Smart renewable electricity portfolios in West Africa

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The worldwide growth of variable renewable power sources necessitates power system flexibility to safeguard the reliability of electricity supply. Yet today, flexibility is mostly delivered by fossil fuel power plants. Hydropower can be a renewable alternative source of flexibility, but only if operated according to adequate strategies considering hourly-to-decadal and local-to-regional energy and water needs. Here we present a new model to investigate hydro-solar-wind complementarities across these scales. We demonstrate that smart management of present and future hydropower plants in West Africa can support substantial grid integration of solar and wind power, limiting natural gas consumption while avoiding ecologically harmful hydropower overexploitation. We show that pooling regional resources and planning transmission grid expansion according to spatiotemporal hydro-solar-wind synergies are crucial for optimally exploiting West Africa's renewable potential. By 2030, renewable electricity in such a regional power pool, with solar and wind contributing about 50%, could be at least 10% cheaper than electricity from natural gas.

Globally, a strong expansion of modern renewable electricity (RE) sources, mainly solar photovoltaic (PV) and wind power, is underway, driven by rapidly declining costs and a desire to decarbonise power supply[1]. As growth in solar and wind power generation continues, hourly, daily and seasonal variability will exert impacts on power systems[2–7]. In light of this growth, many developing regions with low levels of electricity access and rapidly growing power demand are "greenfields" for developing power systems with high RE shares, focusing on solar and wind power integration from the outset[8].

Integrating solar and wind into the power mix requires power system flexibility to enable matching supply and demand[9]. Currently, such ancillary services are often delivered by fossil fuel power plants[10], but deep cuts in CO_2 emissions demanded by the long-term Paris Agreement goals will strongly limit their use in the future[11]. Hydropower plants with reservoirs are Paris Agreement-compatible flexible alternatives, with low minimum loads, quick start-up times, fast ramping rates, low marginal costs and seasonal energy buffering capability[2,9,12–18]. This is especially relevant for regions where hydropower potential remains underexploited and expansions in hydropower capacity are planned, such as sub-Saharan Africa, South America, and

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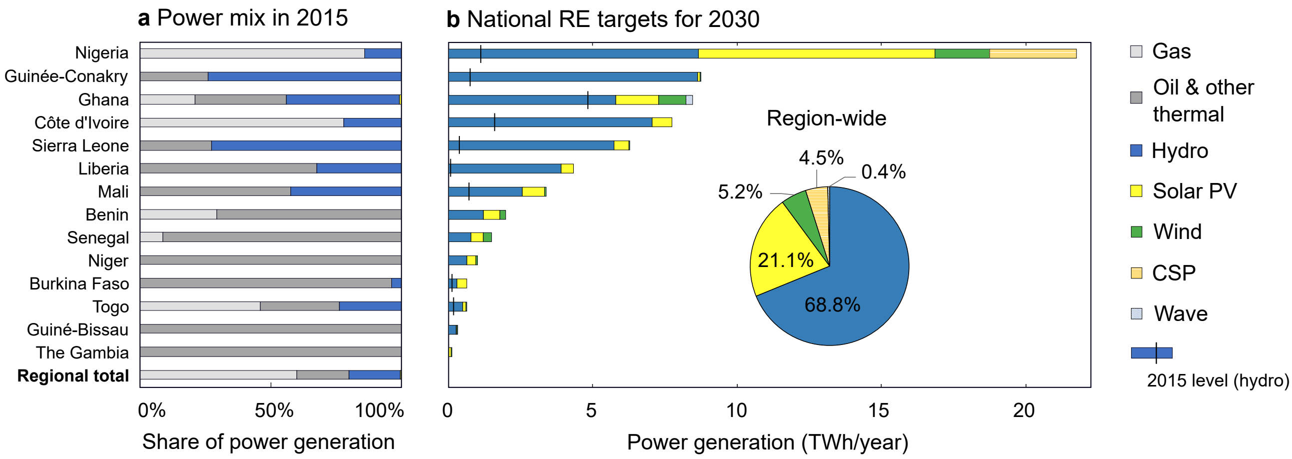

Figure 1: **West African countries' power mix and targeted renewable electricity generation.** (a) The 2015 power generation mix of all mainland West African countries and the regional aggregate[30,31], with electricity exports allocated to the country of generation (see Methods). (b) National RE targets for 2030; bars represent the total amount of hydro, solar photovoltaic (PV), wind, concentrated solar (CSP), and wave power generation targeted according to National Renewable Energy Action Plans (NREAPs) and comparable documents (see Methods). The hydropower generation in 2015, from when most of these plans date, is indicated by vertical lines. Inset: the implied region-wide RE mix targeted for 2030.

South-East Asia[15,19–21].
Hydropower plant operation must consider environmental water needs as well as local and regional water resource availability from seasonal to multiannual timescales[21,22]. To model flexible hydropower operation in systems with considerable solar and wind components, reservoir dynamics must therefore be explicitly coupled to variable solar and wind power generation across a wide range of spatiotemporal scales. A multi-scale framework to investigate the potential of hydro-solar-wind power for load-following, reliable electricity supply, and to design rule curves for the necessary hydropower plant operation, is therefore of high importance[2,7,20], yet research has so far only addressed limited subsets of the involved spatiotemporal scales[23–29].
Here we present a novel modelling framework that addresses this issue. The model combines solar and wind energy meteorology with reservoir operation and hydropower dispatch at hourly resolution across multiple hydrometeorological years. This integrated approach sheds light on the synergies between hydropower, solar power and wind power in enabling reliable electricity supply while complying with sustainable hydropower objectives at all time scales. Applying it to West Africa, we map potential hydro-solar-wind power synergies with spatial detail ranging from individual hydropower plant operation to region-wide potential, and temporal granularity ranging from hourly to multiannual, including climate change effects on RE generation.

Renewables in West Africa

Hydropower provides 20% of West Africa's electricity with the remainder mostly generated from natural gas and oil[30], and thus currently accounts for nearly all of its RE. In a few countries, hydropower dominates the generation mix (Fig. 1a). However, the role of other renewables is increasing, as showcased by the recent commissioning of several pioneering grid-scale solar and wind projects[30,32]. Accordingly, solar and wind power integration is among the main objectives of West Africa's transmission infrastructure plans[32].
Hydropower's established role and the diversification towards other renewables are both reflected in West African national energy strategies[31]. If the renewable targets for 2030 (Fig. 1b; see Methods) are achieved, hydropower will remain the dominant renewable resource in most

countries, providing 69% of RE with solar PV at 21% and wind at 5% (Fig. 1b inset). The planned increase in hydropower and the corresponding construction of new dams and reservoirs will lead to considerable growth of potential flexibility reserves, allowing to support grid integration of solar and wind power and limit natural gas consumption.

We find that there are strong climate-related, environmental, and economic incentives to better streamline hydro, solar and wind power planning across West Africa. This will involve (i) setting RE targets based on renewable resource synergies, supporting renewable portfolio diversification and avoiding hydro-dependency[20,33,34]; (ii) operating hydropower plants with hourly-scale rule curves designed to maximize hydro-solar-wind complementarity; and (iii) expanding cross-border transmission capacity. Together, these can speed up the decarbonisation of electricity supply while avoiding ecologically harmful overexploitation of hydropower[22], limiting natural gas consumption as other storage solutions and renewable energy technologies pave the way for regionally appropriate 100% renewable power systems[35].

Although many continental/global-scale "100% renewable" studies exist in literature[18,35–37], these often lack granular details relevant to particular countries' specific conditions. The key contribution in this work is to examine the synergies between various renewable resources at high spatiotemporal resolution, with a specific focus on hydropower sustainability and diversification.

Modelling flexible hydropower operation

While all dispatchable power plants have limitations in flexibility[9], hydropower has two unique constraints: (i) an environmental flow must always be guaranteed downstream to safeguard ecological integrity[38], and (ii) reservoir water levels must remain within safe ranges on seasonal-to-multiannual time scales. There is thus an intrinsic optimum amount of solar and wind power whose variability hydropower can compensate: if hydropower plants were responsible for compensating variability beyond this optimum level, this would mean either having to violate environmental flow requirements or consistently overdraw from the available water budget. In both cases, sustainable operation of the hydro reservoirs would be sacrificed.

The new model developed for this study (see Methods and Supplementary Note 1-8 for details) simulates how flexible hydropower operation can optimise the reliability of hydro-solar-wind mixes, considering these constraints. The model determines the optimum amount of solar and wind power generation whose variability a (set of) hydropower plant(s) can compensate, as follows. For (i) a given solar/wind resource mix, (ii) a given target load to be followed by hydro-solar-wind, and (iii) a given allowed solar/wind plant "oversizing"[39] (allowing peak solar/wind power to consistently exceed this target share), the model calculates the required hydropower dispatch for each time step to compensate solar/wind shortfalls while enforcing environmental flow. At the next time step, the state of each hydropower reservoir is recalculated, considering the water released in the previous time step and the combined gains/losses from river inflow, evaporation and precipitation. The dispatch calculation is then repeated. The model thus marches forward in time, dispatching hydropower during solar/wind shortfalls. This results in certain seasonal and multiannual reservoir lake level profiles, depending on the combined effect of river flow, load, and solar/wind variability. The model checks whether these lake levels are within safe ranges. The entire simulation is then repeated for a higher target load. The model thus iterates over increasingly ambitious targets, identifying the maximum load at which sustainable operation is guaranteed for each reservoir.

This maximum translates to an optimal amount of solar/wind power generation supportable by hydropower. The corresponding operational rules for hydropower dispatch are distinct for each reservoir. When pooling all hydropower resources and operating each hydropower plant according to its own identified rules, the fraction of total load guaranteed to be met by hydro-solar-wind for the full simulated time series is denoted "total load-following potential".

As input, the model requires (i) technical parameters for each hydropower plant, and time

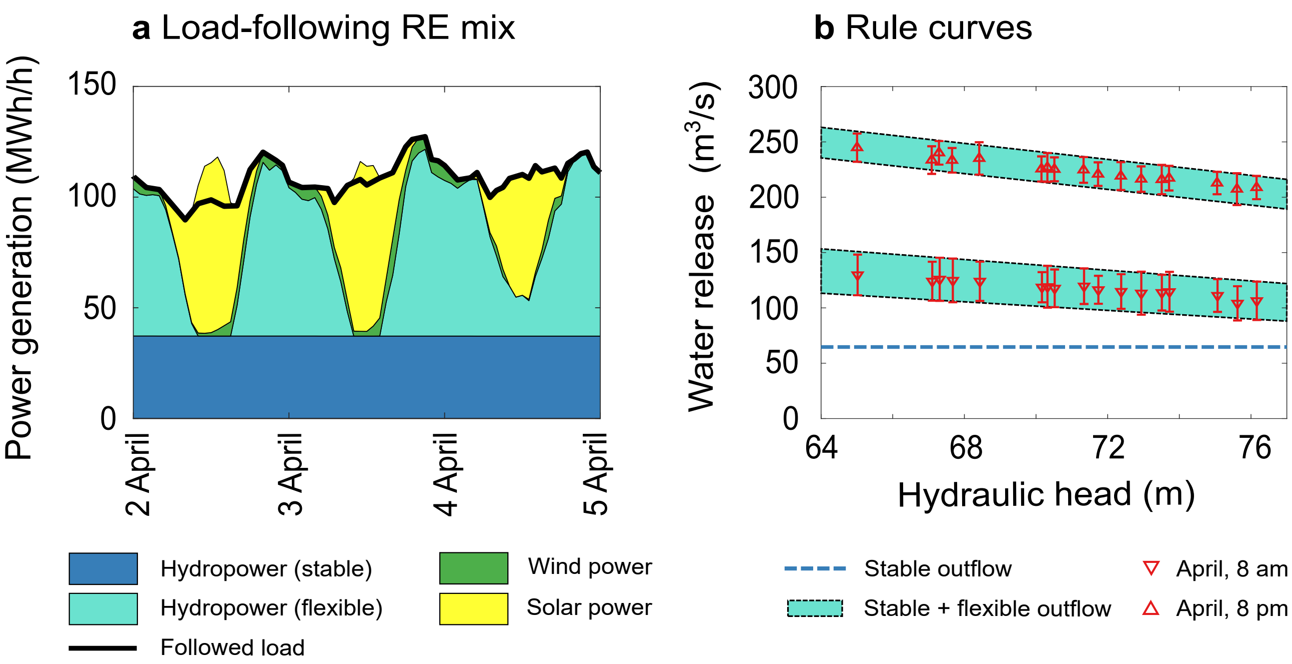

Figure 2: **Example of optimised hydro-solar-wind operation and hydropower rule curves.** Results from a simulation spanning 17 years at hourly resolution for Ghana's Bui hydropower plant alongside solar and wind power, according to simulation settings of the reference scenario (see Methods). **(a)** Hourly power generation for an example sequence representing three days in the 15th year (see Supplementary Fig. 4 for corresponding seasonal and multi-annual profiles). The stable hydropower component is necessary to ensure environmental flow requirements are met (see Supplementary Note 2). The load profile shape reflects Ghana's grid load (see Methods). **(b)** Corresponding generalised reservoir release rules as function of hydraulic head (the elevation difference between headwater behind the dam and tailwater at the turbines) for 8 a.m. and 8 p.m. in April across the simulation period. Every marker represents one month in a single simulation year; ranges are standard deviations.

series of (ii) river flow into each reservoir, (iii) evaporation and precipitation gains/losses, (iv) normalised solar and wind power generation profiles (representing the pooled solar/wind resources on the grid), and (v) the load profile. The model results' spatiotemporal resolution depends on the input's; it can run with input data at any resolution, but hourly-resolved[3,4,9] multiannual[6] data is recommended, as is high spatial detail for hydrometeorological variables to closely represent individual RE plants. Here, simulations were performed at hourly time step across a 17-year period; all details on spatiotemporal resolution of the input data are described in Methods. Minimum environmental flow requirements at each reservoir site were set to 40% of local annual mean river flow, reflecting recent assessments of flows needed to maintain aquatic ecosystem services[38].

We demonstrate the coupling of temporal scales using simulation results for Ghana's Bui hydropower plant as example (Fig. 2). Joint operation of Bui alongside solar and wind power could follow a load corresponding to roughly 7% of Ghana's current on-grid electricity demand[30] (Fig. 2a; Supplementary Fig. 4). The model's optimisation procedure ensures that reservoir release rules keep lake levels within safe ranges on multiannual time scales, comparable to conventional reservoir operation (Supplementary Fig. 6). Despite solar and wind power variability, these release rules can be approximated as regular functions of the reservoir water level, with a different parameterisation for each hour of the day and a distinct seasonality (see Methods). We show the release rules for 8 a.m. and 8 p.m. in April as linear ranges (Fig. 2b), which reflect the fact that load peaks in the evening when solar power is unavailable. During mid-day, when solar power peaks, the stable, environmentally required outflow[38] usually suffices, except on low-irradiation days (e.g. third day in Fig. 2a).

These rules require outflow to be slightly increased as water levels decrease, because as hydraulic head reduces, higher outflow is needed to meet the same (peak) demand. Such rules differ considerably from conventional reservoir operation, which typically requires increasing outflow with increasing water levels to stabilise the latter (Supplementary Fig. 3). Yet, the alternative rules designed here are equally capable of ensuring stable water levels, while additionally balancing out the fluctuations in solar and wind power.

Technical hydro-solar-wind potential across West Africa

We subsequently estimate the total technical load-following potential of hydro-solar-wind power by simulating the (hypothetical) solar and wind power generation from a representative set of locations across all of West Africa, and applying the model for nearly all existing and planned hydropower plants in the region. To this end, we developed a new database of present and future hydro, solar and wind projects, including locations (Fig. 3) and technical characteristics (see Methods and Supplementary Data).

The load-following potential of hydro-solar-wind, and the corresponding hydropower rule curves, may be influenced by several future developments, most notably (i) climate change impacts on RE resources; (ii) strategic solar/wind capacity oversizing[39]; and (iii) increased regional (cross-border) interconnections. We therefore designed five corresponding scenarios (see Methods): (i) a reference scenario with no climate change signals, no oversizing and no interconnections, (ii-iii) a median and dry future scenario, (iv) a scenario with strategic oversizing, and (v) a scenario with strategic oversizing and with a regional power pool interconnecting all countries. Each scenario suggests a different total load-following potential (Fig. 4a; plant-by-plant results in Supplementary Tables 3-7), enabled by a different hydro-solar-wind mix (Fig. 4b). Since existing and planned hydropower schemes would leave a considerable hydropower potential unexploited, their associated load-following potential represents the lower (existing schemes) and middle (existing + planned schemes) bound of total technical load-following potential. We extrapolated the results to cover the hypothetical case of full exploitation of hydropower potential (Supplementary Note 9.2), giving an approximate upper bound (Fig. 4a).

Under the reference scenario, the total load-following potential has lower, middle and upper bounds of 11.4, 23.8 and 43.1 TWh/year (Fig. 4a). This represents respectively 12%, 24% and 44% of current West African electricity demand (97.6 TWh/year[30]) and 5%, 11% and 20% of projected 2030 demand (218.7 GWh/year[30]). In this scenario, hydropower remains the dominant renewable resource (Fig. 4b). The influence of median projected climate change is likely to remain limited (Fig. 4a), with near-zero change in total load-following potential. Even under a scenario projecting a substantially drier future, the loss of load-following potential would remain limited to a few percentage points (Fig. 4a), mostly because the regions with the strongest predicted drying trends are those with the lowest hydropower potential[41].

Strategic oversizing of solar and wind capacity, allowing an overproduction of 25%-30%, would increase load-following capabilities by roughly 20% (Fig. 4a). Oversizing thus aids stability[13,39], and the overproduction, manifested as peaks in mid-day solar power, can additionally displace thermal generation during daytime. Eventually, oversizing could be complemented by pumped hydropower schemes (Supplementary Note 7) and large-scale battery deployment for diurnal-scale storage[13,36,37].

Most importantly, cross-border electricity trade could increase load-following potential considerably further, by up to 60% compared to the reference, boosting lower, middle and upper bounds to 16.5, 37.5, and 69.1 TWh/year, or 17%, 39% and 71% of current West African electricity demand and 8%, 17% and 32% of projected 2030 demand (Fig. 4a). This is because regional interconnections would enable harnessing a cascade of three spatiotemporal hydro-

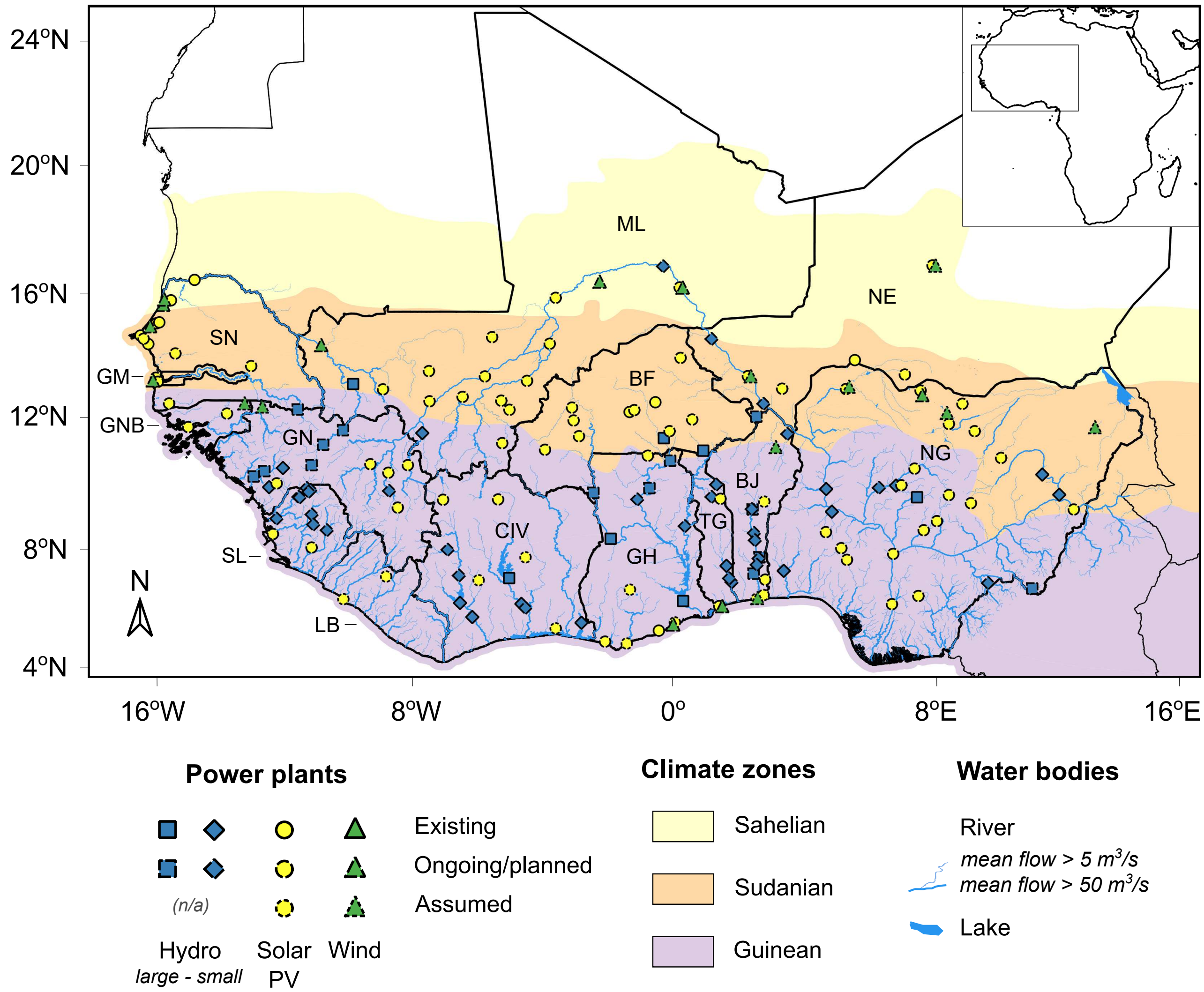

Figure 3: **Locations of modelled hydro, solar and wind power plants.** This map of mainland West African countries (borders in bold) shows the sites of reservoir hydropower, solar PV, and wind power plants modelled in this study, as well as climatological zones and water bodies[40]. See Methods for an explanation of how the set of modelled power plants was chosen and for the classification of hydropower plants as "large" or "small". Countries: BF = Burkina Faso; BJ = Benin; CIV = Côte d'Ivoire; GH = Ghana; GM = The Gambia; GN = Guinée; GNB = Guiné-Bissau; LB = Liberia; ML = Mali; NE = Niger; NG = Nigeria; SL = Sierra Leone; SN = Senegal; TG = Togo. Inset: the current study area in West Africa indicated on a map of the African continent.

solar-wind synergies. First, interconnections allow exploiting the spatial synergy between solar and wind potential in the north[7] and hydropower potential in the south, enabling a balanced mix with all three resources contributing substantially (Fig. 4b). Second, with solar and wind both strongly present thanks to increased interconnection, their diurnal synergies[7], with solar power peaking during mid-day and wind power during evenings and nights, reduce nighttime demand for hydropower dispatch. Third, solar and wind power from the north both peak during the dry season[7], reducing the need for hydropower dispatch during water-scarce months. This allows saving water for the wet season, when solar and wind power generation is reduced; the higher reservoir outflow needed to generate hydropower to balance out this reduction is then compensated quickly from upstream, keeping reservoir water levels comparatively stable and preventing reductions in hydraulic head. In summary, the spatial (north-south) synergy allows to comprehensively harness two temporal synergies (diurnal and seasonal), which both con-

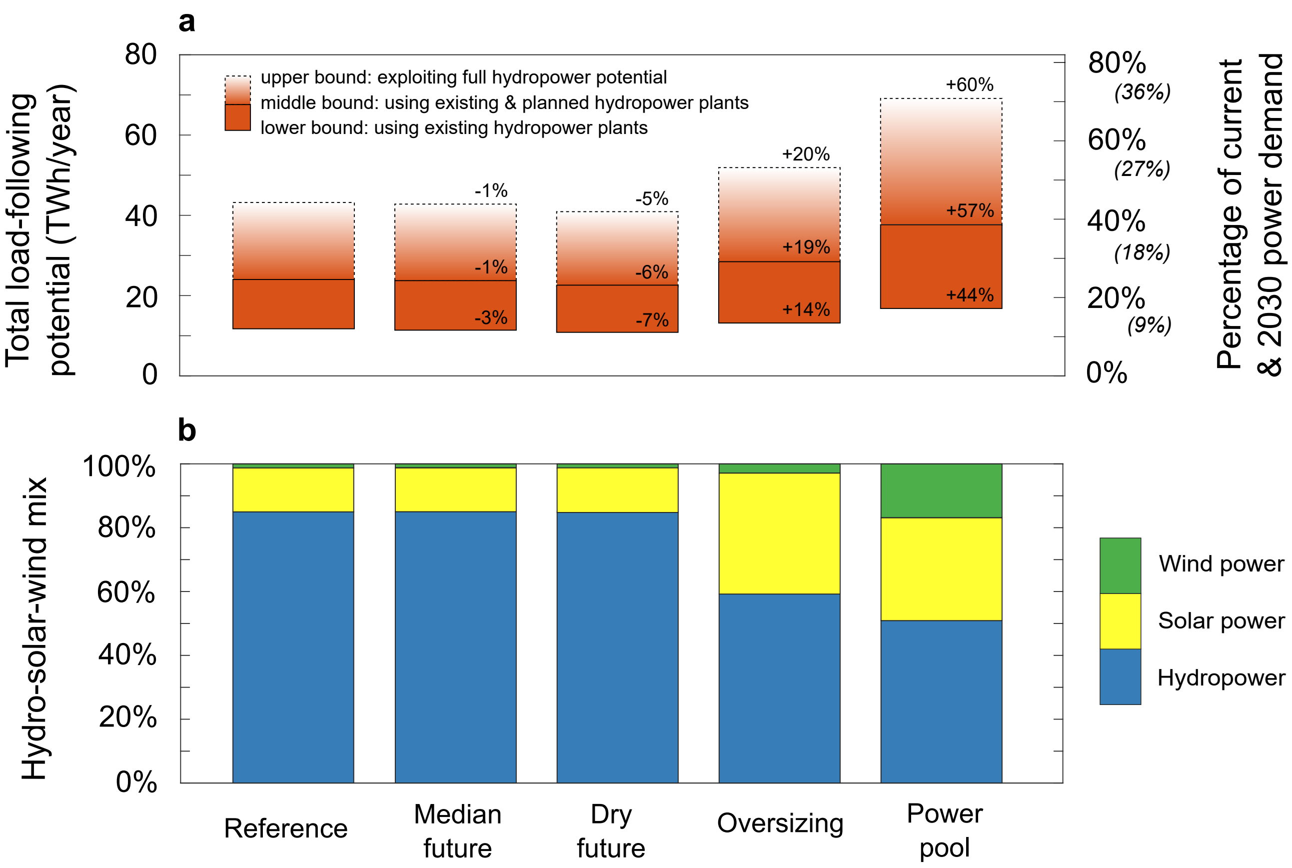

Figure 4: **Total load-following potential and hydro-solar-wind mix.** (a) The total load-following potential under each of the five investigated scenarios. Lower, middle and upper bounds represent exploitation of the flexibility potential of all existing hydropower schemes, all existing and planned hydropower schemes, and the full hydropower potential, respectively. As the latter is the result of an extrapolation, colours towards the top of the boxes are shown as fading to reflect the uncertainty herein (see Supplementary Note 9.2). The right-hand vertical axis indicates the corresponding percentage of current and (in brackets) projected 2030 demand[30]. Percentages on the boxes indicate the change in each bound as compared to the reference scenario. (b) The corresponding contribution of hydro, solar and wind to the RE mix for each scenario (from the middle bound results, but mostly insensitive to choice of bound).

siderably increase the followable load. Simultaneously, this supports sustainable hydropower practices, because reservoir outflow will peak during the wet season, mimicking natural flow regimes[42] even for reservoirs with multi-year storage originally designed to produce year-round steady power (Supplementary Fig. 6c).

What contributions could each country make to such a renewables-oriented power pool? A qualitative example is shown with a Sankey diagram (Fig. 5; Supplementary Note 9.3). Based on which resources are most strongly present nationally, certain countries would be net exporters of hydropower, such as Ghana, and others of solar and wind power, such as Senegal. Part of the hydropower generation would be seasonal (Supplementary Note 2); like excess mid-day solar power, it does not participate in load-following, but it can displace thermal generation during the wet season.

The economic viability of such a regional mix (51% hydro, 32% solar, 17% wind; Fig. 4b) is promising. Even following very conservative levelised cost trends[30], a corresponding mix of new hydro-solar-wind capacity could generate electricity at grid parity with cheap natural gas within less than ten years, and 10% more cheaply by 2030 (Supplementary Note 9.4).

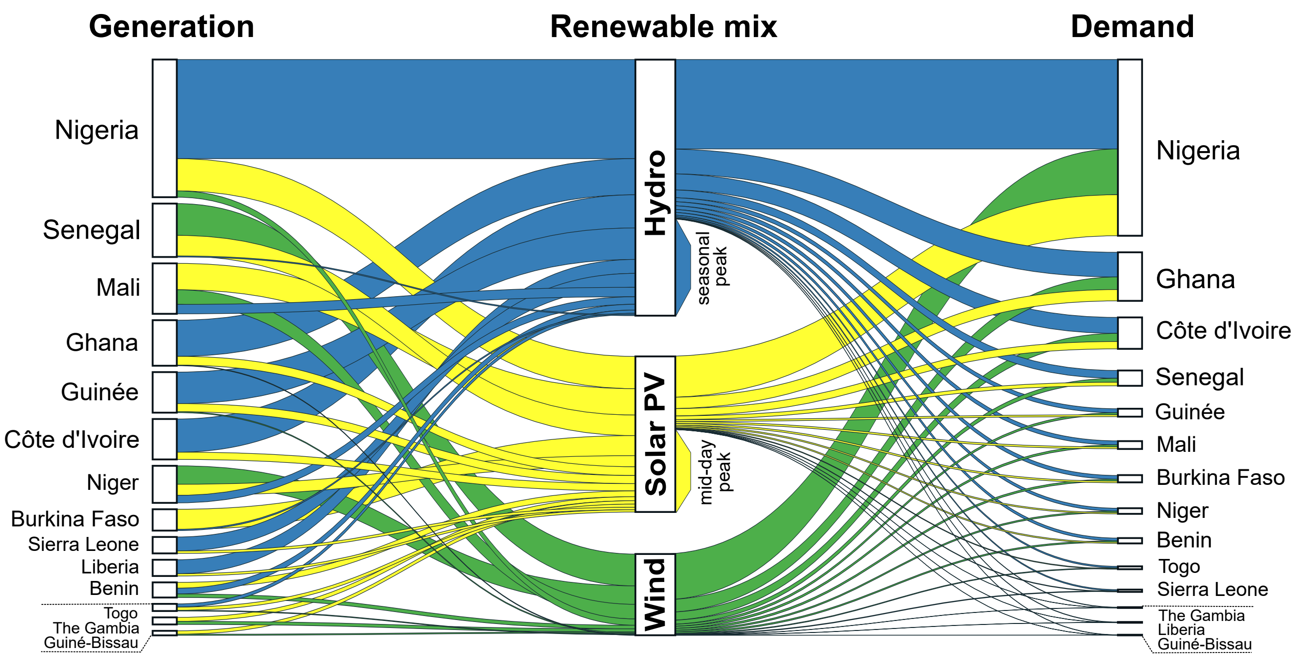

Figure 5: **Contributions by country and RE resource in the power pool scenario.** Sankey diagram based on the power pool scenario, showing power generation by country (left) and source (middle), and the guaranteed power supply to each country (right), divided proportionally to national electricity demand (see Supplementary Note 9.3). The "seasonal peak" of hydropower (increased output during the wet season, when many reservoirs can only store limited amounts of water without overflowing) and the "mid-day peak" of solar PV (overproduction around noontime) have not been allocated to countries on the right-hand side, as the business case for trading these in a power pool would be limited (see Supplementary Note 9.3).

Discussion

The outcomes of this research regarding the high potential of a renewables-oriented West African power pool can contribute to modelling West African power systems, serving as input/constraint to capacity expansion models[30,36,37,43]; inform energy policy targets[44]; and help align investment strategies in hydro, solar, wind and transmission capacity[32]. The modelling framework can also be readily applied to other regions. However, while conducted with great care of achieving realism, several opportunities for improvement deserve highlighting.

First, hourly temporal resolution was the highest achievable, since comprehensive meteorological datasets allowing multiannual assessment of hydro-solar-wind potential are currently unavailable at sub-hourly timescale. Hourly resolution is consistent with recommendations on high-RE systems[3,4,9]; but once datasets at sub-hourly resolution become available, the present study could be repeated with increased granularity. The model could also be extended with modules assessing frequency stability (sub-second) to design separate operational hydropower strategies for frequency control[2,33,45,46].

Second, since our conclusions on north-south synergies hold in general, various north-south country pairs could efficiently harness spatiotemporal hydro-solar-wind synergies without interconnections to other countries, e.g. Senegal/Guinée or Niger/Nigeria. Aiming for well-selected sets of regional interconnections could thus be equally efficient as insisting on fully interconnecting all countries, and more cost-effective. To elucidate such trade-offs, the model could be coupled with network analysis tools[8].

Third, we calculated hydropower potential based on natural flow regimes[15]. In reality, as basins become strongly dammed through hydropower expansion, upstream reservoirs influence downstream flow, flattening seasonal patterns and preventing hydraulic head reductions in downstream reservoirs. The present approach thus leads to somewhat conservative estimates of hydropower potential. Interactively coupling our model with hydrological simulations accounting for reservoir operation could address this. Further, our model did not include preferential cost-based orders-of-dispatch for hydropower plants, which could be addressed by coupling with production cost models[8].

Fourth, we calculated solar and wind potential using a state-of-the-art reanalysis dataset at 31 km resolution[7]. For practical RE plant siting, detailed assessments of e.g. optimal solar panel orientation or wind turbine type by location may be needed, requiring finer spatial resolutions without losing temporal resolution. Environmental and legal siting constraints[47] and fragility/conflict-related risk[48] should also be considered. The latter may necessitate conflict-aware strategies favouring power mix diversification[48].

How could West Africa go beyond the power pool scenario, given its rapidly rising power demand[30]? Uprating hydropower facilities with limited peak power[18] could increase load-following potential by 8% (Supplementary Note 4). Further oversizing, more interconnections (e.g. Chad and Mauritania for solar/wind, Cameroon for hydropower), and grid connection of distributed small-scale solar PV may all enhance RE penetration. Next to power plant-driven measures, storage-driven and demand-driven options should also be considered. Some hydropower plants could be upgraded to pumped-storage plants, with opportunities likely concentrated in Guinée, Ghana and Nigeria (Supplementary Note 7); off-river (closed-loop) pumped hydro storage is another option. Cost trends may lead to large-scale battery plants, power-to-gas technology, and/or concentrated solar power with thermal storage to become economically feasible in the next decades[35]. Demand response, e.g. through sectoral coupling, can be another lever; transport electrification may be a promising example, given this sector's high energy use in West Africa[49]. Finally, a holistic view of the entire energy system, focusing on merging power and other energy sectors including various storage options would be the ultimate stage of planning grid flexibility[50] (Supplementary Note 9.7). Future research could integrate such options, which go beyond this study's focus on sustainable hydropower pathways.

Implications for planning and policymaking

Our results highlight the substantial benefits to be gained by planning regional power pool strategies in West Africa according to hydro-solar-wind synergies. This carries implications for (i) transmission capacity, (ii) RE policy targets, (iii) natural gas demand, and (iv) hydropower exploitation.

Transmission capacity. The power pool scenario requires expansion of regional interconnections, most importantly between West Africa's north and south. Several such interconnections are already in place, and a cooperation of West African national electricity companies currently aims to integrate countries' power systems into a unified regional electricity market[32]. The transmission capacity needed for the power pool scenario is well-aligned with current transmission grid expansion plans (Supplementary Note 9.5), and most of the hydro, solar and wind power sites contributing to the power pool scenario could be readily connected to the planned transmission grid (Supplementary Fig. 14), the main exception being the high-yield solar and wind power plants in the Sahelian zone of Mali and Niger. In these countries, a trade-off is likely to exist between high yield and high infrastructural requirements: an alternative would be to build solar and wind power plants at slightly lower latitudes, where they would reach lower capacity factors (requiring more upfront investment for the same power generation) but be closer to urban areas (avoiding high transmission line costs and transmission losses)[7,8].

RE policy targets. The power pool scenario implies that countries' RE priorities may need to change if the aim were to optimally contribute to a regional power mix. We show how the necessary prioritisations of RE sources differ from those implied by current policy plans (Fig. 6; Supplementary Note 9.6). In particular, countries in southwestern West Africa (e.g.

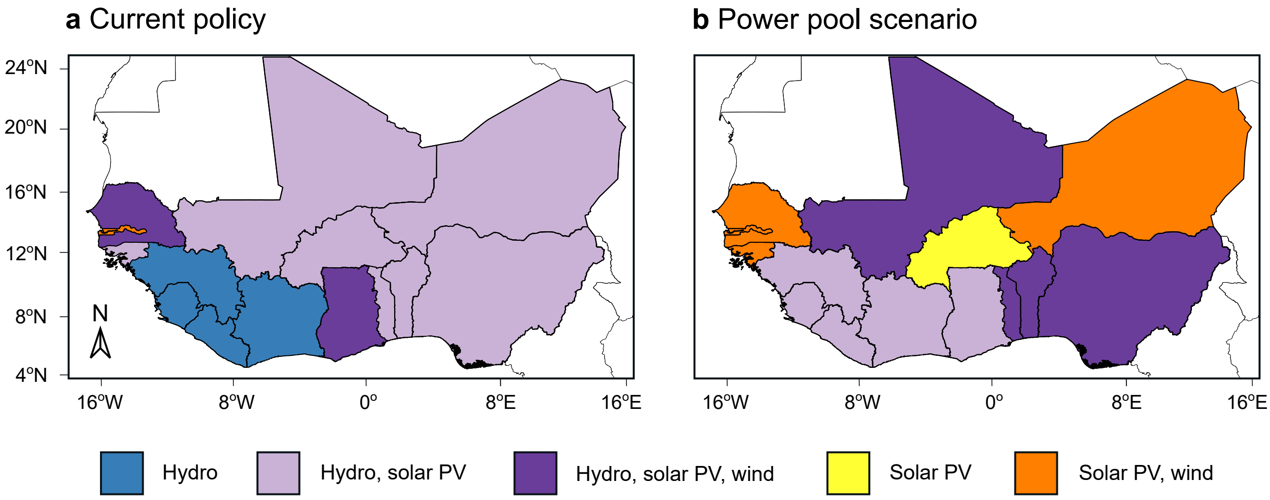

Figure 6: **Prioritisation of renewable resources in West Africa**, as suggested by (a) countries' current policy, and (b) the power pool scenario. Prioritisation under current policy was defined by which resources would account for more than 90% of a country's planned RE generation by 2030 (Fig. 1b). Prioritisation under the power pool scenario was defined by (i) which resources would account for more than 90% of a country's contribution to the power pool (column "Generation" in Fig. 5), and (ii) which countries would account for more than 90% of a resource's contribution to the power pool (column "Renewable mix" in Fig. 5); see also Supplementary Note 9.6.

Guinée, Côte d'Ivoire) could opt to diversify from hydropower-dominated plans towards hydro-solar mixes; and countries in northern West Africa (e.g. Senegal, Niger) could emphasize solar and wind power, deprioritising hydropower. High trust levels between countries would be crucial, since regional security of supply would need to be prioritised over national interests; and so would institutional arrangements for a regional electricity market, to ensure proper remuneration of flexibility[49]. Further, flexibility requirements could be explicitly included in hydropower planning strategies to ensure that hydropower plants can operate according to the needed rule curves (as in Fig. 2b); this could require refurbishing old plants for faster response rates[49]. Concerning long-term strategies, it has been estimated that solar PV could eventually become the most important renewable resource in transitioning to 100% renewable power systems in sub-Saharan Africa, with large-scale battery storage emerging post-2030[35]. Following the recommendations implied by the power pool scenario would help paving the way towards such a transition, with solar PV a suggested priority for all countries (Fig. 6b).

Natural gas. Moving towards a power pool scenario would limit natural gas demand by effectively displacing it with a smart RE portfolio. Accordingly, hydropower should be seen as a climate-resilient means of avoiding natural gas consumption by supporting solar/wind penetration. For instance, the solar/wind contribution of 28 TWh/year to total RE generation under the middle bound of the power pool scenario can directly avoid 28 TWh/year of electricity from natural gas, roughly Ghana's expected on-grid power demand by 2030[30].

Hydropower exploitation. The middle bound of load-following potential in the power pool scenario (Fig. 4a; with 12.3 GW hydro, 7.4 GW solar, and 6.4 GW wind power capacity) is close to the upper bound of the reference scenario (with hydropower potential fully exhausted at 23.4 GW, plus 3.6 GW solar and 1.0 GW wind), and total RE generation under this middle bound (58 TWh/year) approaches West Africa's cumulative 2030 target (67 TWh/year, Fig. 1b). This implies that a coordinated expansion of solar, wind and cross-border transmission capacity presents an alternative to exhausting West Africa's full hydropower potential. This would prevent negative ecological effects of excessive dam-building[22,33], considerably mitigate the risk of hydro-dependency[20,34], and reduce inter-sectoral competition for water resources[42].

Methods

Analysis: Current power mix and renewable electricity targets
The power generation mixes for 2015 in Fig. 1a were based on historical data[30,31] adapted to allocate electricity exports to the generating country. The targets for renewable resources in Fig. 1b were taken from countries' NREAPs (National Renewable Energy Action Plans) and comparable documents[31,51–55]. Wherever NREAPs only provided planned capacity but not generation, we calculated generation using country-average capacity factors[30] for solar and wind power, plant-level capacity factors for hydropower, and a 30% capacity factor for wave power[56].

Model: REVUB
The new model developed for this study (REVUB, "Renewable Electricity Variability, Upscaling and Balancing"; full details in Supplementary Note 1-8) was purpose-built with fully new code, and combines high-fidelity simulations of hydropower plants, including bathymetry and reservoir storage dynamics, with high-resolution solar and wind power potential. Its purpose is to design hydropower operation rules that ensure reliable integration of variable solar and wind power into load-following hydro-solar-wind mixes.
The main idea of these rules boils down to identifying the load-following potential of hydro-solar-wind power, defined as the demand (in GWh/year) that can be met by joint hydro-solar-wind operation without loss of load while ensuring long-term reservoir water level stability and meeting environmental flow needs[38].
To our knowledge, this study's application of REVUB represents the first usage of a model to map out an entire region's integrated hydro-solar-wind potential, coupling hourly-to-decadal and plant-to-regional scales. A valuable research base on hydro-solar-wind complementarity has recently emerged, but typically focused on single hydropower plants without regional upscaling[24,26,27], on continental-to-worldwide scales but with lumped hydropower sectors lacking individual reservoir details[34–37,43], only on a subset of timescales[23,24], or only on non-dispatchable run-of-river hydropower[28]. The rare studies that scale up individual hydropower plants' flexibility potential over larger areas[25,29] do not consider the impacts of interannual variability and climate change, both of which can be substantial[6,57].

Analysis: Hydropower rule curves
The release curve ranges for hydropower (Fig. 2b) were derived by (i) calculating, for each simulation year, the monthly average and standard deviation of required outflow at the corresponding hour of day, and (ii) plotting the resulting data points (one for each simulation year) against the average hydraulic head in the corresponding month (monthly averages of hydraulic head are good approximations for daily values; see Supplementary Fig. 6). The implications of these alternative rule curves for spinning reserves is discussed in Supplementary Note 8.

Database: WARPD
The database of present and future hydro, solar and wind power projects in West Africa developed for this work is named WARPD (West African Renewable Power Database). It combines information from existing databases, scientific papers, technical project descriptions, newspaper articles and tender documents for future projects. The full database (spreadsheet-based) is given as Supplementary Data.
Hydropower: The WARPD database includes existing and future on-grid hydropower projects in mainland West Africa (246 entries). Indispensable data to allow simulation in REVUB model were (i) geographic coordinates of each dam, such that inflow into the reservoir and precipitation/evaporation gains/losses could be inferred (see below, "Simulations: Hydrological data"); (ii) rated capacity P_{turb}^{r} (in MW) (Supplementary Note 3.1); and (iii) maximum reservoir volume V_{max}, lake area A_{max}, and head drop h_{max} (Supplementary Note 3.3). The consulted sources are referenced in WARPD.
For hydropower plants with unknown A_{max}, it was approximated using an empirically derived (V_{max}, A_{max}) relationship (Supplementary Note 3.3). Similarly, for hydropower plants with unknown h_{max}, but known planned dam height H_{dam}, the former was estimated from the latter using an empirical (H_{dam}, h_{max}) relationship (Supplementary Note 3.3).

All hydropower entries in WARPD are classified as existing, ongoing (as of the finalisation of this text), planned or potential. For some plants, the categorisation as either planned or potential was not straightforward, e.g. if certain sources cited the project as being in concrete stages of planning, but no specific technical data was available. We categorised plants as planned if all technical data was available or estimatable using the above-described methods, and as potential if not.

The identified total existing, ongoing and planned hydropower capacity amounts to 14.0 GW (of which 5.5 GW existing). Key target dates for planned projects, e.g. for starting construction or commissioning, are often unknown. Since West Africa's hydropower capacity is targeted [31,58] to reach 13.8-14.5 GW by 2030, many of the hydropower projects classified as planned in the WARPD database are likely to be completed by then. The projects classified as potential add another 12.7 GW, bringing the aggregate of existing, ongoing, planned and potential projects to 26.7 GW, consistent with independent estimates of West Africa's total attractive hydropower potential (25-30 GW) [59,60].

In WARPD, hydropower plants are allocated to the country in which they are/will be physically located, although several cases exist of bi- or multilateral hydropower schemes sharing the produced electricity among neighbouring countries. Wherever relevant, this information is included in WARPD.

Solar and wind power: WARPD includes an overview of locations for existing and planned on-grid solar PV and wind power projects in West Africa (78 entries for solar, 15 for wind). Their geographic coordinates were derived from the (i) ECOWREX geospatial database [40] or (ii) project name (typically designating a town/city) according to project databases [30,61] and NREAPs [31,51–55]. Projects appearing in several sources with identical locations but different names were assumed to refer to the same project. All solar PV and wind power plants in WARPD are classified as existing, ongoing, or planned.

Simulations: Selection of hydropower plants

Hydropower plants to simulate were selected using four criteria: (i) All necessary data must be available or estimatable following the procedures described above (i.e. by definition, no simulations were set up for "potential" hydropower plants); (ii) rated capacity P^r_{turb} must be above 10 MW; (iii) the plant may not be located on the Niger's main branch upstream of the Inner Niger Delta (IND), given the extreme ecological impact its operation could have on the IND [62]; and (iv) in case separate hydropower projects would share the same reservoir, only the one with the highest P^r_{turb} and complying with condition (i) is considered, to prevent double-counting flexibility potential. WARPD includes an overview of which criteria excluded which hydropower plants from being modelled for this study.

We identified 65 entries complying with (i)-(iv), with 12.3 GW cumulative capacity (88% of the capacity of the identified existing, ongoing and planned hydropower plants). These were subsequently categorised into two groups, based on whether average natural inflow would fill the reservoir in more or less than one year (these categories are abbreviated "large" and "small"; see Supplementary Note 2). Since a portion of the incoming water is not storable for small hydropower plants (as storing it would lead to reservoir spillover), there are operational differences between these categories (Supplementary Note 3-5). Fig. 3 displays the selected hydropower plants and their categorisation (existing, ongoing/planned; large, small).

These 65 entries comprised 23 large plants representing 6.8 GW, and 42 small plants representing 5.5 GW, across 11 countries. The hydropower flexibility potential of the remaining countries (The Gambia, Guiné-Bissau, and Liberia) was not explicitly simulated: The Gambia has no attractive hydropower potential, and Guiné-Bissau only for run-of-river schemes; for Liberia, data availability constraints prohibited simulation (with all projects classified as "potential"). However, Liberia's similarity to Sierra Leone allowed a rough estimation of its potential (Supplementary Note 9.2).

Simulations: Selection of solar and wind power plants

Solar and wind power plants to simulate were selected using two criteria: (i) Geographical coordinates must be (approximately) known; and (ii) rated capacity must be above 1 MW. If the selected projects' cumulative capacity exceeded 25% of the 2030 capacity targets (for solar PV and wind, respectively) in a country, those sites were deemed representative for present and future projects in that country; they are labelled "existing" or "ongoing/planned" in Fig. 3. If this was not the case, additional sites,

labelled "assumed" in Fig. 3, were selected as follows.
Since solar resources are relatively evenly distributed within West African countries[7], we added solar PV sites at the first n most populous cities in each country (minimising transmission capacity requirements between generation sites and load centers). For wind power, a different approach was chosen since wind turbine siting will be subject to compromising between closeness to load centers and reaching high capacity factors[7] (see below, "Simulations: Meteorological data"). We added wind sites at the locations of n cities/towns according to a hierarchy based on tiers of population size X separated by factors of ten: (i) cities in the top tier with $X > 10^6$ inhabitants and average wind power capacity factor $> 15\%$; (ii) cities from the same tier with an average solar-wind stability coefficient of $> 25\%$ (a metric introduced in previous work[7] to assess solar-wind synergies); (iii-iv) repeating steps (i-ii), but expanding to the second tier of cities with $X > 10^5$ inhabitants; (v-vi) &c., until n locations were identified. If several cities qualified for the same hierarchy criterion, they were selected in order of average wind power capacity factor[7].
For both solar PV and wind, the number of additional sites n for each country was taken to be $n = 1$ if the targeted 2030 solar or wind capacity was less than 10 MW, $n = 2$ if it was between 10 and 100 MW, and $n = 3$ if it exceeded 100 MW.

Simulations: Hydrological data
To obtain river discharge into reservoirs, we set up a SWAT+ (Soil and Water Assessment Tool, revision 55) simulation covering all of Africa at monthly resolution during 1980-2016. SWAT+ is a time-continuous hydrological model for catchment-scale modelling[63], in which watersheds are delineated into subbasins from which Hydrologic Response Units (HRU, areas with a unique combination of land use, soil type and slope class) are defined. Our SWAT+ model was set up using a 90×90 m DEM (Digital Elevation Model) acquired from the Shuttle Radar Topography Mission (SRTM)[64], land use data from the Land Use Harmonisation (LUH2) dataset[65] at $0.25° \times 0.25°$ resolution, and soil data from the Africa Soil Information Service (AfSIS) dataset[66] resampled to $0.25° \times 0.25°$. Meteorological forcing data were acquired from the EWEMBI dataset[67] at $0.5° \times 0.5°$. Evapotranspiration was estimated using the Penman-Monteith method, surface runoff using the SCS curve number method, and flow routing was done using the variable storage routing method. Subbasins were delineated using 3500 km^2 as threshold, giving 5700 (981) subbasins and 461,829 (71,665) HRUs in Africa (West Africa). We extracted the period 1998-2014 from the simulation results, equal to the reference period of the modeled river discharge in West Africa on the ECOWREX data portal[40,41], hosted by the Economic Community of West African States' (ECOWAS) Observatory for Renewable Energy and Energy Efficiency (ECREEE). We then statistically downscaled the SWAT+ results through bias-adjustment to the multiannual means of monthly discharge in the ECOWREX dataset, reconstructing a monthly 1998-2014 time series with, for each river stretch, the interannual variability of the SWAT+ results and the monthly means of the ECOWREX data. The motivation for combining these datasets was to combine the superior spatial resolution of the ECOWREX data (with 516,087 river stretches across West Africa, compared to 5,502 in SWAT+) with the superior temporal resolution of the SWAT+ data (the full time series behind the ECOWREX dataset are not freely available, having been developed by a commercial party).
Bias-corrected precipitation was obtained from the EWEMBI dataset[67]. Potential evaporation flux was taken from the ensemble mean of nine historical simulations from regional climate models driven by different global climate models, available through the CORDEX-Africa (COordinated Regional Climate Downscaling Experiment Africa) framework initiative at $0.44° \times 0.44°$ resolution and monthly timescale. These runs only covered the years up to 2005, but as evaporation on lake surfaces is nearly invariable multiannually[68], the mean for each month across 1998-2005 was applied across all simulations.
A validation of modelled reservoir dynamics against satellite altimetry observations is described in Supplementary Note 6.

Simulations: Meteorological data
Solar and wind power generation in the identified locations were derived from irradiation, temperature

and wind speed time series from the ERA5 reanalysis for 1998-2014. The methodologies used to convert these to solar and wind power capacity factors are described in previous work[7]. In this study, relative sizes (capacities) of future solar and wind power plants in different locations were assumed proportional to average capacity factors as calculated from ERA5, giving preference to high-potential sites (Supplementary Note 3.2).

Simulations: Load profiles

Hourly load profiles were based on 2018 data (the most recent year available) from the Ghanaian and Burkinese national grid, depending on each country's prevailing climate. This differentiation by climate regime was based on observed correlation between weather/climate and electricity consumption in West Africa[69,70].

Load data for Ghana, obtained from Ghana Grid Company Ltd. (see "Data availability"), was assumed representative for countries dominated by bimodal rainfall, i.e. countries located mostly in the (Sudano)-Guinean zone and on the Guinean coast[71]. Load data for Burkina Faso was assumed representative for countries with unimodal rainfall, i.e. located in the (Sudano)-Sahel[71]; this data was obtained from SONABEL, Burkina Faso's national electricity company, in preparation for a workshop (`https://cireg.pik-potsdam.de/en/cireg/project-diary/workshop-energy-and-water-modelling/`) organised by the CIREG project (see Acknowledgements) in Ouagadougou (18-22 March 2019).

The load profiles were assumed to be functions of each country's local time. The classification of countries by prevailing climate and time zone was therefore as follows:

- Bimodal: Ghana, Côte d'Ivoire, Togo, Liberia (UTC); Nigeria, Benin (UTC+1);
- Unimodal: Burkina Faso, Mali, Senegal, Guinée, Guiné-Bissau, The Gambia, Sierra Leone (UTC); Niger (UTC+1).

This classification is broadly consistent with synthetic load data from literature[72]. Load curve shapes are subject to change as (i) electricity access rises and (ii) countries' industrial and service sectors grow while (iii) energy efficiency improves; in this study, however, they were frozen to their 2018 shape. This choice was made to distinguish power plant-driven flexibility (this study's subject) from demand-driven effects.

Simulations: Scenarios

We designed the following five scenarios for REVUB:

- Reference - Represents current climate, no strategic oversizing, and no cross-border trade. Hydro, solar and wind power are based on hydroclimatic data representing 1998-2014. Hydro, solar and wind power are pooled on national power grids with their own representative load profile (see "Simulations: Load profiles") and their own solar/wind capacity mix based on the NREAPs (Supplementary Table 1). Overproduction is restricted: RE generation may exceed the average carried load only 10% of the time, giving allowed overproduction levels of 1-2% (Supplementary Note 3.2; Supplementary Fig. 5).

- Median future - Illustrates the impacts of climate change on RE potential. The median change (from projections for 2046-2065 relative to 1998-2014) of river discharge is applied to the reference time series of discharge into each reservoir; the corresponding changes in precipitation and potential evaporation at each reservoir are applied to the reference time series of those variables (see "Simulations: Climate projections"). The median (minimum/maximum) projected changes in annual river discharge, precipitation, and evaporation across all simulated hydropower plants are -0.1% ($-8.2\%/+7.9\%$), $+0.3\%$ ($-7.1\%/+15.5\%$) and $+7.1\%$ ($+3.6\%/+9.1\%$) as compared to the reference scenario, respectively. Solar and wind potential are assumed unimpacted by climate change (see "Simulations: Climate projections"). Other parameters are equal to the reference scenario.

- Dry future - Same as median future, but the 25th percentile change in discharge is used instead of the median. The median (minimum/maximum) changes in annual river discharge, precipitation, and evaporation across the set of simulated hydropower plants are -8.0% $(-23.5\%/+1.9\%)$, $+0.0\%$ $(-10.1\%/+7.3\%)$ and $+3.7\%$ $(+2.5\%/+4.9\%)$ as compared to the reference scenario, respectively.

- Oversizing - Illustrates the effect of strategic solar/wind oversizing. The overproduction constraint in the reference scenario is relaxed: RE generation may exceed the average carried load during 40% of the time, giving allowed overproduction levels of 25%-30% (Supplementary Note 3.2; Supplementary Fig. 5)[13,36,39]. This increases the load-following potential at the cost of consistent mid-day solar PV excesses. Other parameters are equal to the reference scenario.

- Power pool - Illustrates the effect of cross-border trade, assuming adequate joint power transmission infrastructure[5,13] among West African countries to harness renewable resources' spatial complementarity[30,32,36,43] (Supplementary Note 9.5). A regional load profile is estimated by aggregating (weighted by projected 2030 electricity demand[30]) national load curves, accounting for time zone differences. Solar and wind power generation is pooled from all actual and assumed locations. The region-wide solar/wind capacity mix is based on the ECOWAS Renewable Energy Policy (EREP[58]) targets. The constraint on overproduction is equal to that of the oversizing scenario (Supplementary Fig. 5). Other parameters are equal to the reference scenario.

Simulations: Climate projections

The median and dry future scenarios are based on an ensemble of CORDEX-Africa regional climate simulations covering the Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios. First, climate change signals on river discharge were taken from the ensemble of hydrological projections for 2046-2065 in the ECOWREX database[41]. We used the ensemble median change for the median future scenario, and the 25th percentile for the dry future scenario. Second, we selected the same ensemble of CORDEX-Africa simulations used to drive the hydrological models from which those results were obtained, identifying the ensemble members representing the median and the 25th percentile of change in region-wide precipitation. Third, we calculated the average change in precipitation and potential evaporation according to those members in 2046-2065 as compared to 1998-2014, for each grid cell. Fourth, we extracted these changes for all grid cells containing hydropower plants, and applied them to each plant's reference time series of lake surface precipitation gains and evaporation losses for the median and dry future scenario, respectively.

As the corresponding future changes in irradiation (mean changes of -0.9% and -0.2% in the median and dry future scenarios, respectively), temperature ($+0.9\%$ and $+0.5\%$) and wind speed ($+1.6\%$ and -0.5%) were small across the study domain, similar to interannual variabilities, we assumed solar and wind power to be unaffected by climate change.

Analysis: Post-processing

All analysis related to extrapolation of load-following potential (upper bounds in Fig. 4a), the Sankey diagram (Fig. 5), levelised cost of electricity (LCOE), transmission capacity, and country-level priorities (Fig. 6), is described in Supplementary Note 9.

Data availability

The ERA5 reanalysis data was downloaded via the Climate Data Store at `https://cds.climate.copernicus.eu/`. Data from the CORDEX-Africa framework is available at `http://cordex.org/data-access/esgf`. EWEMBI forcing data can be accessed via `http://doi.org/10.5880/pik.2019.004`. ECOWREX data and shapefiles are available at `http://www.ecowrex.org/mapView/`. Grid load data from Ghana is available at `http://ghanagrid.com/index.php/loadprofile`. Grid load data from Burkina Faso is available upon request, as is the data on the LCOE of existing and future hydropower plants in West Africa. LCOE data for solar and wind power in West Africa is available in the IRENA report referenced in Supplementary Note 9.4. The SWAT+ simulation results are available via Zenodo[73]. All other plant-level data used in the simulations is available and fully referenced in the WARPD database, provided as Supplementary Data to this paper. Data points behind the data plotted in the Figures can be found on Figshare[74].

Code availability
The REVUB model code (version 0.1.0) is available via `https://github.com/VUB-HYDR/REVUB` under the MIT license, for Python as well as MATLAB. Datasets to run a minimal working example are available in the same repository.

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Author contributions
S.S. and W.T. designed the study. S.S. developed the REVUB model, set up the WARPD database, performed the simulations, and analysed the data. I.V. generated the climate change scenarios. C.J.C. and A.v.G. developed the SWAT+ simulations. D.R. provided the LCOE data. S.S. wrote the paper and designed the figures with contributions from I.V., C.J.C., D.R., R.J.B., A.v.G., N.P.M.v.L. and W.T. All authors proofread and commented on the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary Information for this paper consists of Supplementary Notes 1-10, including a detailed mathematical description of the REVUB model and various Supplementary Figures and Tables. The WARPD database is provided as Supplementary Data.