape, with higher demand during daytime, a higher share of solar capacity than of wind could be considered. The highlighted areas in figure 5 would expand, contract, and/or shift somewhat if the ratio were changed. However, this does not affect the generality of our conclusion, that considering hybrid systems from the start provides information that separate assessments

of solar and wind cannot. Considering demand profiles in this study would have caused large uncertainties; load profile estimations are available for specific locations in WA, see e.g. [70], but subject to high uncertainty, as is widely the case in rural settings in developing economies [71], and poised to undergo substantial changes as energy demand rises across WA. Further, demand management by shifting certain flexible loads to specific times can also be an option [56]. We therefore believe that this supply-side view may be a useful starting point.

Second, this approach is an *indication* of what can be added to RE potential assessments, not a final product. Several factors influence the precise outcome, such as (i) stricter criteria on CF_w and C_{stab} for ‘feasibility’ (tending to shrink and/or move the zones in figure 5 northwards), (ii) wind turbine type [72], and (iii) data product. Therefore we do not claim that the best possible assumptions have been used: this remains to be seen through comparison of data

products and observations. It has been mentioned, for instance, that reanalyses may not be the best available products for solar irradiation [47]. However, using a satellite-based data product for calculating CF_s is unlikely to change our broad conclusions, since the main constraint that solar potential puts on this analysis is the diurnal solar cycle itself, not the uncertainty therein due to cloud cover.

Third, the lack of measurements at 100 m height constitutes a barrier towards validating ERA5 data. While ERA5 near-surface wind speeds have been compared to available measurement data (see supplementary material C–D) and no principal objections to using these was found, this could not be done for 100 m wind speeds. Data at comparably high altitudes from radiosondes in the AMMA campaign have previously been assimilated into ECMWF reanalysis [73, 74]; and data from wind profilers and radiosondes in newer campaigns such as DACCIIWA [32] could conceivably be used for evaluation in the future; such campaigns, however, typically focus on monsoon months, when winds are weakest and thus of least value for energy applications.

Fourth, the ERA5 spatial resolution, while finer than previous reanalyses, is still not sufficient to discern local corridors where wind speed may be high. This is especially relevant in regions with pronounced orography, such as the Fouta Djallon mountains in Guinée-Conakry. It also means that coastal regions may be suboptimally represented: coastal grid cells may represent averages of land and sea conditions.

Fifth, uncertainty ranges of wind (and sometimes solar) power output can be rather broad (see section 3.1). Options for reducing the risks posed by day-to-day variability must still be explored in systems with excellent solar/wind(/hydro) synergies, for example through storage technologies and export/import between countries/regions [24, 26, 75]. Storage technologies are set to play a substantial role in power systems with high shares of renewables in the future; while synergies between solar PV and wind power can be exploited to reduce storage needs and costs, as can demand management options, that does not mean the need for storage can be eliminated. Storage technologies such as thermal storage and pumped hydropower play an important role in near-term high-RE scenarios for sub-Saharan Africa [24, 56]. The methods presented here could thus contribute to estimating such storage needs for WA. Spatially distributing power-generating stations and trading power between regions can also smooth out volatility and thus reduce shocks in power production [76]. The expanded Sahelian area which was suggested as suitable for hybrid solar-wind exploitation in this study (figure 5) already hosts existing grids [25] (as opposed to the more northern territories, where the wind is strongest), and therefore this analysis may also be of interest to West African power pool planning. We therefore intend to focus future research on the

potential for balancing RE generation in WA through storage and transmission.

Sixth, given the potential for CSP as alternative way to harness the Sun's energy [35], one may wonder what our findings imply for future CSP deployment in WA. The EREP, in fact, targets similar amounts of grid-connected capacity to be installed for solar PV, CSP, and wind power by 2030 in WA—about 1 GW for each. All three of solar PV, CSP, and wind power are thus to be viewed as important components of future WA power systems. Due to this matching of scales, the synergies between solar PV and wind power may be quite relevant on the near- to medium-term planning for CSP in WA, since they will codetermine the future needs for storage capacity in CSP installations. Good synergies will reduce balancing and storage needs, and therefore future CSP costs [36], which are currently the bottleneck for CSP deployment according to the EREP [17]. An assessment of possible complementarities between CSP with storage on one hand, and solar PV and wind power on the other, will strongly depend on the amount of assumed storage capacity and time [36, 77–81], and therefore goes beyond the scope of the current work. However, such an assessment should be undertaken as part of our intended future research into the roles of storage and transmission. (NB: we have checked that, if one would replace solar PV by CSP *without* storage in this study using the parameterisation of [82], conclusions on solar-wind synergies would be very similar, as C_{stab} does not differ substantially with the choice of solar PV or CSP in the absence of storage.)

Seventh, the results in figure 4 pertain to annual averages of CF_w and C_{stab} . One may be interested in other parameters than averages: maxima, for instance, if the wind resource were only used during part of the year (in Harmattan conditions), and replaced by hydro-power during the monsoon. Averages are then less interesting, since the additional locations in square B could theoretically be locations where C_{stab} is above threshold owing to higher averages during the monsoon, when wind power would not be crucial anyway. We have checked that taking *maximum* annual CF_w and C_{stab} (i.e. selecting the best month for hybrid solar/wind) leads to the same conclusions presented in section 3.2. This seems logical, given that NLLJs show their strongest signature during Harmattan season [19].

Eighth, analyses like this one are meant to *contribute* to decisionmaking and target-setting in energy policy, not *determine* it. Local circumstances—topographical, socio-economical, legal—should be considered when selecting optimal power plant locations. Several studies have looked at relevant criteria besides resource strength, such as maximum population coverage [83, 84], or exclusion of zones with high agricultural activity, protected/prohibited areas, steep slopes, legal constraints, etc [27]. Studies like this can help pinpoint locations where such criteria should be further investigated.

Last, hybrid RE systems may be susceptible to compound (e.g. low solar plus low wind) events [67, 85]; the methods developed here may be helpful in assessing these in the future.

5. Conclusion

In this study, the ERA5 reanalysis product was used to assess the synergies of solar PV and wind power in WA down to hourly scales. Both of these sources play an important role in many West African countries' energy policy and projected power mixes. We demonstrate that, even though the average wind power potential is not very high across WA, being concentrated in the sparsely-populated north, wind could still be a useful resource in hybrid power systems in a much more extended area, close to centers of population and existing grids in the Soudano-Sahelian zone. This is because at hub heights of large wind turbines, winds blow stronger during nighttime than daytime, especially during the dry season. Wind power could thus provide diurnal stability to hybrid power systems with a substantial solar PV component and limited hydro-power resources. To quantify this, the stability coefficient C_{stab} was introduced to show the suitability of combining solar and wind into a hybrid system. We argue, using a case study and regional upscaling, that consideration of hybrid systems should happen right from the start of RE resource assessments, through a parameter such as C_{stab} , not as second step after establishing individual resource strengths.

This research can help inform policymakers in WA about their countries' RE potential, and allay fears of a spatial mismatch between renewable resources on one hand, and population and existing grids on another [86]. It can also help provide a framework for generating high-resolution input for energy models for WA (countries) to assist power systems planning [87]. The methods and datasets used in our research are globally applicable, and could hopefully contribute to enhancing climate services for sub-Saharan Africa, which are in short supply [88, 89].

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