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Designing diversified renewable energy systems to balance multisector performance

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Renewable energy system development and improved operation can mitigate climate change. In many regions, hydropower is called to counterbalance 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. We develop and apply an artificial intelligence-assisted multisector design framework in Ghana, which shows how hydropower's flexibility alone could enable expanding intermittent renewables by 38% but would increase sub-daily Volta River flow variability by up to 22 times compared to historical baseload hydropower operations. This would damage river ecosystems and reduce agricultural sector revenues by US$169 million per year. A diversified investment strategy identified using the proposed framework, 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 (NDCs) by steering towards diversified and efficient power systems and highlighting their sectoral and emission trade-offs and synergies.

Increased access to sustainable electricity is required to deliver the United Nations Sustainable Development Goals (SDGs). According to the 2022 SDG report, over 700 million people still lack reliable, sufficient electricity access, of whom more than three-quarters live 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 the 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 have

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reduced international financing for renewables, despite the urgency to slow climate change[1]. For example, 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 (ref. [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 (refs. [1,3]).

Renewable sources can be classified into dispatchable (that is, controllable generation, such as storage-based hydropower, bioenergy and geothermal) and non-dispatchable (such as 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 timescales[4,5]. In the short term (that is, seconds to hours), flexibility is required to counteract supply and demand variation to prevent power system failures[6]. In the medium to long term (that is, 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 affect 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. The hydrological alterations of hydropeaking change river thermal regimes[22], erode riverbanks and beds, change river morphology, degrade plant and animal populations[16–19], and affect 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 in which 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[28]. A key policy question of sustainable expansion of renewable energy technologies is how to plan spatially distributed, interdependent multisector systems, for which 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[29]. 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-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 in which 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 to invest in power systems in a way that balances 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 to 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 intersectoral complementarities across time and space in multisector systems. The proposed framework, shown in Supplementary Fig. 1, has two components: an integrated river basin and power system simulator and a multi-objective artificial intelligence-based optimized design process.

The first component (Supplementary Fig. 2) 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 resource allocation and management model[30,31] at discrete time steps. The power system is modelled using a direct current optimal power flow model at hourly time steps[32]. The integration of the system models uses an object-oriented multi-actor simulation framework[33], that integrates and coordinates the inputs and outputs of the models into a single simulation.

The second framework component is a multi-objective artificial intelligence-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 to identify performance trade-offs, synergies and co-benefits the performance trade-offs of the most efficient (that is, 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 Methods.

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 on a national scale. Ghana's total electricity generation comprises a mix of hydropower, gas and oil sources (47%, 30% and 23%, respectively)[34]. The Ghanaian national policy targets large-scale development of intermittent renewables, and hydropower could be used to provide flexible services[35]. The Akosombo Dam, the largest electricity generation plant in the country, with a capacity of 1,020 MW, regulates the world's largest man-made reservoir based on surface area—the Volta Lake[36]—and currently provides ancillary services (for example, voltage and volt-ampere reactor support, and reserve) to the Ghanaian power system[37].

By 2018, the Ghanaian government provided electricity access to 84% of the population through its National Electrification Scheme started in 1991 (ref. [34]). 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 tonne CO_2e (CO_2 equivalent) per year per capita[7]), high electricity losses in the transmission system (around 20%, ref. [34]), and low generation capacity resulting in load shedding or power rationing, which affects the country's economic and social welfare[38]. Ghana's updated NDCs and Renewable Energy Master Plan[35,39] 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.

Sixty-four per cent 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[34]. Figure 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[34]. The natural river flows, before damming of 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[40]. Among those services were a mix of freshwater, marine and saltwater fish, flood recession agriculture, clam picking and aquatic weed control[41,42]. However, after Akosombo and Kpong dams were constructed, the steady flow regime established to favour baseload hydropower production affected the natural dynamics of salt and freshwater in the estuary, decreasing the catch of fish, clams and oysters, and favouring the proliferation of weeds, which resulted in a reduction of the base resources contributing to riverine households' impoverishment and disease proliferation (malaria, schistosomiasis and river blindness)[42]. 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[40,42]. Riverine communities have also adapted to the steady flow regime, which provides year-round freshwater supply for domestic, industrial and agriculture[40]. The new flow regime has encouraged investment in aquaculture and floodplain infrastructure that would be at risk from flooding under the natural river flow regime[40]. Introducing additional changes to the river flow regime by re-operating hydropower plants to integrate intermittent renewables may further negatively impact the ecosystems and communities that have adjusted to the post-dam flow regime[40,42].

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 below. We evaluate the effects on sub-daily river flow alteration and the water resource 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-operating hydropower to support integration of intermittent renewables 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 twofold increase of the electricity demand peak by 2030 (ref. [37]). The three intervention strategy scenarios include the 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 and 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 reallocation and distribution of 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, in which 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: (1) sub-daily hydrological alteration downstream of reservoirs; (2) power load curtailment; (3) CO_2 emissions from power generation; (4) agricultural yields and revenue from irrigation schemes; (5) flood recession agriculture benefits; (6) power system capital costs; and (7) power system operational costs. Sub-daily hydrological alteration is evaluated using the Richards–Baker flashiness index[43]. 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[43–45]. A value of 1 in the Richards–Baker flashiness index implies a flashy stream (hydropeaking operations) and a less desirable sub-daily regime. By contrast, a zero index value characterizes a stable stream (baseload operations) with equal flow throughout the day[14,15,43].

Figure 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 to expand the generation capacity of the intermittent renewables by up to 6.3 GW, 38% of Ghana's power mix (Fig. 2b, blue lines). However, in addition to increasing the sub-daily

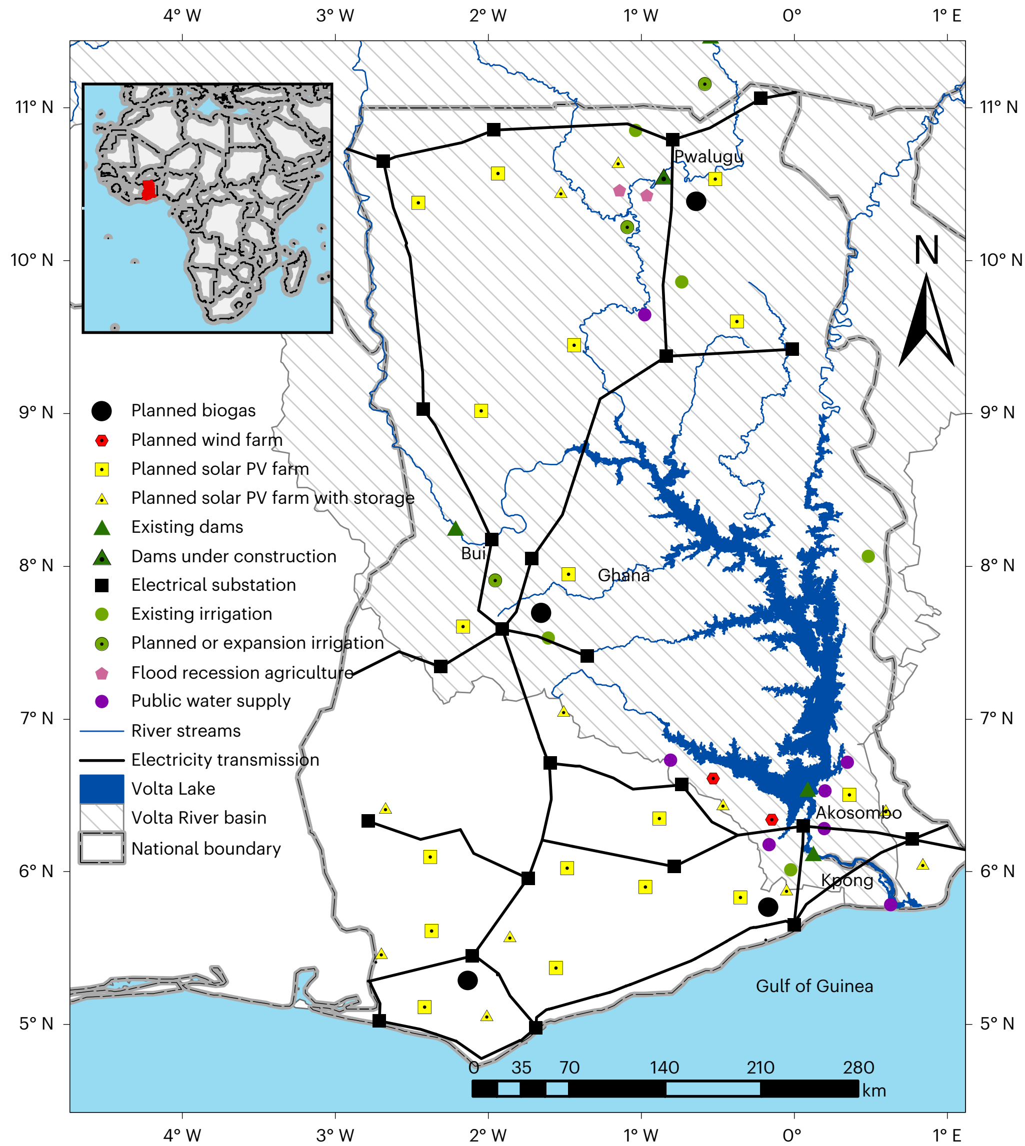

Fig. 1 | Transboundary Volta River basin and Ghana's national power system. The map shows the existing electrical transmission network and the locations of existing and planned storage dams, solar photovoltaic (PV), solar PV with storage, wind power plants, irrigation and public water supply diversions,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

hydrological alteration, this system expansion and operative strategy would result in high power system emissions (14 Mt CO_2e per year), high levels of annual load curtailments (7%), and a decline in agricultural yields of at least 5% annually, reducing the agricultural sector revenues by US$169 million annually.

In intervention strategy two, the expansion of intermittent renewables enabled by new transmission lines (Fig. 2b, yellow lines) drives a reduction in system annual load curtailment by up to 2%, a reduction in CO_2 emissions to 13 Mt CO_2e per year, and a reduction of flow alteration to 0.16 in the Richards–Baker flashiness index compared to the values for 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 (Fig. 2c, red lines). 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 Mt CO_2e per year, without affecting agricultural production or incurring load curtailment compared to intervention strategies one and two.

Figure 2d shows infrastructure expansion by region based on a compromise solution from intervention strategy three (Fig. 2c, black line). This compromise solution is selected because it reduces the power system load curtailment to zero, produces low levels of CO_2 emissions (12.3 Mt CO_2e per year), and maximizes irrigation yields (2,770 kt per year) and its economic returns (US$1,299 million per year), thus resulting in improved all-round system performance compared to solutions in scenarios one and two. The compromise solution includes more infrastructure expansion in northern Ghana, mainly transmission lines (a capacity increase of 1 GW, corresponding to 43% of total transmission expansion in the system) and bioenergy generation plants (a capacity increase of 0.8 GW, corresponding to 76% of total new bioenergy), compared with other regions. This is because the north has a lower generation capacity from its currently installed infrastructure than the south, and the electricity demand in this region is increasing. Strategy three helps to identify strategic system infrastructure designs and hydropower reservoir operations that improve system performance

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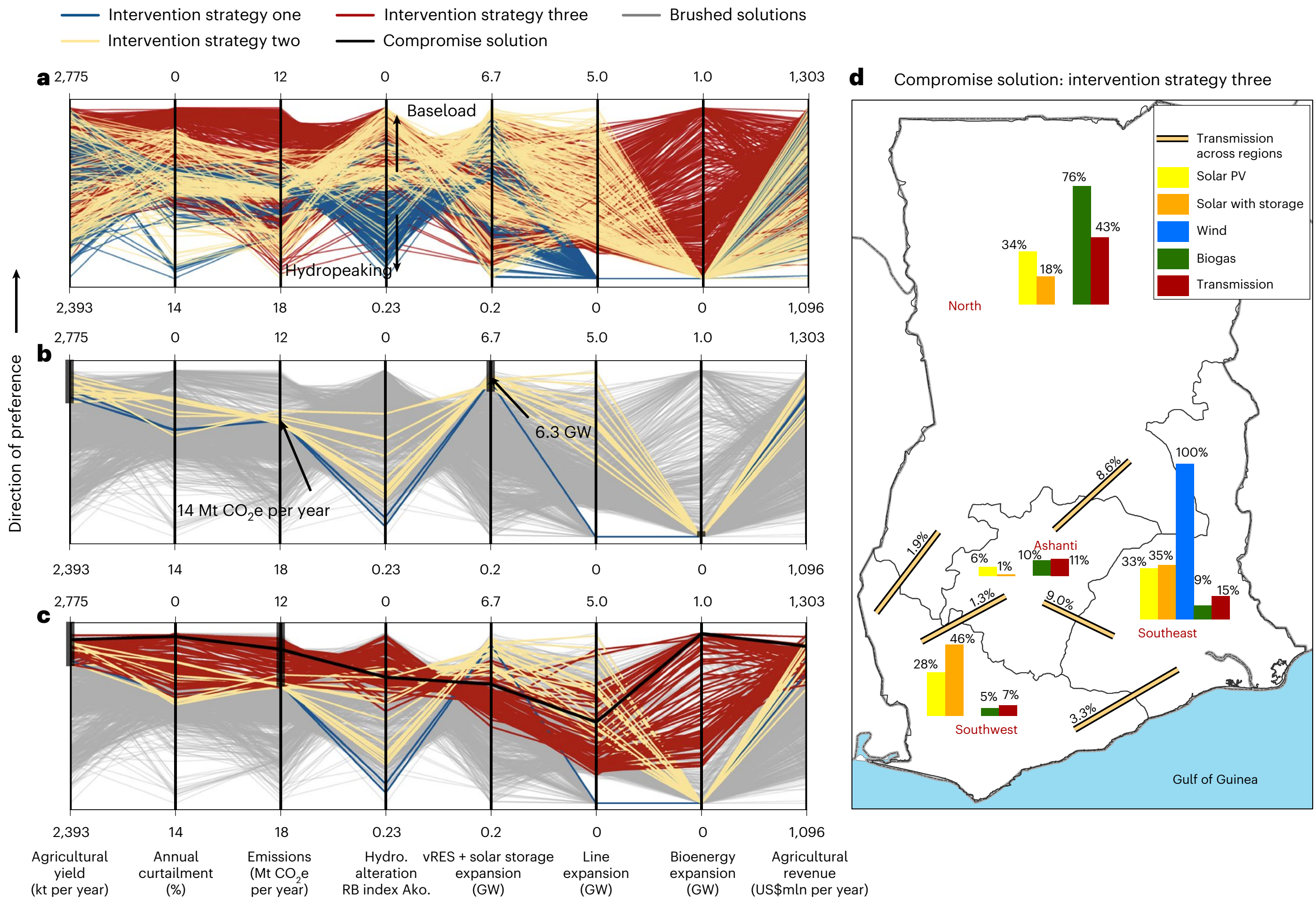

Fig. 2 | Performance trade-offs of the most efficient strategic national-scale river basin–power system designs. a–c, The results for the three intervention strategies. Note, black rectangles on some axes of panels **b** and **c** serve as filters of Pareto optimal solutions shown in panel **a**, thus 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 (that is, 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 of **a**–**c** is the direction of preference for each metric; 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 horizontal line joining two metrics indicates a synergy. ako., Akosombo; US$mln, US$ millions. **d**, The spatial distribution of infrastructure expansion for one selected efficient compromise solution of strategy three (the bold black line in **c**), which includes significant levels of infrastructure expansion in Ghana's northern region (for example, a capacity increase of 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 renewables integration (up to 6.3 GW) and improve power system performance. However, this new role for hydropower would increase hydrological (Hydro.) alteration and decrease agricultural yields up to 5% annually, reducing the agricultural sector's economic revenues by US$169 million per year, strategy one. A mix of intermittent renewable generation and bioenergy technologies can meet electricity demands while improving all-round system performance and decreasing intersectoral 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. vRES, variable (intermittent) renewable energy sources.

and reduce operating costs (by up to US$82 million per year) without requiring large investments in cross-region transmission infrastructure (see Supplementary Fig. 3). This is because more intermittent renewable sources and spatially distributed bioenergy infrastructure reduces the need for costly new cross-region transmission lines. Figure 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 Supplementary Fig. 4, which shows the infrastructure expansion distribution for the solutions in intervention strategy three (Fig. 2a, red lines). Supplementary Fig. 5 shows the distribution of infrastructure selected in the three intervention strategies.

Managing 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.

Figure 3 shows sectoral impacts resulting from changes in hydropower reservoir seasonal releases meant to complement intermittent renewable generation. Figure 3a shows Ghana's monthly load rolling average and solar irradiance, and Fig. 3b presents changes in hydropower generation seasonality that aimed to support the integration of solar resources in months of high resource availability (February to May). In Ghana, the financially viable potential of solar power is higher than that of wind power[37]. 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 higher potential of solar than wind power, the framework

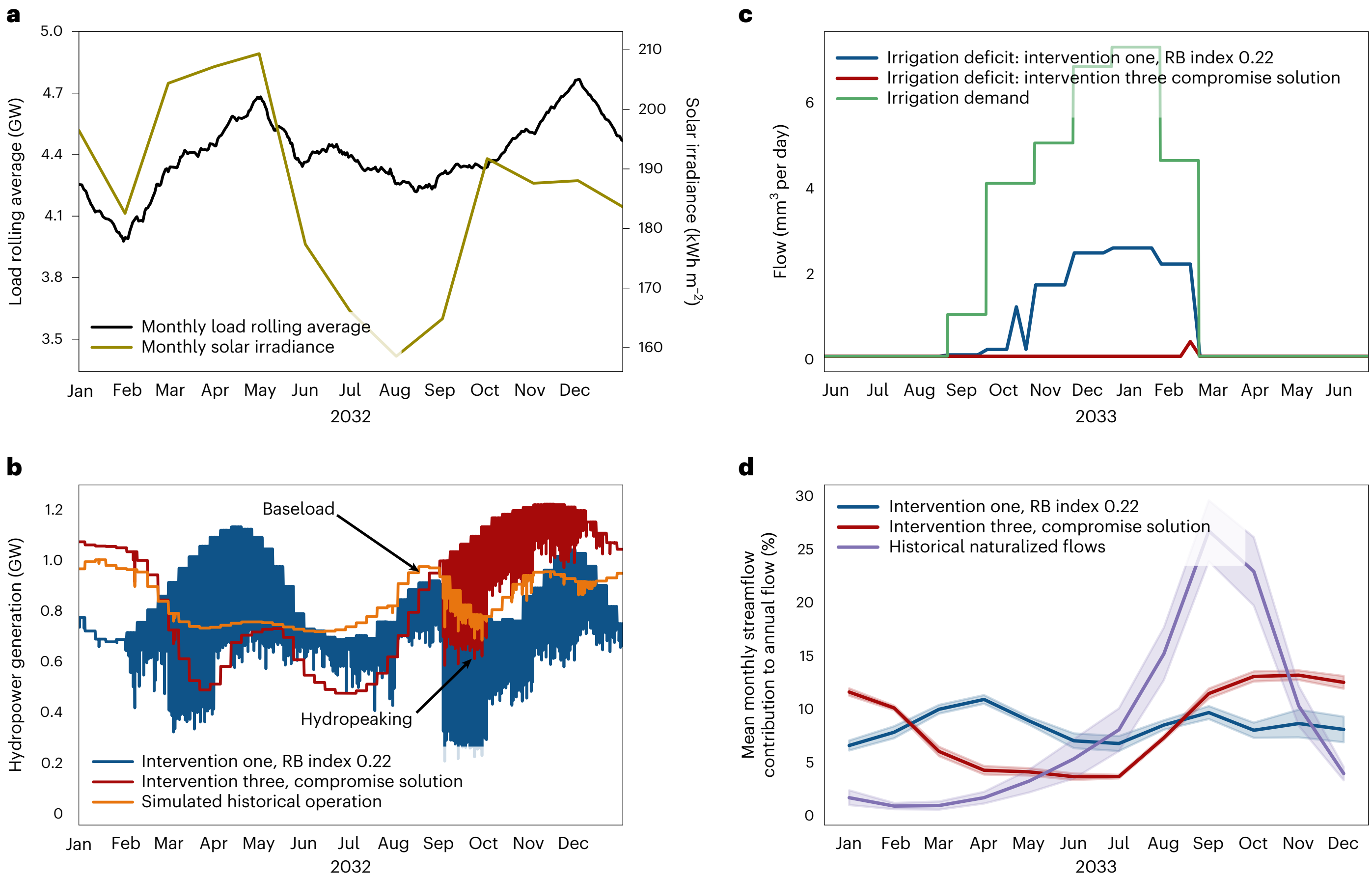

Fig. 3 | Sectoral impacts resulting from changes in hydropower operations to enable more solar and wind generation in Ghana. a, Ghana's monthly load rolling average and solar irradiance. The system load (that is, electricity demand) has two peaks, in May and December, while higher solar irradiance occurs from February to May. **b**, The hourly hydropower generation following the historical operating rules and hydropower re-operation for intervention strategies one and three. **c**, 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**, 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, in which 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 hydrological alternation, RB index 0.22 (Fig. 2b), and the compromise solution selected from intervention strategy three (Fig. 2c, black line). 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.

identifies multiple combinations of intermittent renewable technologies (Supplementary Fig. 6), and decision-makers can evaluate different cross-sectoral performance trade-offs (presented in Fig. 2) and define a system design based on their preferences.

Figure 3d shows that integration of high shares of intermittent renewables in Ghana 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) than in 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 $m^3 s^{-1}$ (ref. [41]), whereas the turbines' maximum capacity is 1,460 $m^3 s^{-1}$ (ref. [34]), 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 2-day hourly pattern. Figure 4 shows the increased hydropower generation fluctuations under intervention strategy one (Richards–Baker 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 Supplementary Fig. 7) because it is the country's largest installed generation plant. Supplementary Fig. 8 also shows the monthly and hourly generation of Ghana's power mix for the two Pareto optimal portfolios presented in Fig. 3b; despite high sub-daily variability in intervention scenario one at a monthly scale, the hydropower generation is stable across the year (Supplementary Fig. 8a) compared to the hydropower generation in the compromise solution (Supplementary Fig. 8c).

Discussion

Intermittent renewable energy development is increasingly recognized as essential to eliminating poverty, providing universal electricity

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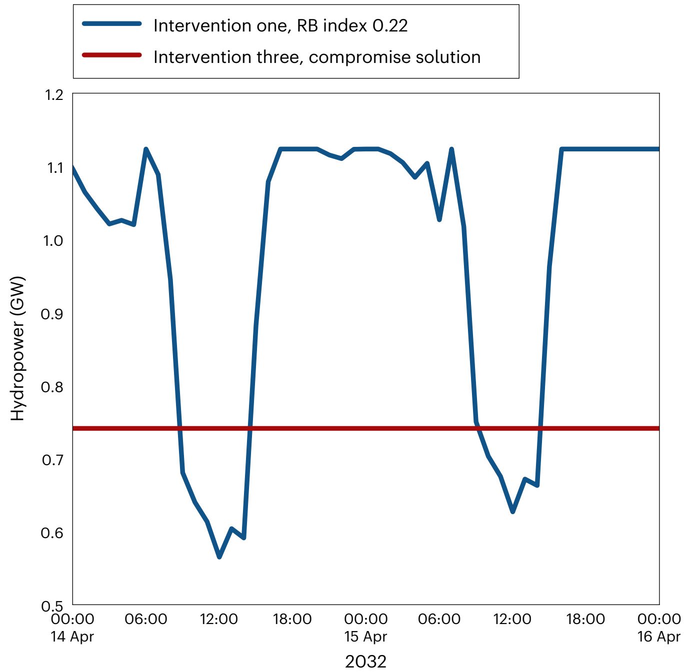

Fig. 4 | Hourly hydropower generation for a typical 2-day period in Ghana. The figure shows the increased hydropower generation variability under intervention strategy one with high hydrological alteration (RB index 0.22), compared to the hydropower generation in the compromise solution (Fig. 2c, black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

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 intersectoral interdependencies and environmental impacts. Intersectoral, 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 when 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 to strategically design and operate national-scale WEFE nexus resource systems.

Although hydropower flexibility is a cost-effective alternative to complement the variability of intermittent renewables at different timescales, we have shown that hydropower that is operated to support the integration of intermittent renewables can adversely alter the sub-daily flow regime of rivers (shown as a 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. In the Ghanaian case, we have shown that integrating high shares of intermittent renewables does not reintroduce or re-establish the natural river flow seasonality or peak downstream of the Akosombo Dam. However, it can introduce high and short-term intermittent flow variability by hydropeaking plants that can wash out macroinvertebrates and phytoplankton that are essential to the food chain of aquatic ecosystems and fish species such as tilapia and *Chrysichthys*[42], and create flood events that affect floodplain infrastructure that was built to support riverine livelihoods. Also, as shown in Ghana, a new water management regime targeting 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[40,41].

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. This 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 coming decades, other measures such as batteries[46], power-to-gas systems[47] and demand-side management[48] might support intermittent renewables 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 crop harvesting, wood logging, and from municipal wastes and other commercial and domestic activities[37]. Our results are consistent with previous studies highlighting the importance of a diversified expansion of renewable technologies to reduce energy system vulnerabilities[49]. The proposed framework enables 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 (Fig. 2d, yellow lines). Although grid expansion in developed countries faces social opposition[50], 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[51].

Future work addressing the adaptability of the agricultural sector to water availability, climate change, and other uncertainties would allow further investigation into 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 5-year plans to meet those goals through 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 to bridge this gap and help decision-makers to 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 (Pynsim) library[33], which coordinates model inputs and outputs to form a single simulation at model run-time representing feedback across the models (see Supplementary Fig. 2). The integrated simulation considers spatially explicit sectoral infrastructure and connectivity within and between the models.

The models run sequentially with feedback across the models' interconnections. In this study, hydropower connector nodes use unidirectional feedback; that is, 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, time step by time step 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[37]. Hourly load profiles and transmission data were provided by the Ghana Grid Company, which operates the national grid. Long-term projections for annual peak load are available in the Ghana Power System Master Plan[37]. Those projections estimate a twofold 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 costs and owner's cost (land, cooling infrastructure, administrative and associated buildings, site works, project management and licenses)[37]. 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[37]. We modelled PV with storage technology using an hourly PV generation profile, similarly to the way in which it was modelled in the Integrated Power System Master Plan for Ghana[37]. The solar-with-storage profile takes out 30% of the PV generation profile during the daytime and discharges it during peak periods, following ref. [37].

River basin model

The river basin model uses the open-source Python Water Resources (Pywr) simulation library[30]. Pywr solves a linear program at every simulation time step deciding the optimal water allocation from different nodes in the system (for example, 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:

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

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

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

where $S_{t,n}$ is the volume of water stored in the reservoirs at node n, in time step t, and $r^{i}_{t,n}$ 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 sum of water releases for water uses (that is, public water supply, irrigation and hydropower), and $\varphi_n(\cdot)$ are the reservoir operating rules, which constrain water allocation decisions. Irrigation demand is defined by the planted area of each crop (ct) that comprises 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 $\left[C^{R}_{j,k} = 1(-1)\ \text{when the node j receives water from (to) node k}\right]$. 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. [31], a previous publication on the model.

Reservoir operating rules

We used Gaussian radial basis functions (RBFs) to represent reservoir operating rules. RBFs have shown good performance representing rules for diverse problems, including reservoir storage and time into release decisions[52–55]. The Gaussian RBF is defined by Eq. (4):

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

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

Power system model of Ghana

The power system model simulates each time step (that is, hour) using a direct current optimal power flow linear program formulation (Eqs. 5, 6 and 7), described in ref. [32]. The simulation minimizes power system costs as denoted by Eq. (5). Equation (6) represents the equality constraints (that is, power balance at each node), while Eq. (7) represents the inequality constraints (that is, power generation and line flow limits):

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

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

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

where u is the vector of control variables that 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, $P_{t,n}$ is the power output per generator in each time step of the simulation model, $\text{LC}_{t,n}$ 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 artificial intelligence-based multi-objective evolutionary algorithm (MOEA) to perform a multi-objective trade-off analysis. This identifies the performance trade-offs of 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[56–58]; that is, 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[56,57,59,60]. Results assist policymakers and stakeholders in designing WEFE nexus resource systems by revealing to them the synergies and trade-offs of 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[14,41]).

Basin irrigation yields are estimated using the Food and Agriculture Organization (FAO) Crop Water Requirements method[61] for the following crops: sugar cane, maize, rice, beans, tomatoes and fresh vegetables.

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

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

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

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

where $\mathrm{CWR}_{t,n}$ 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 (in mm per day), and effective rainfall (in mm per day) obtained from ref. [62]. $A_{(ct\in n)}$ is the area (in ha) of each crop type. $\mathrm{IWR}_{t,n}$ is the irrigation water requirement per irrigation scheme, and α_{ct} and β_{ct} are irrigation and conveyance efficiencies (assumed to be 0.8 and 0.7, respectively, for surface irrigation). $\mathrm{CR}_{t,n}$ is the water supply curtailment ratio, y_n is annual crop yield (in tonnes per 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 (in tonnes per year). 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[63]. 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[31]):

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

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

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

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 (in ha); f_{FRA} is a suitability factor[63]; C_y is crop yield (in tonnes per ha) assuming a typical flood recession agriculture crop mix of maize, beans, Bambara beans, soya, millet and groundnuts[64]; Y_n is total FRA yield (in tonnes per year); β_{FRA} is average regional market price of crops at US\$1,222 per tonne (ref. [65]); and f^{FRA} is the financial benefit (in US\$) 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 a result of hydropeaking can show multiple peaks per day and intensities that exceed those of the strongest natural floods negatively impacting aquatic ecosystems[66]. Sub-daily hydrological alteration is quantified using the Richards–Baker flashiness index[43]. 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 base-load 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[43–45]. Thus, a high Richards–Baker (RB) flashiness index value implies a flashy stream (less natural flow) and a less desirable regime, whereas a low index value characterizes a stable stream[14,15,43,67]. More details on the impacts of altering the flow river regime can be found in a review of refs. [68,69]:

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

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

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 $Td = 24$h. Consequently, if the simulation time horizon is 1 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

The 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 ($\mathrm{LC}_{t,n}$) 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 modelled 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):

$$f^{\mathrm{lc}} = \frac{1}{sy} \sum_{n=1}^{N} \sum_{t=1}^{T} \mathrm{LC}_{t,n} \quad (17)$$

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 ($P_{t,n}$) from the power system simulator in each time step (t) and generator plant by a CO_2 emission factor[70] per generator technology ($ft_n^{CO_2}$):

$$f^{CO_2} = \frac{1}{sy} \sum_{n=1}^{N} ft_n^{CO_2} \times \sum_{t=1}^{T} \mathrm{P}_{t,n} \quad (18)$$

where f^{OPEX} 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:

$$f^{\mathrm{CAPEX}} = \sum_{n=1}^{N} C_n \times \mathrm{NI}_n \quad (19)$$

where f^{CAPEX} is the system capital expenditure.

To calculate the system operating costs, we multiply the operating cost per generator (CC_n) by the power output ($P_{t,n}$) per generation technology (n) in each time step (t):

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

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 minimizing the system load curtailment (f^{lc}), the CO_2 emissions from generation (f^{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}).

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

We use the Borg multi-objective evolutionary algorithm[71,72] to solve the multi-objective optimization design (Eq. 21). Borg handles complex non-linear and non-concave problems when searching for non-dominated solutions[72,73]. The optimization process for each of ten random seeds follows two steps summarized in Supplementary Fig. 1: first, 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 second, 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. The first and second steps 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 the variability of intermittent renewables 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' re-operation 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[37]. 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[37].

Reporting summary

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

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.

Code availability

The river basin model, including parameters, settings and calibration, is described in more detail in an earlier publication[31], and the software library used to build the model is open-source and freely available at https://github.com/pywr/pywr. The Python libraries used to build the power system model[32] and the objective-oriented multisector simulation framework are open-source and freely available at https://github.com/pywr/pyenr and https://github.com/UMWRG/pynsim, respectively.

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Author contributions

J.M.G. conceived the study, developed the methodology, conducted the investigation, developed the software, produced visualizations, and wrote the original draft. J.E.T. developed the software and wrote, reviewed and edited the manuscript. E.A.M.C. developed the methodology, obtained resources and wrote, reviewed and edited the manuscript. E.O. obtained resources and wrote, reviewed and edited the manuscript. M.B. developed the software and wrote, reviewed and edited the manuscript. P.T.P. obtained resources and wrote, reviewed and edited the manuscript. S.A. obtained the resources and wrote, reviewed and edited the manuscript. R.B. obtained resources and wrote, reviewed and edited the manuscript. M.E. developed the software and wrote, reviewed and edited the manuscript. A.H. wrote, reviewed and edited the manuscript and was responsible for project administration. A.B.B. wrote, reviewed and edited the manuscript. J.D. wrote, reviewed and edited the manuscript. D.M.S. wrote, reviewed and edited the manuscript. J.S. obtained resources and wrote, reviewed and edited the manuscript. M.P. conceived the manuscript, developed the methodology and wrote, reviewed and edited the manuscript. J.J.H. conceived the study, developed the methodology, wrote the original draft, supervised the study and was responsible for funding acquisition.

Competing interests
The authors declare no competing interests.

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Software and code

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Data collection	During the study, there was no used software to collect data. Instead, all the data used in the study was provided by Ghanaian local authorities and collected from freely available reports such as the Master Energy Plan for Ghana and river basin data from the WISE-UP to Climate project led by IUCN.
Data analysis	The data analysis in this study was carried out using a purpose-built tool which integrates three Python modules freely available in https://github.com/pywr/pywr; https://github.com/pywr/pywr-dcopf, and https://github.com/UMWRG/pynsim. The full mathematical description is available in the manuscript's Method section.

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The data supporting the conclusions of this article will be made available by the authors upon consultation with the relevant national authorities who own the data. The River basin model, including parameters, settings and calibration, are described in more detail in an earlier publication (https://doi.org/10.3389/fenvs.2021.596612), 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 energy model and the objective-oriented multi-actor 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.

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Study description	The study propose an analytical framework that can help decision makers strategically design national investment portfolios in energy systems that could support sustainable development and progress towards net-zero aspirations. The framework is based on state-of-the-art integrated water-energy-food-ecosystem simulation coupled with artificial intelligence design methods and can help identify investment bundles that achieve Nationally Determined Contributions (NDCs). Second, our state-of-the art multi-sector river basin/power system integrated assessment tool demonstrates how using hydropower alone to incorporate high shares of intermittent renewables would lead to environmental and multi-sector costs.
Research sample	The research sample consisted of all existing and potential power plants (hydropower, thermal, biogas, solar and wind) and transmission infrastructure in Ghana. Also, it includes hydrological information about the Volta River Basin and water and energy demands for the country.
Sampling strategy	The sample size was equal to the complete set of power system infrastructure available (existing and potential). Also, the sample includes all the hydrological information in the basin. The details are fully explained in the Methods section of the manuscript.
Data collection	The input data for the modelling was collected by the team of authors, led by Jose M. Gonzalez, between January 2019 and December 2019, mainly through Internet-based literature. The power system data was provided by colleagues working in the Ghana Grid Company Ltd, the power system operator in Ghana. In addition, observed hydrological and water demands information was provided by the Water Research Institute, Council for Scientific and Industrial Research in Ghana.
Timing and spatial scale	The data collection happened according to the authors' personal schedules in the period between January 2019 and December 2019, with continuous updating of older data in case newer data was found during the process.
Data exclusions	No data was excluded from the analysis.
Reproducibility	The study experiments were designed based on numerical simulations. To ensure that the study experiments are reliable and reproducible, we calibrated and validated the simulation models at multiple sites in the Volta Basin over multi-year periods.
Randomization	The Volta river system simulator was calibrated over the period 1991-2010 at three locations over using historical river flow observations and reservoir and lake water levels. This calibration period was chosen based on the availability of common and continuous historical observed data for the three selected locations.
Blinding	Binding is not relevant to the data because our data are acquired and processed systematically with established computational pipelines.

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