Designing diversified renewable energy systems to balance multisector performance

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Abstract

Renewable energy system development and improved operation can mitigate climate change. In many regions, hydropower is called to counteract the temporal variability of intermittent renewables like solar and wind. However, using hydropower to integrate these renewables can affect aquatic ecosystems and increase cross-sectoral water conflicts. Using an artificial intelligence-assisted multisector design framework applied to Ghana, we demonstrate that relying on hydropower's flexibility can support expanding the use of intermittent renewables in the country's power mix by 38%. However, this would increase sub-daily Volta river flow variability up to 22 times compared to historical baseload hydropower operations, thereby damaging river ecosystems and reducing agricultural sector revenues by 169 M$/yr. Conversely, a diversified investment strategy including intermittent renewables, bioenergy, transmission lines, and strategic hydropower re-operation could reduce sub-daily flow

variability and enhance agricultural performance while meeting future national energy service goals and reducing CO_2 emissions. The tool supports national climate planning instruments such as Nationally Determined Contributions by steering towards diversified and efficient power systems and highlighting their sectoral and emission trade-offs and synergies.

Main

Increased access to sustainable electricity is required to deliver the United Nations Sustainable Development Goals (SDGs). According to the 2022 SDGs report, over 700 million people still lack reliable, sufficient electricity access, with more than three-quarters of them living in sub-Saharan Africa [1]. Renewable energy sources particularly from intermittent sources such as wind and solar, are called to increase access to affordable, reliable, and sustainable energy to meet increasing global electricity demand and climate objectives [1–3]. However, recent global crises such as the COVID pandemic and increasing fuel prices have slowed efforts to meet electrification targets and reduced international financing for renewables, despite the urgency to slow climate change [1]. For instance, an increase of 6% in global energy-related CO_2 emissions was observed as demand for coal, oil and gas rebounded with economic reactivation in 2021 [1]. More alarmingly, based on current Nationally Determined Contributions (NDCs), global emissions are projected to increase by 14% over the current decade [1]. Accelerating the adoption of renewables is necessary to achieve energy and climate objectives by 2030 [1,3].

Renewable sources can be classified into dispatchable, i.e., controllable generation, such as storage-based hydropower, bioenergy, and geothermal, and non-dispatchable, e.g., run-of-river hydropower, wind, and solar. Hydropower accounts for the largest share of the global total with a capacity of 1,230 GW, 40% of the worldwide renewable installed capacity [2]. However, as of 2021, solar and wind energy dominated renewable capacity expansion worldwide, jointly accounting for 88% of all renewable additions in that year [2]. Despite the environmental, social, and economic benefits of intermittent renewables, their variable nature challenges the ability of power system operators to balance electricity supply and demand at any given time. Power system flexibility is needed to compensate for variations in intermittent renewable generation across geographical areas and time scales [4,5]. In the short-term (i.e., seconds to hours), flexibility is required to counteract supply and demand variation to prevent power system failures [6]. In the medium- to long-term (i.e., days to years), flexibility is needed to use resources in the cheapest and most environmentally friendly ways.

Reservoir hydropower is the most attractive technology for providing the flexibility required to accommodate intermittent renewables [6,7], as it can cost-effectively store water over time periods to complement short-, medium- and long-term variabilities of intermittent renewables [6,8,9]. However, dams can adversely impact rivers, as they fragment fish migration routes and change their rivers' physical and chemical characteristics and floodplains [10–12]. Operating dams to provide system flexibility services can alter sub-daily natural river flow regimes [13–15], aggravating negative impacts on aquatic ecosystems [16–19] and intensifying intersectoral water use conflicts mainly due to long-term hydrological alterations [20,21]. Reservoir hydropower in a system with a high share of intermittent renewables will tend to be called to release water downstream with high variability to compensate for short-term differences between power generation and demand [14]. Such operations, called hydropeaking, severely alter sub-daily river flows downstream of hydropower plants affecting aquatic ecosystems. Hydropeaking's hydrological alterations change river thermal regimes [22], erode riverbanks and beds, change river morphology, degrade plant and animal populations [16–19], and impact the incomes and livelihoods of communities that rely on these ecosystem services. Furthermore, dams provide services to sectors such as irrigated agriculture and drinking water supply, which have their own spatial and seasonal water demands. In the medium and long-term, seasonal changes in water releases from dams to match the medium and long-term seasonality of electricity demand and intermittent renewables may produce a mismatch between hydropower releases and the seasonal water demand of other sectors that depend on stored water in reservoirs, possibly leading to sectoral resource conflicts [20,21].

Recent studies suggest that current and future hydropower can support substantial solar and wind power integration, re-introducing river flow seasonality, and reduce fossil fuel consumption by allowing changes in hydropower operations from baseload to peak [6,7,9,23–25]. Other studies have focused on how regional coordination and expansion of solar and wind technologies can reduce the hydropower reliance in Asia's power systems from an integrated energy and river basin planning perspective [26,27]. Although some of these studies consider the impacts of hydropower on river fragmentation, they do not consider the sub-daily flow alteration and the possible multisector conflicts that can be produced by the variability, at different timescales, of intermittent renewables. To our knowledge, no previous work has evaluated how to integrate a mix of low-carbon energy sources while achieving a broad range of other ecological, social, and economic objectives.

Power generation systems are embedded in complex human-natural systems where changes affect water, food, and the environment to differing degrees. This complexity must be considered when designing plans and operating strategies for hydropower dams and intermittent renewables to achieve service level improvements and SDGs simultaneously. A key policy question of sustainable expansion of renewable energy technologies is how to plan spatially distributed, interdependent multisector systems, where performance and sectoral benefit distribution depend not only on what infrastructure is built and where but also on how existing and new infrastructure are operated conjunctively [28]. Navigating trade-offs to reduce greenhouse gas emissions requires significant policy and operational integration, typically across multiple ministries. Few countries, if any, know how to identify and negotiate these issues through climate policy planning such as NDCs.

This article aims to support decision-makers in designing, operating and balancing trade-offs in complex Water-Energy-Food-Ecosystem (WEFE) resource systems by introducing a novel Artificial Intelligence (AI) assisted multi-objective design framework. The framework uses interlinked spatially explicit power and river basin simulators. The study shows how system re-operation aiming to enable intermittent renewables can increase sub-daily river flow variability and aggravate multisector conflicts within human-natural systems unless a diversified set of power system infrastructure investments with appropriate management are put in place. We demonstrate the design framework on a national-scale case study for Ghana in West Africa. The framework can assist decision-making in multisector resource systems with energy-river basin interdependencies and where energy supply and demand growth motivate decision-makers to transition to green growth. Our results encourage planners to consider the negative impacts on water, food and ecosystems of inappropriate energy system development and re-operation aimed at enabling intermittent renewables, and instead invest in power systems to balance multisector performance while reducing CO_2 emissions.

Spatial co-design of river basins and power systems

We introduce a spatially distributed integrated river basin and power system simulation and design framework. It aims to help analysts and stakeholders identify power system designs and hydropower operations that minimize adverse environmental impacts and intersectoral conflicts when addressing the challenge of integrating intermittent renewables. The approach minimizes conflicts and maximizes inter-sectoral complementarities across time and space in multisector systems. The proposed framework, shown in Fig. S1, has two components: 1) an integrated river basin and power system simulator and 2) a multi-objective AI-based optimized design process.

The first component (Fig. S2) considers spatially explicit sectoral infrastructure and connectivity within and between different sectors. Demands for water supply, irrigation and aquatic ecosystems are represented within river basins and are linked to power system elements to represent WEFE nexus dynamics. We use models adopted by each sector and soft link them at model run-time to represent feedback. The models simultaneously represent the various resource system supply-demand networks, connecting them where appropriate (in our work, at hydropower generation nodes). The river basin is modelled using a water resources allocation and management model [29,30] at discrete time steps. The power system is modelled using a direct current optimal power flow model at hourly time steps [31]. The integration of the system models uses an object-oriented multi-actor simulation framework [32], which integrates and coordinates the inputs and outputs of the models into a single simulation.

The second framework component is a multi-objective AI-based search algorithm used to perform WEFE trade-off-informed design, considering many performance dimensions and spatiotemporal scales of the integrated river basin and power system simulator. The approach helps planners and stakeholders identify performance trade-offs, synergies, and co-benefits implied by the most efficient (i.e., approximately Pareto-optimal) and resilient portfolios of synergistic water–energy interventions and their spatial layouts. Further technical details on the framework are provided in the Method section.

National-scale case study for Ghana

We use Ghana as a case study to demonstrate the integrated river basin and power system simulation and design framework at national scale. Ghana's total electricity generation comprises a mix of hydropower, gas, and oil sources (47%, 30%, and 23%, respectively) [33]. The Ghanaian national policy aims for large-scale development of intermittent renewables, where hydropower could be used to provide flexible services [34]. The Akosombo Dam, the largest electricity generation plant in the country (1,020 MW), which regulates the world's largest human-made reservoir based on surface area —the Volta Lake [35], currently provides ancillary services (e.g., voltage and volt-ampere reactor support, and reserve) to the Ghanaian power system [36].

By 2018, the Ghanaian government provided electricity access to 84% of the population through its National Electrification Scheme started in 1991 [33]. However, challenges remain, such as low electrification rates in Northern Ghana, high per capita power system emissions compared with other Sub-Saharan African countries (0.52 ton CO_2e/yr per capita [7]), high electricity losses in the transmission system (around 20% [33]) and low generation capacity resulting in load shedding or power rationing, which affects the country's economic and social welfare [37]. Ghana's updated NDCs and Energy Master Plan [34,38] aim for large-scale renewable energy development (1,363 MW) and to reduce Greenhouse gas emissions by 45% compared with a business-as-usual trajectory emission by 2030. However, what to build, where and why, how to operate the new system, and what impacts would be imposed on river ecosystems remain open questions.

64% of Ghana's land surface is part of the Volta river basin, which is shared by six riparian countries; the basin area within Ghana makes up 42% of the total basin area [33]. Fig. 1 shows Ghana's existing and planned irrigation schemes that depend on water resources stored in existing and under-construction dams (Akosombo, Bui, Pwalugu). The installed hydropower capacity in Ghana is 1,580 MW (Akosombo, Kpong, and Bui), with an additional 59 MW under construction (Pwalugu) and 501 MW potentially developable [33]. The natural river flows pre-damming the lower Volta river were characterized by a high intra-annual variability with a peak in September or October. This natural river flow pattern provided vital ecosystem services and livelihood opportunities to riverine communities and the wider country [39]. Among those services were a mix of freshwater, marine, and saltwater fish, flood recession agriculture, clam picking, and aquatic weeds control [40,41]. However, after Akosombo and Kpong were constructed, the steady flow regime established to favor baseload hydropower production affected the natural dynamics of salt and fresh water in the estuary, decreasing the catch of fish, clams, and oysters and favoring the proliferation of weeds, which resulted in a reduction of the base resources contributing to riverine households' impoverishment and diseases proliferation (malaria, schistosomiasis and river blindness) [41]. However, despite the impacts of constructing these dams, downstream ecosystems have adapted to the post-damming conditions, with a shift in species composition dominated by freshwater species such as Tilapia, Chrysichthys, and Catfish [39,41]. Riverine communities have also adapted to the steady flow regime, which provides year-round freshwater supply for domestic, industrial, and agriculture [39]. The new flow regime has encouraged investment in aquaculture and floodplains infrastructure that would be at risk from flooding under the natural river flow regime [39]. Introducing additional changes to the river flow regime by reoperating hydropower plants to integrate intermittent renewables may further negatively impact the ecosystems and communities that have adjusted to the post-dam flow regime [39,41].

This study highlights the need to balance river ecosystems and multisector responses to the re-operation of hydropower plants aiming to support the integration of intermittent renewables, as detailed in the following two sections. We evaluate impacts on sub-daily river flow alteration and the water resources sector produced by increased hydropeaking and changes in seasonal reservoir releases.

Results

Synergistic low-carbon infrastructure designs for Ghana

Three intervention strategies were used to assess the multisector impacts and trade-offs of re-operate hydropower to support intermittent renewables integration into Ghana's power system. The strategies combine the expansion of new power system infrastructure (solar, solar with storage, wind and bioenergy generation, and transmission lines) and the re-operation of existing hydropower plants, considering a two-fold increase of the electricity demand peak by 2030 [36]. The three intervention strategy scenarios include expansion of solar, wind and solar with storage technologies and the re-operation of the Akosombo, Bui and Pwalugu hydropower plants, but each strategy includes different additional measures/investments to support intermittent renewables, as explained below.

In intervention strategy one, hydropower re-operation and existing thermal generation plants provide the power system flexibility necessary to integrate high levels of intermittent renewables. Here, the power system distribution is constrained by the existing capacity of the transmission network. In intervention strategy two, the expansion of transmission lines is included in the system design. Here, hydropower re-operation and thermal generation plants are still the only technologies providing flexibility; however, expanding the power system network allows reallocating and distributing renewable resources (intermittent or not) to displace existing thermal generation and reduce CO_2 emissions. Finally, intervention strategy three is the most diversified power system infrastructure portfolio strategy where bioenergy and transmission line expansion are included jointly with hydropower re-operation and thermal generation plants to support the integration of intermittent renewables. The three strategies are assessed considering the following performance metrics: i) sub-daily hydrological alteration downstream reservoirs; ii) power load curtailment; iii) CO_2 emissions from power generation; iv) agricultural yields and revenue from irrigation schemes; v) flood recession agriculture benefits; vi) power system capital costs; and vii) power system operational costs. Sub-daily hydrological alteration is evaluated using the Richards–Baker Flashiness Index [42]. Natural sub-daily flows are characterized by a steady flow regime, with infrequent short-term fluctuations where native flora and fauna are adapted to various features of this natural flow regime [42–44]. A value of 1 in the Richards–Baker Flashiness Index implies a flashy stream (hydropeaking operations) and a less desirable sub-daily regime. In contrast, a zero index value characterizes a stable stream (baseload operations) with equal flow throughout the day [14,15,42].

Fig. 2 shows the complete set of Pareto optimal solutions identified in the three intervention strategies. Each line in Fig. 2a is a Pareto optimal portfolio corresponding to a set of new infrastructure expansion and hydropower operations. Different flexible hydropower operation levels are identified using the Richards–Baker Flashiness Index. For example, in intervention strategy one, hydropeaking operation with high sub-daily hydrological alteration (0.22 in the Richards–Baker Flashiness index) can help expanding up to 6,3 GW from intermittent renewables, 38% of Ghana's power mix (blue lines in Fig. 2b). However, in addition to increasing the sub-daily hydrological alteration, this system expansion and operative strategy would result in high power system emissions (14 Mton CO_2e/yr), high levels of annual load curtailments (7%), and a decline in agricultural yields of at least 5% annually; reducing the agricultural sector revenues by 169 M$ annually.

In intervention strategy two, expansion of intermittent renewables enabled by new transmission lines (yellow lines in Fig. 2b) drives a reduction in system annual load curtailment up to 2%, in CO_2 emissions to 13 Mton CO_2e/yr, and sub-daily flow alteration to 0.16 in the Richards–Baker Flashiness Index compared to strategy one. This is because the expansion of transmission lines helps to accommodate renewable generation displacing gas and oil generation. Further performance improvement is achieved in intervention strategy three when hydropower plants are more efficiently used alongside new spatially distributed and dispatchable bioenergy infrastructure enabled by new transmission lines (red lines in Fig. 2c). This reduces sub-daily flow alteration to 0.01 in the Richards–Baker Flashiness Index (to historical baseload hydropower operation levels) and the emissions to 12 Mton CO_2e/yr, without affecting agricultural production or incurring in load curtailment compared to intervention strategy one and two.

Fig. 2d shows infrastructure expansion by region based on a compromise solution from intervention strategy three (black line in Fig. 2c). This compromise solution is selected because it reduces the power system load curtailment to zero, produces low levels of CO_2 emissions (12.3 Mton CO_2e/yr), and maximizes irrigation yields (2770 kton/yr) and its economic returns (1,299 M$/yr) thus resulting in "improved all-around system performance" compared to solutions in scenarios one and two. The compromise solution includes more infrastructure expansion in northern Ghana, mainly transmission lines (1 GW, corresponding to 43% of total transmission expansion in the system) and bioenergy generation plants (0,8 GW, corresponding to 76% of total new bioenergy), compared with other regions. This happens because the north has a lower installed infrastructure capacity than the south, and the electricity demand in this region is increasing. Strategy three helps identify strategic system infrastructure designs and hydropower reservoir operations that improve system performance and reduce operating costs (up to 82 $M/yr) without requiring large investments in cross-region transmission infrastructure (see Fig. S3). This is because more intermittent renewable sources and spatially distributed bioenergy infrastructure reduces the need for costly new cross-region transmission lines. Fig. 2d shows how the new cross-region transmission infrastructure represents only 24% of the total new transmission infrastructure installed in the country for the selected compromise solution. This result is generalized in Fig. S4, which shows the infrastructure expansion distribution for the solutions in intervention strategy three (red lines in Fig. 2a). Fig. S5 shows the distribution of infrastructure selected in the three intervention strategies.

Managing for nexus resource system synergies

Comparing historical hydropower operations with those optimized via the framework presented here allows evaluation of changes in sub-daily hydrological alteration and agricultural yields. The drivers of those changes are the variability at different timescales of intermittent renewables and electricity demand, which hydropower attempts to offset alongside other interventions.

Fig. 3 shows sectoral impacts resulting from changes in hydropower reservoir seasonal releases meant to complement intermittent renewable generation, where Fig. 3a shows Ghana's monthly load rolling average and solar irradiance. Fig. 3b presents changes in hydropower generation seasonality which aimed to support the integration of solar resources in months of high resource availability (February to May). The financially viable potential of solar power in Ghana is higher than wind's [36]. However, the solar resources have opposite seasonality to irrigation demands, leading to a mismatch between hydropower water releases and the basin's irrigation demands, thereby increasing the irrigation deficit during the irrigation season (Fig. 3c). Despite the solar potential being higher than wind's potential, the framework identifies multiple mixes of intermittent renewable technologies (Fig. 6S), and decision-makers can evaluate different cross-sectoral performance trade-offs (presented in Fig. 2) and define a system design based on their preferences.

Fig. 3d shows that Ghana's integration of high shares of intermittent renewables does not reintroduce the natural river flow seasonality or its peak flows downstream of the Akosombo dam. For instance, under intervention strategy one with sub-daily flow alteration, hydropower reservoirs release more water during months of high solar availability (February to May) compared to the compromise solution. Those months of high solar resources occur when natural river flows are lowest. The ability to reintroduce the historical flow pattern through hydropower generation depends on the installed hydropower turbine capacity. Many dams worldwide, including the Akosombo, cannot release the natural river flow peak through hydropower turbines. The mean peak of natural streamflow of the Volta river at Akosombo is around 5,000 m3/s [40], whereas the turbines' maximum capacity is 1,460 m3/s [33], which makes it impossible to reintroduce seasonality using turbine outlets.

The hourly hydropower generation variability shown in Fig. 3b is presented in Fig. 4 for a typical two-day hourly pattern. Fig. 4 shows the increased hydropower generation fluctuations under intervention strategy one (RB-Index 0.22) compared to the compromise solution. This variability in hydropower generation leads to an increase in the sub-daily hydrological alteration, negatively impacting aquatic ecosystems [16–19,22]. The Akosombo hydropower plant shows higher hydrological alteration than others (see Fig. S7) because it is the country's largest installed generation plant. Fig. S8 also shows the monthly and hourly generation of Ghana's power mix for the two Pareto optimal portfolios presented in Fig. 3b, where despite high sub-daily variability in intervention scenario one at a monthly scale, the hydropower generation is stable across the year (Fig. S8a) compared to the hydropower generation in the compromise solution (Fig. S8c).

Discussion

Intermittent renewable energy development is increasingly recognized as essential to eliminating poverty, providing universal electricity access, and reducing the pace of climate change globally [7]. However, sustainable energy development to meet growing electricity demands may be hampered by counter-intuitive inter-sectoral interdependencies and environmental impacts. Inter-sectoral, inter-ministerial cooperation designed to integrate goals for poverty reduction, electricity access, and climate mitigation is rare. In this article, we argue that energy infrastructure planning should consider environmental systems and river-dependent sectors where renewable energy is being expanded and suggest a method to enable these policy objectives. We introduce an integrated multisector framework that helps analysts and stakeholders strategically design and operate national-scale WEFE nexus resource systems.

Although hydropower flexibility is a cost-effective alternative to complement intermittent renewables' variability at different timescales, we have shown that hydropower operated to support intermittent renewable integration can adversely alter the sub-daily flow regime of rivers (shown as higher Richards–Baker Flashiness Index), impacting river ecosystems. River flow can be altered by changing long-term seasonality or short-term sub-daily flows. Ecosystems and livelihoods need not be the cost of decarbonized growth. For the Ghanaian case, we have shown that integrating high shares of intermittent renewables does not reintroduce or reestablish the natural river flow seasonality or peak downstream of the Akosombo Dam. But it can introduce high and short-term intermittent flow variability by hydropeaking plants that can wash out macroinvertebrates and phytoplankton essential to the food chain of aquatic ecosystems and fish species such as Tilapia and Chrysichthys [41], and create flood events impacting floodplain infrastructure that was built to support riverine livelihoods. Also, as shown in Ghana, a new water management regime aiming at flexible hydropower generation negatively impacts irrigated agriculture (lower crop yields and revenues) by changing the seasonality of hydropower releases. River ecosystems and communities downstream of the Akosombo and Kpong hydropower plants have adapted to the steady flow regime of the dams; new hydropower operations could negatively impact these ecosystems and communities [39,40].

The proposed artificial intelligence-assisted approach can improve the design of WEFE resource systems, minimizing intersectoral conflicts and emissions while maximizing energy services and synergies across space and time through a diversified expansion of technologies which contributes to power system flexibility and alleviates pressure on water resource-dependent sectors (red lines in Fig. 2c). We explored the expansion of bioenergy generation for Ghana; however, as they become economically feasible in the following decades, other measures such as batteries [45], power-to-gas systems [46] and demand-side management [47] might support intermittent renewable integration with lower impacts because they do not depend on water resources to produce or store energy. We used bioenergy in our study because the Ghanaian authorities have identified it as the main renewable, dispatchable, and spatially distributed technology available in the country, and it can use the residues from various stages of agricultural and forestry activities; mainly from crops harvesting, wood logging, and residues from municipal wastes and other commercial and domestic activities [36]. Our results are consistent with previous studies highlighting the importance of a diversified expansion of renewable technologies to reduce energy-system vulnerabilities [48]. The proposed framework allows for pragmatic and detailed spatial designs of how the river basin and energy networks should best be connected, expanded, and their operations synergized. Strategic transmission-line expansion can facilitate more effective use of power system flexibility, thus displacing thermal generation, alleviating cross-sector conflicts, and reducing hydropeaking, as we have demonstrated for Ghana (see yellow lines in Fig. 2d). Although grid expansion in developed countries faces social opposition [49], in developing countries the grid systems often have large transmission losses produced by old and damaged components resulting in outages and revenue losses, which justifies reinforcing existing grids [50].

Future work addressing the adaptability of the agricultural sector to water availability, climate change and other uncertainties would allow further investigating the case for renewables integration and their role in climate change adaptation and mitigation programs. Climate change and increasing pressures on WEFE systems could aggravate the negative impacts of power system development blunders and increase intersectoral conflicts. Investment institutions and partnerships such as the World Bank and Green Climate Fund are adding climate targets to their project finance evaluation criteria, even though analytical tools to consider climate goals in planning remain sparse. The UN Paris Agreement specifies global targets for acceptable levels of climate change. It defines a process for national governments to make five-year plans to meet those goals through Nationally Determined Contributions (NDCs). For many countries, climate goals represent a new policy domain with little operational and planning expertise to support national targets; without a multisector planning framework, national climate mitigation goals may incentivize reducing carbon emissions or promoting low-emission energy systems without considering broader impacts. Global climate initiatives have created development targets but the technical and policy tools necessary to meet these targets have lagged behind. The strategic WEFE design framework presented in this study can help bridge this gap and help decision-makers identify and refine the policy and investment mixes that could efficiently and effectively support sustainable development and meet net-zero aspirations.

Methods

Integrated river basin and power system simulation

The multisector simulation model integrates the independent river basin and the power system simulators. The system integration is implemented using the Python Network Simulation library (Pynsim) [32], which coordinates model inputs and outputs to form a single simulation at model run-time representing feedback across the models (see Fig. S2). The integrated simulation considers spatially explicit sectoral infrastructure and connectivity within and between the models.

The models run sequentially with feedback across the model's interconnections. In this study, hydropower connector nodes use unidirectional feedback, i.e., the river basin model decides the hydropower releases and passes the information to the power system. The river basin model runs its first time-step (a week) and generates the weekly average hydropower generation, which is transferred to the power system as a maximum generation capacity constraint for that week. The power system model runs for the same week at an hourly time step, constrained by the information provided by the river basin model. The river basin and power system models repeat this process timestep-by-timestep until the completion of the simulation. The integrated model runs over a 10-year time horizon, from 2030 to 2040; the system performance metrics are calculated once a simulation is completed.

Electricity demand projections, generating resources, operating and capital costs, and hourly profiles of intermittent renewable resources were obtained from the Integrated Power System Master Plan for Ghana [36]. Hourly load profiles and transmission data were provided by the Ghana Grid Company Ltd, which operates the national grid. Long-term projections for annual peak load are available in the Ghana Power System Master Plan [36]. Those projections project a two-fold increase in the peak load by 2030 compared with 2018. We scaled the hourly load profile of 2018 using the 2030 to 2040 peak projections to consider the projected increase in electricity demand in the country. Capital costs include engineering, procurement, construction, start-up, and owner's cost (land, cooling infrastructure, administrative and associated buildings, site works, project management, and licenses) [36]. The operating cost of intermittent renewable technologies is low enough, compared with the costs of hydropower, bioenergy, and thermal plants, to ensure that intermittent renewable technologies' economic dispatch follows the hourly generation profiles [36]. We modelled PV with storage technology using an hourly PV generation profile, similarly as it was modelled in the Integrated Power System Master Plan for Ghana [36]. The solar-with-storage profile takes out 30% of the PV generation profile during the daytime and discharges it during peak periods following ref. [36].

River basin model

The river basin model uses the open-source Python Water Resources simulation library (Pywr) [29]. Pywr solves a linear program at every simulation time step deciding the optimal water allocation from different nodes in the system (e.g., hydropower reservoir releases) by minimizing allocation penalties subject to operating rules. The model solves a mass balance equation Eq. (1) at each node in the network representing incremental catchment inflows and water demands at ecosystem service delivery and infrastructure locations.

$$S_{t+1,n} = S_{t,n} + q_{t,n} - e_{t,n}\left(h_{t,n}\right) + \mathrm{C}^{\mathrm{R}}\left(r_{t,n} - sp_{t,n}\right) \quad \forall t, n \tag{1}$$

$$r_{t,n} = \sum_{\forall i} r_{t,n}^{i} \tag{2}$$

$$0 \leq r_{t,n} \leq \varphi_n(\mathbf{x}) \tag{3}$$

where, $S_{t,n}$ is the volume of water stored in the reservoirs at node n, in time-step t, $r_{t,n}^{i}$ is the water allocation for the water uses (i) in the system, public water supply (pws), hydropower (hp), and irrigation schemes (is). $r_{t,n}$ is the water releases sum of all water uses, and $\varphi_n(\cdot)$ are the reservoir operating rules, which constraint water allocation decisions. Irrigation demand is defined by the planted area of each crop (ct) that composes an irrigation scheme. $sp_{t,n}$ denotes spill flows from reservoirs; $q_{t,n}$ are inflows to nodes, and $e_{t,n}(\cdot)$ represents evaporation, which depends on water level $h_{t,n}$ in reservoir. C^{R} is the network connectivity matrix $\left[\mathrm{C}_{\mathrm{j,k}}^{\mathrm{R}} = 1\ (-1)\ \text{when the node j receives water from (to) node k}\right]$. For releases to irrigation schemes, the network connectivity matrix tracks flows that return to the network as a fraction of the releases. The model includes existing infrastructure in Ghana and Burkina Faso, including the Pwalugu multi-purpose dam which is under construction. More details of the Volta river basin model can be found in ref. [30], a previous publication on the model.

Reservoir operating rules

We used Gaussian radial basis functions (RBF) to represent reservoir operating rules. RBFs have shown good performance representing rules for diverse problems, including reservoir storage and time into releases decisions [51–54]. The Gaussian RBF is defined by Eq. (4).

$$\varphi(\mathbf{x}) = \sum_{\mathrm{i}=1}^{l} \mathrm{w_i} \times \exp\left[-\sum_{j=1}^{\mathrm{m}} \frac{\left(\mathrm{x}_j - c_{j,\mathrm{i}}\right)^2}{b_{j,\mathrm{i}}^2}\right] \tag{4}$$

Where $\mathrm{m} = 2$ is the number of input variables $\mathbf{x}$ (time and reservoir volume); l is the number of RBFs ($l = 4$); $\mathrm{w_i}$ is the weight of the ith RBF (φ_i); $c_{j,\mathrm{i}}$ and $b_{j,\mathrm{i}}$ are the m-dimensional centres and radius vectors of the ith RBF, respectively. The centres and radius take values in $c_{j,\mathrm{i}} \in [-1,1]$ $b_{j,\mathrm{i}} \in [0,1]$ $w_{j,\mathrm{i}} \in [0,1]$ $\sum_{\mathrm{i}=1}^{\mathrm{n}} w_\mathrm{i} = 1$. The parameter vector $\boldsymbol{\theta}$ is defined as $\boldsymbol{\theta} = \left[c_{j,\mathrm{i}}, b_{j,\mathrm{i}}, \mathrm{w_i}\right]$. In Eq. (4), the time and reservoir volume are mapped to decide a target reservoir release at each time of the simulation period.

Ghana's power system model

The power system model simulates each time step (i.e., hour) using a direct current optimal power flow linear program formulation (Eq. 5-7), described in ref [31]. The simulation minimizes power system costs as denoted by Eq. (5). Eq. (6) represents the equality constraints, i.e., power balance at each node, while Eq. (7) represents the inequality constraints, i.e., power generation and line flow limits.

$$\min f_t^{\mathrm{costs}} = \left[\sum_{n=1}^{N} \left(\mathrm{OC}_n \times \mathrm{P}_{t,n}\right) + \left(\mathrm{LC}_{t,n} \times \mathrm{PE}\right)\right] \tag{5}$$

$$G(x,u,y) = 0 \tag{6}$$

$$H(x,u,y) \geq 0 \tag{7}$$

where, u is the vector of control variables which includes the control active power output of a generation unit and load curtailment. x is the vector of state variables, including the voltage angle at each bus, and y is the vector of parameters such as connectivity, reactance and generator limits. OC_n is the operating cost per generator, $\mathrm{P}_{t,n}$ is the power output per generator in each time step of the simulation model, $\mathrm{LC}_{t,n}$ is the load curtailment, and PE is a load curtailment penalty. We simulate network connectivity and impedances, power generation technologies, locations, and demand profiles.

Integrated river basin and power system design process

The multisector simulation model is connected to an AI-based multi-objective evolutionary algorithm (MOEA) to perform a multi-objective trade-off analysis. This identifies the performance trade-offs implied by the most efficient (Pareto optimal) portfolios of synergistic WEFE system interventions without needing to pre-specify preferences or weights for the different objectives. This supports unbiased a posteriori decision-making [55–57], i.e., where stakeholders can assess how much they value each dimension of performance by seeing the implied sacrifice to other dimensions. MOEAs are an established iterative population-based meta-heuristic search method that identifies a multi-dimensional non-dominated ("best achievable") set of objective solutions, using processes that mimic the natural evolutionary process to explore the search space and find the best performing combinations of options [55,56,58,59]. Results assist policymakers and stakeholders in designing WEFE nexus resource systems by revealing to them the synergies and trade-offs implied by the most efficient bundles of interventions.

Performance metrics for the River basin model

Performance metrics used to quantify water use benefits include irrigation yields and revenues from irrigation schemes Eq. (11), flood recession agriculture benefits Eq. (14), and hydrological alteration produced by hydropeaking Eq. (16) (Richards-Baker Flashiness Index [14,40]).

Basin irrigation yields are estimated using the Food and Agriculture Organization (FAO) Crop Water Requirements method [60] for the following crops: sugar cane, maize, rice, beans, tomatoes and fresh vegetables.

$$CWR_{t,(ct\in n)} = \max\left(0, \left(Kc_{t,(ct\in n)} \times ETo_{t,(ct\in n)} - R_{t,n}\right) \times A_{(ct\in n)}\right) \quad (8)$$

$$IWR_{t,n} = \sum_{ct\in n} \frac{CWR_{t,(ct\in n)}}{\alpha_{ct} \times \beta_{ct}} \quad (9)$$

$$CR_{t,n} = \frac{r_{t,n}}{IWR_{t,n}} \quad (10)$$

$$f^{Y} = \frac{1}{sy} \sum_{n=1}^{N} \sum_{t=1}^{T} CR_{t,n} \times (A_n \times y_n) \quad (11)$$

where, $CWR_{t,n}$ is the crop water requirement per node (n) (irrigation scheme). $Kc_{t,(ct\in n)}$, $ETo_{t,(ct\in n)}$ and $R_{t,n}$ are crop factors, reference crop evapotranspiration [mm/day] and effective rainfall [mm/day] obtained from ref. [61]. $A_{(ct\in n)}$ is the area (ha) of each crop type. $IWR_{t,n}$ is the irrigation water requirement per irrigation scheme, α_{ct} and β_{ct} are irrigation and conveyance efficiencies (assumed to be 0.8 and 0.7, respectively, for surface irrigation). $CR_{t,n}$ is the water supply curtailment ratio, y_n is annual crop yield (ton/ha) per irrigation scheme, $r_{t,n}$ is the crop water allocated by the river basin model, sy the number of simulated years, and f^Y is total irrigation crop yield (ton/yr). We used international crop prices to estimate the agricultural sector revenues from FAO.

Flood recession agriculture (FRA) depends on the floodplain's seasonal flooding during the peak rainy season in Northern Ghana (July to September). The magnitude of the annual peak determines the total area sown each year [62]. Low flood peaks result in no overflowing of the riverbanks preventing flood recession activities. Once the flooding threshold is breached, the flooded area increases with the flood peak. Extreme floods negatively affect flood recession activities by removing fertile topsoil. The area suitable for flood recession agriculture reduces to zero for extreme flows (95% exceedance probability [30]).

$$q_n^{\mathrm{FRA}} = \underset{}{mean}\left[\underset{}{max}\left(q_{t,n}^{Aug}, q_{t,n}^{Sep}\right)\right] \quad (12)$$

$$Y_n = A_n^f q_n^{\mathrm{FRA}} f_{\mathrm{FRA}} C_y \quad (13)$$

$$f^{\mathrm{FRA}} = \sum_{n=1}^{N} \beta_{\mathrm{FRA}} \times Y_n \quad (14)$$

where, q_n^{FRA} is the mean flow in August or September during the simulation horizon; $q_{t,n}$ is the mean flow in August and September; $A_n^f(\cdot)$ is flooded area (ha); f_{FRA} is a suitability factor [62]; C_y is crop yield (ton/ha) assuming a typical flood recession agriculture crop mix of maize, beans, Bambara beans, soya, millet and groundnuts [63]; Y_n is total FRA yield (ton/yr); β_{FRA} is average regional market price of crops at \$1,222/ton [64], and f^{FRA} is the financial benefit (\$) of flood recession agriculture activity.

Although variations in flow patterns produced by flood peaks and precipitation patterns are part of the natural flow regimen in streams, flow rates observed as results of hydropeaking can show multiple peaks per day and intensities exceeding those of the strongest natural floods negatively impacting aquatic ecosystems [65]. Sub-daily hydrological alteration is quantified using the Richards–Baker Flashiness Index [42]. This index accounts for the sequence, magnitude, and number of peaking events in a day of a hydropower plant [14]. The index used in this study does not account for seasonal changes induced by re-operating baseload hydropower plants. Natural sub-daily flows are characterized by a steady flow regime, with infrequent short-term fluctuations where native flora and fauna are adapted to various features of this natural flow regime; human alteration of flow regimens often impairs these biological communities [42–44]. Thus, a high Richards–Baker Flashiness Index value implies a flashy stream (less natural flow) and a less desirable regime, whereas a low index value characterizes a stable stream [14,15,42,66]. More details on the impacts of altering the flow river regime can be found in a review of Refs. [67,68].

$$\text{RB index}_{d,n} = \frac{0.5\sum_{t\in d=1}^{Td}\left(\left|qt_{t+1,n} - qt_{t,n}\right| + \left|qt_{t,n} - qt_{t-1,n}\right|\right)}{\sum_{t\in d=1}^{Td} qt_{t,n}} \tag{15}$$

$$f_n^{\text{RB}} = max(\text{RB index}_{d,n}) \tag{16}$$

Similarly to ref. [14], we calculate a daily Richards–Baker index aggregating hourly data, which is calculated as the sum of the difference between turbined flows qt_t of consecutive hours t and $t+1$, normalized by the total turbined flow over time horizon $Td = 24h$. Consequently, if the simulation time horizon is one year at an hourly time step, a time series of 365 values of the Richards–Baker Index is created. The Richards–Baker Index (f_n^{RB}) is calculated for each hydropower plant (n).

Performance metrics for the power system model

Performance metrics used to quantify power system benefits and costs include system load curtailment Eq. (17), CO_2 emission Eq. (18), system capital costs Eq. (19), and system operating costs Eq. (20).

The system load curtailment ($\text{LC}_{t,n}$) is calculated by the power system simulation model at each time step when the balance at each bus (n) is performed. The balance at each bus in the system is modeled as a function of demand, generation, load curtailment, and flows across the transmission lines. At the end of each simulation, the system load curtailment is calculated based on Eq. (17).

$$f^{lc} = \frac{1}{sy}\sum_{n=1}^{N}\sum_{t=1}^{T}\text{LC}_{t,n} \tag{17}$$

where, sy is the number of simulation years and f^{lc} is the average system load curtailment.

To calculate the CO_2 emissions, we multiply the generation ($\text{P}_{t,n}$) from the power system simulator in each time step (t) and generator plant by a CO_2 emission factor [69] per generator technology ($ft_n^{\text{CO}_2}$).

$$f^{\text{CO}_2} = \frac{1}{sy}\sum_{n=1}^{N} ft_n^{\text{CO}_2} \times \sum_{t=1}^{T}\text{P}_{t,n} \tag{18}$$

where, f^{CO_2} is the average CO_2 emissions produced by the power system.

The system capital costs were calculated by multiplying the technology capital cost CC_n by the new infrastructure capacity (NI_n), which is selected in the multi-objective optimization process.

$$f^{\mathrm{CAPEX}} = \sum_{n=1}^{N} \mathrm{C}_n \times \mathrm{NI}_n \tag{19}$$

where, f^{CAPEX} is the system Capital expenditure.

To calculate the system operating costs, we multiply the operating cost per generator (OC_n) by the power output ($\mathrm{P}_{t,n}$) per generation technology (n) in each time step (t).

$$f^{\mathrm{OPEX}} = \frac{1}{sy} \sum_{n=1}^{N} \sum_{t=1}^{T} \mathrm{OC}_n \times \mathrm{P}_{t,n} \tag{20}$$

where, f^{OPEX} is the system Operating expenditure.

Integrated WEFE resource system design problem

The integrated multi-objective optimization design solves the objective function presented in Eq. (21). The design formulation's objectives include minimize the system load curtailment (f^{lc}), the CO_2 emissions from generation ($f^{\mathrm{CO_2}}$), the power system capital costs (f^{CAPEX}), the system operating costs (f^{OPEX}), and the hydrological alteration downstream of the Akosombo, Bui and Pwalugu reservoirs (f_n^{RB}). Also, the design problem maximizes the agricultural yields (f^{Y}) and the flow recession economic activities (f^{FRA}).

$$\mathbf{F}(\mathbf{y}, \boldsymbol{\theta}_n) = (f^{Y}, f^{\mathrm{FRA}}, f_n^{\mathrm{RB}}, f^{lc}, f^{\mathrm{CO_2}}, f^{\mathrm{CAPEX}}, f^{\mathrm{OPEX}}) \tag{21}$$

We use the Borg multi-objective evolutionary algorithm [70,71] to solve the multi-objective optimization design (Eq. 21). Borg handles complex non-linear and non-concave problems when searching for non-dominated solutions [71,72]. The optimization process for each of ten random seeds follows two steps summarized in Fig. S1: 1) initialization of the Borg multi-objective evolutionary algorithm using a set of decision variables for the integrated simulation model (in our analysis, power system infrastructure capacity and reservoir operating rule parameters), and 2) running the integrated WEFE simulation over the 10-year time horizon evaluating performance metrics and sending them back to the search algorithm. The optimization algorithm then selects a new set of decision variables for the next iteration. Steps (1) and (2) are repeated for a set number of evaluations of the objective function vector Eq. (21); in our case 700,000 iterations.

Three intervention strategies are defined to counter intermittent renewables' variability from hourly to seasonal timescales. The intervention strategies are defined around the decision variables $(\mathbf{y}, \boldsymbol{\theta}_n)$ of the objective problem presented in Eq. (21). Where, $\mathbf{y}$ is a vector that combinates the expansion of different power system infrastructure –intermittent renewables (solar and wind), solar with storage, bioenergy, and transmission lines–, and $\boldsymbol{\theta}_n$ is the vector of parameters of the reservoir operating rules presented in Eq. (4), which determines the hydropower plants' re-operation. The different intervention strategies are shown in the following section.

Intervention strategy one

The decision variables in intervention scenario one are the vector of infrastructure expansion $(\mathbf{y})$ including solar, solar with storage and wind generators, and the vector of operating rules parameters $(\boldsymbol{\theta})$ for Akosombo, Bui, and Kpong reservoirs. This intervention strategy aims to evaluate the impacts of the hydropower plants' reoperation and their contribution to the integration of high levels of intermittent renewables. In this strategy, hydropower and thermal generation plants provide the power system flexibility necessary to integrate intermittent renewables. However, existing thermal and hydropower generation is constrained by the existing capacity of the transmission network of the power system.

Intervention strategy two

The decision variables in intervention strategy two are the vector of infrastructure expansion $(\mathbf{y})$ including solar, solar with storage, and wind generators and transmission lines, and the vector of operating rules parameters $(\boldsymbol{\theta})$ for Akosombo, Bui, and Kpong reservoirs. In this scenario, the transmission line capacity in the power system is a decision variable in the optimization problem. Here, the re-operation of hydropower plants and existing thermal generation also provide flexibility to the power system. However, expanding the transmission lines will allow the system to reallocate and distribute the renewable (intermittent or not) resources in the system to displace thermal generation and reduce CO_2 emissions.

Intervention strategy three

Finally, decision variables in intervention strategy three are the vector of infrastructure expansion $(\mathbf{y})$ including solar, solar with storage, wind and bioenergy generators and transmission lines, and the vector of operating rules parameters $(\boldsymbol{\theta})$ for Akosombo, Bui, and Kpong reservoirs. In this strategy scenario, a new technology that provides system flexibility is included. This scenario constitutes a fully diversified power system infrastructure portfolio scenario of renewable (intermittent or not) resources advocated to reduce system CO_2 emissions, meet the increasing electricity demand, and reduce intersectoral conflicts in WEFE resource systems. Bioenergy (Biogas and Biomass) is considered in the design process because it is Ghana's main renewable, dispatchable, and spatially distributed technology. Just from crop residues, bioenergy potential has been estimated at around 75 TJ [36]. Bioenergy in Ghana is available from residues from the various stages of agricultural and forestry activities, mainly from crop harvesting, wood logging, and residues from municipal wastes and other commercial and domestic activities [36].

Data availability

The data for the river basin model that support the findings of this study are available from the corresponding author upon request and consultation with the relevant national authorities who own the data. Data for the power system model, including hourly intermittent renewable profiles, are free to access and can be found in Ghana's Power System Master Plan. The following link provides access to the data (IPSMP GH-IPM v1.2018 Assumptions Book.xlsx) hosted on the Ghanian Energy Commission website: https://energycom.gov.gh/planning/ipsmp/ipsmp-2018/gh-ipm-v1-2018-assumptions-model-results. The link is accessible as of 24/07/2022.

Code availability

The river basin model, including parameters, settings and calibration, is described in more detail in an earlier publication [30], and the software library used to build the model is open-source and freely available in https://github.com/pywr/pywr. The Python libraries used to build the power system model [31] and the objective-oriented multisector simulation framework are open-source and freely available in the following repositories: https://github.com/pywr/pywr-dcopf and https://github.com/UMWRG/pynsim, respectively.

Acknowledgements

The authors acknowledge UKRI research funding through the "Future Design and Assessment of water–energy–food–environment Mega Systems" (FutureDAMS) research project (ES/P011373/1). For the purpose of open access, the authors have applied a Creative Commons Attribution (CC BY) license to any Author Accepted Manuscript version arising. The authors thank the national and regional stakeholders who contributed to the BMU (Germany) funded IUCN-led WISE-UP to Climate project. The authors would like to acknowledge the assistance given by Research IT, and the use of The HPC Pool funded by the Research Lifecycle Programme at The University of Manchester.

Author Contributions

J.M.G: Conceptualization, Methodology, Investigation, Software, Visualization, Writing – Original Draft. **J.E.T:** Software, Writing – Review & Editing. **E.A.M.C:** Methodology, Resources, Writing – Review & Editing. **E.O:** Resources, Writing – Review & Editing. **M.B:** Software, Writing – Review & Editing. **P.T.P:** Resources, Writing – Review & Editing. **S.A:** Resources, Writing – Review & Editing. **R.B:** Resources, Writing – Review & Editing. **M.E:** Software, Writing – Review & Editing. **A.H:** Writing – Review & Editing, Project administration. **A.B.B:** Writing – Review & Editing. **J.D:** Writing – Review & Editing. **D.M.S:** Writing – Review & Editing. **J.S:** Resources, Writing – Review & Editing. **M.P:** Conceptualization, Methodology, Writing – Review & Editing. **J.J.H:** Conceptualization, Methodology, Writing – Original Draft, Supervision, Funding acquisition.

Declaration of Interest

The authors declare that the research was conducted without any commercial or financial relationships that could be constructed as a potential conflict of interest.

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Figure legends/captions

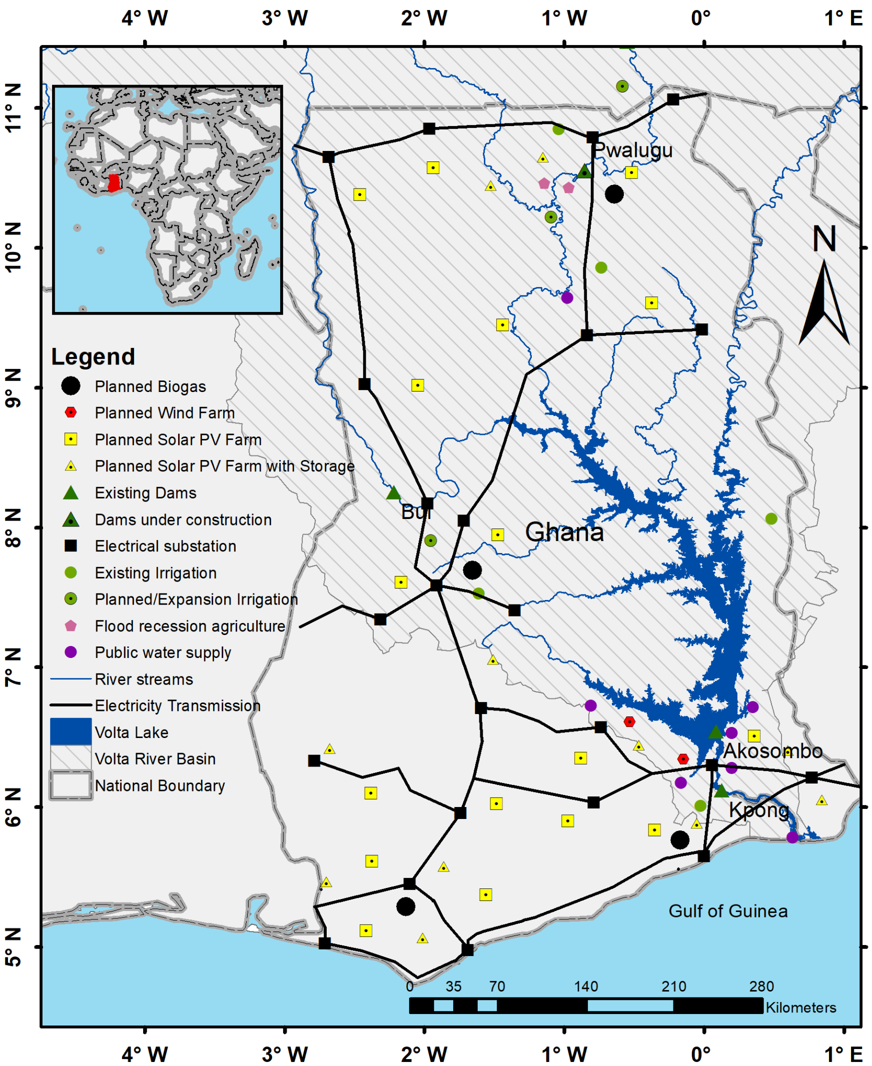

Fig. 1 | Transboundary Volta river basin and Ghana's national power system. The map shows the existing electrical transmission network and the locations of existing and planned storage dams, solar PV, solar PV with storage, wind power plants, irrigation, and public water supply diversions, and flood recession activities in the Volta river basin included in the integrated water-energy simulation.

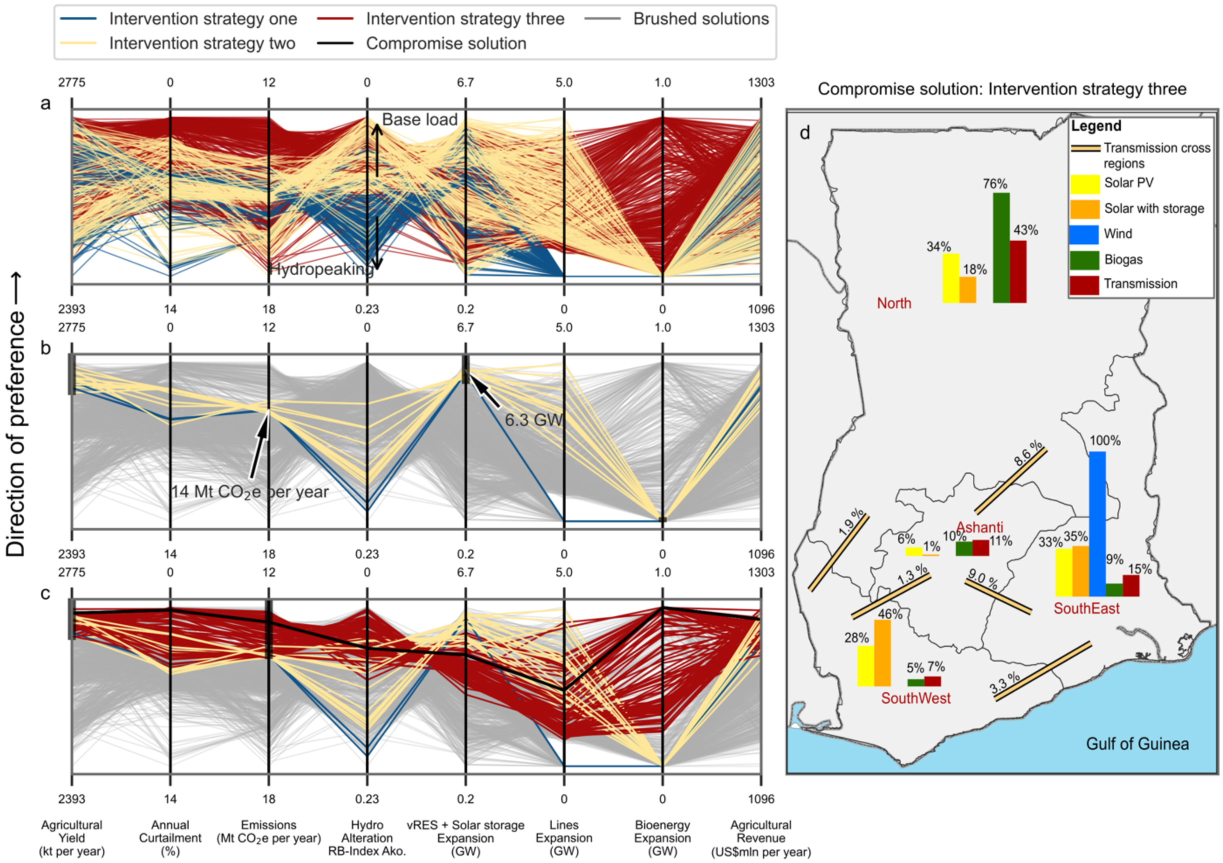

Fig. 2 | Performance trade-offs attained by the most efficient strategic river basin–power system national-scale designs. All three panels on the left-hand side (a-c) show the results for the three intervention strategies. However, the black rectangles on some axes of panels b and c serve as filters of Pareto optimal solutions shown in panel a, thus highlighting some optimized designs (the non-greyed-out solutions) based on their performance levels. The first four axes from left to right in a to c correspond to objectives (i.e., optimized design metrics), and the remaining four axes show three decision variables of the design problem and one tracked metric (Agricultural benefit). The top of panels a to c is the direction of preference for each metric; so a straight line across the top of the y-axis would indicate a "perfect" WEFE intervention portfolio. Crossing lines between axes represent trade-offs among metrics, whereas a roughly straight line joining two metrics indicates a synergy. d, shows the spatial distribution of infrastructure expansion for one selected efficient compromise solution of strategy three (the bold black line in panel c), which includes significant levels of infrastructure expansion in Ghana's Northern region (e.g., 0,8 GW, corresponding to 76% of the total new bioenergy generation plants installed in the country for the compromise solution). Hydropower providing flexibility services can support high levels of intermittent renewable integration (up to 6,3 GW) and improve power system performance. However, this new role for hydropower would increase hydrological alteration and decrease agricultural yields up to 5% annually, reducing the agricultural sector's economic revenues by 169 M$/yr —blue lines, strategy one. A mix of intermittent renewable generation and bioenergy technologies can meet electricity demands while improving all-around system performance and decreasing inter-sectoral conflicts. That is why the red lines (representing the more diverse energy mix of intervention strategy three) are higher up the y-axis – they simply enable better performance. The acronym vRES refers to the variable (intermittent) renewable energy sources.

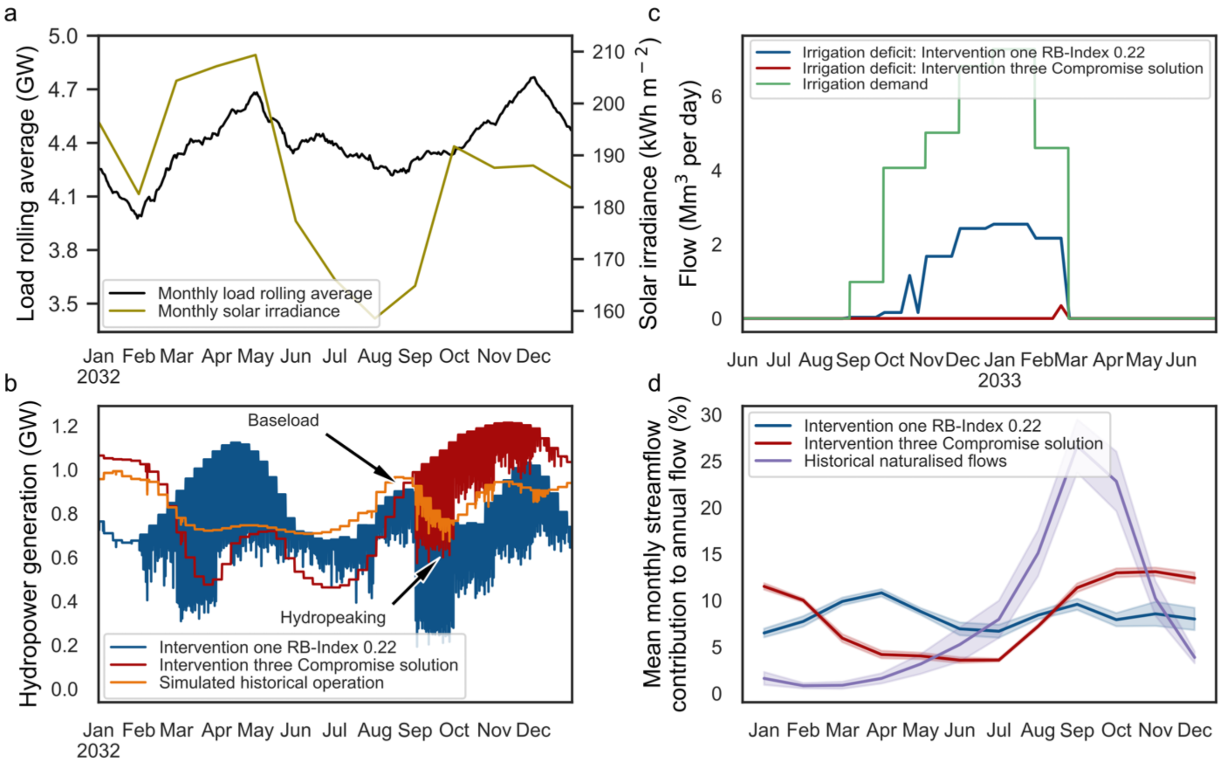

Fig. 3 | Sectoral impacts resulting from changes in hydropower operations to enable more solar and wind generation in Ghana. a, shows Ghana's monthly load rolling average and solar irradiance. The system load (i.e., electricity demand) has two peaks, in May and December, while higher solar irradiance occurs from February to May. b, shows the hourly hydropower generation following the historical operating rules and hydropower re-operation for intervention strategies one and three. c, shows one year of Ghana's total mean irrigation demand from irrigation schemes and the irrigation deficits under the portfolios of the intervention strategy scenarios presented in b. d, shows the mean monthly naturalized streamflow and the simulated flows under the two intervention portfolios presented in b, downstream Akosombo. The mean streamflow is calculated as a percentage of the mean annual flow. In d, the shaded area represents the standard deviation of the mean streamflow, where the historical naturalized flow was calculated for the period 1919 to 2018 and for the simulated series for the period 2030 to 2040. In b, hydropower operation of two resulting portfolios from Fig. 2, corresponds to a portfolio of intervention strategy one with high hydro-alteration, RB-index = 0.22 (Fig. 2b) and the compromise solution selected from intervention strategy three (black line in Fig. 2c). The figure shows how enabling intermittent renewables integration leads to hydropeaking and a seasonal hydropower generation shift that increases sectoral conflict because releases no longer coincide with peak irrigation demand. Short-term variability and long-term changes in hydropower generations are driven by hourly fluctuations and seasonal patterns in electricity demand and intermittent renewables, respectively.

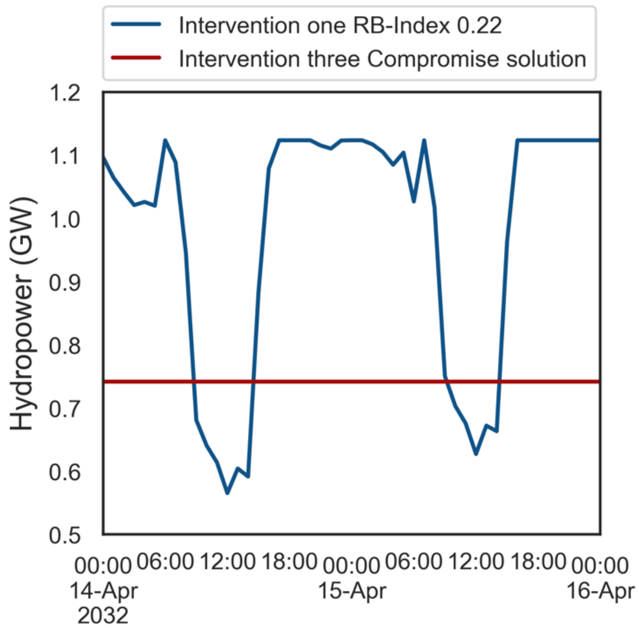

Fig. 4 | Hourly hydropower generation for a typical two-day hour pattern in Ghana. The figure shows the increased hydropower generation variability under intervention strategy one with high hydrological alteration (RB-index = 0.22), compared to the hydropower generation in the compromise solution (black line Fig. 2c).

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