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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 decarbonize 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 flexible alternatives compatible with the Paris Agreement, 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 South-East Asia[15,19–21].

Hydropower plant operation must consider environmental water needs as well as local and regional water resource availability on seasonal to multiannual timescales[21,22]. Therefore, to model flexible hydropower operation in systems with considerable solar and wind components, reservoir dynamics must be explicitly coupled to variable solar and wind power generation across a wide range of spatiotemporal scales. A multiscale 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 hydro, solar and wind power in enabling reliable electricity supply while complying with sustainable hydropower objectives on all timescales. 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[30,31]. Accordingly, solar and wind power integration is among the main objectives of West Africa's transmission infrastructure plans[31].

Hydropower's established role and the diversification towards other renewables are both reflected in West African national energy strategies[32]. 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 a considerable growth of potential flexibility

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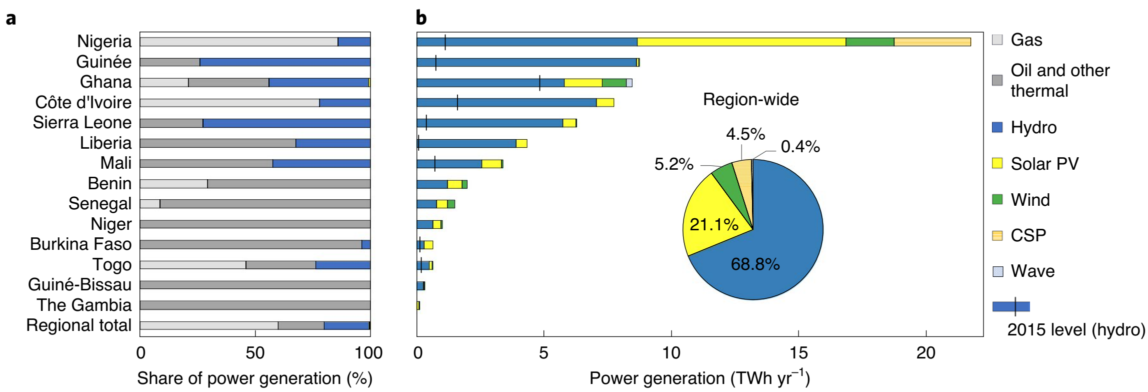

Fig. 1 | West African countries' power mix and targeted RE generation. **a**, The 2015 power generation mix of all mainland West African countries and the regional aggregate[30,32], with electricity exports allocated to the country of generation (see Methods). **b**, National RE targets for 2030. Bars represent the total amount of hydro, solar PV, wind, concentrated solar (CSP) and wave power generation targeted according to National Renewable Energy Action Plans 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.

reserves, allowing grid integration of solar and wind power and limiting 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 (1) setting RE targets based on renewable resource synergies, supporting renewable portfolio diversification and avoiding hydro-dependency[20,33,34], (2) operating hydropower plants with rule curves developed with hourly resolution, designed to maximize hydro–solar–wind complementarity and (3) expanding cross-border transmission capacity. Together, these can speed up the decarbonization 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 have been reported in the literature[18,35–37], these often lack granular details relevant to particular countries' specific conditions. The key contribution of 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: first, an environmental flow must always be guaranteed downstream to safeguard ecological integrity[38] and second, reservoir water levels must remain within safe ranges on seasonal-to-multiannual timescales. 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 Notes 1–8 for details) simulates how flexible hydropower operation can optimize 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 (1) a given solar/wind resource mix, (2) a given target load to be followed by hydro–solar–wind and (3) 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 into 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 the technical parameters for each hydropower plant and time series of (1) river flow into each reservoir, (2) evaporation and precipitation gains/losses, (3) normalized solar and wind power generation profiles (representing the pooled solar/wind resources in the grid) and (4) the load profile. The spatiotemporal resolution of the model's results depends on the spatiotemporal resolution of the input data; the model can run with input data at any resolution, but hourly resolved[3,4,9] multiannual[6] data are recommended, as is high spatial detail for hydrometeorological variables to closely represent individual RE plants. Here, simulations were performed at hourly time steps across a 17-year period; all details on the spatiotemporal resolution of the input data are described in the Methods. The minimum environmental flow requirements at each reservoir site were set to 40% of local annual mean river flow, reflecting recent assessments of the 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 an example (Fig. 2). The 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 and Supplementary Fig. 4). The model's optimization procedure ensures that reservoir release

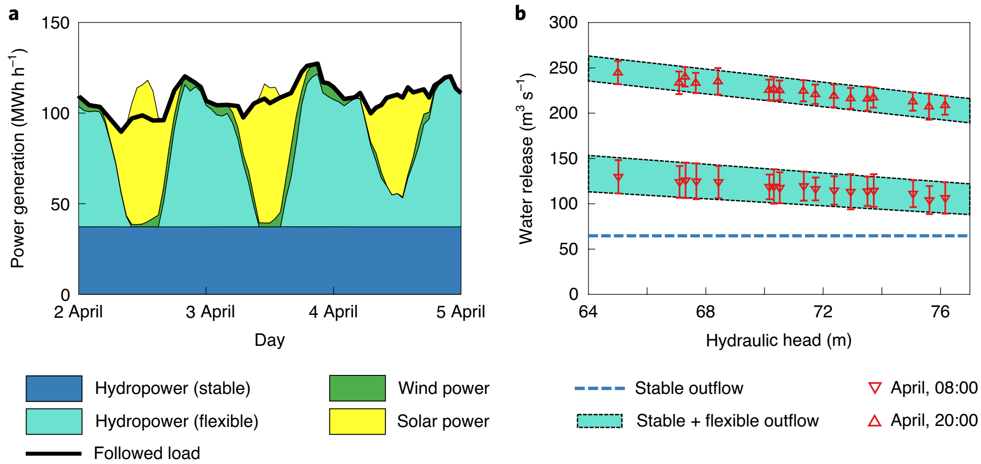

Fig. 2 | Example of optimized hydro–solar–wind operation and hydropower rule curves. Results from a simulation spanning 17 years at hourly resolution for Ghana's Bui hydropower plant alongside solar and wind power, according to the simulation settings of the reference scenario (see Methods). **a**, Hourly power generation showing the load-following RE mix for a sequence of 3 days in the 15th year of the study (see Supplementary Fig. 4 for the corresponding seasonal and multiannual 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 generalized reservoir release rule curves as a function of hydraulic head (the elevation difference between headwater behind the dam and tailwater at the turbines) at 08:00 and 20:00 in April across the simulation period. Every marker represents one month in a single simulation year; the ranges are standard deviations.

rules keep lake levels within safe ranges on multiannual timescales, 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 parametrization for each hour of the day and a distinct seasonality (see Methods). We show the release rules for 08:00 and 20:00 in April as linear ranges (Fig. 2b), which reflect the fact that the load peaks in the evening when solar power is unavailable. At midday, when solar power peaks, the stable, environmentally required outflow[38] usually suffices, except on low-irradiation days (for example, third day in Fig. 2a).

These rules require the outflow to be slightly increased as water levels decrease, because as the 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 stabilize the latter (Supplementary Fig. 3). However, 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 to 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 that included 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 (1) climate change impacts on RE resources, (2) strategic solar/wind capacity oversizing[39] and (3) increased regional (cross-border) interconnections. We therefore designed five corresponding scenarios (see Methods): (1) a reference scenario with no climate change signals, no oversizing and no interconnections, (2) a median future scenario, (3) a dry future scenario, (4) a scenario with strategic oversizing and (5) 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 are presented in Supplementary Tables 3–7), enabled by a different hydro–solar–wind mix (Fig. 4b). Because existing and planned hydropower schemes would leave a considerable hydropower potential unexploited, their associated load-following potentials represent the lower (existing schemes) and middle (existing + planned schemes) bounds of the 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 yr^{-1} (Fig. 4a). This represents, respectively, 12, 24 and 44% of current West African electricity demand (97.6 TWh yr^{-1}; ref. [30]) and 5, 11 and 20% of projected 2030 demand (218.7 GWh yr^{-1}; ref. [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[40].

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 midday 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 with the reference, boosting the lower, middle and upper bounds to 16.5, 37.5 and 69.1 TWh yr^{-1}, or 17, 39 and 71% of current West African electricity demand and 8, 17 and 32% of projected

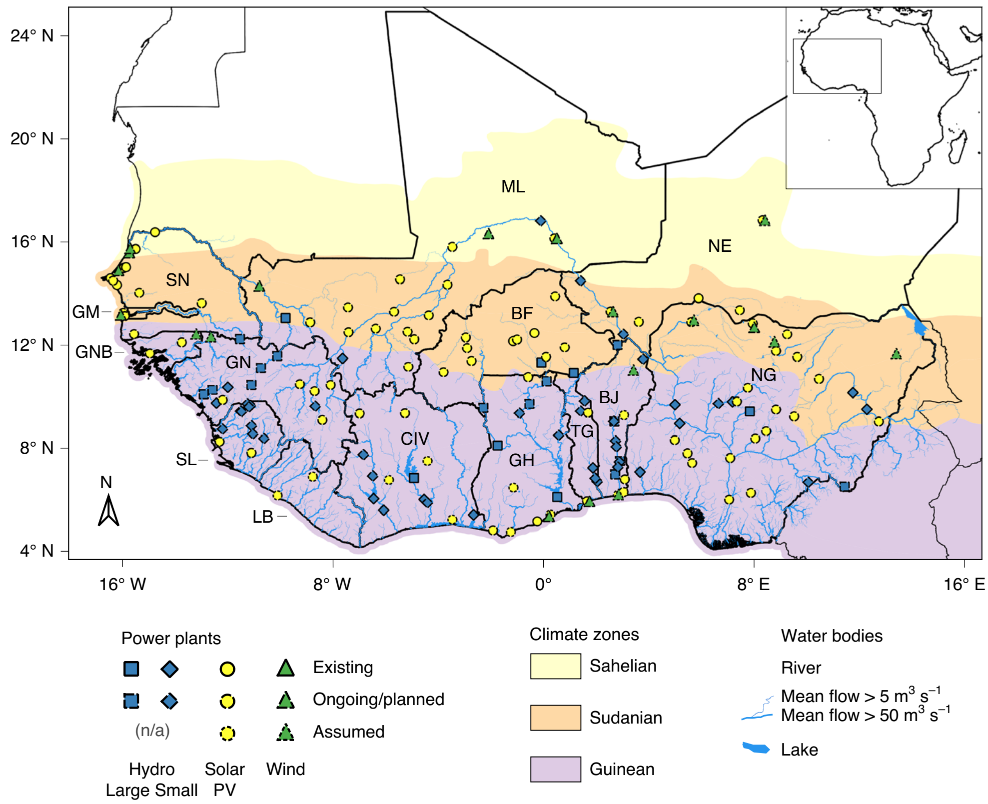

Fig. 3 | Locations of modelled hydro, solar and wind power plants. This map of mainland West African countries (borders in bold) shows the sites of reservoir hydro, solar PV and wind power plants modelled in this study, as well as climatological zones and water bodies[60]. See Methods for an explanation 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. n/a, not applicable.

2030 demand (Fig. 4a). This is because regional interconnections would enable harnessing a cascade of three spatiotemporal hydro–solar–wind synergies. First, interconnections allow exploitation of 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 due to increased interconnection, their diurnal synergies[7], with solar power peaking at midday and wind power during evenings and nights, reduce night-time 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 water to be saved 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 and south) synergy allows two temporal synergies (diurnal and seasonal) to be comprehensively harnessed, both of which considerably increase the followable load. Simultaneously, this supports sustainable hydropower practices, because reservoir outflow will peak during the wet season, mimicking natural flow regimes[41] 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 and 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 midday 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 levelized cost trends[30], a corresponding mix of new hydro–solar–wind capacity could generate electricity at grid parity with cheap natural gas in less than 10 years, and 10% more cheaply by 2030 (Supplementary Note 9.4).

Discussion

The outcomes of this research regarding the high potential of a renewables-oriented West African power pool can contribute to the modelling of West African power systems, serving as input/constraint to capacity expansion models[30,36,37,42], inform energy policy targets[43] and help align investment strategies in hydro, solar, wind and transmission capacity[31]. The modelling framework can also be readily applied to other regions. However, although conducted with great care to achieve realism, several opportunities for improvement deserve highlighting.

First, hourly temporal resolution was the highest achievable, because comprehensive meteorological datasets allowing multi-annual assessment of hydro–solar–wind potential are currently unavailable on a sub-hour timescale. Hourly resolution is consistent with recommendations for high RE systems[3,4,9], but once datasets at sub-hour resolution become available, the present study could be repeated with increased granularity. The model could

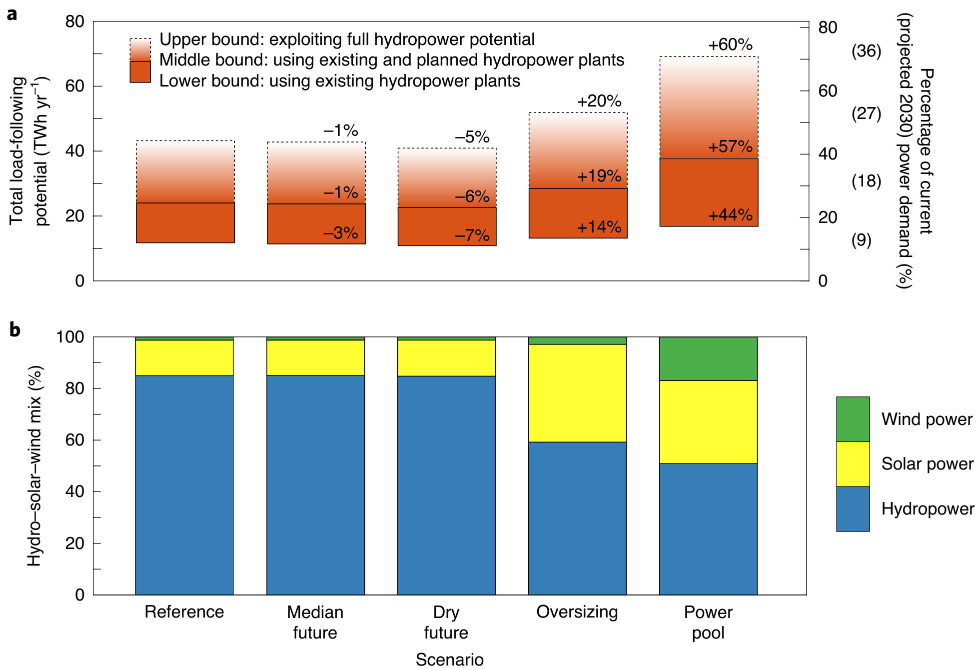

Fig. 4 | Total load-following potential and hydro–solar–wind mix. a, The total load-following potential under each of the five investigated scenarios. The lower, middle and upper bounds represent exploitation of the flexibility potential of all existing hydropower schemes, all existing and planned hydropower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

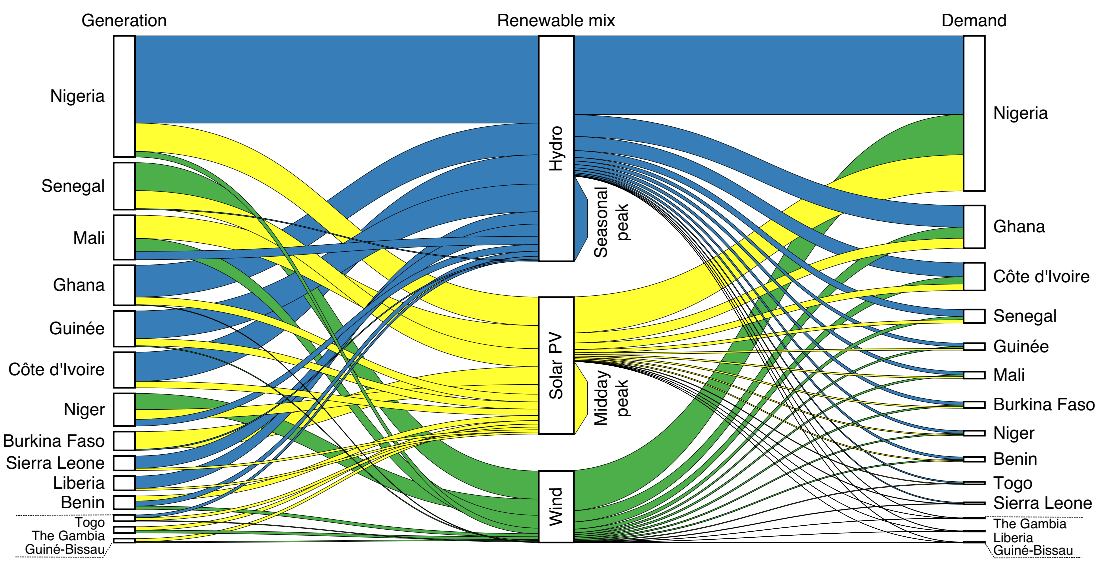

Fig. 5 | Contributions by country and RE resource in the power pool scenario. Sankey diagram based on the power pool scenario, showing power generation by country (left) and source (middle), and the guaranteed power supply to each country (right), divided proportionally to national electricity demand (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 'midday peak' of solar PV (overproduction around noon) 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).

also be extended with modules assessing frequency stability (sub-second) to design separate operational hydropower strategies for frequency control[2,33,44,45].

Second, because in general our conclusions on north–south synergies hold, various north–south country pairs could efficiently harness spatiotemporal hydro–solar–wind synergies without

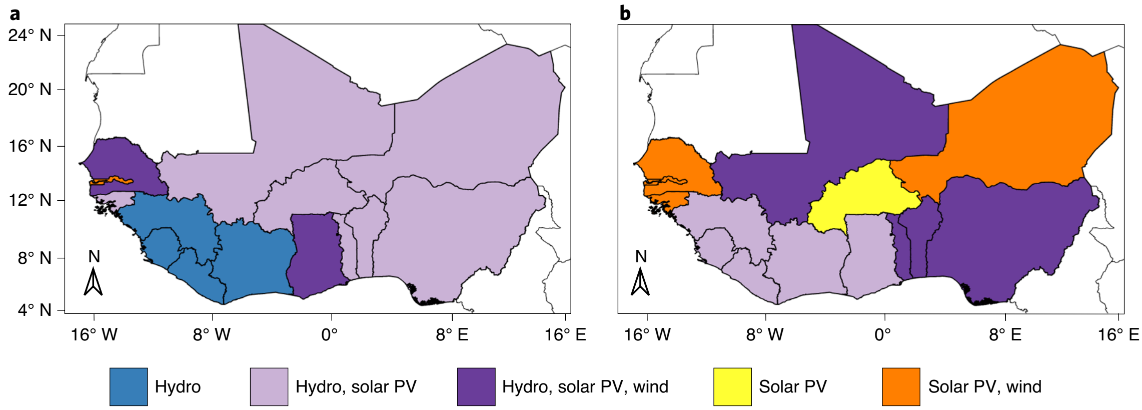

Fig. 6 | Illustration of how the necessary prioritizations of RE sources in West Africa differ from those implied by current policy plans. a,**b**, Prioritization of renewable resources in West Africa as suggested by countries' current policy (**a**) and the power pool scenario (**b**). Prioritization under current policy is defined by which resources would account for more than 90% of a country's planned RE generation by 2030 (Fig. 1b). Prioritization under the power pool scenario is defined first by which resources would account for more than 90% of a country's contribution to the power pool ('Generation' column in Fig. 5) and second, by 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).

interconnections to other countries, for example, Senegal/Guinée or Niger/Nigeria. Aiming for well-selected sets of regional interconnections could thus be as 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 the 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, for example, 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[46] and fragility/conflict-related risk[47] should also be considered. The latter may necessitate conflict-aware strategies favouring power mix diversification[47].

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 (for example, 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- 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 becoming economically feasible in the next decades[35]. Demand response, for example, through sectoral coupling, can be another lever; transport electrification may also be a promising example given this sector's high energy use in West Africa[48]. 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[49] (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 (1) transmission capacity, (2) RE policy targets, (3) natural gas demand and (4) 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 cooperation by West African national electricity companies currently aims to integrate countries' power systems into a unified regional electricity market[31]. 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 contribute optimally to a regional power mix. We show how the necessary prioritizations of RE sources differ from those implied by current policy plans (Fig. 6 and Supplementary Note 9.6). In particular, countries in southwestern West Africa (for example, Guinée and Côte d'Ivoire) could opt to diversify from hydropower-dominated plans towards hydro–solar mixes, and countries in northern West Africa (for example, Senegal and Niger) could emphasize solar and wind power, deprioritizing hydropower. High trust levels between countries would be crucial, because regional security of supply would need to be prioritized over national interests, and so would institutional arrangements for a regional electricity market, to ensure proper remuneration of flexibility[48]. 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 the refurbishing of old plants for faster response rates[48]. Concerning long-term strategies, it has been estimated that solar PVs 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 (ref. [35]). Following the recommendations implied by the power pool scenario would help pave the way towards such a transition, with solar PVs a suggested priority for all countries (Fig. 6b).

Natural gas. Moving towards a power pool scenario would limit natural gas demand by effectively replacing 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 yr^{-1} to total RE generation under the middle bound of the power pool scenario can directly avoid 28 TWh yr^{-1} of electricity from natural gas, roughly Ghana's expected on-grid power demand by 2030 (ref. [30]).

Hydropower exploitation. The middle bound of the 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 yr^{-1}) approaches West Africa's cumulative 2030 target (67 TWh yr^{-1}, 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 intersectoral competition for water resources[41].

Methods

Current power mix and renewable electricity targets. The power generation mixes for 2015 in Fig. 1a were based on historical data[30,32] adapted to allocate electricity exports to the generating country. The targets for renewable resources in Fig. 1b were taken from countries' National Renewable Energy Action Plans (NREAPs) and comparable documents[32,50–54]. Wherever the NREAPs only provided planned capacity and not generation, we calculated the 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[55].

Renewable Electricity Variability, Upscaling and Balancing model. The new model developed for this study ('Renewable Electricity Variability, Upscaling and Balancing', REVUB; for full details see Supplementary Notes 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 the 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 yr^{-1}) 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, the application of REVUB in this study 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 this typically focused on single hydropower plants without regional upscaling[24,26,27], on continental-to-worldwide scales but with hydropower sectors lumped together and lacking individual reservoir details[34–37,42], 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[6,56].

Hydropower rule curves. The release curve ranges for hydropower (Fig. 2b) were derived by first calculating, for each simulation year, the monthly average and standard deviation of required outflow at the corresponding hour of day, and then 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.

West African Renewable Power Database. The database of the present and future hydro, solar and wind power projects in West Africa developed for this work is named the West African Renewable Power Database (WARPD). 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 the REVUB model were (1) the geographic coordinates of each dam, such that inflow into the reservoir and precipitation/evaporation gains/losses could be inferred (see 'Hydrological data' section below), (2) the rated capacity (P^{r}_{turb}, where 'r' represents 'rated' and 'turb' represents 'turbine', in MW; Supplementary Note 3.1) and (3) the 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}, the value 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 finalization of this text), planned or potential. For some plants, the categorization as either planned or potential was not straightforward, for example, if certain sources cited the project as being in the concrete stages of planning, but no specific technical data were available. We categorized plants as planned if all the technical data were 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 is existing). The key target dates for planned projects, for example, for starting construction or commissioning, are often unknown. Because West Africa's hydropower capacity is targeted[32,57] 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)[58,59].

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 ECOWREX geospatial database[60] or the project name (typically designating a town/city) according to the project databases[30,61] and NREAPs[32,50–54]. 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: (1) all necessary data must be available or estimatable following the procedures described above (that is, by definition, no simulations were set up for 'potential' hydropower plants), (2) the rated capacity (P^{r}_{turb}) must be above 10 MW, (3) the plant may not be located on the Niger's main branch upstream of the Inner Niger Delta, given the extreme ecological impact its operation could have on the delta[62] and (4) in cases where separate hydropower projects would share the same reservoir, only the one with the highest P^{r}_{turb} and complying with condition (1) is considered to prevent double-counting flexibility potential. WARPD includes an overview of which criteria excluded which hydropower plants from being modelled in this study.

We identified 65 entries complying with criteria (1)–(4), with 12.3 GW cumulative capacity (88% of the capacity of the identified existing, ongoing and planned hydropower plants). These were subsequently categorized 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). Because a portion of the incoming water cannot be stored by small hydropower plants (as storing it would lead to reservoir spillover), there are operational differences between these categories (Supplementary Notes 3–5). Figure 3 displays the selected hydropower plants and their categorization (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, Guiné-Bissau only for run-of-river schemes and 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).

Selection of solar and wind power plants. Solar and wind power plants to simulate were selected using two criteria: (1) the geographical coordinates must be (approximately) known and (2) the 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, and 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.

Because 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 (minimizing transmission capacity requirements between generation sites and load centres). For wind power, a different approach was chosen because wind turbine siting will be subject to compromising between closeness to load centres and reaching high capacity factors[7] (see 'Meteorological data' section below). 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: (1) cities in the top tier with $X > 10^6$ inhabitants and an average wind power capacity factor of >15%, (2) 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), (3,4) repeating steps (1) and (2), but expanding to the second tier of cities with $X > 10^5$ inhabitants, (5,6) and so on, 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 power, 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.

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 sub-basins from which hydrologic response units (HRUs, areas with a unique combination of land use, soil type and slope class) are defined. Our SWAT+ model was set up using a 90 m × 90 m Digital Elevation Model acquired from the Shuttle Radar Topography Mission[64], land use data from the Land Use Harmonisation (LUH2) dataset[65] at 0.25° × 0.25° resolution and soil data from the Africa Soil Information Service (AfSIS) dataset[66] resampled at 0.25° × 0.25°. Meteorological forcing data were acquired from the EWEMBI dataset[67] at 0.5° × 0.5°. Evapotranspiration was estimated using the Penman–Monteith method, surface runoff using the Soil Conservation Service curve number method and flow routing was carried out using the variable storage routing method. Sub-basins were delineated using 3,500 km^2 as threshold, giving 5,700 (981) sub-basins 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 modelled river discharge in West Africa on the ECOWREX data portal[40,60], hosted by the Economic Community of West African States' (ECOWAS) Centre 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 with 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]. The 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 Coordinated Regional Climate Downscaling Experiment – Africa (CORDEX-Africa) framework initiative at 0.44° × 0.44° resolution and monthly timescale. These simulations only covered the years up to 2005, but as evaporation from lake surfaces is nearly invariable multiannually[68], the mean for each month across 1998–2005 was applied across all simulations.

A validation of the modelled reservoir dynamics against satellite altimetry observations is described in Supplementary Note 6.

Meteorological data. Solar and wind power generation in the identified locations were derived from irradiation, temperature and wind speed time series from the ECMWF Re-Analysis 5 (ERA5), the fifth major global reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), for 1998–2014. The methodologies used to convert these into solar and wind power capacity factors have been described in previous work[7]. In this study, the relative sizes (capacities) of future solar and wind power plants in different locations were assumed proportional to the average capacity factors as calculated from ERA5, giving preference to high-potential sites (Supplementary Note 3.2).

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].

The load data for Ghana, obtained from Ghana Grid Company (see Data availability), were assumed representative for countries dominated by bimodal rainfall, that is, countries located mostly in the (Sudano)-Guinean zone and on the Guinean coast[71]. The load data for Burkina Faso was assumed representative for countries with unimodal rainfall, that is, located in the (Sudano)-Sahel[71]; these data were 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/) organized 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 (coordinated universal time, 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 the synthetic load data from the literature[72]. Load curve shapes are subject to change as access to electricity rises and countries' industrial and service sectors grow while energy efficiency improves. In this study, however, they were frozen in their 2018 shape. This choice was made to distinguish power plant-driven flexibility (the subjectof this study) from demand-driven effects.

Scenarios. We designed the following five scenarios for the REVUB modelling:

- Reference. Represents current climate, no strategic oversizing and no cross-border trade. Hydro, solar and wind power are based on hydroclimatic data from 1998–2014. Hydro, solar and wind power are pooled in national power grids with their own representative load profile (see 'Load profiles' section above) 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 and 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 'Climate projections' section below). 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 with the reference scenario, respectively. Solar and wind potential are assumed unimpacted by climate change (see 'Climate projections' section below). Other parameters are the same as those for the reference scenario.
- Dry future. Same as for the 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 with 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 and Supplementary Fig. 5)[13,36,39]. This increases the load-following potential at the cost of consistent midday solar PV excesses. Other parameters are the same as those for 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 the spatial complementarity of renewable resources[30,31,36,42] (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[57] targets. The constraint on overproduction is equal to that of the oversizing scenario (Supplementary Fig. 5). Other parameters are the same as those for the reference scenario.

Climate projections. The median and dry future scenarios are based on an ensemble of CORDEX-Africa regional climate simulations covering the Representative Concentration Pathway scenarios RCP4.5 and RCP8.5. First, climate change signals on river discharge were taken from the ensemble of hydrological projections for 2046–2065 in the ECOWREX database[40]. 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 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 with 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 scenarios, 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.

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

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The ERA5 reanalysis data were downloaded from the Climate Data Store at https://cds.climate.copernicus.eu/. The data from CORDEX-Africa framework are available at http://cordex.org/data-access/esgf. EWEMBI forcing data can be accessed at https://doi.org/10.5880/pik.2019.004. Shapefiles for rivers and climate zones, used in Fig. 3, are available in the ECOWREX database[60] at http://www.ecowrex.org/mapView/. Country border shapefiles, used in Figs. 3 and 6, are available in the GADM database[73] at https://gadm.org/maps.html. The maps in Figs. 3 and 6 were created using QGIS[74], which can be downloaded from http://qgis.osgeo.org/. Grid load data from Ghana are available at http://ghanagrid.com/index.php/loadprofile. Grid load data from Burkina Faso are available upon request, as are the data on the LCOE of existing and future hydropower plants in West Africa. LCOE data for solar and wind power in West Africa are available in the IRENA report referenced in Supplementary Note 9.4. The SWAT+ simulation results are available from Zenodo[75]. All other plant-level data used in the simulations are available and fully referenced in the WARPD database, provided as Supplementary Data to this paper. The data points behind the data plotted in the Figures can be found in Figshare[76].

Code availability

The REVUB model code (version 0.1.0) is available at 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.

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Software and code

Policy information about availability of computer code

Data collection	Data collection was done without specific software, except for the use of Python scripts used to download climate data from the Climate Data Store, whose principle is described on https://cds.climate.copernicus.eu/api-how-to, and the SWAT+ hydrological model, which can be downloaded through https://swat.tamu.edu/software/plus/. A large part of the collected data has been summarised in a spreadsheet-based and fully referenced database by the authors; this database is provided as Supplementary Data along with the paper.
Data analysis	The data analysis in this study was performed using a purpose-built tool called REVUB, whose code is available on GitHub: https://github.com/VUB-HYDR/REVUB and whose full mathematical description is available in the Supplementary Information. Certain pre- and post-processing calculations to prepare inputs into REVUB and process output from REVUB was done using Excel-based spreadsheets.

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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 under the Methods section "Analysis: Levelised cost of electricity". The SWAT+ simulation results are available via https://

doi.org/10.5281/zenodo.3580663. 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.

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Study description	The study focuses on modelling smart management strategies of present and future hydropower plants in West Africa to support substantial grid integration of solar and wind power and thus limit natural gas consumption, while avoiding ecologically unsustainable effects of hydropower (over)exploitation. The modelling is done from point to subcontinental and hourly to decadal scales.
Research sample	The research sample consisted of all existing, planned and potential hydropower plants in West Africa, as well as all existing and planned, plus a representative set of assumed potential, solar and wind power plants in West Africa.
Sampling strategy	The sample size was equal to the full set of hydro, solar and wind power plants in West Africa which either already exist or which could be constructed in the coming decades according to current plans and/or assessments of overall resource potential. The details are fully explained in Methods and a complete overview of the sampled plants is given in Supplementary Data.
Data collection	The input data for the modelling was collected by the team of authors, led by Sebastian Sterl, in the period between July 2018 and November 2019, largely through internet-based literature and data collection. Meteorological data from the ERA5 reanalysis were obtained from the Climate Data Store via https://cds.climate.754 copernicus.eu/. Hydrological data were obtained from SWAT+ model simulations and bias-corrected to ECOWREX data available via http://www.ecowrex.org/756 mapView/. EWEMBI forcing data were obtained via http://doi.org/10.5880/pik.2019.004. Grid load data from Ghana was obtained from http://ghanagrid.com/ index.php/loadprofile. Grid load data from Burkina Faso 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 in which several authors participate (see Acknowledgements) that took place in Ouagadougou from 18 to 22 March 2019 (this data is available upon request). LCOE data for hydro, solar and wind power in West Africa were obtained from a recent IRENA report (https://www.irena.org/publications/2018/Nov/Planning-and-prospects-for-renewable-power), and some of the underlying data of that report was provided by its authors (this data is available upon request).
Timing and spatial scale	The data collection happened according to the authors' personal schedules in the period between July 2018 and November 2019, with continuous updating of older data in case newer data was found during the process.
Data exclusions	No data were excluded from the analysis a priori, e.g. the full set of collected data is available in Supplementary Data. However, certain hydropower plants were not included in the quantification according to the following criteria (as explained in Methods): if their rated capacity was under 10 MW; or if they were to be located on the main river section upstream of the Inner Niger Delta because of the extreme ecological impacts dam construction would have there.
Reproducibility	The results from the analysis are fully reproducible using the code (provided open-access) and the referenced datasets used by the researchers. The GitHub entry contains data files for a minimal working example, which can be used to reproduce a representative part of the results and several of the Figures in the manuscript and the Supplementary Information. The SWAT+ simulation results used as input for the simulations are available via https://doi.org/10.5281/zenodo.3580663. The reanalysis data from the ERA5 dataset used as input for the simulations can be obtained free of charge by any user from the Climate Data Store. The WARPD database, containing power plant-level data needed as input for the simulations, is given as Supplementary Data along with the paper. Any data that is not included in these repositories and/or available open-access via the references provided in the paper, can be obtained from the authors upon request.
Randomization	Given that the different scenarios that were assessed were simulated according to fully deterministic conditions (modelled with provided code and with fully documented and referenced input data), and based on the exact same set of hydropower generation plants with the same technical characteristics and the same set of locations for solar and wind power generation, no biases based on "study groups" could occur. Therefore, no randomization procedures were necessary.
Blinding	Given that the simulated scenarios are fully deterministic (modelled with provided code and with fully documented and referenced input data), and no observer-expectancy effects are possible in the given study setup, no blinding procedures were necessary.

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