nature portfolio

https://doi.org/10.1038/s41560-021-00799-5

Supplementary information

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

In the format provided by the authors and unedited

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

Sebastian Sterl[1,2,3,4*], Dalia Fadly[2], Stefan Liersch[5], Hagen Koch[5], Wim Thiery[1]

[1] Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Brussels, Belgium
[2] Department of Earth and Environmental Sciences, KU Leuven, Leuven, Belgium
[3] Center for Development Research (ZEF), University of Bonn, Bonn, Germany
[4] International Renewable Energy Agency (IRENA), Bonn, Germany
[5] Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany

[*] Corresponding author, email: sebastian.sterl@vub.be

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Supplementary Note 1 Modelling flowchart

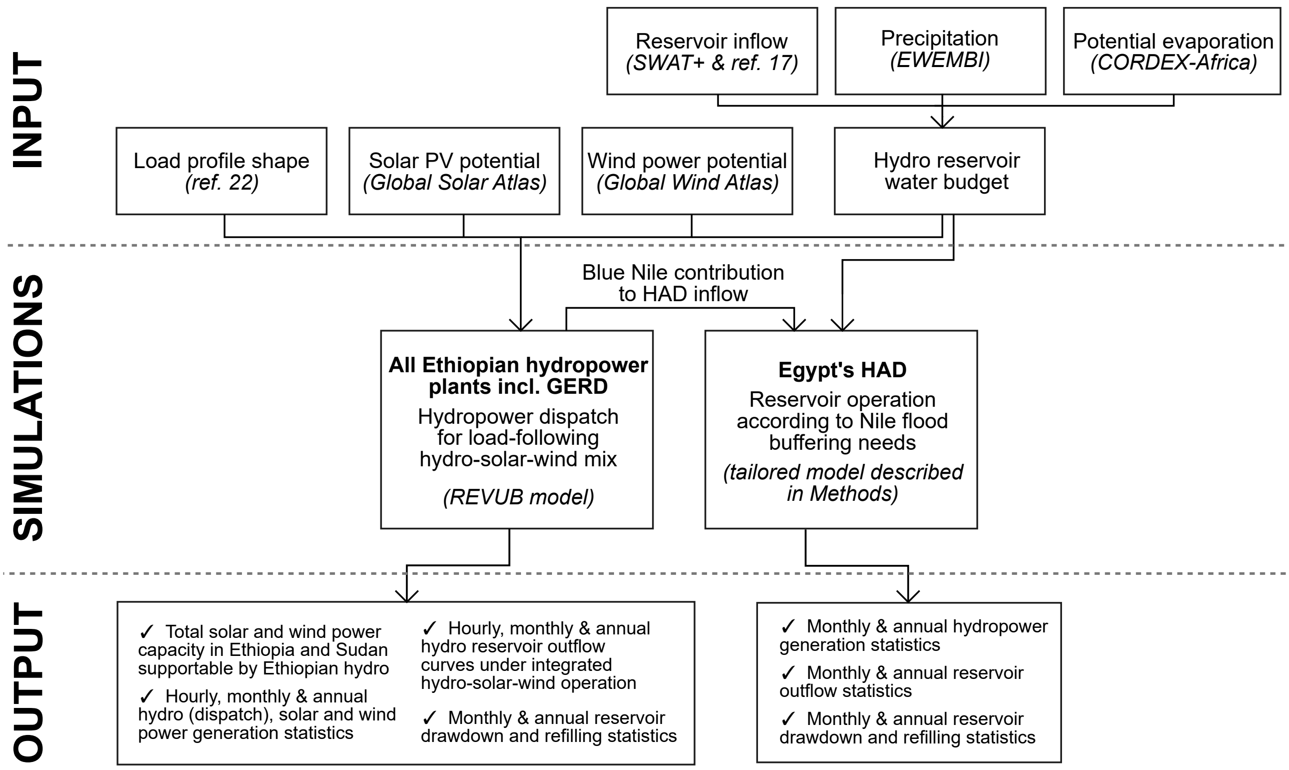
Supplementary Figure 1 displays an infographic that clarifies the various steps from input via simulations to output that were used in this paper. The Figure shows the various parameters needed as input to the modelling, the models used for performing the simulations, and the pertinent types of data output used in the paper.

Supplementary Note 2 Coordinates of VRE locations

In Supplementary Table 1, we show the geographical coordinates of the solar and wind power sites displayed in Figure 1a of the main paper, as used to extract the relevant information on solar PV and wind power yield from the Global Solar Atlas[1] and the Global Wind Atlas[2] (cf. Methods section "Solar PV and wind power generation"). The coordinates were based on either (i) the actual locations of existing and planned power plants where available, or (ii) the locations of towns or cities lending their name to the projects. All locations for solar PV and wind power generation considered in this study are expected to be connected to the respective national grids of Ethiopia and Sudan in the future[3,4].

Supplementary Note 3 Overview of GERD outflow curves

Supplementary Figure 2 shows median monthly flow curves at GERD under natural conditions as well as under S1-S4. The minimum environmental flow requirements (EFR) according to the adapted Tessmann method[6] used in this study is also shown. It is clear that all scenarios S1-S4 (i) increase



Supplementary Figure 1: **Modelling infographic**. Flowchart describing the various data types needed as input to the modelling, the data sources and models used for performing the simulations, and the pertinent types of data output used in the paper. References denote the numbering of the main paper.

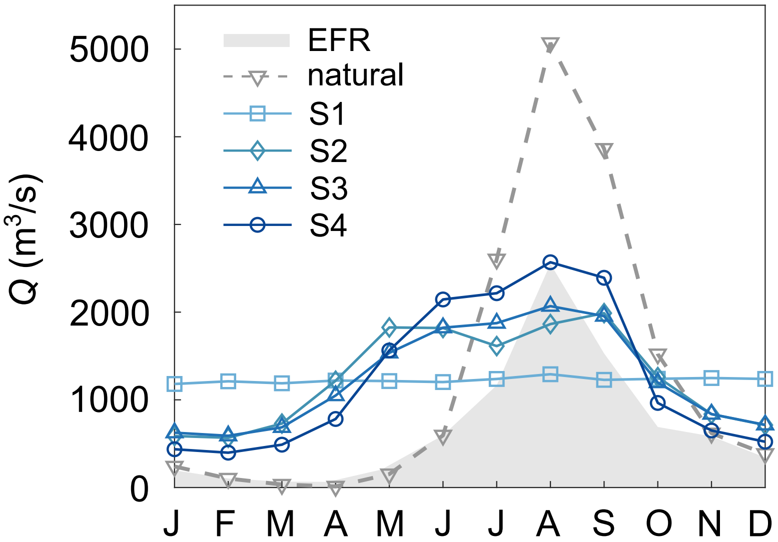
ID in Figure 1a	Location	Country	Resource	Latitude (°N)	Longitude (°E)	Based on
A	Metehara	Ethiopia	Solar PV	8.90	39.92	ref.[3]
B	Dicheto	Ethiopia	Solar PV	11.81	41.72	ref.[3]
C	Gad	Ethiopia	Solar PV	9.96	41.93	ref.[3]
D	Humera	Ethiopia	Solar PV	14.29	36.61	ref.[3]
E	Mekelle	Ethiopia	Solar PV	13.50	39.48	ref.[3]
F	Khartoum	Sudan	Solar PV	15.59	32.53	ref.[5]
G	Niyala	Sudan	Solar PV	12.09	24.91	ref.[5]
H	Al Fashir	Sudan	Solar PV	13.62	25.36	ref.[5]
I	Al Geneinah	Sudan	Solar PV	13.44	22.45	ref.[5]
i	Adama	Ethiopia	Wind	8.64	39.21	existing project
ii	Ashegoda	Ethiopia	Wind	13.44	39.56	existing project
iii	Aysha	Ethiopia	Wind	10.76	42.56	ref.[3]
iv	Asela	Ethiopia	Wind	8.11	39.11	ref.[3]
v	Dongola	Sudan	Wind	19.16	30.36	ref.[5]
vi	Niyala	Sudan	Wind	12.09	24.91	ref.[5]
vii	Red Sea (Hayya)	Sudan	Wind	18.36	36.39	ref.[5]

Supplementary Table 1: **The coordinates of the considered sites for VRE generation.** These locations are shown graphically in Figure 1a of the main paper, along with all modelled hydropower plants.

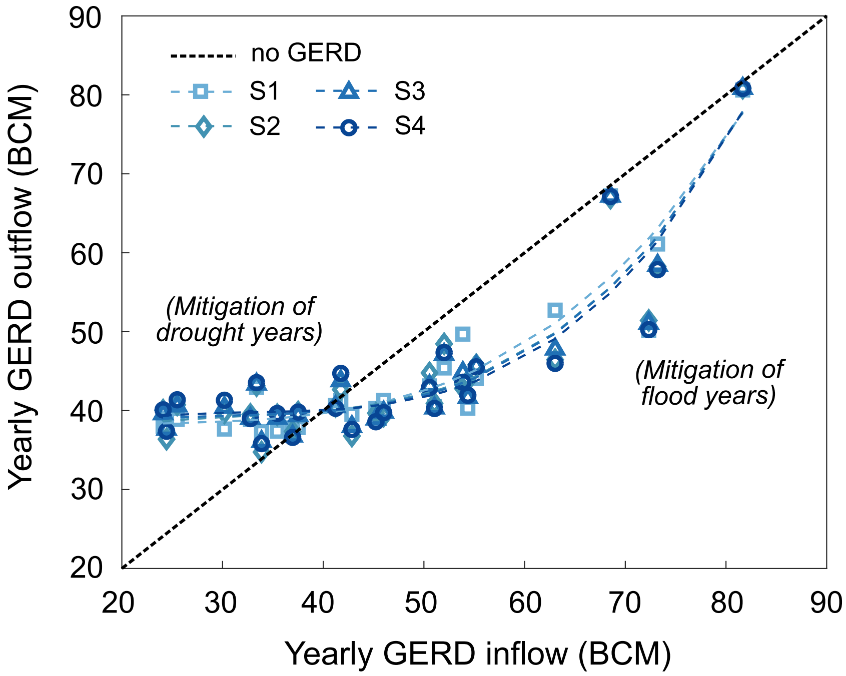
dry-season outflow, protecting Sudan from droughts, and (ii) attenuate the flood peak, protecting Sudan from floods. Further, S2-S4 progressively improve the compliance with environmental flow requirements and progressively match the natural seasonality profile better.
Aside from seasonal outflow curves, it is of high relevance for GERD negotiations what the annual downstream water releases from GERD will be. Here we demonstrate that annual water releases from GERD would be affected only marginally by whether or not Ethiopia would opt for a controlled seasonality in GERD outflow. We show this in Supplementary Figure 3 in which annual releases from GERD under S1-S4 are plotted against the annual inflow from the 26-year time series used in our simulations. It is clear from this Figure that (i) differences between S1-S4 are marginal in terms of annual outflow volumes; and (ii) GERD is able to mitigate dry years by providing more outflow than would have been the case without GERD, as well as wet years by storing water that could otherwise have flooded downstream areas, under all scenarios.

Supplementary Note 4 GERD operation sensitivity to load profile changes

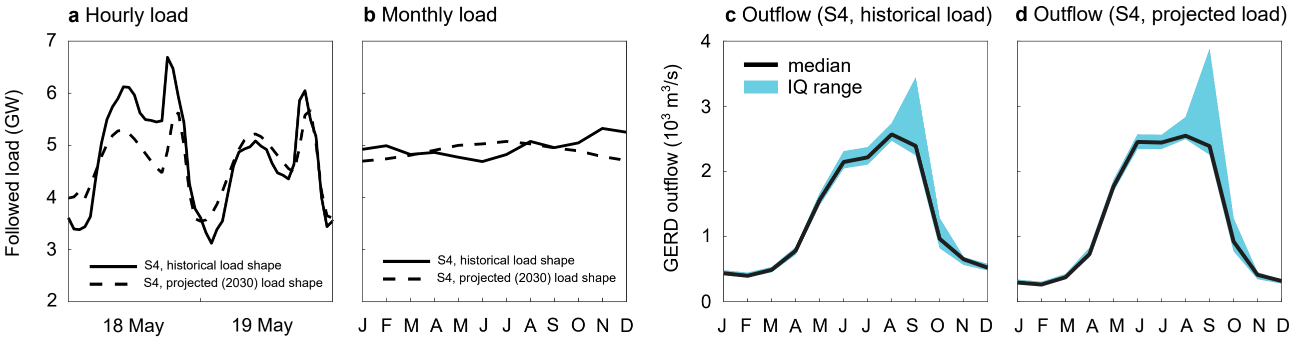
The analysis presented in the main paper was based on historical load profiles from Ethiopia's grid[7]. It is to be expected that this load profile may undergo substantial changes in the future, for instance with a changed seasonal profile and changed diurnal peak loads, owing to the combined effect of several factors. For example, population and welfare growth will lead to an increase in energy intensity of electricity use in households and industry, and simultaneously energy efficiency measures may be conducive to trends in the opposite direction.
To establish whether this would have substantial effects on our results, we reran the simulations with the projected 2030 load profile for Ethiopia from ref.[7] instead of the historical time series, which considered various expected changes in final energy use (e.g. increased airconditioning use during hot times; increased industrialisation and electrification; etc.). Results are shown in Supplementary Figure 4 for the example of scenario S4. Supplementary Figure 4(a-b) show the hourly and monthly followed load according to the historical data (as used in the main paper) and the 2030 projections. As can be seen, the hourly load curves are somewhat changed and the seasonality in demand is reversed according to these projections. By itself, this represents quite a substantial change. Despite this, the



Supplementary Figure 2: **Comparison of outflow curves**. Monthly median curves of Blue Nile flow at GERD under natural flow and scenarios S1-S4. The gray range shows the minimum environmental flow requirements (EFR) according to the adapted Tessmann method[6].



Supplementary Figure 3: **Annual water releases under S1-S4**. Yearly GERD outflow plotted against yearly GERD inflow under scenarios S1-S4; each data point represents one year of the 26-year simulation period for each scenario. The dashed curves are cubic polynomials fitted to each set of 26 data points. The dashed straight line represents the situation without GERD.



Supplementary Figure 4: **Sensitivity of GERD operation to demand profile shape.** (a-b) Comparison of the hourly (a; example time slice as in Figure 2a-d of the main paper) and monthly (b) load followed by GERD + VRE under scenario S4, assuming historical and projected (2030) load profile shapes[7]. (c-d) GERD outflow under the historical (c) and projected 2030 (d) load profile shapes.

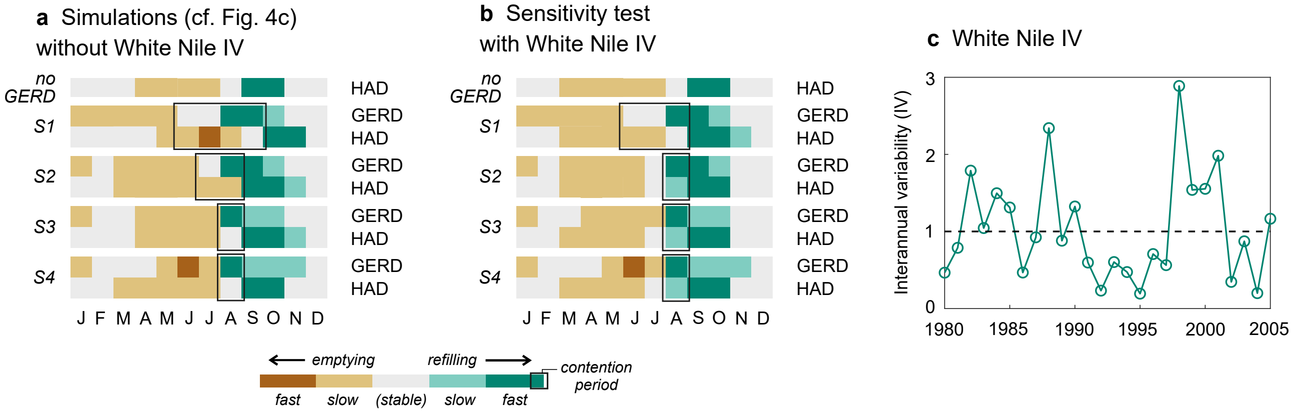
change in total followed load (in TWh/year; cf. Figure 2e of the main paper) only amounts to 1.6% as compared to the historical-load case, since the change in demand seasonality - while significant by itself - pales by comparison to the hydro, solar and wind resource seasonalities (cf. Figure 1b-c of the main paper), which thus determine the GERD dispatch nearly completely. As Supplementary Figure 4(c-d) shows, as a result, the seasonality in GERD outflow undergoes very little change between the two scenarios.
Thus, the projected changes in the demand profile are by far not strong enough to substantially influence the results. We conclude that our conclusions are insensitive to potential (and probable) future changes in electricity demand profiles at hourly and seasonal scales.

Supplementary Note 5 HAD operation sensitivity to White Nile flow

The sensitivity of HAD operation outcomes to the modelling of White Nile flow was tested by resimulating with an alternative White Nile flow time series that included interannual variability. In the main text, the White Nile flow was taken to represent its monthly average (measured at Mogren) from ref.[8], without interannual variability, in order to fully discern the influence of GERD operation on HAD emptying and filling. For this sensitivity study, we superposed upon the monthly average time series from Mogren the interannual variability in White Nile from the SWAT+ simulations described in Methods in the same location[9]. Note that this approach only uses the interannual variability from the SWAT+ simulations, and does not base itself on the seasonality in the SWAT+ simulations which, for the reasons outlined in Methods (complicated lags and retention mechanisms caused by the Sudd swamp), is deemed unrepresentative and therefore not used in this study.
Results are shown in Supplementary Figure 5 in terms of the GERD-HAD filling schedule (cf. Figure 4c of the main paper). It can be seen that, while using the White Nile flow including interannual variability would logically affect the precise lake level changes from month to month, the general conclusion that stable GERD outflow (S1) leads to potentially controversial delays in HAD filling compared to GERD, and that this can be mitigated by complementary GERD-VRE operation (S2-S4), does not change. We thus conclude that the results presented in the main paper are robust to the modelling of White Nile flow.

Supplementary Note 6 HAD operation sensitivity to $f_{seasonal}$

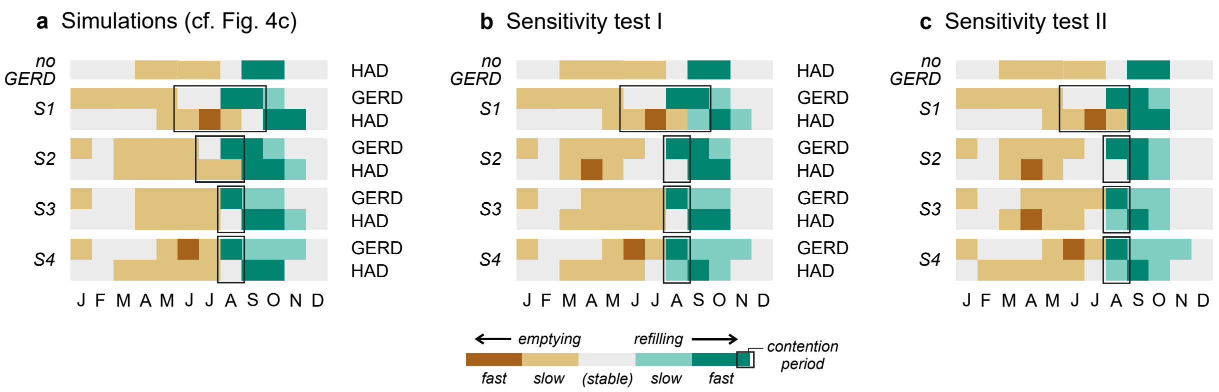
Supplementary Table 2 shows the monthly values of $f_{seasonal}$ as used in the modelling of HAD operation (cf. Methods section in the main paper), as obtained from ref.[10]. The Table also includes two additional



Supplementary Figure 5: **Sensitivity tests to White Nile interannual flow variability**. GERD-HAD filling schedules according to (a) Figure 4c of the main paper, and (b) White Nile flow including SWAT+ interannual variability (IV); this IV (at Mogren) is shown in (c), where annual average flows are shown as normalised to their 1980-2005 average.

Month	$f_{seasonal}$ as used in simulations	$f_{seasonal}$ sensitivity test I	$f_{seasonal}$ sensitivity test II
January	0.52	0.72	0.85
February	0.87	0.93	0.96
March	0.83	0.91	0.95
April	0.96	0.98	0.99
May	1.17	1.08	1.04
June	1.52	1.23	1.11
July	1.50	1.22	1.11
August	1.36	1.17	1.08
September	1.02	1.01	1.00
October	0.82	0.91	0.95
November	0.75	0.87	0.95
December	0.68	0.83	0.91

Supplementary Table 2: The correction factor $f_{seasonal}$ as used in the simulations, as well as under two sensitivity tests whose results are shown in Supplementary Figure 6.



Supplementary Figure 6: **Sensitivity tests on $f_{seasonal}$**. GERD-HAD filling schedules according to (a) Figure 4c of the main paper, (b) $f_{seasonal}$ set according to column "Sensitivity test I" in Supplementary Table 2, and (c) idem, according to column "Sensitivity test II".

adapted series of $f_{seasonal}$ which were used to conduct sensitivity tests on the outcomes. These represent, respectively, the square root and the fourth root of the reference values of $f_{seasonal}$. These values were chosen so as to progressively flatten the seasonality in $f_{seasonal}$ to shed light on the effects of a weaker drawdown period pre-August.

Results are shown in Supplementary Figure 6 in terms of the GERD-HAD filling schedule (cf. Figure 4c of the main paper). It can be seen that, while changes in $f_{seasonal}$ would logically affect the precise lake level changes from month to month, the general conclusion that (a) stable GERD outflow (S1) leads to potentially controversial delays in HAD filling compared to GERD, and that (b) this can be mitigated by complementary GERD-VRE operation (S2-S4), does not change. We thus conclude that the results presented in the main paper are robust to adaptations of the parameter $f_{seasonal}$.

Supplementary Note 7 Levelised cost of electricity (LCOE)

Supplementary Figure 7 shows the expected LCOE of GERD and the VRE projects in Ethiopia and Sudan considered in this paper. The calculations were performed using the data summarised in Supplementary Table 3. Clearly, VRE in both countries could very soon compete with hydropower on an economic level (as soon as 2025); thus, scenarios S2-S4 could be economically beneficial as compared to scenario S1 (without VRE "firmed" by hydropower). The data show that Ethiopia could likely further reduce its already-cheap hydropower-based power generation costs by increasing VRE, given the very low associated running costs and ever-decreasing overnight costs of VRE. In scenarios S3-S4, Sudan could benefit from generating its own very cheap VRE whenever available and thus avoid fuel costs for fossil-powered plants (mostly during the dry season), and import somewhat more expensive but still comparatively cheap Ethiopian hydropower when VRE is not available, next to its own hydropower whose generation will be stabilised by GERD.

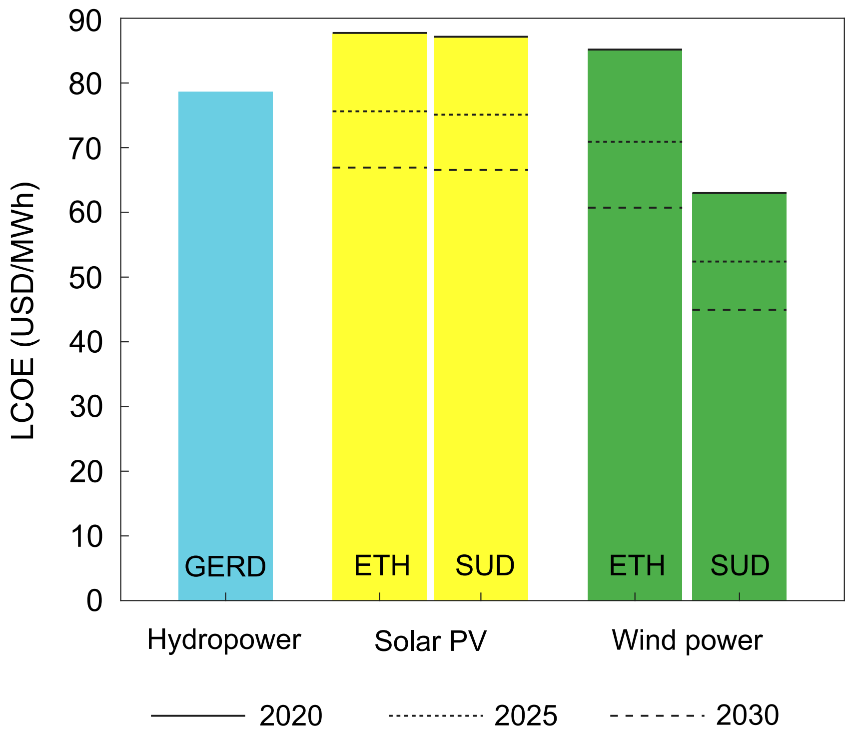
Future hydropower projects in Ethiopia are expected to produce electricity in the same price range as GERD[3]; and the decreasing trends of VRE costs are expected to continue[11]. This lends further credence to the hypothesis that high VRE infeed, incentivising a controlled seasonality in GERD outflow, will benefit the involved countries not only in energy and water terms, but also financially.

Source	I_y	M_y (fixed)	M_y (variable)	r	Y
GERD	4.7 billion USD (ref.[12])	66 EUR/kW/y (ref.[13])	0.003 EUR/kWh (ref.[13])	10% (ref.[3])	50y (ref.[3])
Solar PV	1075 EUR/kW (2020; ref.[3]) 900 EUR/kW (2025; ref.[3]) 775 EUR/kW (2030; ref.[3])	21 EUR/kW/y (ref.[3])	0 EUR/kWh (ref.[13])	10% (ref.[3])	20y (ref.[3])
Wind	1650 EUR/kW (2020; ref.[3]) 1300 EUR/kW (2025; ref.[3]) 1050 EUR/kW (2030; ref.[3])	46 EUR/kW/y (ref.[3])	0 EUR/kWh (ref.[13])	10% (ref.[3])	20y (ref.[3])

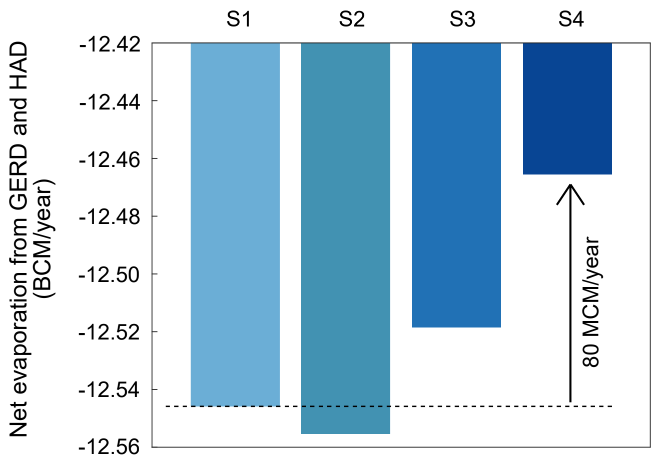
Supplementary Table 3: **Data used for LCOE calculations.** EUR = Euro, USD = United States Dollars. For the EUR-USD conversion, we used a factor of 0.84 EUR/USD according to the exchange rate of 31 August 2020. y = year.

Supplementary Note 8 Evaporation from GERD and HAD reservoirs

Supplementary Figure 8 shows the differences in average net evaporation from the GERD and HAD reservoirs under scenarios S1-S4. These inter-scenario discrepancies result from the different ways in which the timelines of GERD and HAD refilling (which increases lake surface from which water can evaporate) and emptying (which decreases lake surface) match those of the drier and wetter months and the hotter and cooler months in Ethiopia and Egypt. As can be seen, S4 results in the lowest evaporation losses, avoiding the loss of about 80 MCM/year as compared to S1. We note that about 88%-89% of net evaporation is due to HAD under all scenarios.



Supplementary Figure 7: **Expected LCOE of GERD and evaluated VRE projects**. The estimated Levelised Cost of Electricity (LCOE) of GERD and the solar and wind power projects in Ethiopia and Sudan (aggregated by country) as evaluated in this paper. For initial costs of solar PV and wind power, we considered the projected data for the years 2020, 2025 and 2030 from ref.[3] to showcase the impact of their strongly reducing trend. ETH = Ethiopia; SUD = Sudan.



Supplementary Figure 8: **Evaporation losses from GERD and HAD reservoirs**. The annual average net evaporation losses from the reservoir surfaces of GERD and HAD under S1-S4. Negative numbers indicate losses of water.

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