Linking solar and wind power in eastern Africa with operation of the Grand Ethiopian Renaissance Dam

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Ethiopia, Sudan and Egypt are currently embroiled in a politically charged conflict surrounding the soon-to-be-completed Grand Ethiopian Renaissance Dam (GERD), with Ethiopia's energy objectives purportedly conflicting with water needs in Sudan and Egypt. Here we show that multiple political and environmental challenges surrounding GERD could be mitigated by explicitly coupling its operation to variable solar and wind power, which would create an incentive for Ethiopia to retain a seasonality in Blue Nile flow. We find that this could deliver fivefold benefits across the three countries: decarbonising power generation in the Eastern Africa Power Pool (EAPP), allowing compliance with Sudan's environmental flow needs, optimising GERD infrastructure use, harmonising the yearly refilling schedules of GERD and Egypt's High Aswan Dam, and supporting strong diversification of Ethiopian power generation for domestic use and EAPP exports. These results argue for an explicit integration of complementary hydro-solar-wind strategies in GERD operation and EAPP expansion planning.

Recently, considerable diplomatic and media attention has been dedicated to the ongoing construction of the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile^{1,2}, which will be Africa's largest hydropower plant with more than 5 GW installed capacity. Since Ethiopia started its construction in 2011, GERD has been highly controversial because of the trade-offs between power generation, water availability, and river ecology it may create across Ethiopia, Sudan and Egypt¹⁻⁵.

Located near the Ethio-Sudanese border (Figure 1a), GERD will substantially increase Ethiopian electricity generation, supporting economic development, electrification and industrialisation^{2,6}. The river flow control that GERD will allow stirs mixed feelings for Sudan: it could mitigate anomalously dry periods, improve flood control, reduce sedimentation, and benefit hydropower and irrigation^{2-4,7-9}, but also cause water shortages and negative environmental impacts^{8,10,11}. Further downstream, Egypt, which already controls the Nile flow with Lake Nasser and the High Aswan Dam (HAD; Figure 1a) to serve its own water needs^{12,13}, is strongly opposed to GERD. Egypt primarily fears that GERD, in damming the Blue Nile which contributes up to 60% of overall Nile flow², may negatively affect Lake Nasser refilling by holding water back during dry years^{2,5,14}. Additionally, GERD's control of river flow may lead to increased water abstraction in Sudan by facilitating dry-season irrigation^{2,5,12}, potentially reducing the flow reaching Egypt.

Central to the current geopolitical struggle surrounding GERD are therefore the seemingly conflicting interests between countries, with Ethiopia seeking to increase power generation, Egypt afraid of losing its hegemony over Nile flow control and the consequences for its agricultural areas, and Sudan torn between sides^{3,4,14}. This struggle has numerous implications. On the short-term, disagreement persists over the first filling of GERD’s reservoir (74 billion m³ in volume, or 1.6 years of average Blue Nile discharge), whose timeframe will directly impact the flow reaching Egypt⁴. On the long-term, GERD’s intended operational strategies and their consequences for downstream water availability are under discussion^{5,14}.

Most political attention is currently being devoted to the filling time^{1,2}, with Egypt heavily contesting Ethiopia’s proposed 4-7 years¹. Consequently, scientific studies on GERD are also mostly centered on the filling time^{4,5,12,14–18}. But as reservoir impoundment will take years rather than decades^{2,14}, any compromise on filling time will allay concerns around GERD only for a limited period. Since GERD infrastructure and the downstream impacts of post-filling operation may last beyond a century, it is of high importance that long-term strategies with benefits for all involved parties be identified for GERD operation. This may help addressing certain objections that the downstream countries currently have to GERD, and support moving the ongoing negotiations forward in the absence of basin-wide comprehensive water-sharing agreements. This paper presents a proposal for arriving at such strategies.

Our results highlight the clear added value of linking the long-term operational scheme of GERD with the development of solar and wind power infrastructure in Ethiopia and other countries in the Eastern Africa Power Pool (EAPP). Based on dedicated modelling of hydro, solar and wind power generation at high spatiotemporal resolution, we identify multiple energy- and water-related benefits that this may bring across the region: (i) better grid integration of variable renewable electricity (VRE), (ii) higher compliance with environmental flow requirements, (iii) improved valorisation of GERD infrastructure, (iv) harmonisation of yearly GERD and HAD operation, and (v) strategic diversification of Ethiopia’s power mix.

Long-term GERD operational strategies

The GERD reservoir storage capacity would allow near-full control of the Blue Nile’s seasonal flow (Figure 1b), suggesting that GERD was designed for year-round power generation following electricity demand². Given that Ethiopian electricity demand is relatively unseasonal²², Ethiopia’s preferred objective for long-term GERD operation is thus presumably a near-constant outflow from month to month^{2,18,23–25}. The corresponding benefits for Ethiopian power generation may conflict with downstream water needs for three reasons.

First, since HAD has its own seasonally specific outflow to safeguard Egypt’s water needs and mitigate floods, Egypt is likely to demand harmonised GERD-HAD operation^{2,5,12,14,15}, which could be precluded if Ethiopia insisted on near-constant GERD outflow. Most likely, Egypt would prefer a discharge regime resembling pre-GERD conditions; for example, the outflow of Uganda’s Nalubaale dam on the White Nile, at Lake Victoria’s outlet, is still governed by a colonial-era “agreed curve” resembling natural flow²⁶. However, such an option would clearly be unfair to Ethiopia and out of line with its electricity needs. Second, while the potential value of GERD in guaranteeing a minimum dry-season flow for Sudan is undisputed, a near-constant GERD outflow would increase dry-season flow by such an extent that water extraction for dry-season irrigation in Sudan may reach levels beyond what Egypt considers acceptable^{2,25,27}. Third, near-constant GERD outflow may endanger ecological river integrity up to Lake Nasser^{18,27–30}, since safeguarding river ecology typically requires dam outflow to mimic the natural discharge seasonality^{18,28}.

From the Egyptian and Sudanese point of view, a long-term agreement on GERD operation could thus likely benefit from the inclusion of a *controlled seasonality* of GERD outflow. If well-designed, this would allow for coordinated Ethio-Egyptian GERD-HAD operation, allay

Figure 1: **Hydro, solar and wind power in the Blue Nile countries.** **a**, The study area consisting of Ethiopia, Sudan and Egypt, including all current and future locations for hydropower, solar power and wind power generation considered in this study (GERD = Grand Ethiopian Renaissance Dam; HAD = High Aswan Dam). Major lakes (“*L.*”) and rivers with hydropower projects are indicated in italics. Hydro, solar and wind power parks that are not yet operational (either in construction or in planning) are marked with an asterisk^{17,19}. **b**, The median and interquartile (IQ) range of the Blue Nile’s monthly flow profile at GERD as modelled for this study, based on 26 years of simulation data (see Methods). **c**, Monthly average capacity factors for solar PV panels (top) and wind turbines (bottom) at the considered locations in Ethiopia (left) and Sudan (right), based on Global Solar Atlas²⁰ and Global Wind Atlas²¹ data (see Methods). The legends refer to the existing/future power plants listed in **a**.

Egyptian fears of lower water availability, and reduce GERD’s environmental impact on Sudan’s river ecology, while still protecting Sudan from droughts and flooding, guaranteeing a minimum dry-season flow, and benefitting Sudanese hydropower generation compared to the present-day^{2,25}. The principal challenge with controlled seasonality is that Ethiopia has no obvious reason to accept it over near-constant outflow, since it would still be out of line with power demand^{2,18,23}. By itself, a controlled seasonality appears unreasonable for Ethiopia. This gap between Ethiopian energy objectives and Sudanese-Egyptian water objectives must be urgently addressed.

Here, we propose a solution that would provide strong incentives to Ethiopia to operate GERD according to controlled seasonality, simultaneously benefitting regional energy and water objectives. This solution lies in the complementary operation³¹ of GERD with a strongly expanded power generating fleet of variable renewable electricity (VRE), namely solar PV and wind power, in Ethiopia and other EAPP countries. Using hydropower to compensate the inherent fluctuations of VRE on hourly and seasonal timescales^{31,32} would allow for a firm, reliable hydro-solar-wind power portfolio highly suited for load-following and supporting year-round reliable power supply for Ethiopia. Such a portfolio would naturally favour increased hydropower

dispatch during the wet season, when regional VRE potential drops considerably³¹ (Figure 1c). The contribution of our study thus lies in proposing (i) a massive expansion of regional VRE generation, at a scale substantially beyond what current policy foresees, and (ii) an explicit coupling of GERD operational strategies with regional cooperation on renewable electricity generation, to stimulate new discussions that could alleviate certain elements of the ongoing conflict around GERD.

Complementary GERD-VRE operation

We design four scenarios (S1-S4) for GERD operation and analyse their potential for harmonising regional energy and water objectives, using a high-fidelity dispatch model for hydropower with VRE³¹ (see Methods and Supplementary Note 1). Given GERD’s large storage capacity and dispatch flexibility, current literature usually assumes that its operation will strongly flatten out the Blue Nile’s flow seasonality by following hourly electricity demand^{2,18,23–25} (Figure 2a). This situation, with near-constant outflow on monthly timescales, represents the reference scenario S1 (“no VRE”).

Given the region’s seasonal hydro-solar-wind complementarity (Figure 1b-c), we consider three other scenarios in which GERD is explicitly operated to support VRE uptake^{17,31}. In scenario S2 (“Ethiopian VRE”), substantial solar PV and wind power capacity is deployed in Ethiopia (Figure 1a, see Methods and Supplementary Note 2) and GERD is operated to compensate VRE fluctuations relative to electricity demand. In scenario S3 (“Power Pool”), GERD additionally compensates shortfalls in VRE generated in Sudan (Figure 1a, see Methods and Supplementary Note 2), leveraging Sudan’s higher solar power yield and higher hydro-wind complementarity relative to Ethiopia (Figure 1c). Last, in scenario S4 (“Power Pool+”), more ambitious VRE deployment takes place in both countries, with very high instantaneous VRE penetration becoming the norm, requiring GERD’s full flexibility potential.

Each scenario increases the potential for GERD to supply reliable power together with VRE (Figure 2b-d). At hourly scales, increasing VRE infeed requires GERD to ramp up and down more sharply (Figure 2b-d, top). Complementary operation also requires a clear increase in reservoir outflow and hydropower generation during the wet season (Figure 2a-d, bottom; cf. Supplementary Note 3). In S2, hydropower peaks in May and September (Figure 2b); this bimodality disappears in S3-S4 where hydropower peaks in August, simultaneously with Blue Nile flow, thanks to the better hydro-VRE complementarity enabled by Ethio-Sudanese electricity exchange (Figure 2c-d). In S4, the strongly increased VRE generation compared to S3 further reduces the need for dispatching GERD in the dry months. Here, GERD frequently ramps down to its minimum power output during episodes of substantial surplus VRE generation. This saves water for even higher peak hydropower in August compared to S3 (Figure 2d). The total load followed by flexible GERD operation, nominally 12.3 TWh/year in S1 (comparable to Ethiopia’s current power generation³³, cf. Figure 6), thus increases substantially in combination with VRE, reaching 27.4 TWh/year in S2, 29.7 TWh/year in S3, and 41.2 TWh/year in S4 (Figure 2e). We note that these results are not sensitive to projected future changes in electricity demand profiles²² (see Methods and Supplementary Note 4).

Additionally, GERD outflow reflects the natural seasonality better under each successive scenario (Figure 3a-d). We assess the extent to which natural seasonality is mimicked by comparing outflow with minimum Environmental Flow Requirements (EFRs)²⁷. Applying stringent EFR criteria (see Methods), we calculate the outflow deficit compared to EFRs, both in volume and in relative monthly flow (Figure 3e; see also Supplementary Note 3 for a visualisation of how EFRs compare to natural flow). Clearly, while the near-constant GERD outflow in S1 would be highly EFR-deficient, the VRE scenarios S2-S4 improve the situation substantially, with scenario S4 nearly always in line with EFRs. Notably, annual downstream releases are only marginally affected by the introduction of controlled seasonalities, and GERD mitigates

Figure 2: **Load following with GERD and VRE.** a-d, Hourly and seasonal load following under (a) scenario S1, with only GERD and no VRE; (b) scenario S2, with GERD supporting VRE deployment in Ethiopia; (c) scenario S3, with GERD supporting VRE deployment in Ethiopia and Sudan; and (d) scenario S4, with more ambitious VRE deployment in both countries requiring the deployment of GERD’s full range of flexibility. Simulations spanned 26 years of GERD operation (see Methods); shown are example 48-hour time slices from the 12th simulation year (top row), as well as average monthly profiles (bottom row). e, Total annual load followed hour-by-hour under each scenario by GERD hydropower in combination with VRE. Numbers in brackets indicate the VRE capacity deployed in each scenario (total solar + wind in both countries; see Methods).

anomalously dry and wet years in nearly equal measure between S1-S4 (see Supplementary Note 3), to Sudan’s benefit.

The monthly average outflow hides the sub-daily hydropeaking performed by GERD (Figure 2a-d), which may require simultaneous deployment of many hydroturbines (Figure 3f). In S1, at most six out of sixteen turbines will be in use simultaneously, echoing past allegations that GERD’s turbine capacity is substantially “oversized”⁴. Under VRE integration, turbine usage spread increases considerably; in S4 all sixteen turbines are necessary to ensure proper operation, providing justification to GERD’s design. We note that environmental impacts of this hydropeaking³⁴ will remain limited, given that Sudan’s close-by Roseires reservoir (Figure 1a) can easily smooth out such fluctuations while preserving GERD outflow seasonality due to its tenfold smaller storage capacity⁷.

Benefits for coordinated GERD-HAD operation

Having established that complementary GERD-VRE operation and Ethio-Sudanese electricity exchanges benefit VRE integration, EFR compliance, and GERD infrastructure use, we now investigate the implications of GERD operation for the yearly refilling of HAD’s reservoir, Lake Nasser. HAD is a multipurpose, multi-year storage dam protecting Egypt from peak floods, providing year-round irrigation and navigation benefits, and generating hydropower. Normally, HAD reservoir refilling happens during the August-November flood, after which lake levels stabilise and then decrease for several months; by the next August, they must again be low enough to enable buffering the next flood^{15,35}.

Although GERD can mitigate extreme high flows, its presence will not fully preclude flood peaks from reaching HAD in scenarios S1-S4. The GERD reservoir can hold 1.6 years of average Blue Nile flow, but during relatively wet years with substantially above-average flow, GERD will not be able to hold the full flood peak (cf. interquartile ranges in Figure 3a-d). For instance, although the median GERD outflow is unseasonal under S1, a flood peak still arrives at HAD

Figure 3: GERD outflow, environmental flow deficit, and hydroturbine use. **a-d,** Median and interquartile (IQ) range of monthly average GERD outflow under scenario S1-S4, from simulations spanning 26 years. **e,** Deficits of GERD outflow compared to minimum environmental flow requirements (EFR, see Methods) by scenario. Shown are absolute flow deficits per year (top; percentages indicate EFR deficit relative to annual average Blue Nile flow) and relative monthly deficits during months in which EFRs are violated (bottom; percentages indicate the deficit relative to monthly EFR values, and medians/IQ ranges are taken across all months during which EFRs are not met). **f,** Total spread of GERD hydroturbine use under flexible operation by scenario, calculated by (i) creating a histogram of the instantaneous power output required from GERD at each time step, and (ii) binning this data into categories with each increment representing one additional active turbine. Vertical lines indicate the maximum number of simultaneously active hydroturbines in each scenario.

once every three years on average in this scenario. For this reason, in the following, we assume that HAD would have to keep following the historical practice of drawdown by August to buffer potential incoming floods, even if these may not arrive every year once GERD becomes fully operational.

Under this assumption, the specifics of GERD operation may substantially affect the HAD emptying-refilling cycle (Figure 4a-b; see Methods and Supplementary Note 1). We compare typical GERD and HAD lake levels during GERD emptying (January-July; Figure 4a) and refilling (July-December; Figure 4b). The near-constant GERD outflow in S1 results in considerable delay of both the emptying and refilling of HAD compared to a pre-GERD state, whereas each of S2-S4 brings the result closer to pre-GERD conditions (Figure 4a-b, where pre-GERD would be a vertical line).

Egypt’s concern would presumably not be a delay as such, but rather the resulting lag of HAD compared to GERD: prolonged periods could occur during which GERD water levels would be stable or rising while HAD would lag behind, at worst still emptying fast while GERD would refill. We define these as “contention periods”; the longer these periods, the more likely Egypt’s fear of Ethiopia hoarding water will be provoked^{2,5,14} (see Methods and Supplementary Notes 5-6). We show typical GERD-HAD emptying-refilling calendars in Figure 4c. Clearly, under S1, the lag in HAD refilling compared to GERD is so substantial that four-month-long contention periods would be the norm. The VRE scenarios S2-S4 mitigate this, harmonising GERD-HAD refilling by mimicking the pre-GERD situation. In S3-S4, HAD refilling would typically lag GERD by only one month, reflecting the natural delay between flood peak arrival at GERD and HAD³⁶. Thus, high VRE integration could substantially allay Egyptian fears of GERD holding water back while allowing Ethiopia to fully benefit from increased year-round power generation, leading to a regional win-win situation.

Figure 4: **Coordinated GERD-HAD operation.** **a-b**, HAD water levels versus GERD water levels during the GERD’s emptying (**a**) and refilling (**b**) stages (masl = metres above sea level). Numbers represent median monthly values from simulations spanning 26 years (see Methods). Each data point represents one month; arrows represent forward direction in time from January-July (**a**) and July-December (**b**). **c**, Typical yearly GERD-HAD refilling schedules pre-GERD and under S1-S4, with colours reflecting the emptying/refilling speed of either dam’s reservoir (see Methods), and squares indicating the contention period (see text and Methods). **d**, HAD water levels pre-GERD and under S1-S4; boxplots showing median, interquartile range, and minimum/maximum values from full simulated time series. **e**, Mean monthly outflow curves for HAD, separated by turbinized flow¹² (top) and spilled flow (bottom) (see Methods). **f**, Mean monthly HAD capacity factor.

Given that GERD will reduce the Blue Nile flow’s interannual variability, how will HAD hydropower generation and flood protection be impacted? Compared to pre-GERD, HAD will receive more inflow during dry years, and less during wet years. This has skewed impacts on HAD water levels: more inflow in dry years would raise water levels, but less inflow in wet years would not have the same inverse effect, since very wet periods typically raise water levels to such an extent that spillways are activated¹⁵; mitigating very wet periods would primarily reduce spilling, instead of translating to lower water levels. Average Lake Nasser levels may thus be higher under S1-S4 compared to pre-GERD (Figure 4d), with extreme highs and extreme lows mitigated as compared to pre-GERD.

By reducing extreme high flows, all scenarios S1-S4 lower the amount of spilled flow at HAD in favour of turbinized flow (Figure 4e). The effects on HAD power generation are positive but small, at roughly one percentage point increase for S1-S4 compared to pre-GERD. More substantial is the change in seasonality of HAD power generation (Figure 4f), with somewhat reduced (increased) output in October-November (December-March) under S1 compared to pre-GERD. The scenarios S2-S4 incrementally bring the seasonality in power generation closer to the pre-GERD state, with S4 again closest.

Figure 5: **Cross-border electricity exchanges between Ethiopia and Sudan enabled by joint GERD-VRE operation.** The average (a) monthly and (b) hourly by-month profiles of electricity exchanges between Ethiopia and Sudan, assuming Ethiopia is entitled to 60% of the power generated by the GERD-VRE portfolio of scenario S4. The allocation of exports to the different resources (hydro, solar, wind) is to be interpreted as proportional to the respective average contribution of each resource to the GERD-VRE portfolio in the shown months/hours.

To summarise, a controlled seasonality in GERD outflow in response to high VRE penetration would help to harmonise GERD-HAD filling timelines while safeguarding all power generation benefits of both GERD and HAD.

GERD-VRE contribution to the EAPP

Ethiopia currently exports substantial power in the EAPP¹⁷, and seeks to become Africa’s largest electricity exporter with GERD³⁷. We investigate the implications of synergetic GERD-VRE operation for cross-border electricity trade, in this case between Ethiopia and Sudan, whose cooperation could trigger the quadruple benefits for VRE integration, EFR compliance, GERD infrastructure use, and GERD-HAD cooperation discussed above.

To illustrate the potential of GERD-VRE to contribute to the EAPP objectives of leveraging power system interconnectivity to optimise regional energy resource usage³⁸, we consider a hypothetical Ethio-Sudanese power exchange agreement based on the GERD-VRE portfolio of S4 (Figure 2d), with Ethiopia receiving 60% of instantaneously generated power and Sudan 40% (totalling 24.7 and 16.5 TWh/year, respectively; cf. Figure 2e). This can be considered a fair allocation as it reflects the share of what Ethiopia (GERD + VRE) and Sudan (VRE) would generate annually on average in this portfolio; power exchanges would then be necessary because VRE is frequently not available when needed (requiring GERD dispatch) or overproduced when not needed (allowing GERD to ramp down). Based on which power plants produce electricity where and when, the necessary import-export profiles between both countries will therefore show typical hourly and seasonal patterns (Figure 5).

Seasonally, cross-border electricity trade will be relatively low during October-May as VRE across both countries makes up the portfolio’s bulk (Figure 5a). Ethiopia would mostly export hydropower from GERD during the evening to help meet Sudanese peak demand, and import VRE during morning and midday hours when Sudan’s solar and wind farms produce large volumes of electricity (Figure 5b). During June-September, when Sudanese VRE potential slumps to a minimum, Ethiopia would export large volumes of hydropower to Sudan (Figure 5a), especially during mornings and evenings (Figure 5b).

The total Ethiopian exports to Sudan would amount to 2.5 TWh/year on average (15% of

Sudan’s current electricity demand¹⁷), with 1.0 TWh/year going the other way. The minimum net transfer capacity between Ethiopia and Sudan needed to always guarantee transmission of such amounts is 2.4 GW, fully consistent with the current plans to increase Ethio-Sudanese transfer capacity to 3.2 GW by 2025¹⁷. Further, on the long term, such seasonally-dependent electricity trade under scenario S4 is likely to constitute a better business case for Ethiopia as compared to a case without seasonality in GERD output; the reason is that solar and wind power are expected to play strong roles in Sudan’s future power mix as the country has among the highest VRE resources in Africa^{20,21,38,39}; but these leave a shortfall in the rainy season (cf. Figure 1c) that could be filled by dispatchable plants like GERD. If Sudan pursues an exploitation of its VRE potential, the added value of GERD exports will be maximised by introducing a controlled seasonality. Given all of the above, we consider such a GERD-VRE power exchange agreement to be a realistic avenue for valorising enhanced Ethio-Sudanese power system interconnectivity and displacing fossil fuel-based power generation in Sudan, again showcasing the suitability of scenario S4 to foster regional win-win situations.

The spatiotemporal hydro-solar-wind complementarity observed here for Ethiopia and Sudan can be equally well unlocked through Ethiopian exchanges with other EAPP countries. Among Ethiopia’s direct neighbours in the EAPP, Djibouti, Kenya and South Sudan have excellent solar resources which can complement Ethiopian hydropower²⁰; strong and complementary wind resources are found in Djibouti and specific locations in Kenya and South Sudan²¹. Ethiopia already exports power to Djibouti and interconnections to Kenya^{17,38} and South Sudan⁴⁰ are planned, which may thus all benefit integrated hydro-VRE operation. In this context, Egypt, which is currently the largest electricity consumer among EAPP countries, could benefit from reinforced Ethiopia-Sudan-Egypt interconnection corridors to leverage its own excellent solar PV and wind resources as another potential complement to Ethiopian hydropower³⁸.

Prospects for Ethiopia’s electricity mix

Last, we consider Ethiopia’s overall electricity mix. Ethiopia’s current plans foresee a renewables-based future with hydropower as principal source, but important contributions from solar, wind, geothermal, and biomass co-generation plants^{17,23}.

Clearly, Ethiopia stands before important policy choices. Given its rapidly increasing demand¹⁷, and assuming geothermal and biomass plant development goes ahead, Ethiopia may have to prioritise between hydropower and VRE to close the remaining supply-demand gap. Thus, it will have to weigh the consequences of negative socio-environmental effects of hydropower exploitation, often a subject of critique in Ethiopia^{28,41–43}, and of increased deployment of VRE resources, requiring substantial system flexibility and investment shifts. Here, based on the concept of hydro-VRE complementarity, we propose an alternative pathway to Ethiopia’s current policy plans which could benefit environmental sustainability, irrigation prospects, and electricity generation costs. We note that the purpose of this proposal is primarily to stimulate debates around the wider potential benefits of hydro-VRE integration.

By 2030, Ethiopia’s power demand may reach 54.8 TWh/year¹⁷, and current forecasts¹⁷ for 2030 still foresee a major role for hydropower by then (Figure 6). We show that applying hydro-VRE complementary operation to Ethiopia’s existing hydropower fleet plus GERD can deliver the flexibility to support much higher VRE penetration as compared to the forecasts (Figure 6), reducing the need for additional hydropower to meet 2030 demand while allowing Ethiopia to remain a regional electricity exporter. We estimate that Ethiopia would need only around 32% of the additional hydropower (aside from GERD) currently planned by 2030 (1.8 GW instead of 5.4 GW) for such a scenario (see Methods). For example, the potential Karadobi (1.5 GW) and Yeda I-II (0.3 GW) hydropower projects in the Blue Nile basin¹⁷, upstream of GERD, could be candidates to deliver the additional hydropower needed by 2030 for such a scenario with high solar and wind power penetration. A strong diversification of Ethiopia’s power generating fleet

Figure 6: **Ethiopian power mix by 2030.** The forecasted (“2030 - forecast”) Ethiopian installed capacity (a) and power generation (b) mix compared to the 2017 situation (“2017 - historical”) ¹⁷, as well as an additional scenario based on this study’s consideration of hydro-VRE complementarity (“2030 - hydro-VRE”) in which GERD, all existing Ethiopian hydropower, and a selection of the additionally planned hydropower capacity by 2030 is flexibly deployed to aid VRE integration. Under both a and b, we show absolute (left panel) and relative (right panel) values. The dashed line in b is the forecasted 2030 electricity demand in Ethiopia ¹⁷; power generation does not equal demand because of exports to and imports from other EAPP countries, like Sudan. Calculation details are explained in Methods.

can therefore help reaching 100% renewable electricity in 2030 while reducing sustainability concerns around additional hydropower ^{28,43}.

Such a diversification would also imply that future needs for irrigation and power generation in Ethiopia could be more readily decoupled. In multipurpose hydro projects, the dual objectives of irrigation and electricity generation are often at odds with one another ⁴⁴. A shift away from hydropower dominance to a balanced mix of hydro and VRE means that future water infrastructure projects in Ethiopia could be designed to more fully benefit irrigation purposes in environmentally friendly ways, reducing the need to co-optimize irrigation and electricity needs which may result in trade-offs.

Given hydropower’s comparatively high capital costs ⁴⁵, such a diversification strategy would avoid substantial upfront expenses for new hydro plants, which could be directly reallocated to finance the needed VRE. Regional VRE may also have higher chances of benefitting from international donors’ support than hydropower ⁴⁶, given that large hydropower projects have largely fallen out of favour with the international community in recent years (China being a notable exception) due to their environmental footprint ²⁸. With levelised costs of both solar PV and wind power expected to continue their reducing trend and approach the typical range of hydropower in Ethiopia well before 2030 (ref. ¹⁷), it is likely that a diversification towards more VRE would not endanger the low costs of power supply in Ethiopia ³³. We estimate that the proposed VRE plants in Ethiopia and Sudan, if constructed a few years from now, could achieve even lower levelised costs of electricity (LCOE) than GERD, thus implying substantial financial long-term benefits of joint hydro-VRE operation as compared to continued hydropower dominance (see Methods and Supplementary Note 7). Moreover, such a diversification would be in line with the expectation that VRE-plus-storage may eventually become the backbone of power systems worldwide ^{39,45}.

While both solar and wind power could synergise well with hydropower on their own, diurnal solar-wind ⁴⁷ and solar-load ²² complementarity is substantial in the Ethiopian case (Figure 2b-d). We therefore consider a continued development of joint hydro-solar-wind strategies for all existing and upcoming hydropower plants, similar to the GERD-VRE strategies presented

here and emphasizing the value of all three resources, to be a no-regret near-term policy for Ethiopia’s power sector.

Discussion

Operating GERD in complementarity with solar and wind power in Ethiopia and neighbouring countries marks a strong potential for alleviating certain elements of political tension around GERD between Ethiopia, Sudan and Egypt, and could provide useful input for consideration in the ongoing trilateral GERD negotiations. We find that such complementary operation, which safeguards year-round power generation targets while mitigating GERD’s effects on downstream flow profiles, could provide fivefold benefits relative to the currently foreseen GERD operation: (i) higher VRE penetration in the EAPP, (ii) compliance with environmental flow requirements, (iii) improved valorisation of GERD infrastructure, (iv) harmonisation of yearly GERD-HAD refilling schedules, and (v) diversification of Ethiopia’s power mix, theoretically reducing the need for new hydropower dams while safeguarding Ethiopia’s export objectives in the EAPP. There are various other benefits that GERD may provide to downstream regions⁴. If complementary GERD-VRE operation is to be a viable option, these other benefits must not be negatively affected. The most important such benefits include (i) reducing sedimentation behind Sudanese dams and HAD, (ii) protection of downstream regions from both droughts and floods, and (iii) enabling more efficient water storage than HAD. Benefits for sedimentation control are present in all scenarios presented here, since these are directly related to the presence of GERD itself as barrier behind which sediment may accumulate; operating GERD with a controlled seasonality does not change this. Flood and drought mitigation is also effective in all scenarios, since GERD will stabilise outflows around a certain median curve as compared to the natural situation, whether or not seasonality is present (cf. Figure 3a-d and Supplementary Note 3). Lastly, GERD has often been promoted as a more efficient means of storing water than HAD⁵, as it is located in a cooler and wetter zone, thus leading to fewer evaporation losses than HAD. We find that complementary GERD-VRE operation under S4 may further enhance this effect as compared to S1 (Supplementary Note 8). Operating GERD with a controlled seasonality, in complementarity with VRE, therefore does not harm any of the other beneficial aspects of GERD.

In our VRE scenarios, all involved countries would benefit in a regional win-win situation. Ethiopia would capitalise on year-round reliable power generation to support electrification and industrialisation with a robust mix of hydropower and VRE, making optimal use of GERD’s infrastructure and strengthening its position in the EAPP. Sudan would receive more reliable Blue Nile flow each year, even during the dry season, and reduce its reliance on fossil fuels, while changes in ecological river conditions would be limited. Finally, Egypt’s concerns about GERD’s impact on water management would be mitigated since GERD outflow profiles would appear like those of a relatively small reservoir. Our analysis thus demonstrates a holistic viewpoint of the GERD in the context of the water-energy nexus, beyond hydropower and water politics only. It shows that transboundary water and renewable energy issues are not only linked, but can be harmonised with positive outcomes for all involved parties.

Important questions remain as to the political viability of the proposed solutions. Even with all the above benefits present, some factors could pose risks to complementary GERD-VRE development, for instance (i) financial concerns and (ii) conflicts in fragile regions. On the financial side, our calculations (see Supplementary Note 7) indicate that VRE may become cost-competitive with hydropower in the region within the next decade in terms of levelised costs. The necessary transmission grid reinforcement would entail further costs; however, this study only considered locations whose grid integration already forms part of policy plans anyway (see Methods), and our scenarios were shown to be in line with the planned strengthening of Ethio-Sudanese cross-border transmission capacity as well. As far as conflict situations in

the region are concerned, these may present barriers to the rollout of an integrated power grid; however, VRE development could be argued to be well in line with conflict adaptation strategies, since e.g. VRE plants are unaffected by potential conflict-induced fuel shortages and more modulisable than big hydro and thermal plants⁴⁸. Therefore, our VRE scenarios may be more conflict-aware than the regional status quo for expanding electricity generation, dominated by large hydropower and thermal plants.

We note here that the ongoing GERD negotiations are taking place in the context of wider uncertainty and disagreement on water allocation by country⁹. Beyond GERD, the consensual development of further water infrastructure in the Blue Nile basin for irrigation and other water storage purposes in the future will be strongly contingent upon whether or not countries can arrive at comprehensive future water-sharing agreements. This topic is outside the principal scope of this study, which focuses primarily on the regional disagreements surrounding future GERD operation.

While the presented conclusions are robust enough to suggest a roadmap for Ethiopia's and Sudan's power sector and their contribution to the EAPP, various remaining uncertainties warrant further research, e.g. around the precise locations of future VRE plants, irrigation water extraction in Sudan, initial GERD filling time, Ethio-Egyptian willingness for compromise, Ethiopia's strategic objectives for further hydropower development to remain the main EAPP feeder, future river damming interventions to serve non-energy purposes such as irrigation, future negotiations on water-sharing agreements among Nile riparian countries, and future climate change. On the latter, we consider complementary hydro-VRE development to provide a potential sixth benefit: power sector diversification may lessen hydropower shocks due to increased interannual variability in Nile River flow caused by climate change^{49–52}.

Methods

GERD and other hydropower plants in Ethiopia

Flexible dispatch of hydropower plants was modelled using the REVUB (Renewable Electricity Variability, Upscaling and Balancing) software introduced in previous work³¹; all equations and modelling principles are explained therein and summarised hereafter. The REVUB model serves to derive hydropower reservoir operation rules under certain flexibility requirements determined by VRE infeed and electricity demand at hourly resolution across multi-year time periods, while enforcing minimum flow rules and ensuring seasonal lake level stability within safe ranges.

In brief, the model starts from an initial reservoir state and marches forward in time, dispatching hydropower as necessary for each time step to follow a certain target load together with VRE, recalculating the reservoir state at each next time step depending on released water, river inflow, precipitation gains and evaporation losses. After a simulation, the model verifies whether lake level safe ranges are followed, and resimulates for a higher target load, iterating until the highest target load is identified with which lake level criteria can be adhered to. This target load is denoted “followed load” in Figure 2.

As input data, the REVUB model requires (i) various technical data on hydropower plants: rated capacity (MW), maximum reservoir volume (m^3), maximum area (m^2), maximum hydraulic head (m), reservoir bathymetry (volume-area-head relationships), live/dead storage ratio, minimum required outflow (e.g. based on minimum stable load), efficiency, and maximal ramping rates (MW/min); as well as (ii) time series of reservoir inflow (m^3/s), lake surface precipitation ($\text{kg}/\text{m}^2/\text{s}$) and potential evaporation ($\text{kg}/\text{m}^2/\text{s}$), normalised VRE power generation profiles (i.e. hourly capacity factors of solar PV and wind; see below, “Solar PV and wind power generation”), and a normalised target load curve (see below, “Load profile”).

REVUB simulations were carried out for GERD and for all existing (as of May 2020) hydropower reservoirs in Ethiopia covering monthly-resolution reservoir inflow during a 26-year period (following the hydrometeorological conditions of 1980-2005), with typical hourly-resolution profiles for solar PV, wind power and load applied to each simulation year (see below, “Solar PV and wind power simulation” and “Electricity demand”). Existing run-of-river hydropower plants were also simulated, assuming instantaneous outflow equals instantaneous inflow at all times. In all cases, hydropower generation $P_{hydro}(t)$ (in MW) was calculated as

$$P_{hydro}(t) = Q_{out,turbined}(t) \eta g \rho h(t) \cdot 10^{-6}, \quad (1)$$

where $Q_{out,turbined}(t)$ is turbinised water release (m^3/s), η the hydroturbine efficiency (%), $g = 9.81 \text{ m}/\text{s}^2$ the gravitational acceleration, $\rho = 1000 \text{ kg}/\text{m}^3$ the density of water, $h(t)$ the instantaneous hydraulic head (m), and the factor 10^{-6} converts from W to MW.

For all reservoirs, bias-corrected precipitation was obtained from the EWEMBI dataset⁵³ and potential evaporation flux was taken from the ensemble mean of ten historical simulations from regional climate models driven by different global climate models, available through the Coordinated Regional Climate Downscaling Experiment Africa (CORDEX-Africa) framework initiative. Maximum turbinised flow $Q_{out,turbined}^{max}$ was assumed to be the outflow that would generate peak power at maximum hydraulic head; maximum ramping rates were assumed to be 2.6% of full capacity per minute^{31,54,55}; and efficiency η was assumed to be 95% in all cases^{31,32}. Note that in practice, η will vary in function of the variations in load on the turbine, and partial loads below certain thresholds should therefore be avoided to ensure turbines keep operating in the high-efficiency range. In our modelling, this is assured throughout by enforcing suitable minimum stable loads, obtained from ref.¹⁷, for all plants such that turbines will always run in their high-efficiency range, both for single- and multi-unit plants. Plant-specific data and sources are summarised below:

1. GERD: Reservoir inflow from a SWAT+ (Soil and Water Assessment Tool, revision 55) simulation covering Africa’s major rivers for the period 1980-2016, described in previous research^{31,56}. The period 1980-2005 was extracted and bias-corrected to the long-term average value of 47.2 BCM/year from ref.¹⁸. Rated capacity (6450 MW) from ref.¹; maximum reservoir volume ($7.4 \times 10^{10} \text{ m}^3$, with 80%/20% live/dead storage), maximum area ($1.9 \times 10^9 \text{ m}^2$), maximum head (133 m), and full reservoir bathymetry curves (see Acknowledgements) according to ref.¹⁸. For the data in Figure 3f, GERD was assumed to have 16 hydroturbines of equal rated capacity⁵⁷. We note that there has been recent uncertainty in media reports around the amount of hydroturbines and the total installed capacity for GERD: some note that the number of turbines has been brought down from 16 to 13 and the total capacity reduced to 5150 MW accordingly⁵⁸, while others confirm the former but refute the latter⁵⁹, and yet others cite a capacity inbetween 5150 MW and 6450 MW⁶⁰. For this study, we have opted to go with the most recently cited numbers in publicly available scientific¹ and technical¹⁷ studies, notwithstanding the change these numbers may be subject to as GERD construction works near completion. We note here that re-running the simulations with an installed capacity of 5150 MW instead of 6450 MW, and with 13 instead of 16 turbines, does not change any of the principal conclusions.

2. Fincha: Reservoir inflow from 1980-2005 from ref.¹⁷; rated capacity (134 MW), maximum volume ($6.5 \times 10^8 \text{ m}^3$) and maximum area ($2.9 \times 10^8 \text{ m}^2$) from ref.⁶¹; volume-area relationship using the approach from ref.⁶² assuming reservoir depth equal to dam height (20 m, ref.⁶¹); head (555 m, constant) from ref.⁶³; ratio between live/dead storage assumed to be 80%/20% (inspired by the GERD, Melka Wakena and Gibe I values).
3. Fincha-Amerti-Neshe (FAN): Reservoir inflow from 1980-2005 from ref.¹⁷; rated capacity (95 MW) from ref.⁴²; maximum volume ($4.5 \times 10^8 \text{ m}^3$) and maximum area ($2.9 \times 10^7 \text{ m}^2$) from ref.⁶⁴; volume-area relationship using the approach from ref.⁶² assuming reservoir depth equal to dam height (38 m, ref.⁴²); head (579 m, constant) estimated from the elevation difference between the dam outlet and the powerhouse on Google Earth; live/dead storage ratio assumed to be 80%/20% (inspired by the GERD, Melka Wakena and Gibe I values).
4. Tekeze: Reservoir inflow from 1980-2005 from ref.¹⁷; rated capacity (300 MW), maximum volume ($9.2 \times 10^9 \text{ m}^3$, with 57%/43% live/dead storage) and maximum area ($1.5 \times 10^8 \text{ m}^2$) from refs.^{65,66}; maximum head (163 m) from ref.⁶¹; bathymetry using the approach from ref.⁶² approximating reservoir depth with maximum head.
5. Melka Wakena: Reservoir inflow from 1980-2005 from ref.¹⁷; rated capacity (153 MW), maximum volume ($7.6 \times 10^8 \text{ m}^3$, with 79%/21% live/dead storage) and head (297 m, constant) from ref.⁶⁷; maximum area ($8.2 \times 10^7 \text{ m}^2$) from ref.⁶⁸; bathymetry from ref.⁶⁹.
6. Genale Dawa III: Reservoir inflow from 1980-2005 from ref.¹⁷; rated capacity (254 MW) from ref.⁷⁰; maximum volume ($4.9 \times 10^9 \text{ m}^3$, with 53%/47% live/dead storage), maximum area ($9.8 \times 10^7 \text{ m}^2$) and maximum head (188 m) from ref.⁷¹; bathymetry using the approach from ref.⁶² assuming reservoir depth equal to dam height (110 m), from ref.⁷⁰.
7. Gibe I: Reservoir inflow from 1980-2005 from ref.¹⁷; rated capacity (200 MW) and maximum head (110 m) from ref.⁷²; maximum volume ($8.4 \times 10^8 \text{ m}^3$, with 78%/22% live/dead storage) and maximum area ($6.0 \times 10^7 \text{ m}^2$) from ref.⁷³; bathymetry using the approach from ref.⁶² assuming reservoir depth equal to dam height (40 m, ref.⁷²).
8. Gibe II (run-of-river): Throughflow (diverted from Omo river via a tunnel through a mountain ridge, rejoining the Omo river downstream) assumed to be equal to Gibe I outflow (just upstream) as simulated, minus minimum guaranteed runoff of $2 \text{ m}^3/\text{s}$ into the Omo river (ref.⁷⁴). Rated capacity (420 MW) and head (505 m) from ref.⁷⁵.
9. Gibe III: Reservoir inflow from 1980-2005 from ref.¹⁷; rated capacity (1870 MW), maximum volume ($1.4 \times 10^{10} \text{ m}^3$) and maximum area ($2.0 \times 10^8 \text{ m}^2$) from ref.⁷⁶; maximum head (220 m) from ref.⁷⁷; bathymetry using the approach from ref.⁶² approximating reservoir depth with maximum head; live/dead storage ratio assumed to be 80%/20% (inspired by the GERD, Melka Wakena and Gibe I values).
10. Tana Beles (run-of-river): Throughflow (diverted from Lake Tana, assumed constant at $77 \text{ m}^3/\text{s}$) and head (311 m) from ref.⁷⁸; rated capacity (460 MW) from ref.⁶¹.
11. Tis Abay I + II (run-of-river): River flow from 1980-2005 from ref.¹⁷; rated capacity (84.4 MW) from ref.⁷⁹; head (53 m) from ref.⁶¹.
12. Awash I (Koka): Reservoir inflow from 1980-2005 from ref.¹⁷; rated capacity (43 MW), maximum volume ($1.9 \times 10^9 \text{ m}^3$), maximum area ($1.8 \times 10^8 \text{ m}^2$) and maximum head (42 m) from ref.⁶¹; bathymetry using the approach from ref.⁶² assuming reservoir depth equal to maximum head; live/dead storage ratio assumed to be 80%/20% (inspired by the GERD, Melka Wakena and Gibe I values).
13. Awash II + III (run-of-river): Throughflow assumed to be equal to Awash I (Koka) outflow (just upstream) as simulated; rated capacity (64 MW) from ref.⁶¹; head (60 m) from ref.⁸⁰.

A modelling flowchart showing the various steps taken in the modelling of Ethiopian hydropower plants, and the most important outputs of these simulations for the purposes of the present study, is given in Supplementary Note 1.

HAD operation in Egypt

HAD inflow $Q_{in}^{HAD}(t)$ was estimated as the sum of the inflow from the Blue Nile and White Nile, merging in Khartoum, and the Atbara, joining a little further north (cf. Figure 1a), based on the assumption that little to no water is added to Nile flow after these rivers join the main branch in the desert³⁶ and that the bulk of evaporation happens on Lake Nasser itself. The Blue Nile contribution was taken equal to GERD outflow, given that historical average Blue Nile flows measured just downstream of GERD (Roseires/El Deim gauge) and at Khartoum are within 1% of each other³⁶, reflecting the net effect of water gained from runoff and the

Rahad and Dinder tributaries being compensated by water withdrawn for irrigation and other losses between the Ethio-Sudanese border and Khartoum. The Atbara contribution was taken from the same SWAT+ simulation used for GERD (see above), bias-corrected to the average observed flow at the Atbara's mouth reported in ref.³⁶. For the White Nile contribution, instead of using the SWAT+ simulation results, we directly applied the average monthly observed flow at Khartoum (Mogren gauge) in ref.³⁶ to all simulation years, given that South Sudan's Sudd wetland has complicated seasonal effects on water retention, losses, and flow lags which many hydrological models, including SWAT+, do not accurately reproduce^{81,82}. We note that while this approach neglects any interannual variability in White Nile flow, this is inconsequential for the assessment of typical GERD-HAD emptying-refilling schedules, since the seasonality of Nile flow, which drives the HAD emptying-refilling cycle, is almost fully determined by the Blue Nile and the Atbara. This approach also has the advantage of allowing to more easily distinguish the effects of changes in the Eastern Nile sub-basin (Blue Nile + Atbara) from effects in the Equatorial Nile sub-basin (White Nile), whose hydroclimate is relatively uncorrelated to that in the Eastern Nile⁵⁰, and thus to better discern their impact. A sensitivity study on the effect of including interannual variability in White Nile flow has been carried out and is described in Supplementary Note 5.

We assumed a one-month delay between these rivers joining in Sudan and their combined flow arriving at HAD, given typical water travel times from southern to northern Sudan³⁶. We neglected any potential lag introduced by operation of the Roseires and Merowe reservoirs in Sudan (Figure 1a), as both these reservoirs have a much smaller capacity than their respective inflow, mostly letting water pass unimpeded during the wet season⁷. Lastly, the substantial evaporation losses and near-negligible precipitation gains on Lake Nasser were estimated from the same EWEMBI and CORDEX datasets used for the Ethiopian reservoirs (see above, "GERD and other hydropower plants in Ethiopia").

Given that HAD is primarily a flood protection and irrigation dam, with hydropower generation as secondary function (providing less than 10% of Egyptian power demand), we did not use REVUB to model flexible HAD operation in function of Egyptian solar/wind power. Instead, HAD operational rules were defined based on logarithmic-exponential release rules^{31,83} as a function of Lake Nasser volume $V_{LN}(t)$ aimed at keeping lake levels stable on multiannual time scales, corrected by a seasonal factor $f_{seasonal}$ to reflect standard monthly variations in HAD outflow (see below). The release from HAD at each time step t , denoted $Q_{out}^{HAD}(t)$, is thus given by

$$Q_{out}^{HAD}(t) = Q_{out,turbined}^{HAD}(t) + Q_{out,spill}^{HAD}(t). \quad (2)$$

The first term $Q_{out,turbined}^{HAD}(t)$ represents the standard turbined outflow, given^{31,83} by

$$Q_{out,turbined}^{HAD}(t) = \begin{cases} Q_{claimed} \left[d_{min} + \ln \left(\kappa \left[\frac{V_{LN}(t)}{V_{LN}^{max}} \right]^\phi + 1 \right) \right] f_{seasonal}, & \text{for } V_{LN}(t)/V_{LN}^{max} < f_{opt} \\ Q_{claimed} \left[\exp \left(\gamma \left[\frac{V_{LN}(t)}{V_{LN}^{max}} - f_{opt} \right]^2 \right) \right] f_{seasonal}, & \text{for } f_{opt} \leq V_{LN}(t)/V_{LN}^{max} < f_{spill} \\ Q_{out,turbined}^{max}, & \text{for } V_{LN}(t)/V_{LN}^{max} \geq f_{spill} \end{cases} \quad (3)$$

Here, $Q_{claimed}$ is Egypt's claimed share of Nile waters at 55.5 BCM/year (see also the authors' note in the Acknowledgements on colonial-era water allocations between Nile countries); $d_{min} = 26.9\%$ is the fraction of yearly average inflow required as minimum stable outflow; V_{LN}^{max} is Lake Nasser's storage capacity of $1.47 \times 10^{11} \text{ m}^3$ (with 79%/21% live/dead storage ratio⁶¹); $Q_{out,turbined}^{max}$ is the maximum turbine throughflow of $3125 \text{ m}^3/\text{s}$; $f_{opt} = 75\%$ is the optimal filling fraction, determined as the crossover point between the conservation zone below 175 masl (metres above sea level) lake level elevation and the flood buffering zone above 175 masl; and $f_{spill} = 80\%$ is the filling fraction at which spilling starts, i.e. whenever Lake Nasser's water level exceeds 178 masl. All these data were directly taken from ref.¹⁵ unless otherwise indicated; Lake Nasser bathymetry was also taken from ref.¹⁵. The seasonal correction factor $f_{seasonal}$, reflecting the usual operational choice of increasing outflow in the months preceding peak Nile flow to make room for buffering the annual flood^{12,15}, was derived from the monthly outflow curve in ref.¹², who in turn obtained it from Egypt's Water Resources Research Institute (WRRI), which falls under the Ministry of Water Resources and Irrigation. Tabulated values of $f_{seasonal}$ are given in Supplementary Note 6; a sensitivity test of our results to changes in $f_{seasonal}$ is also described therein. Further, κ , ϕ and γ are constants, with κ and ϕ given by^{31,83}

$$\kappa = f_{opt}^{-\phi} [\exp(1 - d_{min}) - 1] ; \phi = \alpha \tau_{fill}^{1/2}. \quad (4)$$

Here, τ_{fill} is the HAD's filling time (reservoir volume divided by average annual inflow). We use $\alpha = 2/3$ and $\gamma = 10$ based on generalised reservoir operation rules^{31,83} and calculate $\tau_{fill} = 1.57$ based on average inflow as simulated.

The second term $Q_{out,spill}^{HAD}(t)$ represents the non-turbined outflow diverted via spillways at high lake levels. It

is defined as follows:

$$Q_{out,spill}^{HAD}(t) = \begin{cases} 0 & \text{for } V_{LN}(t)/V_{LN}^{max} < f_{spill} \\ \max\left(0; \min\left[Q_{in}^{HAD}(t) - Q_{out,turbined}^{max}; Q_{max,spill}^{HAD}\right]\right) & \text{for } V_{LN}(t)/V_{LN}^{max} \geq f_{spill} \end{cases}, \quad (5)$$

where $Q_{max,spill}^{HAD}$ represents the maximum allowed spilled flow rate, taken to be 5000 m³/s (ref.¹⁵). HAD power generation was calculated using equation (1).

A modelling flowchart showing the various steps taken in the modelling of HAD, and the most important outputs of these simulations, is given in Supplementary Note 1.

Environmental flow requirements

Minimum seasonal EFRs used for the analysis presented in Figure 3e were based on the adapted Tessmann method, representing the most stringent EFR analysed in ref.²⁷. In this method, each month m is characterised by a low, intermediate, or high flow regime, based on the mean natural flow $\langle Q_{nat} \rangle_m$ in that month:

$$\text{Flow regime in month } m : \begin{cases} \text{Low,} & \text{for } \langle Q_{nat} \rangle_m \leq 0.4 \times \langle Q_{nat} \rangle_y \\ \text{Intermediate,} & \text{for } 0.4 \times \langle Q_{nat} \rangle_y < \langle Q_{nat} \rangle_m \leq \langle Q_{nat} \rangle_y \\ \text{High,} & \text{for } \langle Q_{nat} \rangle_m > \langle Q_{nat} \rangle_y \end{cases}. \quad (6)$$

where $\langle Q_{nat} \rangle_y$ is the annual mean of natural flow Q_{nat} . Subsequently, the minimum environmental flow $Q_{env,m}$ is defined by category for each month m , depending on the prevailing flow regime in that month:

$$Q_{env,m} = \begin{cases} 0.80 \times \langle Q_{nat} \rangle_m, & \text{in the Low flow regime} \\ 0.40 \times \langle Q_{nat} \rangle_y, & \text{in the Intermediate flow regime} \\ 0.40 \times \langle Q_{nat} \rangle_m, & \text{in the High flow regime} \end{cases}. \quad (7)$$

We note that the outcomes of this EFR definition are in line with independent EFR assessments for the Blue Nile in other literature^{18,29}. In addition to minimum EFRs, there may also be maximum EFRs during dry months when river ecology may depend critically on low flows⁸⁴. While we do not have quantitative measures of maximum EFRs for the Blue Nile, scenarios S2-S4 bring dry-season outflows closer to the natural flow than S1 (Figure 3a-d), meaning that joint GERD-VRE operation may also increase compliance with maximum EFRs.

GERD/HAD emptying-refilling speed

The typical emptying-refilling speeds in Figure 4c were defined through the relative change in median monthly water levels as compared to each previous month (medians taken for each of the twelve months of the year across the full 26-year simulation). With z_m the median lake level elevation in month m , and $\Delta z = \max(z) - \min(z)$ the range spanned by z_m across all m , the emptying-refilling speed v_m^{fill} for month m was defined as

$$v_m^{fill} = (z_m - z_{m-1})/\Delta z. \quad (8)$$

Subsequently, each value of v_m^{fill} was allocated to one of five symmetrical categories: fast emptying ($v_m^{fill} < -30\%$); slow emptying ($-30\% \leq v_m^{fill} < -10\%$), stable ($-10\% \leq v_m^{fill} < 10\%$), slow refilling ($10\% \leq v_m^{fill} < 30\%$), and fast refilling ($v_m^{fill} > 30\%$). ‘‘Contention periods’’ were defined as any sequence of months in which v_m^{fill} was categorised as stable or refilling for GERD, but at least one category behind for HAD. Note that the cutoffs of these ranges can be defined in multiple ways without changing the generality of the conclusions drawn from Figure 4c.

Solar PV and wind power generation

The locations for VRE power plants considered in this study (Figure 1a) were based on the already existing on-grid projects, plus those with priority index 1-3 (out of 6) in ref.¹⁷ (for Ethiopia) and those indicated as ‘‘in pipeline’’ in ref.¹⁹ (for Sudan). The geographical coordinates for the locations of planned VRE plants were determined based on project name, reflecting towns or cities; they are given in tabular format in Supplementary Note 2. We note that, according to current plans for transmission network expansion^{17,85}, all locations for solar PV and wind power generation considered in this study are to be connected to the respective national grids of Ethiopia and Sudan in the future.

Hourly-resolution solar PV yield (one curve per month) per unit installed capacity for ground-mounted large-scale crystalline silicon PV systems was derived from the Global Solar Atlas for each set of solar PV plant coordinates²⁰. Similarly, hourly-resolution wind speed at 100 m height (one curve per month) was derived from the Global Wind Atlas for each set of wind power plant coordinates²¹ before being converted to hourly wind turbine yield per unit installed capacity, based on the characteristics of Vestas V100-1.8 wind turbines with 100 m hub height and cut-in, rated, and cut-out wind speed of 3, 12 and 20 m/s, respectively (ref.⁸⁶).

These databases do not contain day-to-day variability within a month or interannual variability, and thus have less temporal detail than e.g. global reanalysis datasets, whose applicability for VRE resource assessment from

hourly to multiannual time scales has been well-documented^{31,47}. However, reanalysis datasets typically have a relatively coarse spatial resolution, in the order of tens of kilometers. For Ethiopia, in whose highlands solar PV and (especially) wind power potential vary strongly at the kilometer-scale, the state-of-the-art reanalysis products are therefore mostly unsuitable for discerning high-potential VRE sites^{17,87}. Our choice of dataset thus represents a compromise between achieving the necessary spatial resolution and retaining adequate detail on hourly and seasonal profiles.

Load profile

The hourly electricity demand curve used as input (target load) for the REVUB simulations was based on the actual Ethiopian grid load from 2013 available in ref.²². Since such data for Sudan was not available, we assumed the hourly profile of Sudanese grid load to follow Ethiopia's.

We performed an additional sensitivity analysis to establish that our conclusions will not change under future shifts in load profile shapes, reflecting the combined effect of increased electricity access, higher use of cooling and other household appliances, increased industrial activity, and energy efficiency gains that is to be expected in the coming years²². The results of this analysis are provided in Supplementary Note 4.

Scenarios

The modelling differences between the four scenarios developed for this study are described in detail below:

- S1 (“No VRE”): GERD performs load-following without any VRE contribution.
- S2 (“Ethiopian VRE”): GERD performs load-following in combination with VRE from Ethiopian solar PV and wind power plants. We assumed the capacity mix of solar PV and wind power to be 50%/50%, based on current projections which foresee roughly comparable capacities for both resources by 2030 (ref.¹⁷); further, we assumed solar PV and wind power capacity to be equally divided over the selected locations (Figure 1a). Surplus VRE generation compared to the followed load was constrained to occur at most 10% of the time³¹.
- S3 (“Power Pool”): Equal to S2, except that Sudanese solar PV and wind power plants were added to the VRE mix, assuming an equal division of capacity of either resource across both countries and adequate cross-border transmission capacity.
- S4 (“Power Pool+”): Equal to S3, but relaxing the constraint on surplus VRE from 10% to 35% of the time, such that GERD's flexibility potential is fully utilised. The latter is defined as GERD's full range of flexibility being deployed, but without turbine capacity being exhausted more than 1% of the time (to avoid frequent loss of spinning reserves)³¹.

Ethiopian power mix

The historical (2017) and forecasted (2030) capacity mix (Figure 6a) was taken from ref.¹⁷. We estimated historical and forecasted power generation (Figure 6b) by (i) calculating hydro, solar PV and wind power generation using capacity factors as calculated in this study (for future hydropower plants aside from GERD, we applied the average capacity factor across the existing fleet), (ii) assuming biomass power plants would run flexibly at 90% efficiency, but only during the cropping period October-May¹⁷, (iii) assuming geothermal power plants would run as baseload at 90% efficiency¹⁷, and (iv) assuming gasoil capacity to be meant solely for backup, not normally being dispatched¹⁷.

The “hydro-VRE” (2030) option was then calculated as follows. First, we took biomass, geothermal, and gas capacity and power generation to be equal to the forecasted values. Second, we assumed GERD to be operated according to scenario S4, and all other existing Ethiopian hydropower plants according to the settings of scenario S2. Third, having run the corresponding REVUB simulations, we summed up the cumulative capacity and generation from hydropower (existing + GERD) plus the Ethiopian VRE supported by this hydropower fleet. Fourth, we calculated the deficit between expected 2030 demand (assumed to follow the same relative profile as the historical load; see “Load profile”) and the sum of hydropower (existing + GERD), VRE (supported by existing hydropower + GERD), biomass and geothermal power generation, both in terms of peak power (GW) and total power generation (TWh/year), correcting for the exports to and imports from Sudan (Figure 5). Fifth, we estimated the additional hydropower and VRE capacity that would be necessary to compensate the identified peak power and power generation deficits, assuming that such additional hydropower plants would have similar capacity factors and could deliver similar flexibility for VRE integration as the existing fleet's average. This additional hydropower and VRE capacity and generation was then added to the results from the third step.

As far as overall VRE potential in Ethiopia and Sudan is concerned, our study remains well within these limits. Ethiopia's overall theoretical potential for wind power is estimated at 1350 GW¹⁷, and that for solar PV power at 5.85 kWh/m²/day⁸⁸. In our hydro-VRE scenario of Figure 6, the installed wind power capacity in Ethiopia is 4.84 GW, less than 1% of Ethiopia's total potential. Further, the average daily solar power generation needed

in that scenario is 24 GWh/day, which is roughly equivalent to the irradiation received on only 4 km²; with typical solar panel efficiencies of 20%, this would require a surface area of only about 20 km² covered by solar PV panels. The resource characteristics in Ethiopia would thus be by far sufficient for scenarios S2-S4.

In Sudan, the overall wind power potential appears not to have been calculated, but it is clear from e.g. the Global Wind Atlas²¹ that it is even higher than that of Ethiopia; this also applies to its solar PV potential, which reaches 6.32 kWh/m²/day⁸⁸. Therefore, Sudan’s contributions to scenarios S3-S4, with the same amounts of installed wind and solar PV power capacity as Ethiopia (because of the proposed 50/50 capacity split between the countries; see Methods section “Scenarios”), is also well within the limits of the resource characteristics.

Levelised cost of electricity

The levelised cost of electricity (LCOE) is equal to the sum of a power plant’s costs over its lifetime, divided by the total electricity output cumulatively generated over its lifetime:

$$\text{LCOE} = \frac{\sum_y \frac{I_y + M_y + F_y}{(1+r)^y}}{\sum_y \frac{E_y}{(1+r)^y}}, \quad (9)$$

where y represents the year of the plant’s lifetime ($0 \leq y \leq Y$, with Y the plant’s lifetime); I_y are the initial (overnight) costs related to construction of the plant in each year y ; M_y are the operational and maintenance costs in each year y ; F_y are the fuel costs in each year y (these are zero for renewable resources, like hydro and VRE); E_y is the total electricity generated by the plant in each year y ; and r is the discount rate.

To assess the financial viability of the proposed hydro-solar-wind mixes, we estimated the LCOE of GERD and the proposed VRE plants in Ethiopia and Sudan based on cost estimates for 2020, 2025 and 2030 as reported in literature^{2,17}, and based on plant capacity factors as elaborated in this study. Results and calculation details are given in Supplementary Note 7.

Data availability

The map in Figure 1a was created using QGIS, which can be downloaded from <http://qgis.osgeo.org/>. The river shapefiles in Figure 1a are available from ref.⁵⁶, as are the SWAT+ simulation results. The country shapefiles in Figure 1a are available from <https://gadm.org/data.html>.

CORDEX-Africa data are available at <http://cordex.org/data-access/esgf>. EWEMBI forcing data can be accessed at <https://doi.org/10.5880/pik.2019.004>.

Data related to solar PV yield were obtained from the “Global Solar Atlas 2.0” (ref.²⁰), a free, web-based application developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilising Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). Additional information is available via <https://globalsolaratlas.info>.

Data related to wind turbine yield were obtained from the “Global Wind Atlas 3.0” (ref.²¹), a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU). The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, utilising data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program (ESMAP). Additional information is available via <https://globalwindatlas.info>.

Code availability

The REVUB model code is available at <https://github.com/VUB-HYDR/REVUB> under the MIT license, for Python as well as MATLAB. All data used to run the REVUB simulations and perform other calculations can be obtained from the authors upon request.

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Author contributions

S.S. conceived the study, collected the data, carried out the simulations, and analysed the results. S.L. and H.K. provided the GERD bathymetry data. S.S. wrote the paper and designed the figures with contributions from D.F., S.L., H.K. and W.T.

Competing interests

The authors declare no competing interests.