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Floating photovoltaics may reduce the risk of hydro-dominated energy development in Africa

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Floating photovoltaics (FPV) is fast becoming cost-competitive, but its social and environmental impacts are under debate. Meanwhile, developing economies anticipate hundreds of new dams over the next decade, with social and environmental implications for the next century. In this context, we estimate that FPV could produce 20–100% of the electricity expected from Africa's planned hydropower depending on the scale of FPV deployment and its cost and efficiency relative to land-based photovoltaics. Here, at the system scale, we show that the same capital investment earmarked for planned dams in the Zambezi watercourse could be used more efficiently by building fewer reservoirs and substituting the energy supply with FPV. This approach yields an energy output 12% less variable and more robust to long-term hydrological changes. Our findings suggest that FPV's potential to avoid the environmental, social and financial risks of hydro-dominated energy development may outweigh its potential impacts on existing reservoir uses.

Despite the environmental, social and financial risks, developing countries are increasingly pursuing hydropower[1,2]. More than 80% of newly added hydropower capacity over the preceding decade has been concentrated in developing economies[3], and profitable potential remains largely untapped even after incorporating environmental constraints[4]. Despite this appreciable growth, severe droughts have caused the first decline in global hydroelectric generation in two decades[5]. Such events, which expose power grids in hydro-dominated countries to electricity shortages that can slow economic development[6,7] and exacerbate poverty[8], are anticipated to intensify with climate change[9–12], escalating the financial and societal risks associated with hydropower-reliant energy development schemes[13–15]. But the exuberance for hydropower remains high, bolstered by the pursuit of net zero emissions, with some estimates calling for a doubling of global hydropower capacity by 2050 (ref. 16).

A restrained hydropower capacity expansion aligns well with global change scenarios predicting accelerated technological advancements and rapid cost reductions in renewables and battery storage[17,18]. Floating photovoltaics (FPV), an emergent solar technology that can be placed on and integrated with existing hydroelectric facilities, presents such a transformative advancement with an extensive global opportunity. Estimates suggest that, if FPV were to cover 30% of the world's reservoir surfaces, these systems would generate more than one-third of the current global electricity production[19]. Similarly, a modest 5% coverage could suffice in delivering the solar power necessary to decarbonize the grids of numerous countries in South America and Africa by 2050 (ref. 20). The deployment of FPV systems on hydropower reservoirs offers the advantage of cost savings, facilitated by utilizing the grid connections of hydroelectric facilities and regularizing the total power output through coordinated operation of dispatchable hydropower[21–24]. This introduces the compelling prospect of FPV installation on existing dams as a substitute—not simply a complementary measure—to planned hydroelectric dams as a trajectory for sustainable, low-carbon energy development. Such a shift in the energy landscape would have profound implications for people's lives, energy security, poverty alleviation, economic development and energy policy.

Recent projections forecast unprecedented population growth[25] and economic development across Africa in the coming decades.

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Coupled with increased electrification and electricity access on the Continent[26], Africa's electricity demand is predicted to triple by 2050 compared with current levels[27]. Analyses of Africa's future energy needs for this rapid transformation reveal photovoltaics (PV) markedly outpacing other technologies in added generation capacity by mid-century and supplanting over one-third of the continent's planned hydropower expansion[18]. Given the anticipated surge in land-based photovoltaics (LPV), the first part of our work considers FPV's potential contribution in Africa. We estimate that FPV could produce 20–100% of the electricity expected from planned hydropower dams and find that 40–100% of that potential FPV capacity is part of Africa's long-term, cost-optimal energy mix.

However, our continental-scale evaluation of FPV is merely a starting point. Recent research underscores the efficiency gains and low regrets of strategic system-wide incorporation of renewables that can eliminate many of the large hydroelectric projects favoured in regional and national energy plans[28–32]. Furthermore, constructing and operating reservoirs solely to maximize energy production almost always conflicts with other water management objectives, disrupting natural flow regimes important for terrestrial and aquatic ecosystems, impacting water availability for crop irrigation and other water demands, and increasing the risk of downstream flooding[33–36]. Thus, tradeoffs-aware hydropower expansion planning that maximizes synergies across multiple sectors requires system-scale evaluation of hydroelectric projects within the larger river basin systems and electricity grids of which they are a part[37,38].

In this Article, to address these aspects, we present a detailed system-scale study of the transboundary Zambezi watercourse (ZW) in the South African Power Pool (SAPP) to jointly investigate FPV and hydropower capacity expansion while incorporating the techno-economic constraints and objectives of electricity system operations. The ZW is emblematic of many regions where economic progress is escalating energy and water demands but uncertainties in population growth, energy and climate could result in overbuilding of hydropower capacity[18]. Our results suggest that the same capital investment earmarked for constructing hydroelectric dams in the ZW is used more efficiently by erecting fewer reservoirs and supplementing the energy supply with FPV installations on existing reservoirs, altogether avoiding the negative social and environmental impacts of dam construction and operation. Compared with intensive hydropower-dependent energy development, this strategic approach generates an electricity output that has 12% less interannual variability and is more robust to long-term hydrologic changes. Moreover, we show a strong potential for FPV to effectively offset hydropower losses from system re-operation, thus internalizing tradeoffs over competing uses and management of shared water resources.

Cost-optimal FPV expansion in Africa

To evaluate FPV's potential contribution to Africa's energy future, we extend the multi-scale, multi-scenario integrated OSeMOSYS-TEMBA modelling framework in ref. 18 to include various cases of FPV deployment (Methods). By combining data on hydropower and reservoir characteristics with PV efficiencies from TEMBA, we first estimate the total possible electricity production of FPV installed at existing and under-construction dams where FPV peak capacities are set to incremental multiples (1×, 2× and 10×) of adjacent hydroelectric dam generating capacities as well as a case where FPV systems are limited only by maximum surface area constraints ('Max'). As shown in Fig. 1, FPV power production could equate to 26–145% of planned dam hydropower generation in the SAPP, 40–126% in the Eastern Africa Power Pool (EAPP), 18–151% in the West African Power Pool (WAPP), less than 1% in the Central African Power Pool (CAPP) and 20–100% Africa-wide. Although there are no major planned hydroelectric dams in the North African Power Pool (NAPP), the pool could increase its power output by 33–480% of existing hydropower with FPV. Thus, in a maximal deployment case, our results suggest that FPV could conceivably substitute the hydropower production of all planned dams in four of Africa's five major power pools and collectively supply 6–7% of the continent's projected electricity demand by 2050.

We use the OSeMOSYS-TEMBA model to obtain cost-optimal FPV investments through 2050 that reflect techno-economic competition among energy technologies. Under our nominal assumptions of FPV capital cost and efficiency (10% and 5% higher than LPV, respectively) we find that the majority of potential FPV is invested for all FPV deployment cases, with slightly higher investment in the emission-constrained Shared Socioeconomic Pathway (SSP) 1 scenario (Fig. 2). The WAPP and SAPP show the highest FPV, while the lowest proportion (39–43%) of potential FPV built is in the EAPP. For the 10× deployment case, an Africa-wide total of 65 GW (60%) and 81 GW (74%) of FPV capacity is invested in the SSP 4 and SSP 1 scenarios, respectively displacing 35–47 GW of LPV and 6–10 GW of wind. A small amount (~3 GW) of the planned hydropower is replaced by FPV in the SSP 4 scenario, but we emphasize that this is in addition to the more than 40% (~40 GW) of planned hydropower not built in any scenario due to its non-competitiveness with solar and wind in general.

Additional OSeMOSYS-TEMBA scenarios show the sensitivity of FPV expansion to capital cost and capacity factors set relative to that of LPV (Supplementary Fig. 1). Towards the higher range of FPV efficiency (13% higher than LPV), all potential FPV is invested for all power pools even when FPV's capital cost is 15% higher than LPV. At the mid-range of FPV efficiency (8% higher than LPV), ~70% of potential FPV is invested at a 5–15% higher capital cost than LPV, ~80% at FPV–LPV capital cost parity and 100% of potential FPV when its capital cost is 5% less than LPV. Towards the lower range of FPV efficiency (3% higher than LPV), more than 40% of potential FPV is invested even when its capital cost is 15% higher than LPV. The competitiveness of FPV is greatest in the WAPP and SAPP, whereas the EAPP and CAPP only see higher FPV investment with higher efficiency. On closer inspection of capacity expansion over time, we find that the WAPP and SAPP exhibit similar sensitivity to the EAPP and CAPP but at shorter time horizons (Supplementary Fig. 2). FPV is invested earlier (later) in the WAPP and SAPP when cost and efficiency assumptions are favourable (unfavourable) for FPV, whereas, for the EAPP and CAPP, these assumptions only affect FPV investment towards the end of the modelled period. This suggests that cost-optimal FPV capacity expansion in Africa is largely a matter of timing.

Strategic hydropower–FPV expansion in the ZW

Given the strong potential emerging from the continental scale analysis, we consider the ZW-SAPP case study for navigating synergies and tradeoffs of hydropower and FPV capacity expansion at the river basin and electricity grid scale. Our system-scale assessment captures two feedbacks between the regional electricity grid and the river basin's reservoir operations. The first is the grid penetration of available hydropower and solar generation at hourly timescales where electricity load and constraints of transmission and thermoelectric power generation control power dispatch. We configure the electricity system model PowNet[39] to prioritize the dispatch of floating solar over hydropower when the total available generation is greater than transmission capacity, thus yielding a 24-h dispatch curve representing the best possible integration of FPV at each dam. Second, we assess the economic benefit of hydropower and FPV expansion in terms of reduced operating costs (OPEX)—specifically, OPEX is the objective value of the electricity system operations model that we find is largely modulated by hydropower and solar availability (Methods)—and its tradeoffs with other water management sectors, including irrigation and ecosystem services. Thus, our system-scale assessment reveals additional social and environmental dimensions on which FPV may outperform hydropower development by simply avoiding new dam construction or facilitating reservoir re-operation towards other water management objectives.

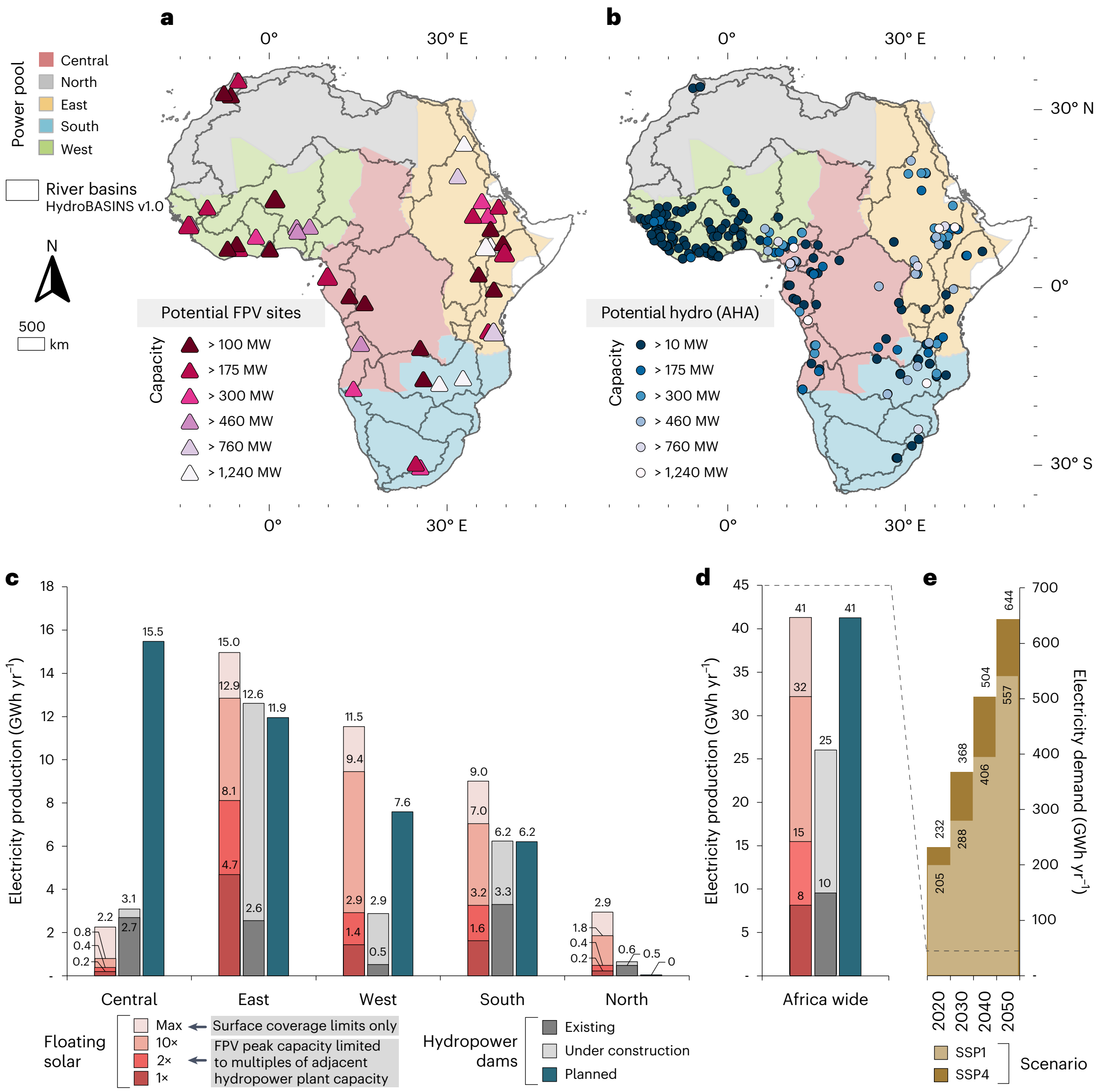

Fig. 1 | FPV electricity production could match or exceed that of planned hydroelectric dams in Africa. a, The map of potential FPV sites where capacity is set equal to that of the adjacent hydroelectric dam (1× deployment case). **b**, The map of all planned hydropower facilities in the AHA database. **c**,**d**, The total potential FPV electricity production by deployment case (red-shaded bars), total hydropower production of existing and under-construction dams (dark- and light-grey bars), and total hydropower production of all planned dams (blue bars) by power pool (**c**) and Africa-wide (**d**). **e**, Two scenarios of SSP-driven final electricity demand (Africa-wide) for each decade through 2050.

There are three major planned reservoirs in the ZW and, thus, eight possible reservoir networks (including the existing network) depending on which combination of the dams is built. The multi-purpose and coordinated operations for each reservoir can differ under each network, so we optimize reservoir operating policies together with FPV peak capacities for each network separately. The optimization process generates many solutions representing Pareto-efficient tradeoffs across the ZW's energy, food and environmental objectives, a capital cost objective (CAPEX), and the OPEX objective of the SAPP electricity system. We post-process these solutions to identify benchmarks of hydropower and FPV capacity expansion along two Pareto-efficient fronts represented by the OPEX–CAPEX tradeoff shown in Fig. 3: a 'Holistic' front where solutions achieve at least the 90th percentile or above on both irrigation and environmental objectives, and an 'Energy' front where no such filter is imposed. Although OPEX and CAPEX could be combined into a total (net) cost, meaningfully doing so necessitates jointly modelling system-scale operations with the optimization of capacity expansion sequencing over time, which is beyond the scope of our analysis. The OPEX–CAPEX tradeoff nevertheless indicates the relative dominance of solutions on cost alone.

Analysing the OPEX–CAPEX tradeoff across all dam portfolios in Fig. 3, the post-processed Energy and Holistic solutions show OPEX savings of approximately \$130 million per year and \$120 million per year, respectively, for every \$1 billion of CAPEX invested. Analysing the OPEX–CAPEX tradeoff in relation to a specific number of reservoirs in a network, we observe a declining marginal value of OPEX savings per dollar CAPEX due to hydropower and FPV curtailment (the difference between available and dispatched power as estimated from the SAPP PowNet response model). The decreasing marginal value is more prominent in the energy solutions, where reservoir operating policies prioritize hydropower production leading to an increased frequency of curtailment.

Considering only existing reservoir network solutions with FPV (outlined 'Existing reservoirs +FPV' circles in Fig. 3), up to ~\$6–7 billion

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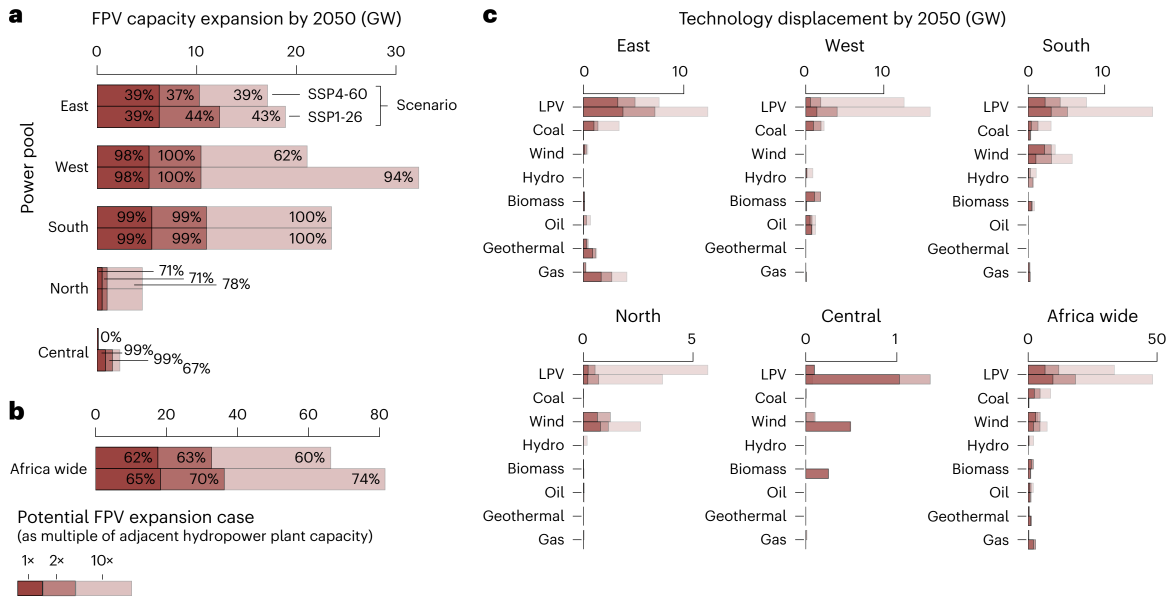

Fig. 2 | OSeMOSYS-TEMBA scenarios of FPV capacity expansion and displacement of LPV and other technologies through 2050. a–c, The FPV capacity expansion by power pool (**a**) and Africa-wide (**b**) and technology displacement (**c**) through 2050 for two SSP-driven energy demand scenarios assuming FPV has 10% higher capital cost and 5% higher efficiency than LPV. In **a–c**, the bar shading represents 1×, 2× and 10× potential FPV deployment as multiples of adjacent hydropower plant capacities. The bar annotations on **a** and **b** indicate FPV capacity expansion in OSeMOSYS-TEMBA as a percentage of the total potential FPV capacity in each deployment case. Technology displacement is calculated by comparing the capacity expansion of technologies in the same scenario with and without the FPV technology option in TEMBA.

of FPV installed at Kariba and Cahora Bassa results in OPEX savings of ~\$700–750 million per year. This level of OPEX savings is comparable to constructing two new reservoirs without FPV (outlined 'Two reservoirs (no FPV)' grey markers in Fig. 3). However, while FPV deployed at the existing reservoirs could meet the same power production levels as constructing two new reservoirs, it would come at a greater capital cost due to the declining marginal value at higher FPV peak capacities. A more cost-effective approach is to construct one new reservoir together with FPV expansion, such as the Mphanda Nkuwa (MN) solutions (outlined 'One reservoir +FPV' triangle markers in Fig. 3) that, for the same CAPEX investment, provide up to \$250 million per year lower OPEX than the existing network solutions and the same OPEX savings as the two-reservoir solutions without FPV. Similarly, there is an Energy 6-Res (MN; FPV) benchmark solution that provides the same OPEX savings (\$1.1 billion per year) as the benchmark three-reservoir Energy 8-Res (BG–DG–MN) solution (where 'BG' is 'Batoka Gorge' and 'DG' is 'Devils Gorge') for the same capital cost (\$7.9 billion). Altogether, this strongly suggests that, when FPV is deployed at capacities that can be optimally integrated into hydropower dam operations, FPV can substitute any of the planned dams in the ZW, thereby avoiding the social–environmental costs they may have.

Turning now to the tradeoffs of reservoir management in the ZW, the Holistic solutions have overall higher OPEX due to reservoir operations tailored towards meeting environmental flow and irrigation objectives (any reduction in hydropower requires a corresponding increase in the thermoelectric generation to balance the electricity load). This tradeoff starts at around \$200 million per year higher OPEX under the existing reservoir network and increases to over \$350 million per year with the construction of all three reservoirs (a complete visualization of all solutions and tradeoffs is shown in Supplementary Fig. 3). What is key to recognize here is how the tradeoff of hydropower production with other basin objectives can be compensated by FPV investment. For example, by investing an additional \$2.5 billion in FPV capacity, the Holistic 6-Res (DG; FPV) solution (\$10.4 billion CAPEX) reaches \$1 billion per year in OPEX savings, only \$100 million per year less than the benchmark Energy 8-Res solution. Thus, incorporating FPV as a component of river basin management can internalize the costs of compromising with other system objectives while maintaining power production levels comparable to solutions that construct more reservoirs.

Reduced exposure to hydrologic variability with FPV

Figure 4 illustrates differences in the variability of electricity supply between Energy and Holistic solutions by comparing the coefficient of variation (CV) of annual power production simulated over the historical hydrologic record (1986–2005). Adding hydropower capacity increases the variance of annual production while adding FPV reduces it since FPV power production has minimal year-to-year variability. For example, the CV for the benchmark Energy 8-Res solution is 67% higher than the Energy 6-Res solution and 30% higher than the Holistic 6-Res solution. This variability manifests in the most severe historical simulated drought period (1995–1996) where the Energy 8-Res solution produces 23 TWh yr^{-1} and the 6-Res FPV solutions produce 28–29 TWh yr^{-1}. Thus, adopting FPV in place of intensive hydropower development results in a more predictable output over longer timescales, which could lead to greater electricity reliability and lower reliance on imports in times of drought.

The benchmark solutions undergo re-simulation across a wide sampling of plausible future hydrologic conditions using a synthetic stochastic streamflow ensemble of 450 members derived from climate model-forced hydrologic simulations (Supplementary Text 4). Although the average annual hydropower production of the Energy 8-Res solution is higher than other solutions, its performance range over the ensemble is also wider, varying from −37% to +25% compared with the historical hydrologic condition (Supplementary Fig. 4). Conversely, the 6-Res solutions with FPV cannot fully capitalize on wetter hydrologic conditions but display greater resilience in drier ensemble members. For instance, both 6-Res FPV solutions achieve an OPEX of \$20 billion per year in 98% of the ensemble members, compared with

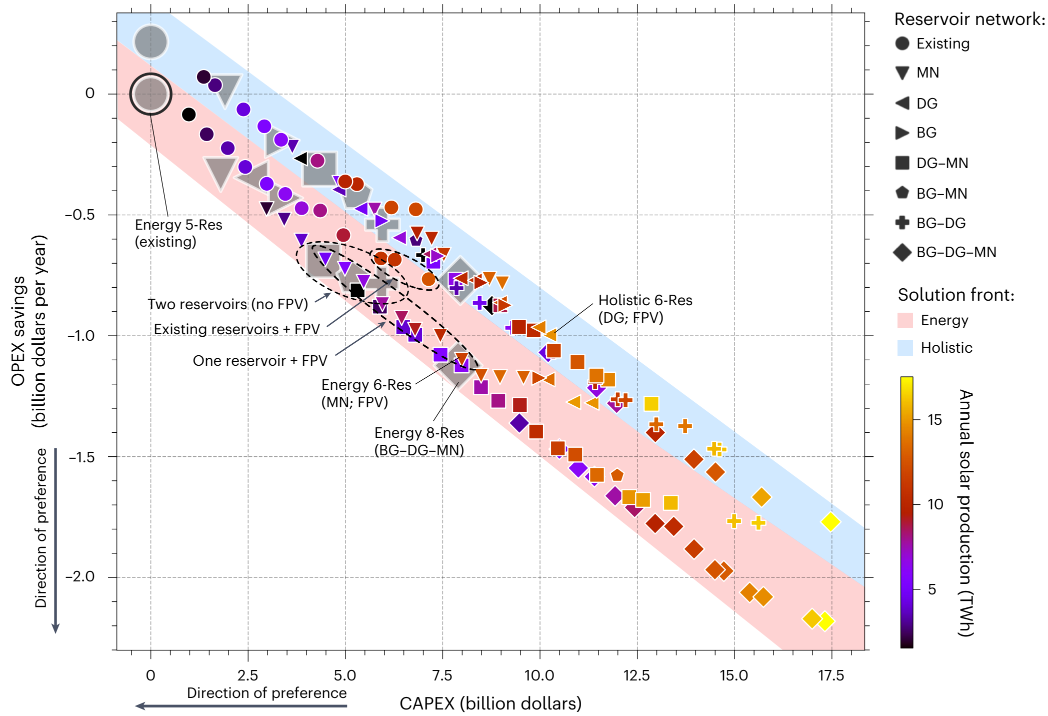

Fig. 3 | Solutions of reservoir operation and joint hydropower–FPV capacity expansion along the Pareto tradeoff of operational savings (OPEX) and capital expenditure (CAPEX). Solutions along the 'Energy' front are Pareto sorted on energy objectives only, while those along the 'Holistic' front are filtered to meet at least the 90th percentile performance on both environmental and irrigation objectives. The marker symbols indicate the reservoir network of the solution, including the existing network and combinations of expanding to one or more of the three major planned reservoirs: MN, DG and BG. The large grey-shaded markers indicate hydropower expansion solutions that have no FPV capacity. All other solutions are coloured according to the annual electricity production from FPV. OPEX is plotted relative to the benchmark 'Energy 5-Res' solution.

only 75% for the Energy 8-Res solution. This disparity is further evident in the ensemble performance of the fifth percentile of total monthly power production. For instance, the Energy 8-Res solution has lower fifth percentile monthly production than the existing reservoir network (5-Res) solution in ~20% of the ensemble members. In contrast, 6-Res solutions with FPV have higher fifth percentile monthly production than the Energy 8-Res in almost all of the ensemble members. The ensemble performance results suggest that intensive hydropower development carries substantial downside risk compared with solutions with FPV and that FPV can reduce the vulnerability of the ZW's electricity supply to drier futures.

Discussion

Our study illustrates that FPV is a cost-competitive alternative to land-based solar and the construction of new hydroelectric dams. FPV installed at existing dams could substitute the hydropower production of all planned dams in four of Africa's five major power pools and collectively supply 6–7% of the continent's projected electricity demand by 2050, but the timing and extent of such FPV capacity investment is sensitive to its efficiency and cost relative to land-based solar. In the ZW, FPV can enhance total power production or internalize the costs of forfeiting hydropower to prioritize reservoir operations towards other competing river basin objectives, such as irrigation deliveries and environmental flows. As a substitute, FPV can match the energy performance of planned hydroelectric dams for the same capital cost, thereby avoiding the negative social and environmental impacts of dam construction and operation. Compared with risky hydropower investments, FPV's insensitivity to hydrology and operational flexibility through hybridized hydropower operations could lead to greater reliability of electricity supply and robustness to future conditions much drier than historically observed.

While our strategic, system-scale multi-objective reservoir planning framework has produced many promising solutions for joint hydropower–FPV expansion, certain limitations should be acknowledged. First, smoothing the hourly variability of non-dispatchable solar power with reservoir releases for hydropower generation—an operation known as 'hydropeaking'—can substantially alter subdaily flow regimes and impact terrestrial and aquatic ecosystems[40–42]. We did not control for this possibility, allowing the electricity system model to schedule the dispatch of available hydropower with full flexibility. Future research could incorporate the minimization of hydropeaking as an objective, such as done in ref. 42, or apply ramping constraints to hydropower plants in the electricity system operations model. We expect this would decrease the marginal value of FPV investment, thus adding another environmental tradeoff to consider. Additionally, our power system model simplifies the complexity of the SAPP electricity grid. Increasing the level of detail in the model could result in more complex and nonlinear OPEX and unit commitment response to renewable power availability. However, given the time and spatial scales at which the long-term expected value objectives are computed, the impact of this simplification is probably negligible. Finally, the system-scale modelling framework used in this study is incapable of jointly optimizing reservoir and electricity system operations with the sequencing of hydropower and FPV investments over time. Such advancement would enable the identification of cost-optimal infrastructure expansion solutions that link multi-sectoral objectives at the local level to regional energy planning and scenarios of societal change.

Although our study affirms FPV's prospects at the continental and river basin scales, several site-specific factors may challenge the expansion of FPV. While FPV deployment on artificial lakes and reservoirs may benefit from the fact that these infrastructures have already crossed regulatory barriers, there could be legal and security concerns related

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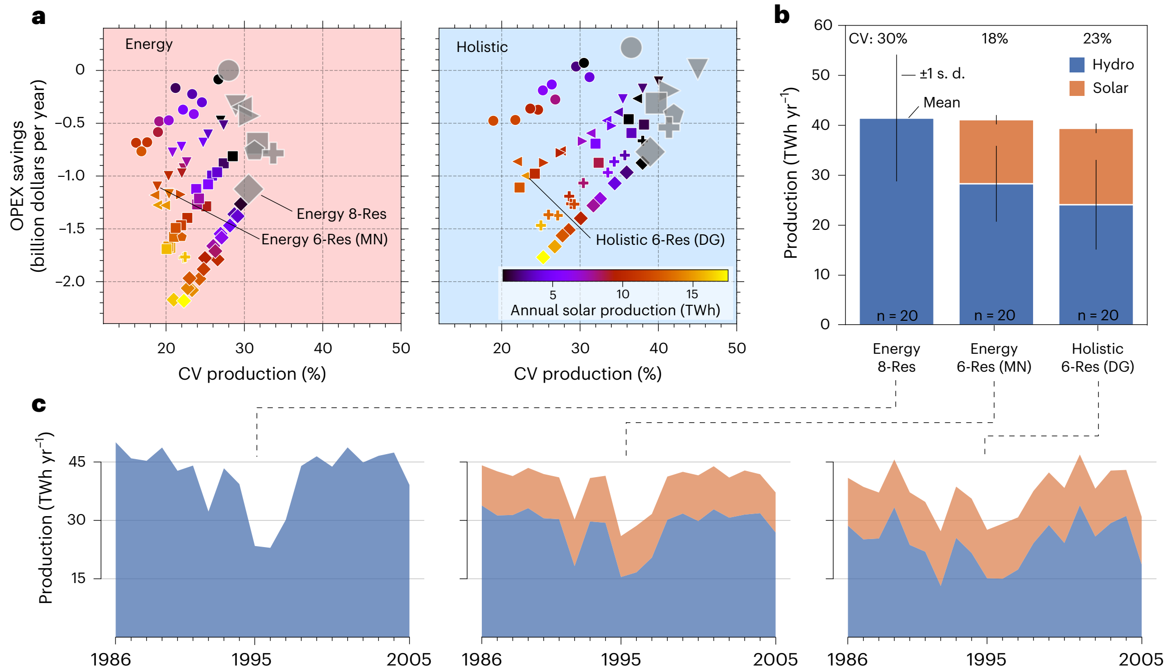

Fig. 4 | Variability of electricity supply in hydropower–FPV capacity expansion solutions for the ZW. a, The annual power production CV for the Energy and Holistic reservoir operation and joint hydropower–FPV capacity expansion solutions. **b**, The annual production ($n = 20$) of three benchmark solutions broken out by hydropower and solar contributions where the bar height is the mean, lines extend by one s.d. and the CV is annotated above. **c**, The time series of annual production over the historical simulated period (1986–2005) for each benchmark solution.

to the connection and integration of FPV systems into the hydroelectric dam facilities[43]. On the technical side, FPV installation may be physically impracticable at certain reservoirs or the costs of ongoing maintenance issues particular to FPV systems[44,45] may be prohibitive. On the societal side, large-scale FPV systems that cover a large portion of reservoirs—particularly those used for recreation and fishing or with cultural value—are likely to arouse negative public opinion[46,47]. Ultimately, all technologies have their disadvantages and potential risks that must be weighed by decision-makers at multiple levels. To this end, the joint hydropower–FPV infrastructure solutions generated in this study will be incorporated into the ZW's GoNEXUS 'nexus dialogues', a participatory stakeholder process to build trust and identify solutions that best address water, energy, food and ecosystem tradeoffs[48].

In conclusion, our study has demonstrated the potential of strategically integrating FPV and hydropower for sustainable, low-carbon energy development. These benefits should be appreciated in light of recent scepticism over the environmental impacts of FPV[20]. Although considerations of technical feasibility or conflicts with other reservoir uses may preclude FPV in site-specific cases, it is difficult to imagine FPV installations having larger social and environmental costs than new hydroelectric dams, particularly when FPV investments are paired with improvements to reservoir operations that enhance competing uses of water as we have shown. By embracing FPV and reducing reliance on hydropower, developing countries can ensure a more stable energy supply that is robust to long-term hydrological uncertainties. Beyond these demonstrated energy benefits, FPV avoids the need for acquiring land, is a less capital-intensive option compared with hydroelectric dams prone to cost overruns, and avoids the difficult-to-calculate (but nearly assured) damaging impacts of dams on downstream communities and river ecosystems.

Methods

FPV capacity expansion in Africa with OSeMOSYS-TEMBA

We use OSeMOSYS-TEMBA, an energy system model for long-term capacity planning in Africa[49,50], to evaluate cost-optimal trajectories of FPV expansion over the period 2015–2050. Uncertainty in future socio-economic development, energy demand and emissions policy is considered through two scenarios: the first represents no climate policy efforts and uses energy demands developed from SSP 4, an SSP based on heterogeneous development across regions; the second institutes a carbon emission constraint compatible with 2 °C end-of-century global warming and uses energy demands developed from SSP 1, an SSP based on sustainable and equitable development. Ref. 18 extended TEMBA[49] with these two scenarios of SSP-driven final energy demands by leveraging simulations from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b)[51]. In addition, ref. 18 incorporated all existing and planned hydropower units from the African Hydropower Atlas (AHA)[52] into TEMBA. Here, we extend the ref. 18 version of TEMBA to include the option of FPV expansion. Hydropower dams currently under construction are constrained in TEMBA to be invested in the year of anticipated completion. Meanwhile, all planned hydropower dams and potential FPV deployments can be invested in TEMBA in any year after 2023.

We consider potential FPV deployments at 37 existing and 9 under-construction dams across Africa with a capacity of at least 100 MW. Because we develop hybridized hydropower–FPV capacity factors that depend on an FPV system's peak capacity (described below), we consider three nominal cases of FPV capacity deployment in TEMBA where FPV system capacities are set to incremental multiples (1×, 2× and 10×) of the adjacent hydroelectric dam plant capacities. Importantly, the 1× case represents a minimum bound where FPV deployment would not require any new grid connection infrastructure (a case with potential cost savings). Then, we limit final FPV capacities for each of these deployment cases to assumptions of maximum reservoir surface area coverage: 30 km^2 or 30% of the reservoir surface area. These limits—the same as used in ref. 19—are meant to avoid overstating physical engineering limits of FPV installations (for example, in years of drought when reservoir surface areas can be substantially reduced) and to limit FPV's potential interference with other reservoir uses and local ecosystems.

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We configure TEMBA inputs for FPV technology (emission activity ratio, availability factor, capacity to activity unit, fixed cost, variable cost, input activity ratio, output activity ratio and operational life) to be equivalent to TEMBA's centralized, LPV technology except for two key distinguishing parameters: capital cost and capacity factor. There are limited data available on the capital costs of FPV. The most cited figure of $0.81–1.20 per watt-peak[53] currently places FPV 0–25% higher than LPV. The higher cost is attributed mainly to the added complexity of the floating structure. Capital costs are expected to decline as the cumulative installed capacity of FPV grows. Furthermore, there remains the potential for FPV systems to save on land acquisition and grid connection costs compared with LPV.

For FPV capacity factors, we use TEMBA's LPV capacity factors as a starting point to avoid favouring one or the other merely due to differences in PV capacity factor development (for example, data sources, aggregation and so on). From there, we differentiate FPV from LPV on account of two factors. First, we increase FPV efficiency according to the cooling effect theory that posits that PV modules over water perform better than those on land because water keeps air temperatures closer to the standard operating temperature of PV panels. Studies suggest 3–15% higher efficiency of floating versus land-based panels depending on system type, location and climate[54–56]. Second, the dispatchable nature of hydropower plants with reservoirs can aid the integration of variable renewable energy (VRE) sources by, for example, balancing more hydropower generation in the nighttime to accommodate higher daytime solar production. Importantly, the hydropower capacity factors in the AHA dataset are the output of continental-scale hydrological modelling, statistical analysis and post-processing with reservoir and plant characteristics that capture the seasonal constraints of hydropower availability[52]. This allows subsequent energy modelling studies such as ours to represent VRE integration at each hydropower plant constrained by average seasonal availability. Using a small linear program to solve the optimal seasonal day-part dispatch of hydropower provided an FPV peak capacity, we adjust FPV's capacity factor inputs to TEMBA (leaving the adjacent hydropower plant factors as-is) to represent the remainder of the linear solution's joint hydropower–FPV production. Although the same VRE integration could be achieved with a LPV project sited immediately adjacent to a hydropower plant, we consider this a site-specific consideration extraneous to the continental-scale assessment of FPV's role in Africa's future energy needs.

ZW reservoir system model

The ZW model is a river basin-scale reservoir system model that has been used to explore synergies, tradeoffs and vulnerabilities within and across hydropower, irrigation supply and environmental objectives[35,36,57]. The ZW model combines conceptual and data-driven models, including the hydrologic model of the subcatchments, the dynamic model of the reservoirs, and the irrigation diversions serving the agricultural districts along the river. The model includes five existing reservoirs (Kariba, Itezhi-Tezhi, Kafue Gorge Upper and Lower, and Cahora Bassa), one run-of-the-river hydropower plant at Victoria Falls, eight irrigation districts and up to three of the major planned reservoirs (BG, DG and MN). A monthly time step captures the ZW's reservoir operation dynamics through mass balance equations (Supplementary Text 1).

SAPP electricity system model

An electricity system operations model of the SAPP developed with PowNet[39] has been used to explore the ZW's connections with the regional electricity grid and the impact of hydropower production variability on grid operations. PowNet is a freely available, open-source modelling tool for simulating the operations of large-scale power systems. The model solves a unit commitment economic dispatch optimization problem to schedule least-cost operations that balance supply and demand over a 24 h period. The electricity system is represented by a set of nodes that include demand units, power-generating units and substations. Intermittent renewable energy is represented as an externally specified time series of available power, while the optimization algorithm determines the actual renewable power dispatched to satisfy demand. Thus, PowNet computed generation mix accounts for the technical and economical constraints of power plants and transmission lines that can limit penetration of renewable electricity generation into the grid. In addition to an hourly schedule of availability from renewable power sources, PowNet requires economic and technical input data of the following types:

1. Power plants: maximum and minimum capacity, rate of fixed cost, start-up fuel price, minimum up and down time, ramping limits and heat rate.
2. Load: hourly demand for each node.
3. Transmission lines: electrical transmission network line capacity and line susceptance.

These specifications have been gathered from available public data to build a simplified representation of the existing country-level interconnections of the SAPP power grid with the potential expansion of reservoirs and FPV installations in the ZW (Supplementary Table 1 and Supplementary Fig. 5). Because only one connection is permitted between two nodes in PowNet and lines between countries typically number more than one, the capacity of multiple country interconnections is summed, and an arithmetical mean is applied for line susceptance. Hourly power demand time series for each country were built with different load curves representative of different typical days of the year (for example, winter and summer days or weekday and weekend days). These daily profiles were scaled and calibrated to match 2018 demand data.

Soft linkage of SAPP electricity and ZW reservoir models

An overview of the policies, objectives and exogenous drivers included and linked between ZW and SAPP PowNet models is shown in Supplementary Fig. 6, and a schematic of model features and topology is shown in Supplementary Fig. 5. Soft linking the ZW to SAPP PowNet is achieved via a response model of PowNet output from a single 24 h period corresponding to the highest observed SAPP electricity system load during the year, thus reflecting an upper bound on power production and costs. The 24 h SAPP PowNet optimization is repeated under 25,000 Latin Hypercube samples of 14 randomly combined inputs of daily ZW hydropower availability at up to eight reservoirs (five existing and three planned), and FPV generation at up to five reservoirs (two existing and three planned). The input–output sampling is used to generate three response models of SAPP PowNet for incorporation into the ZW model simulation–optimization routine:

1. A linear regression model that predicts SAPP electricity system operation cost (OPEX) from the total ZW hydropower and solar dispatched to the grid. Residuals of the linear model are normally distributed with a maximum underestimation error of 0.6% and >99% of predicted values are within ±0.1% of the PowNet modelled cost (Supplementary Fig. 7).
2. Look-up tables that map FPV peak capacity into the expected daily power dispatch. FPV dispatch scales linearly with peak capacity until transmission line capacity constrains it (Supplementary Fig. 8).
3. Look-up matrices that map FPV dispatch and hydropower availability to curtailment of hydropower. In general, there is sufficient line capacity to dispatch 100% of the available hydropower and solar production at each hour; however, as solar production increases, the curtailment of daily hydropower can reach over 30% of the available hydropower generation (Supplementary Fig. 9).

The soft link validation was performed by simulating the SAPP PowNet model over the historical 1986–2005 period with solutions developed from the ZW model. Thirty solutions were randomly selected from each of the eight possible reservoir network configurations (for a total of 240 solutions), where each solution specifies FPV peak capacities and a coordinated multi-reservoir operating policy. The monthly hydroelectric production of the ZW model simulation output is allocated evenly over a month to specify the daily hydroelectric availability constraint in PowNet. In addition, hourly solar power availability is constrained to an observed record of power output developed from a global dataset of hourly solar radiation and ambient conditions for a unit-peak capacity system[58]. The hourly solar power availability is scaled by the peak capacity specified in the ZW model solution. Results of the validation show that the linear response modelled OPEX simulated in the ZW model has a \$1.97 billion per year positive bias relative to OPEX determined in the PowNet simulation (Supplementary Fig. 10). The positive bias varies little over the wide range of hydropower operations, reservoir network configurations and hydrologic conditions. The soft link is thus considered robust, with the bias reflecting an adjustment to the lower power demands seen over the course of a full year.

ZW-SAPP joint hydropower–FPV capacity expansion optimization

The ZW model is coupled with an optimization engine to design alternative reservoir operating rules, irrigation diversion policies, and FPV capacities. The optimization is performed using evolutionary multi-objective direct policy search[59], a reinforcement learning method that implements a simulation-based optimization of parametric rules using multi-objective evolutionary algorithms (Supplementary Text 2). The optimization generates a set of Pareto-efficient solutions representing tradeoffs across the objectives. Three objectives were formulated to represent the sectors of energy (hydropower production), food (irrigation deficits) and environment (streamflow deficits) at the river basin scale in previous ZW assessments[36,57]. In addition to these three, we include OPEX (to be minimized) and CAPEX (to be minimized) to represent the economic value of electricity production in the watercourse and the cost of capital investment for new reservoirs and FPV, respectively. The formulation of these objectives is included in Supplementary Text 3.

ZW-SAPP FPV grid integration and feasibility

FPV generation is released on the same transmission line connecting hydropower generation to demand node(s). A major constraint is thus the transmission line capacity of hydropower units to country demand nodes and congestion of these lines for dual use of FPV and hydropower dispatch. In our study, we place a small persuasion penalty on hydropower dispatch so that PowNet prioritizes FPV power dispatch first. This results in a 24 h dispatch curve that curtails hydropower when the total available solar and hydropower generation is greater than the transmission capacity of the line connecting the hydropower unit to the country demand node(s). Thus, PowNet determines the optimal scheduling of hydropower over a 24 h period.

The range of feasible FPV peak capacities was initially determined in PowNet by sampling solar dispatch as a function of solar peak capacity and transmission line capacity of the hydropower unit to the demand node(s). As expected, solar dispatch scales directly with FPV peak capacity until transmission line capacity begins to sharply constrain (Supplementary Fig. 11). While we test different line capacities, we ultimately limit our study to the existing line capacities at the reservoirs (or planned capacities at the planned reservoirs). The initial estimate of the feasible limit of FPV peak capacity is assumed to be where additional peak capacity added would provide greatly diminished power to the grid. The second feasibility check for FPV peak capacity was based on the area of FPV panels required to provide power output equal to the specified peak capacity. For Kariba and Cahora Bassa, minimum operating storage volumes correspond to relatively large surface areas of 4,400 km^2 and 1,000 km^2, respectively. Therefore, transmission line capacity is the primary constraint, limiting FPV peak capacity to 5 GWp at Kariba (35 km^2 footprint) and 4 GWp at Cahora Bassa (28 km^2 footprint). However, minimum operating volumes of the planned reservoirs correspond to relatively small surface areas of 20 km^2 at BG and DG and 120 km^2 at MN. Therefore, we assume that the panel footprint area becomes the primary constraint and limit floating solar peak capacity at BG and DG to 0.9 GWp (6 km^2 footprint) and at MN to 1.8 GWp (12 km^2 footprint).

Data availability

Data for the OSeMOSYS-TEMBA model, the ZW-SAPP experiments and the post-processing scripts for developing figures are available from the open-source repository Zenodo at https://doi.org/10.5281/zenodo.10576226 (ref. 60). The historical hydrologic data on the Zambezi River Basin are protected by a nondisclosure agreement with Zambezi River Authority (ZRA). However, the climate model data used for the temperature and precipitation projections are freely available at http://www.csag.uct.ac.za/cordex-africa/ (ref. 61).

Code availability

The OSeMOSYS-TEMBA model[18] is available from the open-source repository Zenodo at https://doi.org/10.5281/zenodo.7931050 (ref. 62). As the ZW reservoir operations simulation model contains sensitive hydrologic data and hydropower plant characteristics from the Zambezi River Authority (ZRA), Zambia Electricity Supply Corporation (ZESCO) and Hidroeléctrica de Cahora Bassa (HCB), it cannot be made public. The code of the HBV model for streamflow simulation is available from the open-source repository Zenodo at https://doi.org/10.5281/zenodo.5726941 (ref. 63). The PowNet model developed for the SAPP is available on GitHub at https://github.com/EILab-Polimi/ZRB-PowNet (ref. 64).

References

1. Moran, E. F., Lopez, M. C., Moore, N., Müller, N. & Hyndman, D. W. Sustainable hydropower in the 21st century. *Proc. Natl Acad. Sci. USA* **115**, 11891–11898 (2018).
2. Zarfl, C., Lumsdon, A. E., Berlekamp, J., Tydecks, L. & Tockner, K. A global boom in hydropower dam construction. *Aquat. Sci.* **77**, 161–170 (2015).
3. *Hydropower Special Market Report* (International Energy Agency, 2021).
4. Xu, R. et al. A global-scale framework for hydropower development incorporating strict environmental constraints. *Nat. Water* **1**, 113–122 (2023).
5. *Hydroelectricity—Analysis and Key Findings* (International Energy Agency, 2022).
6. Karanfil, F. & Li, Y. Electricity consumption and economic growth: exploring panel-specific differences. *Energy Policy* **82**, 264–277 (2015).
7. Almeida Prado, F. et al. How much is enough? An integrated examination of energy security, economic growth and climate change related to hydropower expansion in Brazil. *Renew. Sustain. Energy Rev.* **53**, 1132–1136 (2016).
8. Aweke, A. T. & Navrud, S. Valuing energy poverty costs: household welfare loss from electricity blackouts in developing countries. *Energy Econ.* **109**, 105943 (2022).
9. Yalew, S. G. et al. Impacts of climate change on energy systems in global and regional scenarios. *Nat. Energy* **5**, 794–802 (2020).
10. Spalding-Fecher, R., Joyce, B. & Winkler, H. Climate change and hydropower in the Southern African Power Pool and Zambezi River Basin: system-wide impacts and policy implications. *Energy Policy* **103**, 84–97 (2017).
11. van Vliet, M. T. H., Wiberg, D., Leduc, S. & Riahi, K. Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nat. Clim. Chang.* **6**, 375–380 (2016).

12. Conway, D., Dalin, C., Landman, W. A. & Osborn, T. J. Hydropower plans in eastern and southern africa increase risk of concurrent climate-related electricity supply disruption. *Nat. Energy* **2**, 946–953 (2017).
13. Foster, B. T., Kern, J. D. & Characklis, G. W. Mitigating hydrologic financial risk in hydropower generation using index-based financial instruments. *Water Resour. Econ.* **10**, 45–67 (2015).
14. Hamilton, A. L., Characklis, G. W. & Reed, P. M. Managing financial risk trade-offs for hydropower generation using snowpack-based index contracts. *Water Resour. Res.* **56**, e2020WR027212 (2020).
15. Almeida, R. M. et al. Climate change may impair electricity generation and economic viability of future Amazon hydropower. *Glob. Environ. Change* **71**, 102383 (2021).
16. *Global Renewables Outlook: Energy Transformation 2050* (International Renewable Energy Agency, 2020).
17. Zhang, Y. et al. Long-term basin-scale hydropower expansion under alternative scenarios in a global multisector model. *Environ. Res. Lett.* **17**, 114029 (2022).
18. Carlino, A. et al. Declining cost of renewables and climate change curb the need for African hydropower expansion. *Science* **381**, eadf5848 (2023).
19. Jin, Y. et al. Energy production and water savings from floating solar photovoltaics on global reservoirs. *Nat. Sustain.* **6**, 865–874 (2023).
20. Almeida, R. M. et al. Floating solar power could help fight climate change—let's get it right. *Nature* **606**, 246–248 (2022).
21. Kougias, I., Szabó, S., Monforti-Ferrario, F., Huld, T. & Bódis, K. A methodology for optimization of the complementarity between small-hydropower plants and solar PV systems. *Renew. Energy* **87**, 1023–1030 (2016).
22. Ming, B. et al. Optimizing utility-scale photovoltaic power generation for integration into a hydropower reservoir by incorporating long- and short-term operational decisions. *Appl. Energy* **204**, 432–445 (2017).
23. Fang, W. et al. Optimal sizing of utility-scale photovoltaic power generation complementarily operating with hydropower: a case study of the world's largest hydro-photovoltaic plant. *Energy Convers. Manag.* **136**, 161–172 (2017).
24. Lee, N. et al. Hybrid floating solar photovoltaics-hydropower systems: benefits and global assessment of technical potential. *Renew. Energy* **162**, 1415–1427 (2020).
25. *World Population Prospects 2022: Summary of Results* (United Nations, 2023).
26. Puig, D. et al. An action agenda for Africa's electricity sector. *Science* **373**, 616–619 (2021).
27. *Africa Energy Outlook* (International Energy Agency, 2022).
28. Schmitt, R. J. P., Kittner, N., Kondolf, G. M. & Kammen, D. M. Joint strategic energy and river basin planning to reduce dam impacts on rivers in myanmar. *Environ. Res. Lett.* **16**, 054054 (2021).
29. Siala, K., Chowdhury, A. K., Dang, T. D. & Galelli, S. Solar energy and regional coordination as a feasible alternative to large hydropower in southeast asia. *Nat. Commun.* **12**, 4159 (2021).
30. Sterl, S. et al. Smart renewable electricity portfolios in west africa. *Nat. Sustain.* **3**, 710–719 (2020).
31. Wu, G. C. et al. Strategic siting and regional grid interconnections key to low-carbon futures in african countries. *Proc. Natl Acad. Sci. USA* **114**, E3004–E3012 (2017).
32. Chowdhury, A. F. M. K. et al. Enabling a low-carbon electricity system for Southern Africa. *Joule* **6**, 1826–1844 (2022).
33. Winemiller, K. O. et al. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science* **351**, 128–129 (2016).
34. Schmitt, R. J. P., Bizzi, S., Castelletti, A., Opperman, J. J. & Kondolf, G. M. Planning dam portfolios for low sediment trapping shows limits for sustainable hydropower in the mekong. *Sci. Adv.* **5**, eaaw2175 (2019).
35. Bertoni, F., Castelletti, A., Giuliani, M. & Reed, P. M. Discovering dependencies, trade-offs, and robustness in joint dam design and operation: an ex-post assessment of the Kariba Dam. *Earths Future* **7**, 1367–1390 (2019).
36. Giuliani, M., Lamontagne, J. R., Hejazi, M. I., Reed, P. M. & Castelletti, A. Unintended consequences of climate change mitigation for African River Basins. *Nat. Clim. Chang.* **12**, 187–192 (2022).
37. Opperman, J. J. et al. Balancing renewable energy and river resources by moving from individual assessments of hydropower projects to energy system planning. *Front. Environ. Sci. Eng. China* **10**, 1036653 (2023).
38. Almeida, R. M. et al. Strategic planning of hydropower development: balancing benefits and socioenvironmental costs. *Curr. Opin. Environ. Sustain.* **56**, 101175 (2022).
39. Chowdhury, A. F. M. K., Kern, J., Dang, T. D. & Galelli, S. PowNet: a network-constrained unit commitment/economic dispatch model for large-scale power systems analysis. *J. Open Res. Softw.* **8**, 5 (2020).
40. Hauer, C., Siviglia, A. & Zolezzi, G. Hydropeaking in regulated rivers—from process understanding to design of mitigation measures. *Sci. Total Environ.* **579**, 22–26 (2017).
41. Liu, X. & Xu, Q. Hydropeaking impacts on riverine plants downstream from the world's largest hydropower dam, the three gorges dam. *Sci. Total Environ.* **845**, 157137 (2022).
42. Gonzalez, J. M. et al. Designing diversified renewable energy systems to balance multisector performance. *Nat. Sustain.* **6**, 415–427 (2023).
43. Matheu, E. E., Yezierski, M. E., Rtzer, K. S. & Freer, C. Security considerations for protecting dams and levees. *J. Dam Saf.* **19**, 40–48 (2022).
44. Liu, H., Krishna, V., Lun Leung, J., Reindl, T. & Zhao, L. Field experience and performance analysis of floating PV technologies in the tropics. *Prog. Photovolt. Res. Appl.* **26**, 957–967 (2018).
45. Sen, A., Mohankar, A. S., Khamaj, A. & Karmakar, S. Emerging OSH issues in installation and maintenance of floating solar photovoltaic projects and their link with sustainable development goals. *Risk Manag. Healthc. Policy* **14**, 1939–1957 (2021).
46. Cousse, J. Still in love with solar energy? Installation size, affect, and the social acceptance of renewable energy technologies. *Renew. Sustain. Energy Rev.* **145**, 111107 (2021).
47. Kohsaka, R. & Kohyama, S. Contested renewable energy sites due to landscape and socio-ecological barriers: comparison of wind and solar power installation cases in Japan. *Energy Environ.* **34**, 2619–2641 (2023).
48. Blumstein, S. & Kramer, A. *Deliverable 6.1: Common Approach and Methodological Roadmap for the Nexus Dialogues at Local and Basin level* (Adelphi Consult, 2022).
49. Pappis, I. et al. *Energy Projections for African Countries* (European Commission Joint Research Centre, 2019).
50. Taliotis, C. et al. An indicative analysis of investment opportunities in the African electricity supply sector—using TEMBA (the electricity model base for Africa). *Energy Sustain. Dev.* **31**, 50–66 (2016).
51. Frieler, K. et al. Assessing the impacts of 1.5 °C global warming—simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b). *Geosci. Model Dev.* **10**, 4321–4345 (2017).
52. Sterl, S. et al. A spatiotemporal atlas of hydropower in Africa for energy modelling purposes. *Open Res. Eur.* **1**, 29 (2021).
53. *Where Sun Meets Water: Floating Solar Market Report* (World Bank, 2019).
54. Lee, Y.-G., Joo, H.-J. & Yoon, S.-J. Design and installation of floating type photovoltaic energy generation system using FRP members. *Sol. Energy* **108**, 13–27 (2014).

55. Oliveira-Pinto, S. & Stokkermans, J. Assessment of the potential of different floating solar technologies—overview and analysis of different case studies. *Energy Convers. Manag.* **211**, 112747 (2020).
56. Dörenkämper, M. et al. The cooling effect of floating PV in two different climate zones: a comparison of field test data from the netherlands and singapore. *Sol. Energy* **219**, 15–23 (2021).
57. Arnold, W., Salazar, J. Z., Carlino, A., Giuliani, M. & Castelletti, A. Operations eclipse sequencing in multipurpose dam planning. *Earths Future* **11**, e2022EF003186 (2023).
58. PVGIS 5.2 (2022). EU Science Hub. *European Commission Joint Research Centre* https://re.jrc.ec.europa.eu/pvg_tools/en/ (2023).
59. Giuliani, M., Castelletti, A., Pianosi, F., Mason, E. & Reed, P. M. Curses, tradeoffs, and scalable management: advancing evolutionary multiobjective direct policy search to improve water reservoir operations. *J. Water Resour. Plan. Manag.* **142**, 04015050 (2016).
60. Data and code in support of 'Floating PV reduces risks of hydro-dominated energy development in Africa'. *Zenodo* https://doi.org/10.5281/zenodo.10576226 (2024).
61. CORDEX Africa. *Climate System Analysis Group* http://www.csag.uct.ac.za/cordex-africa/ (2013).
62. Data in support of 'Declining cost of renewables and climate change curb the need for African hydropower expansion'. *Zenodo* https://doi.org/10.5281/zenodo.7931050 (2023).
63. First release of ZambeziWatercourse_GCAM code. *Zenodo* https://doi.org/10.5281/zenodo.5726941 (2021).
64. ZRB-PowNet. *GitHub* https://github.com/EILab-Polimi/ZRB-PowNet (2024).

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W.A., M.G. and A.C. designed the research. W.A. conducted the numerical experiments, and led the data analysis and the writing of the original paper's draft. M.G. and A.C. contributed to the analysis of results, review and editing of the paper.

Competing interests
The authors declare no competing interest.

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