

Energy trade tempers Nile water conflict

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The demand for energy, water and food in Africa continues to increase, resulting in growing pressure on contentious multisector resource systems like the River Nile. The ongoing dispute over Nile resources could become a zero-sum game if addressed from a water-centric viewpoint. Understanding how energy system management impacts water infrastructure introduces new opportunities to solve water conflicts. Although benefit-sharing of water resources in the Nile Basin has been promoted to counteract water volume disputes, it has not yielded actionable solutions to the toughest negotiations over the past two decades. Here we develop a detailed and integrated energy–river basin system simulator of 13 East African countries, including the Nile Basin, and show how new electricity trade agreements between Ethiopia, Sudan and Egypt could help resolve the ongoing water dispute over the Grand Ethiopian Renaissance Dam. The results show that increasing energy trade can reduce Egyptian water deficits, reduce regional greenhouse gas emissions, increase hydropower generation in all three countries, reduce energy curtailment in Sudan and increase Ethiopia’s financial returns from electricity. This study underscores how spatial quantification of river–energy system interdependencies can help decision-makers find actionable multisector benefit-sharing solutions.

Transboundary rivers provide essential socio-economic and environmental services, with 310 transboundary river basins globally geographically shared among 150 nations¹. Around half the world’s population resides within transboundary river basins¹. Managing transboundary river basins is becoming increasingly challenging due to population growth, growing demand for resources and the impacts of climate change². Benefit-sharing has become the recommended strategy for fostering cooperation and creating and maintaining sustainable water infrastructure in transboundary river basins^{3–5}. Sharing the benefits of water resources (for example, electricity, crops, fisheries) rather than allocating water volumes can increase the space for mutually beneficial agreements^{6,7} and help solve disputes. This concept has yet to lead to acceptable large-scale solutions in the Nile region.

Benefit-sharing requires identification of non-water concerns that can be resolved through joint investment or collaborative infrastructure management^{6,7}. Previous benefit-sharing attempts have been implemented on a project-by-project basis and do not involve multisector system-scale schemes^{6–8}. This is partly due to the complexity of identifying such solutions at system scale and the need for multisector analytical tools that can estimate benefits and costs ex ante at the planning stage, the absence of which could lead to later discontent if the promised benefits are not delivered⁷. One challenge facing benefit-sharing aspirations in complex river basins is that it requires an agreed quantified representation of the benefits and costs of cooperation, and the rules for managing these benefits between stakeholders^{7,9}. The design of benefit-sharing schemes requires backing from technical

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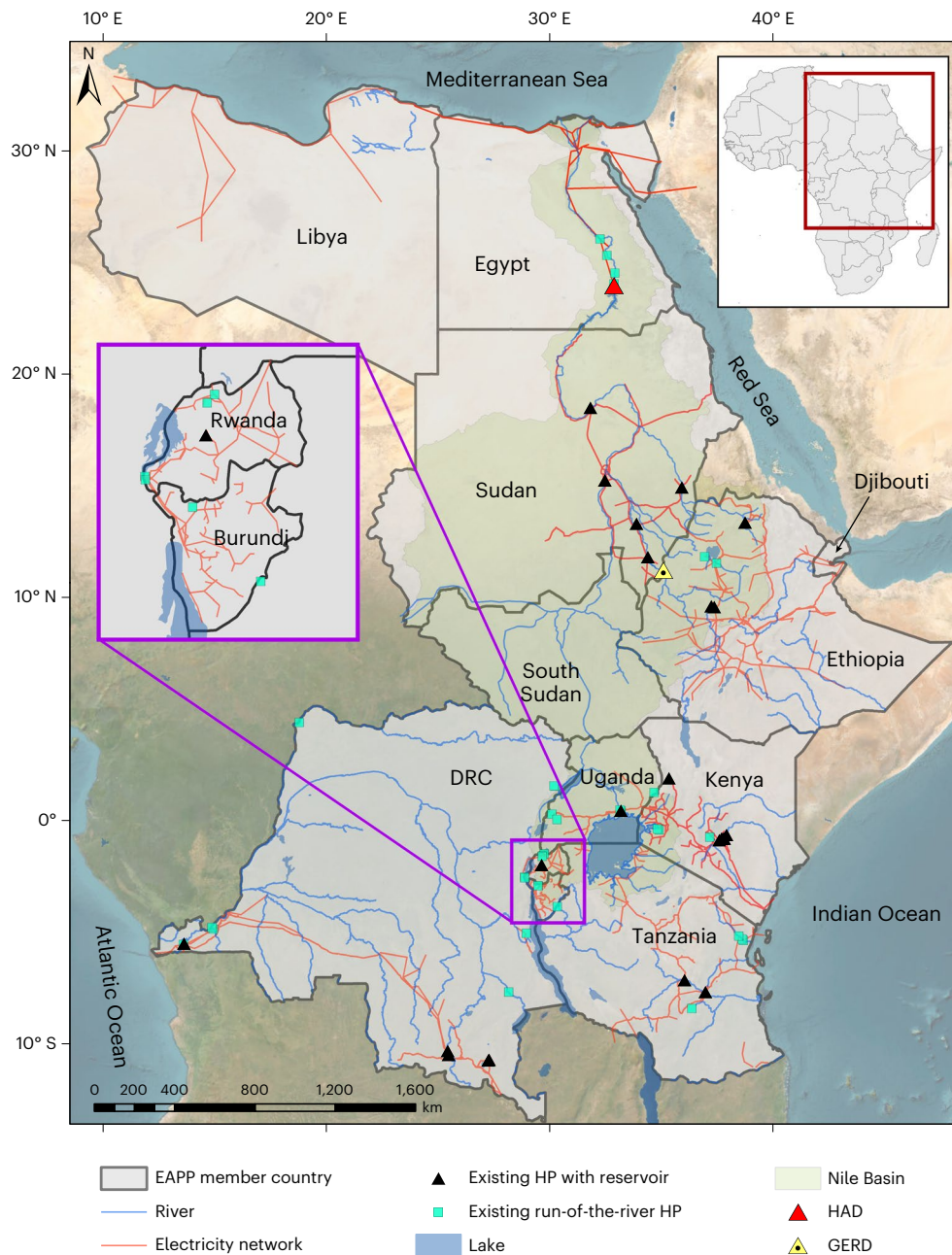


Fig. 1 | Major existing water and energy infrastructures (hydropower and transmission lines) in the EAPP, to 2030. Our integrated spatial river basin–energy system model simulates all infrastructure shown in the figure (in addition to natural lakes and water consumption), except that outside of the eastern part of the DRC. HP, hydropower. The electricity network layer is based on a database

from the World Bank Group; the existing hydropower and run-of-the-river hydropower layers are based on a database from Hydroshare; the river and lake layers are based on the Koordinates database; the countries' boundary layer is based on a database from OpenDataSoft. Credit: background satellite image, ESRI.

approaches that can accurately capture the multisector dynamics of river basins and energy systems and communicate credible solutions at high spatial and temporal resolution. To this end, the assessment approach and the solutions it investigates should be produced through a transparent process capable of securing political commitment.

The Nile is one of the longest rivers in the world and has a basin area that expands to over one-tenth of Africa and 11 countries (Fig. 1). Some of the Nile Basin countries suffer some of the highest levels of water stress and energy poverty in the world¹⁰. Several of these countries rely on hydropower as a primary source of electricity—for example, hydropower generation contributes more than 80% of the electricity mix in the Democratic Republic of Congo (DRC), Burundi, Ethiopia and

Uganda. As of 2020, only 19% of the Nile Basin's hydropower potential had been utilized¹⁰ but large-scale hydropower development in the basin is gathering momentum. To promote system-level thinking and change existing sectorally siloed practices, regional institutions—such as the Eastern African Power Pool (EAPP) and the Nile Basin Initiative (NBI)—have been formed in recent decades as platforms for regional cooperation and coordination^{11,12}.

Although benefit-sharing between riparian countries has shown promising outcomes in some transboundary river basins, including the Senegal⁷, Columbia⁶ and Orange-Senqu⁸ basins, its implementation in the Nile Basin has been either on a small scale or unsuccessful. An example of a successful small-scale benefit-sharing project on the Nile is the Rusumo

hydroelectric plant, currently under construction on the border between Rwanda and Tanzania¹³. Rwanda, Burundi and Tanzania jointly invested in the project to generate 80 MW that will be shared among the three countries. The Joint Multi-purpose Project, initiated in 2005 between Ethiopia, Sudan and Egypt¹⁴, is an example of an intended benefit-sharing project that did not reach its goals. This project encountered difficulties due to water-related political disagreements between the countries that influenced the evaluation of investment options¹⁵. National-level water security goals have been the focus of negotiations over Nile water development for several decades, but this approach is no longer viable due to the increasing demand for, and pressure on, Nile water resources.

The construction of the Grand Ethiopian Renaissance Dam (GERD) on the Nile in Ethiopia (Fig. 1) offers a new opportunity for large-scale benefit-sharing in the Nile Basin. The GERD is under construction and is expected to double Ethiopia's electricity generation. Following completion, it will have an installed power capacity of 5,150 MW and a maximum reservoir storage capacity of 74 billion m³ (bcm)¹⁶, equivalent to 1.5 times the natural average annual river flow at the dam location. Filling and operating the GERD will affect both inter- and intra-annual variabilities of the Blue Nile flow, creating opportunities and challenges for Ethiopia, Sudan and Egypt. The trilateral negotiations over the initial filling and long-term operation of the GERD have so far been water-centric. For example, from November 2019 to February 2020 the United States Administration and the World Bank convened and observed several rounds of negotiations between the three countries¹⁷, eventually producing a draft proposal that was rejected by Ethiopia (hereafter referred to as the Washington draft proposal; further details are provided in Supplementary Information and Methods). This proposal focused on defining water releases from the dam under different conditions to minimize disruptions to water users in Sudan and Egypt during the initial filling and long-term operation phases. From an Ethiopian viewpoint, the draft proposal would limit hydropower generation from the GERD and constrain future upstream development¹⁸. Subsequent negotiations led by the African Union have not yielded a publicly available draft agreement, but the scope of negotiations has remained similar to those of 2020 (ref. 19). Previous studies^{20–22} did not consider the influence of energy demand on the operational dynamics of the GERD. These studies implicitly assumed sufficient electricity demands that would consume the generated power from GERD and did not dynamically adapt the dam's operating rules based on the energy supply–demand balance. Although the GERD was initially portrayed as a benefit-sharing project in the launching speech of the late Ethiopian Prime Minister Meles Zenawi²³, the negotiations have remained within a country-centred, water-centric approach.

In this Article we argue that large-scale benefit-sharing cooperation in the Nile Basin requires quantification of complex spatiotemporal water–energy–food–environment interdependencies. We develop an analytical approach that represents the river basin and energy systems of the EAPP and their interdependencies and variations through space and time at a high resolution. We use the case of the GERD to show that detailed multisector analyses can demonstrate the value of benefit-sharing to decision-makers by providing quantified evidence. We show that moving from country-centred, water-focused solutions to a cross-border, multisector, benefit-sharing scheme, namely electricity trade from Ethiopia to Sudan and Egypt, provides six benefits: (1) reduction in Egypt's and Sudan's irrigation water deficits; (2) increase in Ethiopia's hydropower generation; (3) increase in power generation from existing hydropower stations in Sudan and Egypt; (4) reduction in Sudan's energy demand curtailment; (5) reduction in regional CO₂ emissions; and (6) increase in Ethiopia's financial return from power trade. Our results highlight that, with increased ties between Ethiopia, Sudan and Egypt on electricity trade, the dispute between the three countries over water releases from the GERD becomes less relevant, highlighting the potential role played by evidence-based, multisector, benefit-sharing solutions.

A multisector benefit-sharing approach for the GERD

Figure 1 shows the geographical extent of the river basin and energy system simulation framework developed in this study for the EAPP region. The framework represents major water–energy–food–environment system elements, including 51 dams (41 existing, 4 under construction and 6 planned), 89 run-of-river hydropower schemes (47 existing, 7 under construction and 35 planned), 1 large lake, 474 existing transmission lines, 12 solar (5 existing, 2 under construction and 5 planned) and 45 wind farms (11 existing and 34 planned), 197 thermal power stations (72 existing and 125 planned), 19 existing irrigation schemes and minimum environmental flows in the EAPP region. Supplementary Fig. 1 provides a schematic of the simulated integrated river basin and energy system. It enables high-resolution spatiotemporal simulation of water–energy–food–environment performance through a new iterative process that reconciles the various temporal resolutions of water and energy simulations at each simulated time step to ensure that hydropower generation in the river system model equals hydropower consumption in the energy system model. The simulation framework allows the consideration of, for example, scenarios such as energy trade, new infrastructure and dam operating rules and filling and operation of the GERD.

The potential impacts of the initial filling and long-term operation of the GERD on energy, irrigation and municipal and industrial water users in Sudan and Egypt have created political tensions. The purpose of the GERD is electricity generation, which requires the release of water through hydropower turbines. Therefore, electricity trade between Eastern Nile countries could create a demand for GERD's electricity, ensuring sufficient water releases to Sudan and Egypt whilst providing financial benefits to Ethiopia. Such trade could take the form of a power purchase agreement (PPA), which is a long-term electricity supply agreement between electricity-producing and -consuming countries²⁴. PPAs define the amount of electricity to be supplied, electricity price and penalties for non-compliance. PPAs face challenges, however, including negotiation complexity, regulatory uncertainties, financial risks, market price volatility, grid infrastructure requirements, environmental considerations, contractual disputes and operational performance risks²⁵. Nevertheless, PPAs are the predominant form of electricity trade in the EAPP, as evidenced by EAPP power balance statements^{26–28} which show that all EAPP power exchanges use PPAs. For instance, there is an existing 100 MW PPA between Ethiopia and Sudan whereby Ethiopia supplies 100 MW of firm power at US\$ 0.05 kWh⁻¹, and there is a 100 MW PPA between Ethiopia and Djibouti at US\$ 0.05 kWh⁻¹. To demonstrate how benefit-sharing in the form of energy trade between Ethiopia, Sudan and Egypt can help provide technical solutions to the GERD dispute, we create and examine five power trade scenarios and assess their river basin and power system implications compared with the Washington draft proposal. Although we are aware of Ethiopia's rejection of the Washington proposal, it was selected as a baseline in this study because it is the most recent publicly accessible technical proposal on which Ethiopia, Sudan and Egypt have all negotiated.

Table 1 summarizes the scenarios and their assumptions. The baseline scenario includes existing power trade combined with the Washington draft proposal for operation of the GERD (that is, the water release constraints set within the proposal). The remainder of the scenarios are based on 100 MW (refs. 29–31) incremental increases in firm power trade between Ethiopia, Sudan and Egypt; in these scenarios, GERD water releases are governed by power supply–demand balance (that is, there are no water release constraints apart from a minimum environmental flow). Comparison of these scenarios enables the exploration of how benefit-sharing through different levels of power trade impacts river system performance. All scenarios assume that initial filling of the GERD reservoir is carried out in stages following a filling plan

Table 1 | Specification and main assumptions of the power trade scenarios examined in this study

Scenario	Trade between Ethiopia and Sudan	Trade between Ethiopia and Egypt	Assumptions
Washington draft proposal	100MW	No trade	<ul style="list-style-type: none"> • GERD is assumed to target 1,600MW and generate at full capacity (that is, 5,150MW) only if reservoir storage reaches 72bcm (that is, 97% of storage capacity). GERD generation is adjusted based on energy supply–demand balance. • A minimum daily environmental flow of 43millionm³ downstream is maintained when physically possible. • Ethiopia prioritizes power export to Sudan and Egypt over Kenya, Djibouti and Tanzania. GERD water releases follow the drought mitigation measures specified in the Washington draft proposal.
Low trade	200MW	100MW	<ul style="list-style-type: none"> • GERD is assumed to target 1,600MW and generate at full capacity (that is, 5,150MW) only if reservoir storage reaches 72bcm (that is, 97% of capacity). GERD generation is adjusted based on energy supply–demand balance. • A minimum daily environmental flow of 43millionm³ downstream is always maintained when physically possible. • Ethiopia prioritizes power exports to Sudan and Egypt over Kenya, Djibouti and Tanzania.
Medium–low trade	300MW	200MW	
Medium–high trade	400MW	300MW	
High trade	500MW	400MW	

In all scenarios we assume the following based on published feasibility studies^{29–31}.

- (1) Ethiopia supplies 400MW to Kenya, 300MW to Djibouti and 300MW to Tanzania.
- (2) There is no change to existing and planned power trade and transmission interconnection between either countries in the northern portion of the EAPP (Egypt, Libya and Sudan) or those in the southern portion (Kenya, Tanzania, Uganda, DRC, Burundi and Rwanda). The transmission line between Sudan and Egypt is assumed to be upgraded from the existing capacity, to comply with Ethiopia's assumed power trade agreement. Further details are provided in Methods.

discussed as part of the Washington draft proposal³² (Supplementary Table 1). The filling plan was modified to accommodate the progress in GERD filling achieved in 2020 and 2021, and to consider construction delays³³. At the time of finalizing this article for publication, the initial filling phase of the GERD reservoir was nearly completed³⁴ and is expected to transition to long-term operations in the 2024/2025 hydrological year.

We assumed that changes to the current PPA between Ethiopia and Sudan and a new PPA between Ethiopia and Egypt will begin once the GERD reaches the steady-state operation phase (storage reaches 49.3 bcm). Trade during the steady-state phase ensures a more reliable electricity supply. To account for high interannual variability in river flows, we examined the five power trade scenarios across 30 twenty-year-long river flow sequences ('hydrological traces'). These hydrological traces were created using the indexed sequential method³⁵ based on the 1972–2002 historical flow record of EAPP river systems. In the multisector simulation we use the status quo consumptive water demands in the EAPP region to quantify how benefit-sharing could impact system performance. These assumed water demands do not reflect an endorsement by the authors of status quo water allocations. Further details on how the five scenarios are implemented in the integrated river basin–energy system model of the EAPP are provided in Methods.

Impact of power trade on river system performance

Figure 2a,b shows the exceedance probability of annual irrigation water supply deficits in Sudan and Egypt for the five power trade scenarios. It illustrates how increasing power trade from Ethiopia to Sudan and Egypt reduces annual irrigation water supply deficits in Egypt and Sudan by a maximum of 5.1 and 1.3 bcm, respectively. This occurs because Ethiopia increases downstream water releases to meet electricity demand with higher power trade. Figure 2a demonstrates that, compared with the Washington draft proposal, increasing power trade reduces peak annual irrigation water supply deficit in Sudan by around 1.3 bcm. Nonetheless, the probability of an annual irrigation deficit occurring in Sudan, even under the Washington draft proposal, is low compared with Sudan's total aggregate yearly water supply of 15.16 bcm. Supplementary Table 2 summarizes Sudan's annual water supply deficits under different exceedance probabilities. The upstream geographical location of Ethiopia results in a consistent annual water abstraction across the five power trade scenarios under investigation.

Compared with the Washington draft proposal, the highest power trade scenario leads to the largest reduction in Egypt's peak annual irrigation water shortage and reduces the frequency of shortages (Fig. 2b). Figure 2b shows that Egypt's maximum yearly irrigation water deficit would decline by 4.0, 1.87, 1.7 and 1.9 bcm in the high-, medium–high-, medium–low- and low-power trade scenarios, respectively, compared with the Washington draft proposal. Furthermore, the frequency of annual water supply deficits declines with increasing power trade. Compared with the Washington proposal, the probability of occurrence of an annual water supply deficit in Egypt would drop by 1.7, 10.3, 16.5 and 15.2% in these four power trade scenarios, respectively.

The High Aswan dam (HAD) is a large, multiyear-storage reservoir located in Egypt near the Sudan–Egypt border (Fig. 1). Downstream water demands in Egypt are fully satisfied when the HAD reservoir is in the normal zone, and water releases from it are reduced in Zones 1, 2 and 3 by 5, 10 and 15%, respectively. Figure 2c indicates the number of weeks in the 20-year simulation period in which the HAD reservoir fell within either normal operation or one of the three drought-management zones (Zones 1–3; Fig. 2). This figure shows an increase in the number of weeks in the normal zone alongside a decline in Zones 1 and 2 with increasing power trade compared with the Washington draft proposal, a trend mirrored in Zone 3 with a corresponding decline. The number of weeks in Zone 1 declines by 4, 32, 64 and 96%, and in Zone 2 by 26, 67, 90 and 98%, in the low-, medium–low-, medium–high- and high-power trade scenarios, respectively. Operation of the HAD in the normal zone more often reduces irrigation water shortages in Egypt and confirms the benefit to that country from increasing power trade.

Figure 3a,b shows reservoir storage of the GERD and HAD for the driest river flow sequence (that is, a sequence similar to historical conditions from 1977), and Fig. 3c,d shows the corresponding change in annual irrigation water deficits in Sudan and Egypt relative to the Washington draft proposal. No difference is observed between the power trade scenarios in regard to yearly water supply deficits in Sudan and Egypt during the initial filling of the GERD (2020–2024). The initial filling of the GERD reduced HAD reservoir storage in all scenarios but did not result in irrigation water deficits in Egypt during those years. This is because the HAD reservoir is currently almost full³⁶ and thus can supplement river flows to avoid irrigation supply deficits during the GERD's initial filling. Results show that, during the steady-state operation phase, the GERD operates at lower levels with increasing power trade, resulting in higher storage at the HAD. Decreased levels of energy export require the GERD to operate at lower power targets due to reduced electricity exports, resulting in reduced downstream water releases.

As pointed out in the Washington draft proposal³², besides GERD's water releases under a normal hydrological year, additional water releases are determined by drought-mitigation measures (Methods).

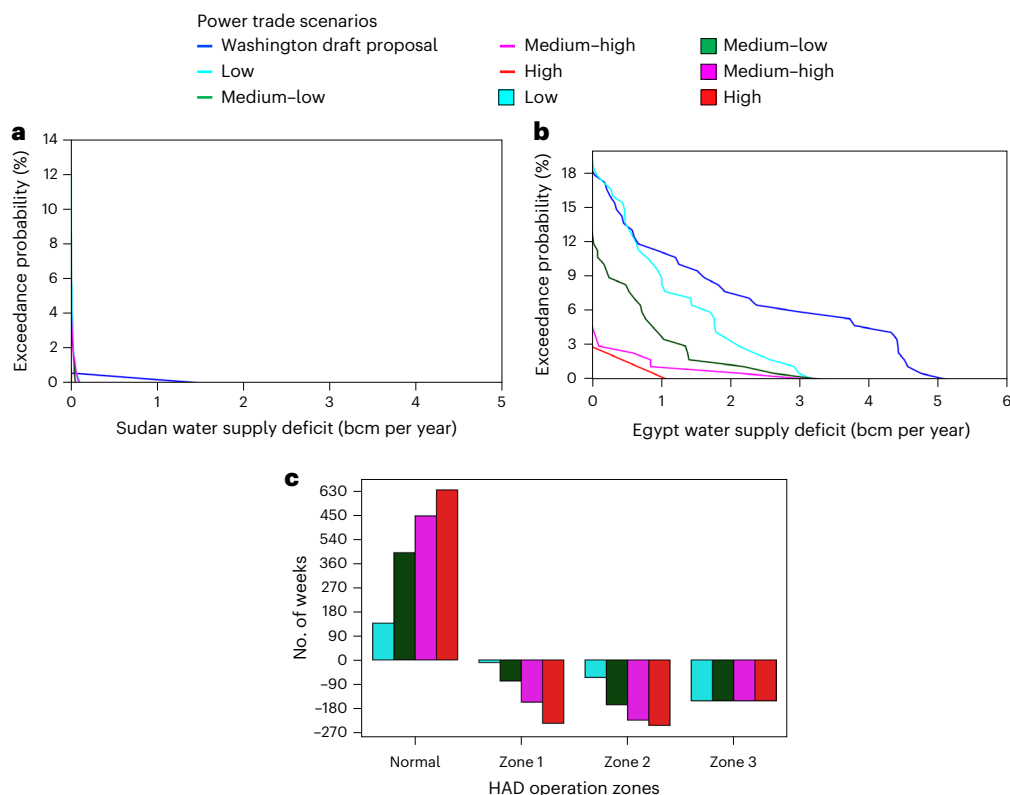


Fig. 2 | Irrigation water supply deficits in Sudan and Egypt for the five examined power trade scenarios using 30 river flow sequences. a, b, Exceedance probability of annual irrigation water supply deficits in Sudan (a) and Egypt (b). **c.** Change in the number of weeks in which the HAD reservoir falls within each of three zones of water management in Egypt compared with the Washington draft proposal scenario. Egypt uses the three zones shown to ration

water releases from the HAD under drought conditions. In the normal zone, water is released from the HAD to fully satisfy downstream demands. In zones 1, 2 and 3, HAD water released to meet downstream demands is reduced by 5, 10 and 15%, respectively. The normal zone occurs with reservoir storage ≥ 60 bcm, zone 1 at 55–60 bcm, zone 2 at 50–55 bcm and zone 3 at < 50 bcm (ref. 22).

As a consequence of these mitigation measures, Fig. 3b shows that the Washington draft proposal results in higher HAD water levels in the years 2025 and 2026 during the initial filling of the GERD compared with the other four power trade scenarios. However, during normal hydrological years, GERD's release is reduced because of the lower level of power trade in the Washington draft proposal scenario. Hence, HAD Reservoir (HADR) volume drops to a low level between the years 2029 and 2033 compared with the four power trade scenarios, which results in higher annual water supply curtailment in Egypt compared with that in scenarios with increased power trade (Fig. 3d). Increasing power trade from the Washington proposal scenario to the high-trade scenario resulted in a yearly reduction in Egypt's irrigation water supply deficits of up to 4.0 bcm (7.3% of annual Egyptian water demand). GERD frequently operates at lower levels in the high- and medium-high-power trade scenario, resulting in HADR volumes above its drought-management zones. Figure 3b demonstrates a notable increase in high- and medium-high-power trade scenarios in HAD volume compared with both low and medium-low. This marked difference can be attributed to the higher pressure exerted on the GERD to meet domestic and export demands.

Power trade boosts hydropower and cuts CO₂ emissions

Figure 4 shows the impact of increasing power trade on (1) the ability of each country to meet its electricity demand (expressed as demand curtailment), (2) hydropower generation and (3) CO₂ emissions associated with electricity generation. Figure 4a shows that increasing power trade reduces annual electricity demand curtailments in Sudan, with an intangible difference in Ethiopia's curtailments compared with the

Washington draft proposal. Results show that Egypt would have no electricity demand curtailments in any modelled scenario, including the Washington draft proposal. Because it was assumed that Ethiopia exports power to Sudan and Egypt only after satisfying its domestic electricity demand, that country's electricity demand curtailment is similar in all power trade scenarios. Furthermore, the agreed power trade with Sudan and Egypt is satisfied in all scenarios.

Figure 4b–d shows a higher likelihood of hydropower generation increases in Ethiopia, Sudan and Egypt with the power trade scenarios compared with the Washington draft proposal. With increasing power trade, accumulated total hydropower generation in Sudan showed an increase of 80% of the examined river flow sequences compared with the Washington draft proposal, due to a regulated flow from the GERD (Fig. 4b). Figure 4c shows an increase in annual hydropower generation in Egypt between the Washington draft proposal and the other examined trade scenarios in 32, 69, 73 and 82% of the examined river flow sequences in the low-, medium-low-, medium-high- and high-power trade scenario, respectively. The increase in Egypt's hydropower occurs mainly because of an increase in the release from the GERD with increased export of electric power. Ethiopia's annual hydropower generation increases 65, 90, 96 and 97% of river flow sequences in the four trade scenarios, respectively, compared with the Washington draft proposal. Ethiopia's aggregated annual hydropower generation of all existing and planned capacity shows a maximum increase of 9 and 10 TWh, respectively, in the low- and medium-low-power scenarios and of 12 TWh in the medium-high- and high-power trade scenarios. Annual hydropower generation from the GERD exhibits a maximum increase of 6.0, 6.8, 9.0 and 10.1 TWh in the four trade scenarios, respectively, compared with the Washington draft proposal. The predominant increase

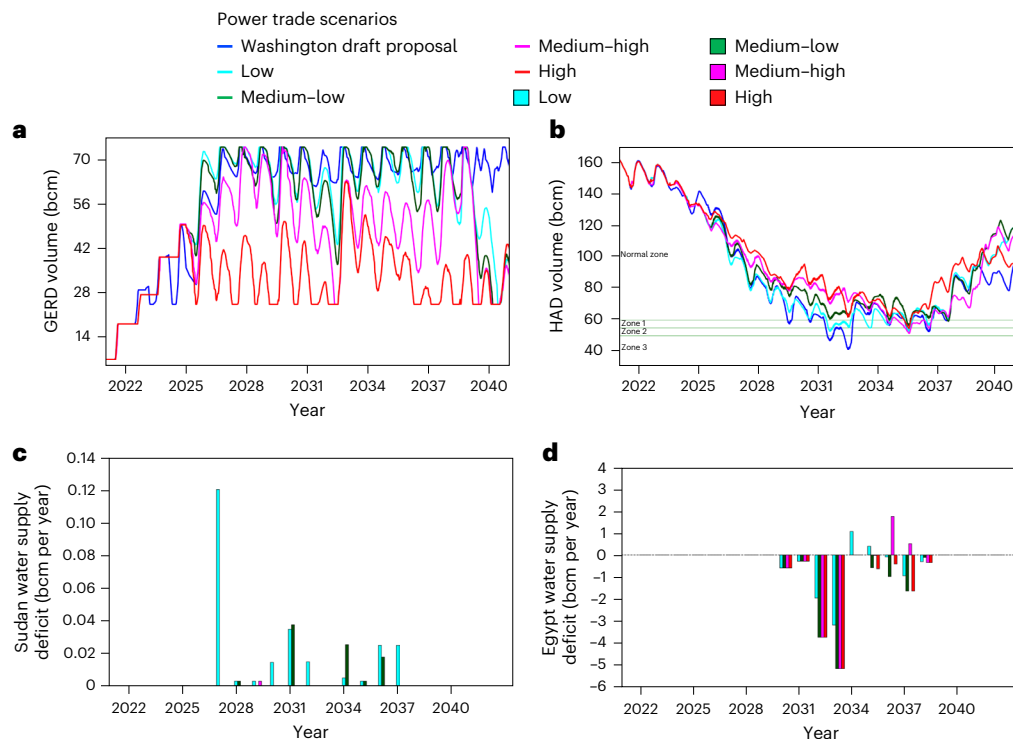


Fig. 3 | Time series of river system performance metrics for the five power trade scenarios under a dry hydrologic sequence. a. GERD reservoir storage. **b.** HAD reservoir storage. **c, d.** Annual change in irrigation water supply deficits for Sudan (**c**) and Egypt (**d**) compared with the Washington draft proposal trade

scenario. Negative numbers denote desirable decreases in water deficits. For clarity, different maximum y axis values are used. The dry hydrologic sequence is under conditions similar to the sequence that occurred starting in 1977.

in the GERD's annual hydropower generation with increasing power trade compared with the Washington draft proposal results from the proposal following existing power trade levels. Because there is insufficient domestic and export demand to absorb hydropower generated from the GERD, the Washington draft proposal has to use other GERD outlets to transfer drought-mitigation releases downstream without generating hydropower.

Following increasing power trade with Sudan and Egypt, exports to Kenya and Tanzania declined, resulting in a slight increase in electricity demand curtailment and the use of thermal power generation in the latter two countries. This is because we assume that Ethiopia prioritizes power trade with Sudan and Egypt, following the sixth principle of the declaration of principles on the GERD signed between Ethiopia, Sudan and Egypt in 2015. Supplementary Fig. 2 shows the exceedance probability of Ethiopia's power and annual energy export to Kenya and Tanzania and electricity demand curtailment in Tanzania. In all examined trade scenarios, Ethiopia supplied the agreed power trade with Kenya and Tanzania 95 and 90% of the time, respectively (Supplementary Fig. 2a, c). Results show that, due to the decrease in export to Sudan and Egypt, Ethiopia's export to Kenya and Tanzania is higher in the low- and medium-low-power trade scenarios compared with the Washington draft proposal. In the medium-high- and high-trade scenarios, Tanzania's annual electricity demand curtailment increased by a maximum of 0.2 TWh compared with the Washington draft proposal (Supplementary Fig. 2e).

Increasing power trade from Ethiopia to Sudan and Egypt reduces regional electricity generation from thermal power stations because the operational cost of hydropower is lower than that from thermal power plants. As a result, electricity generation from hydropower displaces electricity generation from thermal power plants. The change in total annual electricity generation from thermal power plants in the three countries drops by a median of 2.08, 3.48, 3.0 and 4.4 TWh in the four scenarios, respectively, compared with the Washington draft

proposal (Table 2 shows the change for each country). In addition, due to an increase in both power trade and hydropower generation from the GERD and existing dams in Sudan and Egypt, annual CO₂ emissions decrease (Fig. 4c). Supplementary Table 3 summarizes the reduction in mean annual CO₂ emissions associated with electricity generation in the three countries, showing a total decline of 1.15, 1.98, 3.20 and 4.54 million tonnes (Mtonnes) in the four scenarios, respectively, compared with the Washington draft proposal. To put these changes into perspective, the maximum annual decline in carbon emissions associated with electricity generation due to energy trade in the three countries is about 25% of Sudan and Ethiopia's total emissions in 2020 (ref. 37).

Figure 5 shows Ethiopia's annual financial income from cross-border power trade from 2026 to 2041 in the Washington draft proposal, in and the four trade scenarios, for the 30 simulated river flow sequences. Ethiopia's annual financial income from 2022 to 2025 is similar in all trade scenarios because changes to power trade levels were assumed to start with the GERD's steady-state operation. Supplementary Fig. 3 shows Ethiopia's annual financial income discounted at 3%. Results show an increase in Ethiopia's annual financial return over the period 2026–2041, depending on river flow sequence, ranging from US\$71 million to US\$128 million and from US\$ 296 million to 498 million for the low- and high-trade scenarios, respectively, compared with the Washington draft proposal. Because Ethiopia was assumed to prioritize meeting domestic electricity demand over electricity exports, its financial return from exports is lower in some hydrological sequences for a given agreement. However, there is an overall rise in annual financial return with increasing power trade. Sudan and Egypt can achieve net annual financial savings from power trade with Ethiopia resulting from increased hydropower generation and electricity import that displace expensive thermal generators. In the low- and high-power trade scenarios these savings amount to approximately US\$36 million and US\$369 million per year, respectively, when discounted at 3% (Supplementary Table 4). Further details about the assumptions used to estimate Egypt's and Sudan's

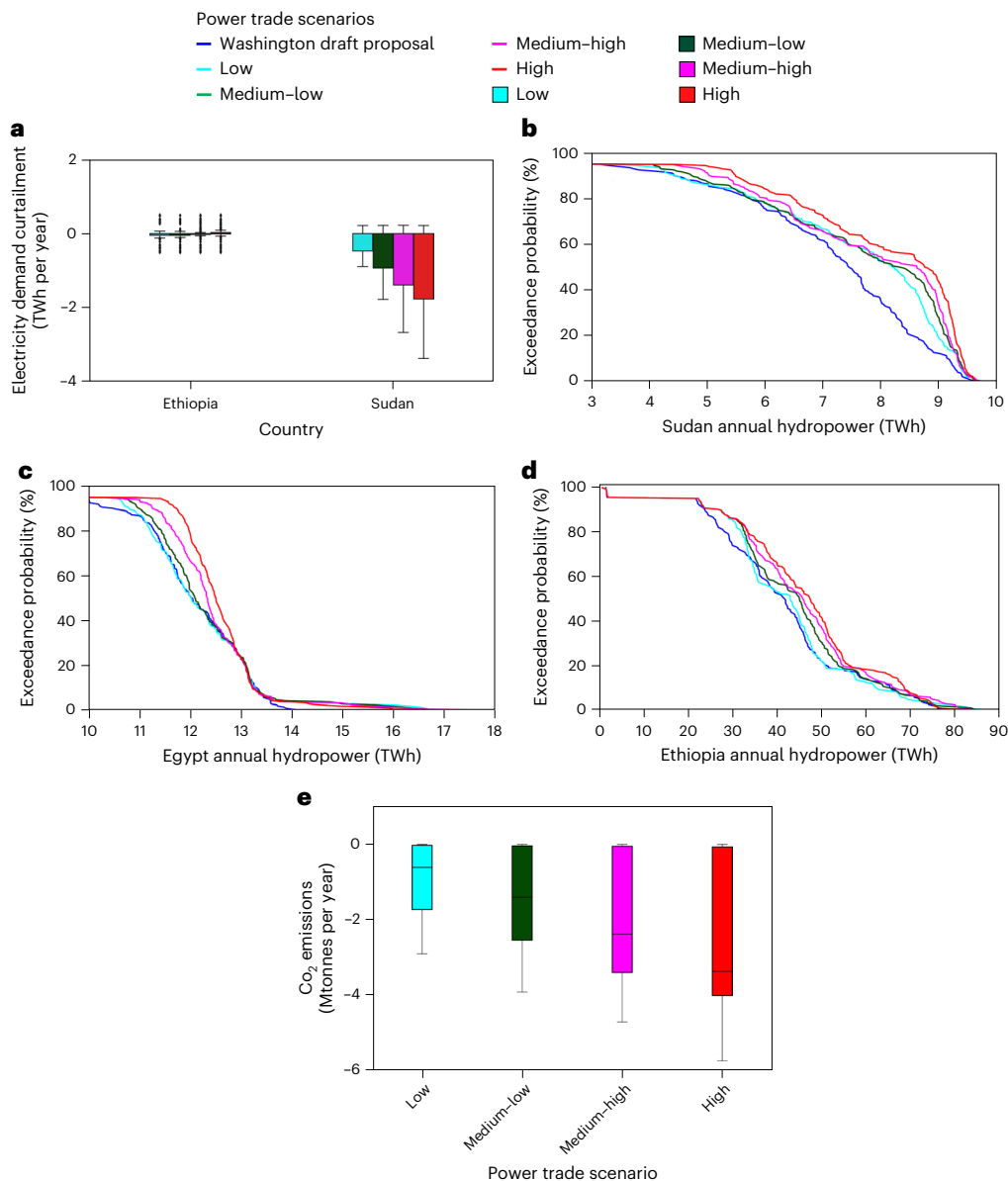


Fig. 4 | Power system performance under the five examined power trade scenarios and 30 river flow sequences. **a**, Annual changes in electricity demand curtailments in Ethiopia and Sudan compared with the Washington draft proposal trade scenario. **b–d**, Exceedance probability of hydropower generation in Sudan (**b**), Egypt (**c**) and Ethiopia (**d**). **e**, Annual changes in carbon emissions

from electricity generation in Ethiopia, Sudan and Egypt compared with the Washington draft proposal. Electricity curtailment in Egypt is zero in all scenarios and is therefore not presented in the figure. **a, e**, Box plots derived from a sample size of 600.

Table 2 | Change in median annual thermal electricity generation (TWh) in Ethiopia, Sudan and Egypt compared with the Washington draft proposal

Scenario	Ethiopia	Sudan	Egypt
Low trade	0.1	-1.6	-0.6
Medium-low trade	0.3	-2.6	-1.2
Medium-high trade	0.6	-2.0	-1.6
High trade	0.8	-2.7	-2.5

financial savings are provided in Methods. Following Article 6 of the Declaration of Principles on the GERD signed between Ethiopia, Sudan and Egypt that Ethiopia prioritizes satisfying electricity export to Sudan and Egypt, export demand to those two countries is always satisfied

and the financial saving remains the same for the two countries in all hydrological sequences for a given agreement.

Discussion

Sharing benefits in transboundary river basins offers the potential for solving water disputes and fostering cooperation. However, the absence of analytical means to quantify and investigate multisector benefit-sharing possibilities across the water, energy and food resource systems both spatially and temporally has hampered the evaluation and application of benefit-sharing in practice. Large hydropower dams on transboundary rivers often have regional implications for the water, energy and food sectors, and these implications vary both spatially and temporally³⁸. Accurate spatial multisector simulation can help stakeholders better evaluate benefit-sharing proposals and explore multisectoral interdependencies within and across countries rather than focusing on volumetric water sharing.

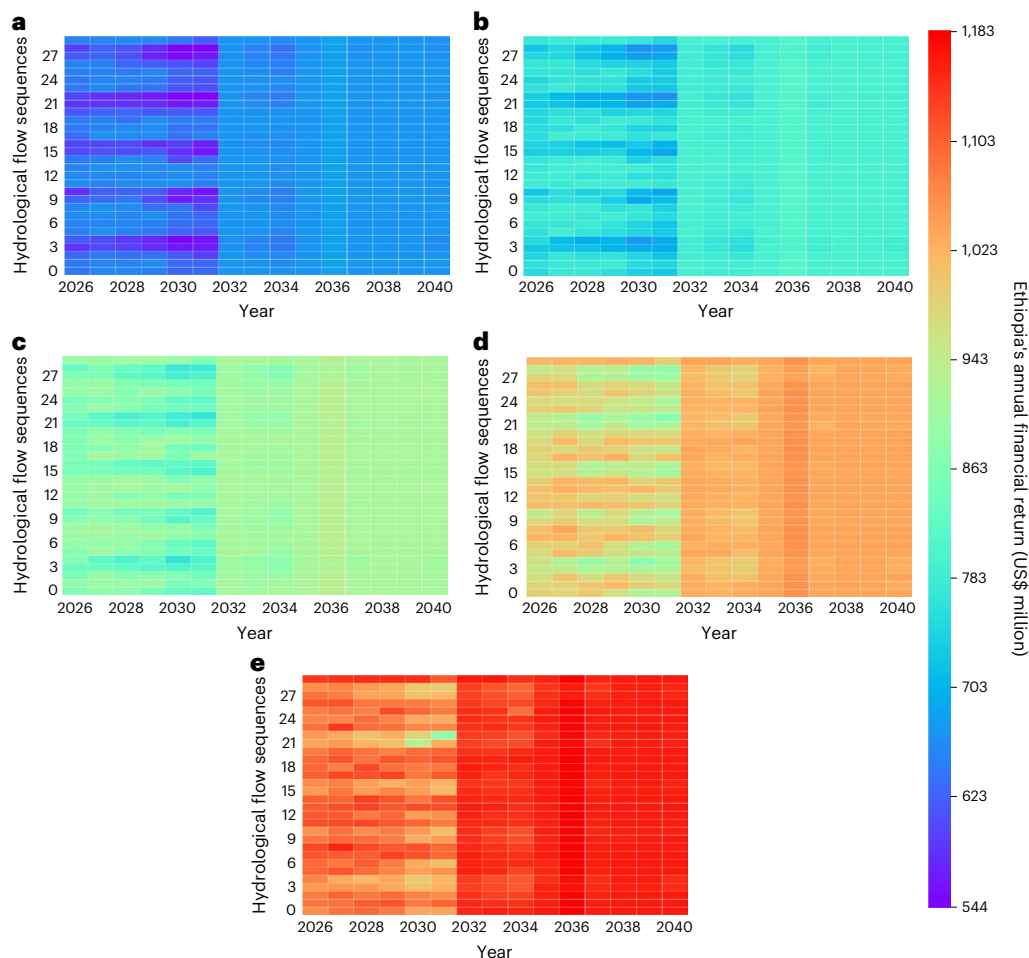


Fig. 5 | Ethiopia's annual financial income (in US\$ million) resulting from power trade. a–e, Ethiopia's income from power trade in the period 2026–2041 under 30 river flow sequences with the Washington draft proposal (a) and under the low- (b), medium- (c), medium–low- (d) and medium–high- (e) power trade scenarios.

In this study we argue that large-scale benefit-sharing negotiation and implementation in East Africa should be augmented by detailed multisector simulation of the water, energy, food and environment systems. We demonstrate how benefit-sharing among Ethiopia, Sudan and Egypt in the form of increased energy trade can benefit all three countries. Results show that GERD operating policies, including increased power trade from Ethiopia to Sudan and Egypt, can reduce agricultural water deficits in Egypt and increase hydropower generation in Ethiopia and Sudan, reduce energy demand curtailment in Sudan, increase Ethiopia's financial return from power trade and reduce regional CO₂ emissions compared with the Washington draft proposal. Despite Egypt having nearly zero electricity deficit, increasing power trade with Ethiopia displaces expensive thermal generation yielding financial savings and contributing to a reduction in CO₂ emissions.

Pressure on the Nile water resource system is expected to grow as the population of the riparian countries reaches more than 1 billion by 2050 (ref. 39). Irrigation water demand is expected to increase by 15% (ref. 40) by 2050 and electricity demand to double by 2040 (ref. 27). Investments in the power sector, the evolution of future electricity demand, future PPAs and transboundary water agreements among the Eastern Nile Basin countries will influence the ability of the Nile river to sustainably provide much-needed socio-economic and ecosystem services. In addition to the benefits that increasing power trade holds for riparian countries, this study shows how power trade among the Eastern Nile countries could impact the long-term operation of the GERD.

Initiatives for benefit-sharing and electricity trade in the Nile Basin have previously been explored and studied^{41,42}. For example, the Nile Basin Regional Power Trade Project under the NBI aimed at, among other goals, conducting basin-wide analysis of power trade opportunities to inform river basin management⁴¹. While such studies can foster cooperation among the Nile riparian countries, they failed to gather political momentum. The multisector impacts of power trade on Nile water resources have not been evaluated through a detailed approach that simultaneously considers river basins and energy systems. As such, the integrated water–energy method presented in this paper can help quantify the impacts of power trade on both the water and energy systems and demonstrate to decision-makers that technical win–win solutions for both regional water and energy systems are possible if the two systems are planned and operated in an integrated, interdisciplinary and collaborative manner.

This study did not explore the potential effects of increasing power trade among Eastern Nile countries under climate uncertainties. Climate change is projected to impact the mean annual naturalized flow of the Nile, but there is uncertainty in projections^{29–31,43–46}. For instance, based on 29 CMIP6 climate simulations with some projections adjusted for the Eastern African Paradox^{47,48}, Basheer et al.⁴³ estimated changes in the naturalized flow of the Nile ranging from –13 to +90% by 2050 compared with the historical flow mean. Another study on the Nile found that the long-term mean and standard deviation of runoff (based on 18 CMIP5 simulations) are expected to increase by 15 and 50%, respectively³¹. Under wetter climatic conditions an increase in hydropower

generation would be expected. This, in turn, would result in a reduction in the utilization of thermal generation and a decline in electricity supply shortages. On the contrary, if the flow of the Nile decreases due to climate change, this would lead to a decrease in hydropower generation and place additional stress on water resources in the region. Exploring the potential implications of increasing power trade between the Eastern Nile countries in the context of climate uncertainties is relevant because climate change is likely to impact energy generation and water resource management in the region. Future research should look into these implications.

In this study we explore one form of benefit-sharing in the Nile Basin (that is, energy trade), but benefit-sharing can exist in many other forms. For example, Sudan is endowed with agricultural land resources that could be used to produce food to be shared among all Nile Basin countries. Lake Victoria in Kenya, Uganda and Tanzania could be a fishery source for all Nile countries, and Egypt's industrial know-how could contribute to the manufacturing and export of products to the rest of the world through vital shipping routes such as the Suez Canal. These promising multisector solutions and others remain to be investigated and could further aid the seemingly intractable task of sharing the Nile River.

Methods

This study introduces and demonstrates a multisectoral benefit-sharing framework. The analytical approach accurately captures the complex interdependencies and spatiotemporal variations within the EAPP river and energy systems, offering a high-resolution representation. The study aims to address future energy and water resource scarcity challenges using multisector river basin–energy system analysis. Effective bidirectional communication between energy dispatch and dam operations allows the multisector river basin and energy system simulation models to be accurate and realistic. In the following sections we introduce the components of the river basin and energy systems, discuss the iterative integration process and present the integrated river basin and energy models developed for the EAPP.

River basin component

The river basin simulation component was developed using Python Water Resources (Pywr), an open-source water resource systems simulation tool⁴⁹. Pywr uses a linear programming approach alongside system-operating rules to drive water allocations and quantify water flows through different nodes and storage at different reservoir nodes over time. Different node types can be represented using Pywr. Input (for example, catchments), output (for example, water abstraction and reservoir evaporation), storage (for example, reservoirs) and their links are among standard nodes for water resource system models in Pywr.

Power system component

The power simulator is a security-constrained, direct-current, optimal power flow model that considers intertemporal constraints and generation costs. The power simulator minimizes the total cost of generation throughout the power system at each time step (for example, hourly) subject to the physical constraints of the system (for example, thermal limits, available hydropower and so on). Different power system elements can be represented, such as various forms of generators, buses and transmission lines. The equality and inequality constraints considered in the power system model are the power balance for every bus and the capacity of transmission lines. The simulator can represent different generation technologies, such as conventional generation, renewables and runoff hydropower and hydropower with reservoir storage (for example, taking water flow inputs from a water model), and curtail demand when required. The model is used to simulate energy flows for representative days at hourly resolution to capture the intermittency of renewables.

Integrated river basin–energy simulator

The integrated water–energy simulator allocates water and energy resources through the spatial network at each time step. The spatially and temporally disaggregated water and energy system networks enable capture of cross-sector feedback. The water and power system components are linked using a soft-linking, two-way integration approach⁵⁰ using an open-source, multi-agent simulation framework called the Python Network Simulation framework (Pynsim)⁵¹. Pynsim manages iteration among the river basin and energy system components, model run sequencing and time stepping.

The river basin and energy components are connected at locations of hydropower production, linking a river basin model hydropower node with the corresponding bus in the power system model. This connection uses a new iterative process at each simulated time step to ensure that (1) hydropower generation in the river basin model and hydropower consumption in the power system model are equal and (2) the magnitude of hydropower generation is adjusted based on the level of energy demand curtailment. Supplementary Fig. 4 shows the iterative river basin–energy systems integration method. The iterative approach is applied using two iterations as follows.

- (1) In the first iteration, if generated hydropower from a power plant in the water model exceeds the need for hydropower at the corresponding bus in the energy model, excess hydropower value is converted to an equivalent volume of water. Based on the new water release value, a second iteration is performed whereby hydropower is simulated again in the river basin model and the hydropower value is used by the corresponding bus in the energy model.
- (2) In the second iteration, if energy demand curtailment occurs in the energy model, we apply a conditional rule whereby the water model determines how much additional hydropower to generate. The water model chooses a discrete water release value to modify the water allotted for hydropower following the level of energy demand curtailment. The volume of demand curtailment that triggers additional hydropower release is assumed to be 15% of peak power demand based on reservoir operation rules in EAPP member countries.

Multisector river basin–energy simulator of the EAPP

The spatial extent of the integrated river basin and energy system simulator covers EAPP member countries (with the exception that only the eastern part of DRC is covered). The river basin and energy simulator use a weekly time step. In this study we use an electricity trade price of US\$0.05 kWh⁻¹ for existing trade between Ethiopia and Sudan, following the agreement between the two countries. For other existing trade and planned electricity trade a price of US\$0.07 kWh⁻¹ was used, which was obtained from a power trade proposal between Ethiopia and Kenya⁵².

To implement PPA rules, the EAPP energy system model was divided into three interconnected parts (without spatial aggregation): the Ethiopian power system, the southern portion of EAPP (Kenya, Uganda, DRC, Tanzania, Rwanda and Burundi) and the northern portion of EAPP (Sudan, Egypt and Libya). Supplementary Fig. 5 shows cross-border power trade between the three parts of the EAPP energy system and hydropower transfer between the water and energy system components.

EAPP power system model. The EAPP energy system model has 300 buses. The type and number of nodes in the EAPP energy model are summarized in Supplementary Table 5. Supplementary Fig. 1 shows a schematic of the EAPP energy model. Hourly load values for different electricity demand locations were based on 2014 load profile data obtained from EAPP; these load profiles were assumed to remain the same throughout the simulation period. The percentage of annual

power demand growth for the next 20 years was obtained primarily from the EAPP and was used to project power demands (Supplementary Table 6).

The operating costs of power plants decrease in the following order of technology: variable renewables (such as wind and solar), run-of-river hydropower, hydropower with reservoir, geothermal, nuclear power plants and conventional thermal generators. However, conventional power plants also have different operational costs depending on the technology, fuel types and country of operation. Supplementary Table 7 summarizes the unit cost of operation and maintenance for various EAPP generation technologies and fuel types. The locations of existing and proposed variable energy sources were used to extract hourly renewable generation profiles.

The energy model uses a weekly time step with one representative day divided into 24 h. The decision to use a representative day for the weekly time step takes into account the negligible variation in hourly energy demand profiles between weekdays and weekends in the study area. The hourly profiles for wind and solar for large-scale, ground-mounted, crystalline silicon photovoltaic systems and a wind turbine of height 100 m were extracted from existing databases^{53,54}. Hourly wind⁵³ and solar⁵⁴ profiles for the year 2020 were used for the entire simulation period. Available hourly wind and solar generations were calculated by multiplying profile values with the maximum generation capacity of respective solar and wind generators. The EAPP energy model was calibrated using transmission line loss against the member country's total energy demand supplied. Total energy demand supplied data for 2020 were obtained from the EAPP database. Supplementary Table 8 shows the calibration result for each member country.

All power trade between countries within the southern and northern parts of the EAPP is assumed to be bidirectional. Planned cross-border interconnections and upgrading of existing transmission lines until 2032 are triggered during the simulation following the EAPP master plans. For the years 2032–2041 we assumed that transmission line capacity between countries will remain the same, due to a lack of data. The net financial saving from power import for Sudan and Egypt from Ethiopia was calculated considering the fuel cost of displaced thermal generators⁵⁵ and the unit price of power import.

EAPP river basin model. Supplementary Fig. 1 shows a schematic of the EAPP river basin model. The model was developed in collaboration with EAPP and NBI regional organizations. The model includes a detailed representation of storage dams, hydropower and consumptive water uses such as irrigation and domestic, and environmental flows. The historical model uses naturalized inflow data for the period 1972–2002 and simulates using a weekly time step. The river basin model has a detailed representation of existing and planned hydropower infrastructure in the EAPP region until 2041, including multiyear reservoirs such as the HAD and GERD. Hydrological inflow data, reservoir characteristics, water abstraction for irrigation, domestic and industrial water supply, hydropower characteristics and the commissioning dates of infrastructures were obtained from the NBI, EAPP Master Plan and EAPP Power Balance Study^{27,56}.

The river basin model is divided into two components: (1) the Eastern Nile model, encompassing the eastern portion of the Nile river (Ethiopia, Sudan and Egypt) and (2) the EAPP water system outside the Eastern Nile, representing the remaining portion of the river basin that lies outside the Eastern Nile river basin but within the EAPP. Supplementary Table 11 shows the annual average water withdrawal for Ethiopia, Sudan and Egypt from the Nile river. A calibrated river basin model for the Eastern Nile was obtained from a previous study²⁰ and was combined with the remainder of the EAPP river basin model. The model outside the Eastern Nile, which is referred to as 'EAPP water system outside the Eastern Nile', was calibrated against observed river data at five key locations using historical records of river flows and reservoir water levels for 1972–1992: observed river flow data obtained from the

Global Runoff Data Centre database⁵⁷ for Stieglers and Bigupu stations in Tanzania; reservoir water level data for Masinga and Kamburu and river flow data for Metara station were acquired from a study conducted on Kenya's Tana river basin⁵⁸. The timeframe 1972–1992 was selected due to the availability of reliable observed data. The model performance in regard to simulation of the EAPP water system outside the Eastern Nile is presented in Supplementary Fig. 6 and Supplementary Table 9. Calibration and validation performance varies, ranging from poor to excellent. Hydropower dams outside the Eastern Nile region are simulated assuming an operation based on a constant target power that has been calibrated to closely approximate the annual hydropower generation of these projects.

Supplementary Table 9 presents the details of installed capacities for existing and planned hydropower plants, along with the corresponding annual hydropower generation. The table includes values derived from the project's master plan and the model output. The analysis excluded hydropower plants located upstream from the hydrological inflow points and those with an installed capacity of <10 MW. Natural lakes are not included in the river basin model outside the Eastern Nile. We relied on inflow data for all hydropower plants in the equatorial lakes region to simulate hydropower generation. This approach was used to simulate hydropower plants downstream of Lake Victoria, including Owen Falls, Narubale, Kira and Bujagali, Karuma Falls and Murchison upstream of Lake Albert, and Ruzizi I, Ruzizi II, Ruzizi III and Kabu downstream of Lake Albert. Hydropower plants (such as Mpanda and Jiji) are on smaller tributaries and do not affect each other.

We generated thirty 20-year river flow sequences using the indexed sequential method (ISM) to address the interannual variability observed in river flows. These sequences were based on historical flow data for the period 1972–2002. The ISM involves the generation of multiple synthetic sequences based on past data using each year in the data as a possible starting point³⁵. By shifting over each water year by one index and repeating this process n times, where n corresponds to the length of the historical record, the ISM produces a set of n synthetic sequences, making it effective in capturing the interannual variability in river flow. This method allows the model to incorporate uncertainties associated with future hydrology by considering a broad range of potential sequences that may occur in the future.

GERD filling and long-term operation. Supplementary Table 1 shows the 5-year plan for the initial filling of the GERD assuming normal or above-average hydrological conditions. For the four trade scenarios described above, the stage filling of GERD follows the plan shown in Supplementary Table 1 regardless of hydrological condition.

The operating rules of the GERD under the Washington draft proposal scenario follow the guidelines and rules annexed in a letter from Egypt to the United Nations Security Council dated 11 June 2020 (ref. 32). In the remaining scenarios the GERD adheres to the 5-year, stage-based filling plan outlined in the Washington draft proposal without abiding by its drought-mitigation strategies. The Washington draft proposal scenario assumes existing levels of power trade from Ethiopia to Sudan and Egypt. In all scenarios we assumed that, after achieving the water retention target of the first and second years (7.0 bcm), two 375 MW turbines would become operational. The remainder of the turbines would become operational after achieving the third year's water retention target (18.4 bcm)²². Once the filling targets of the second and third years are achieved, GERD's storage is always maintained above these targets to keep the turbines operational. Water retention is limited to July and August, with a minimum environmental release of 43 million m³ per day.

In all power trade scenarios, the long-term operation of the GERD begins when reservoir storage reaches 49.3 bcm. It was assumed that, when reservoir storage is ≥ 49.3 and < 72 bcm, water is released through the turbines to target 1,600 MW to increase 90% power generation reliability⁵⁹. This power target is increased or decreased depending on

the level of energy demand curtailment in Ethiopia and power trade based on feedback from the energy system model, as explained above. To reduce water spill from GERD, it was assumed that the dam targets generation at maximum capacity if storage exceeds 72 bcm. Power targets are adjusted over individual simulation time steps considering electricity demand, PPA and power network constraints to ensure electricity supply–demand balance. If power demand implies a need for lower power generation at any time step, the hydropower target is reduced, as explained above. In all scenarios, a minimum daily environmental flow of 43 Mm³ is maintained when physically possible³². All scenarios assume that Ethiopia prioritizes satisfying domestic electricity demand over exports.

Karadobi is a hydropower dam upstream of GERD that is planned to start filling in 2032, according to a plan created by various countries plan and collected by EAPP. We assumed that Karadobi would start initial filling in 2032 and finish by 2036. We adopted filling stages for Karadobi similar to those for the GERD, with yearly filling targets scaled based on the ratio of the total storage capacities of the two dams. Similar to the GERD, the first two turbines of Karadobi will become operational after achieving the filling target of the second year. On achieving steady-state operation of the reservoir, the Karadobi hydropower project is assumed to adopt a target of 800 MW to maximize annual hydropower generation.

Data availability

The data that support the study's conclusions are available via Zenodo at <https://doi.org/10.5281/zenodo.7594112> (ref. 60). Due to proprietary restrictions, the model and data for the East African Power Pool and Eastern Africa River systems are not publicly accessible. Access to the model and data for the East African Power Pool and Eastern Africa River systems can be granted by the corresponding author upon presentation of the necessary permissions from authorities that own the data, which are the Nile Basin Initiative and the Eastern African Power Pool.

Code availability

The Pywr, Pynr and Pynsim python libraries used to develop the integrated water and power system model are open-source and freely available via GitHub at <https://github.com/pywr/pywr> (ref. 61), <https://github.com/pywr/pynr> (ref. 62) and <https://github.com/UMWRG/pynsim> (ref. 63).

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Author contributions

M.E. and M.B. wrote the original paper. M.E. and M.B. led the visualization of results. M.B., J.J.H., E.M., M.P., R.B., J.G., A.E., J.M.G., A.H. and J.T. reviewed and edited the paper. M.E. and M.B. developed the Eastern Africa River system model. M.E., R.B., J.G. and A.E. developed the Eastern Africa Power system model. M.E. integrated the river system and power system models. J.J.H., M.E., M.B., M.P. and E.M. conceptualized the study. M.E., M.B., E.M., M.P., A.E. and J.J.H. developed the power trade scenarios. J.J.H., M.P., M.B. and E.M. supervised the work. J.J.H. acquired funding for this work. All authors contributed to validation and interpretation of the results.

Competing interests

The authors declare no competing interests.

Additional information

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