Hydropower dependency and climate change in sub-Saharan Africa: a nexus framework and evidence-based review

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Abstract

In sub-Saharan Africa, 160 million grid-connected electricity consumers live in countries where hydropower accounts for over 50% of total power supply. A warmer climate with more frequent and intense extremes could result in supply reliability issues. Here, (i) a robust framework to highlight the interdependencies between hydropower, water availability, and climate change is proposed, (ii) the state-of-the art literature on the projected impacts of climate change on hydropower in sub-Saharan Africa is reviewed, and (iii) supporting evidence on past trends and current pathways of power mix diversification, drought incidence, and climate change projections is provided. We find that only few countries have pursued a diversification strategy away from hydropower over the last three decades, while others' expansion plans will reinforce the dependency. This will occur irrespective of the fact that some of the largest river basins have experienced a significant drying during the last century. Agreement is found on likely positive impacts of climate change on East Africa's hydropower potential, negative impacts in West and Southern Africa, and substantial uncertainty in Central Africa. Irrespective of the absolute change in gross technical potential, more frequent and intense extremes are projected. One possible paradigm to increase resilience and fulfil the pledges of the Paris Agreement is a synergetic planning and management of hydropower and variable renewables.

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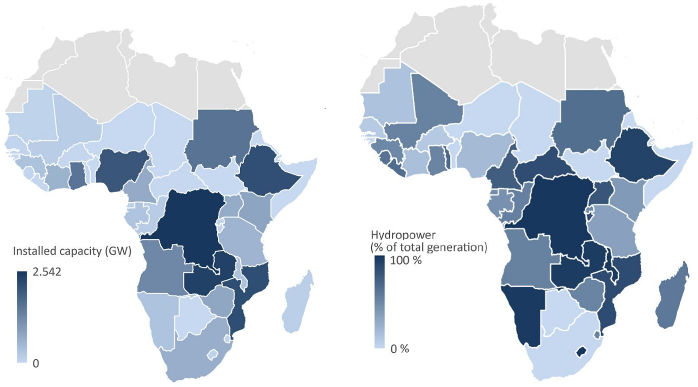
List of abbreviations

Bcm: Billion cubic meter; CDM: Clean Development Mechanism; CMIP5: Coupled Model Intercomparison Project - phase 5; CSP: Concentrated solar power; EJ: Exajoule; GCM: General circulation model; GDP: Gross domestic product; GHG: Greenhouse gas; GW: Gigawatt; HFO: Heavy-fuel-oil; HPP: Hydropower plant; IAM: Integrated assessment model; IPCC: Intergovernmental Panel on Climate Change; IPP: Independent Power Producer; MTC: Megatonne carbon; MW: Megawatt; MWh: Megawatt-hour; NDCs: Nationally Determined Contributions; PWh: Petawatt-hour; RE: Renewable energy; RCPs: Representative concentration pathways; RoR: Run-of-river; SRES: Special Report on Emissions Scenarios; SSA: Sub-Saharan Africa (South Africa excluded); SPEI: Standardized Precipitation-Evaporation Index.

1. Introduction

In sub-Saharan Africa (SSA; throughout the text, excluding South Africa), the installed hydropower capacity stands at 27 GW (39% of the total), with additional 15 GW planned or under construction (International Hydropower Association, 2018). In 2016, hydropower generation stood at 98.6 TWh (US EIA, 2017). A gross technical untapped potential of 7.7 PWh/year (Hoes et al., 2017) has been estimated, of which between 1.4 (below a cost of $0.10/kWh) (Gernaat et al., 2017) and 2.9 (below a cost of $0.09/kWh) PWh/year (Zhou et al., 2015) remaining and techno-economically feasible. The IEA (2017) forecasts that hydropower capacity in SSA will increase at a rate of 6% per year during the 2020s (and thus be the fastest-growing technology in terms of capacity additions), reaching 95 GW by 2040 (IEA, 2014). Currently, total generation capacity in the continent amounts to around 70 GW (Fig. 1a), although around 25% is currently unavailable because of obsolete plants and poor maintenance (Findt et al., 2014). In many countries - and chiefly in Central and East Africa - the electricity generation mix is weakly diversified (Fig. 1b), with hydropower accounting for a large part of total generation and few back-up options available. Together, hydropower-dependent countries - defined as countries where hydropower represents more than 50% of total electricity generation - host 45% of the total SSA population, or 160 million grid-connected users.

In the last decades (in particular during the wet season in unimodal rainfall climates, where rain falls only during one period per year) prolonged droughts have resulted in severe power crises in several hydropower-dependent countries (including for instance, in Kenya, Tanzania, Ghana, Zimbabwe and Zambia during the 2015-16 El Niño period, characterized by oceanic and atmospheric shifts in the Pacific Ocean which affect weather and climate across the tropics, and in Malawi in 2017), with frequent outages, power rationing (Van Vliet et al., 2016a), adverse business experience (Gannon et al., 2018) and switching



(a) (b)

Figure 1: Maps of sub-Saharan Africa representing (a) the total installed hydropower capacity in 2016 and (b) the share of hydropower over the total power generated domestically in 2016. Data source: (US EIA, 2017).

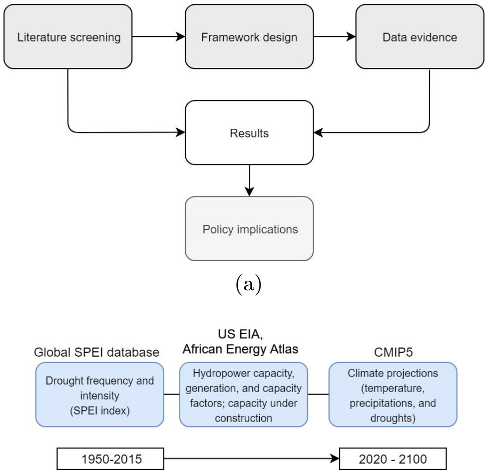
to emergency (and costlier) IPP (independent power producer)-provided diesel-fired generators (Karekezi et al., 2012). Water availability issues represent a growing source of risk in different areas, also due to an increasing competition between water use for power generation, irrigation, and municipal water supply (Zeng et al., 2017; Kling et al., 2014).

A vivid debate is taking place in the academic literature and in decision-making spheres on whether and how in the coming years anthropogenic climate change - and thus changing precipitation and evaporation patterns - will affect hydropower potential and reliability, next to additional demographic and socio-economic stressors. A number of studies have been carried out to assess the impact of past extreme events (including both droughts and floods) on hydropower at different geographical scales in SSA (Stanzel et al., 2018; Kabo-Bah et al., 2016; Uamusse et al., 2017; Loisulie, 2010; Gannon et al., 2018) and to model projections for future trends in water availability and hydropower output (Sridharan et al., 2019; Conway et al., 2017; Turner et al., 2017b; Cervigni et al., 2015; Van Vliet et al., 2016c). However, there appears to be a lack of a systematic review paper focusing on the specific issue of hydropower dependency in SSA, building on a robust theoretical framework, and analyzing relevant data to account for the current capacity expansion plans and for different climate change scenarios.

1.1. Review approach

To address the gap, this paper adopts an analytic approach to provide a state-of-the-art picture of the issue of hydropower dependency across SSA under the projected impacts of climate change. The review is carried out in three steps, as described in Fig. 2a. First, the relevant literature is collected and screened.

An explicit decision to assess studies focusing on the relationship between climate change and hydropower in SSA, rather than water resources in general or in other specific contexts is made. At the same time, the review adopts a forward-looking perspective on the *status quo* and on projected future pathways and impacts, rather than systematically reviewing past drought-induced disruptions. Subsequently, a framework to highlight the range of relationship linking hydropower generation, water availability, GHG (greenhouse gas) emissions, climate impact, and energy system development is derived and represented. Specific implications for the three main types of hydropower plants (run-of-river, reservoir and pumped-storage) are discussed. Thirdly, based on a selected number of aspects of the conceptual framework (focusing on hydropower, droughts, and climate change) and on the literature screening, the review is supported by data evidence (Fig. 2b). Data sources include the US IEA International Energy Statistics database (US EIA, 2017), the SPEI (Standardized Precipitation-Evaporation Index) global droughts database (Beguera & Vicente-Serrano, 2017), the African Energy Atlas 2017-18 power infrastructure data (Cross-Border Information, 2017), and CMIP5 (Coupled Model Intercomparison Project - phase 5) climate projections (Taylor et al., 2012). Lastly, insights from the three analytical steps are presented in the discussion section, where the key implications of the review are highlighted to the research community, the private sector, and public decision makers.



(a)

(b)

Figure 2: (a) Schematic of the review approach. An initial literature screening underpins the design and discussion of a framework of relationships for the climate-water-energy nexus considered. Data evidence supports the findings of the literature reviewed and addresses conclusions and policy implications. (b) Schematic of the data evidence section. Drought data is used to assess the trends in frequency and intensity of drought events recorded over nine major river basins throughout the twentieth century. Hydropower data is analysed to assess past trends and current pathways of hydropower dependency and diversification. CMIP5 climate projections are reported to discuss implications for the coming decades.

The remainder of the paper is structured as follows: in Section 2, a theoretical framework of the interlinkages between the power sector, the climate system, and the broader economy is presented, with specific focus on hydropower generation and water availability. Sections 3 and 4 report the results of the literature review process and of the data evidence on (i) the historical evolution of hydropower installed capacity, generation and capacity factors, (ii) current and planned generation capacity additions, (iii) the trends in the frequency and intensity of drought events, and (iv) future climate change projections. Section 5 discusses the most relevant findings and the key implications for energy-water systems planners and researchers. Section 6 concludes the paper.

2. Theoretical framework

Fig. 3a represents the diagram of relationships derived from the initial literature screening. This is aimed at highlighting the key elements of the climate-water-energy nexus (Frumhoff et al., 2015) which is taken as a reference throughout the review. These include drivers, impacts, their linkages, and feedbacks. The focus is put on the power sector, and the framework is designed so as to be particularly suited to analyze the case of SSA.

The following considerations characterise the conceptualised relationships:

(i) Demand for power is strongly associated with economic growth. Despite the direction of the causal link between the two being a controversial question in the literature (Dlamini et al., 2016; Inglesi-Lotz & Pouris, 2016; Eggoh et al., 2011; Louw et al., 2008; Iyke, 2015; Wolde-Rufael, 2006), with some studies pointing at the simultaneous causality hypothesis, and others suggesting a mono-directional or a less clear link, it is acknowledged that a strong correlation exists. Other drivers include population, urbanisation, and employment levels (Ubani, 2013). Power demand contributes to determining energy policy, which drives supply-side decisions.

(ii) Power can be generated in several ways, and chiefly: (i) with thermal generation, i.e. fossil fuel-fired plants and nuclear units, but also geothermal and biomass power generation, or CSP (concentrated solar power); (ii) mechanically, from kinetic energy, including hydropower facilities (hydropower plants and pumped storage), wind turbines, or tidal energy; (iii) through solar photovoltaic (PV) units. Thermal generation from fossil fuels results in multiple externalities, as it is associated with greenhouse gas emissions and (together with nuclear energy) it implies the consumption of substantial volumes of water for cooling purposes (albeit consumption largely depends on the technology installed, Macknick et al. (2012)).

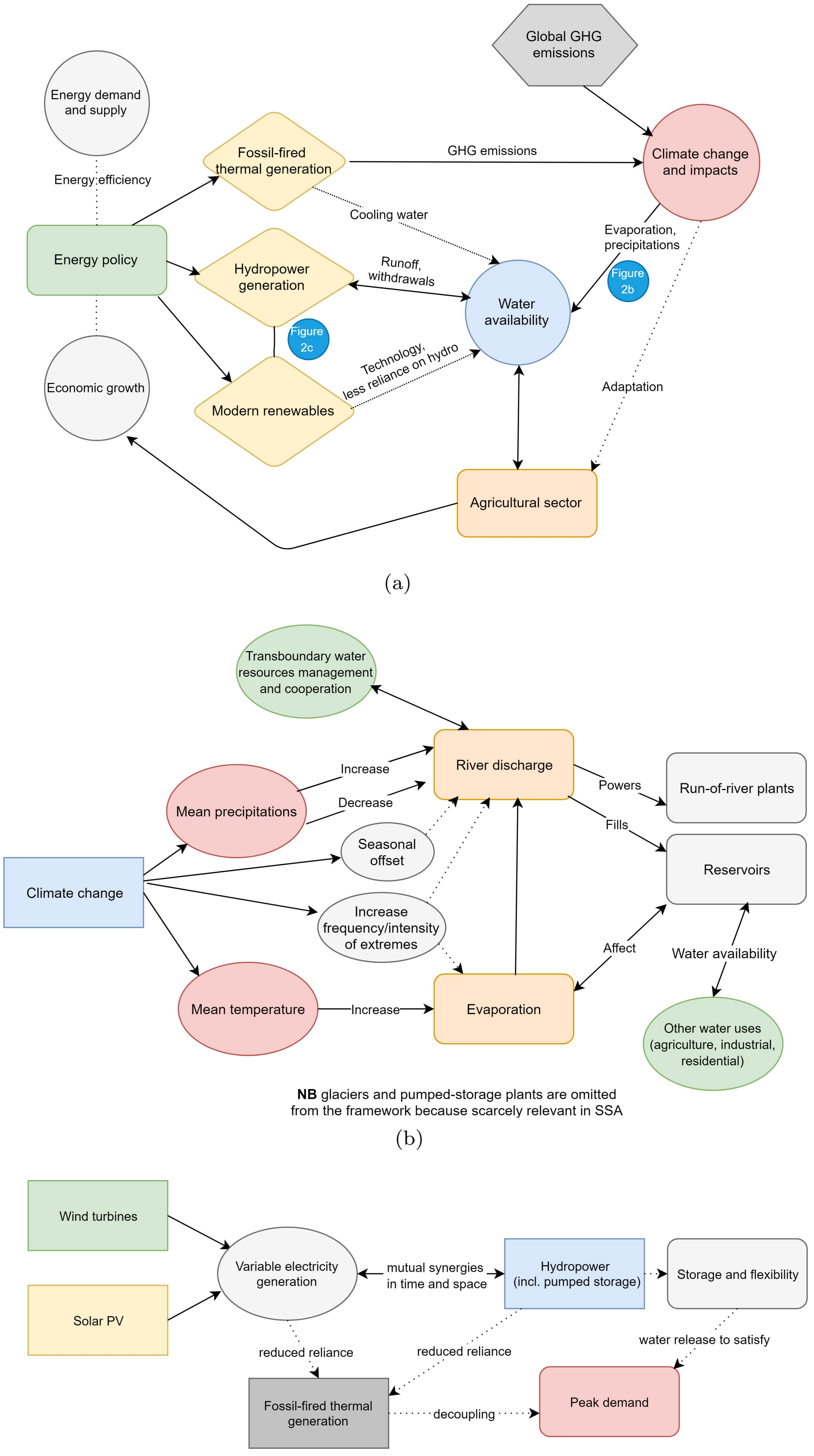
(iii) GHG emissions from fossil fuels combustion contribute to climate change (Pachauri et al., 2014), raising mean temperatures and affecting precipitation and evaporation patterns. Modelling studies show that climate change could exert substantial impacts on water availability in SSA (Faramarzi et al., 2013), although large uncertainty exists regarding the magnitude of these changes in different regions. In turn, climate change may impact virtually every sector of the economy, affecting productivity, energy demand, and infrastructure (through increasing the likelihood of extreme events). The adaptive capacity of each country determines the effects of such linkages.

(iv) Water availability is key for many economic sectors, and primarily for agriculture. This is of great importance to SSA, where agriculture accounted for 17.5% of value added to GDP (gross domestic product) in 2016 (World Bank, 2018), with the figure standing at more than 30% in several countries largely reliant on subsistence agriculture. Hence, increased water pressure can have substantial impacts on food security and on economic growth as a whole.

(v) Hydropower generation is tightly linked to water availability, since turbines require the streaming of large volumes of water to generate power. At the same time, artificial reservoirs can affect both the seasonal flow (releasing more water during the dry season and holding it back during the wet season), and the overall flow because of increased evaporation (Bakken et al., 2013; Mekonnen & Hoekstra, 2012). Again, this depends on the hydrological basin in question, the type of hydropower facility, and the other prevalent water uses in the region. Moreover, an important upstream-downstream coordination dimension also exists and is highly relevant to the case of SSA, in particular for transboundary water resources management (Namara & Giordano, 2017).

(vi) Non-hydro RE (renewable energy) sources can have the benefits of generating power without contributing to greenhouse gas emissions, while affecting the supply of water to a much lesser extent and of reducing greenhouse gas emissions. They can also serve to extract water (e.g. via water pumping) and mitigate competition over reservoirs in dry areas, and thus help to serve irrigation needs in the agricultural sector. Furthermore, if properly planned, hydropower can work in tight complementarity with intermittent RE such as solar and wind, serving as a technology for energy storage (as reservoir water) to accommodate demand peaks and seasonality (Francois et al., 2014; Sterl et al., 2018; Rogeau et al., 2017; Sterl et al., 2019; Barasa et al., 2018), and not solely as a source of baseload power (see also Fig. 3c) later.

(vii) Finally, the treatment and distribution of water can require a considerable quantity of energy (Opperman et al., 2015).



(a)

(b)

(c)

Figure 3: (a) The climate-water-energy nexus framework considered in this review. Solid lines express direct drivers and impact, while dashed lines describe indirect relationships, where mediating factors play a role. Arrows express whether effects are uni- or bidirectional. (b) Schematic of the key channels of climate change impact on hydropower schemes reliability. (c) Example framework of greenhouse gas emissions mitigation via VRE-hydropower complementarity.

Fig. 3b expands the framework of Fig. 3a to explore the interdependencies between climate, water, and hydropower generation. In particular, it suggests that:

(i) Hydropower generates electricity via falling water hitting a turbine connected to a generator. The power output is a function of both the flow impacting the turbine and the hydraulic head. As a result, changes in hydro-climate may affect hydropower generation (Lumbroso et al., 2015). The channels through which climate change affects hydropower capacity and effective output include alterations in the gross stream flow, shifts in the seasonality of flows and a greater variability (including flood and drought extremes), increased evaporation from reservoir lakes, but also changes in sediment fluxes (World Commission On Dams, 2000).

(ii) Anthropogenic climate change determines changes in the long-term mean of hydroclimatic parameters - chiefly temperature and precipitative fluxes - , as well as the seasonal shifts and the probability and intensity of extremes (droughts and floods) (Pachauri et al., 2014).

(iii) The extent to which such changes affect power generation and the actual capacity factor of hydropower plants depends on multiple factors, including: the direction and magnitude of the change; the type of dam in question; and for the case of reservoirs, the features and size of reservoir; among multipurpose dams (which are usually also the largest), the withdrawal from concurrent uses and thus the use of shared water resources in the region by the agricultural sector, the industry, and residential areas (Lee et al., 2009); and the transboundary basin management (Conway et al., 2015).

(iv) Hydropower includes plants of three main categories: RoR (run-of-river), reservoir-based, and pumped storage plants. Plants however often operate intermittently as RoR and reservoir-based. For example, plants with multi-year reservoir lake capacity can buffer inflow across multiple years, whereas plants with within-a-year capacity can only do it for several months before they would overflow. The first type utilizes the river's flow to produce electricity without blocking water upstream; the second partially stops the flow of a river with a dam and floods an area upstream to create a reservoir lake. Reservoirs are capable of buffering fluctuations in flow over longer time periods, and hydropower plants with reservoirs can thus be well-suited for providing base power (relatively constant output) and peak power (increased power output at particular moments). Depending on the vulnerability of the plant's technical equipment (such as the turbine equipment) to the impacts of variable discharge rates, it might be decided to operate only for baseload provision. Conversely, depending on the vulnerability of downstream ecosystem services to the impacts of constant discharge rates, it might be decided to operate plants mostly as run-of-river facilities (Liersch et al., 2019). As of 2019, no pumped-storage facilities are in operation throughout SSA. Four schemes are operating in South Africa in conjunction with the constant generation. These facilities serve to meet the intra-daily variations in the electricity demand, but can also be used to store generation potential from other variable RE (such as solar and wind) during moments of overproduction from the latter, reducing curtailment rates.

(v) Considerations related to the cooperative (or competitive) dynamics of water resources management are necessary. Transboundary river basins cover 62% of the total surface of Africa, and water availability (and water infrastructure management) downstream is largely affected by political and infrastructural choices upstream (Grey et al., 2016). Cooperative governance can reduce water conflicts, increase efficiency in resource use - including hydropower output - and create economic value by internalizing externalities stemming from a lack of coordination, and therefore boost investment and financing of shared water infrastructure (such as Pareto-efficiently located dams, The World Bank (2017).

(vi) The relationship between hydropower and irrigation in multipurpose reservoirs is pivotal: it has been evaluated that while today roughly 54% of global installed hydropower capacity competes with irrigation and 8% complements it, competition is expected to intensify under a warmer climate (Zeng et al., 2017).

(vii) Besides long-term alterations in the climate system, droughts and floods pose short-term disruption risks to the power sector, with statistically significant reductions in average hydropower utilization rates (-5.2%) and thermoelectric power generation (-3.8%) during drought years compared to the long-term average having been observed (Van Vliet et al., 2016c). Overall, water shortages from both long-lived changes in precipitation, evapotranspiration, and extreme events pose the risk of reducing electricity production in hydropower plants, while energy outages can themselves disrupt water distribution facilities.

Co-integration of multiple RE (Fig. 3c), - e.g. of variable sources like solar PV and wind and hydro used as a solution to increase flexibility and provide power storage (in particular to satisfy peak demand) has multiple benefits. It can trigger win-win solutions for emissions mitigation, renewables share increase in the generation mix, climate resilience of the power sector, and sustainability in the use of water resources.

3. Literature review results

The screened literature has been classified into three main categories: (i) studies assessing the potential impacts of climate change on hydropower supply and reliability, both at the global and at the river basin level; (ii) research contributions focusing on the impact of power generation on water availability as a result of withdrawals or consumptive uses e.g. for thermal plants cooling; (iii) the literature on the broad array of additional stressors for water availability, e.g. as a result of economic growth. Before introducing the results of the literature screening, we also report recent studies offering techno-economic analysis of hydropower and power mix expansion pathways for SSA carried out at different scales.

3.1. Techno-economic analysis of hydropower in SSA

A gross technical untapped potential of 7.7 PWh/year (Hoes et al., 2017) has been estimated for SSA, of which there remain between 1.4 PWh/year below a cost of \$0.10/kWh (Gernaat et al., 2017) and 2.9 PWh/year below a cost of \$0.09/kWh (Zhou et al., 2015), i.e. techno-economically feasible compared to other local generation options. These assessments mostly rely on spatially-explicit digital elevation and river discharge information within a cost-optimisation modelling framework. Discharge is based on historical long-run averages, although Gernaat et al. (2017) also test the effect of climate change (under scenario RCP 8.5) on runoff and thus on the remaining technical potential. They observe a moderate increase (4 to 18%) consistently occurring in Africa.

A significant share of the potential is concentrated in sites with very large potential capacity, such as the Grand Inga, in the Congo River (up to 42 GW). Taliotis et al. (2014) analyse the impact of the project of the continental energy system in a modelling framework, and found that - provided sufficient high-voltage transmission interconnection infrastructure is put into place - the dam could satisfy a substantial part of the power demand in all power pools of SSA. However, the authors do not account for any externality of the project. Also, open questions remain on the continental impact of potential (including climate-induced) generation disruptions at such large-scale projects. With regards to the issue, Deshmukh et al. (2018) assess the feasibility and cost-effectiveness of RE alternatives to the Inga 3 scheme. They find that under most scenarios, the hydropower project would be comparatively more costly than a mix of wind, solar PV, and some natural gas to meet future demand. Similar results are highlighted by Oyewo et al. (2018).

Irrespective of the large and cheap untapped hydropower potential, a number of studies show that cost-effective pathways that are alternative to heavily relying on new dams exist for SSA. For instance, Wu et al. (2017) claim that the current generation capacity expansion paradigm in SSA, which largely relies on domestic large-scale hydropower schemes, is dominating because of the insecurity and high costs of fossil fuels. The authors however highlight a large number of concerns related to this paradigm, including many aspects discussed in this paper. To provide an alternative, they create a framework for multicriteria analysis for planning RE and map and characterize solar and wind energy zones in the Southern African Power Pool (SAPP) and the Eastern Africa Power Pool (EAPP). They find that RE potential is several times greater than demand in many countries and mostly economically competitive, and thus it significantly contribute to meeting this demand. International interconnections are however necessary to render this potential economically feasible for the region as a whole. Also, interconnections that support the best RE options are different from those planned for a counterfactual scenario of domestic large-scale hydropower expansion. The same direction is pointed by Barasa et al. (2018), who estimate electricity generation potential throughout SSA (divided into 16 sub-regions) at a hourly resolution according to four scenarios over the transmission grid development. They show that RE is alone sufficient to cover 866 TWh electricity demand for 2030, and that existing hydro dams can be used to balance large-scale solar PV and wind integration. All scenarios represent pathways of substantial diversification away from hydropower, which compared to other RE would have a significant smaller share. The authors highlight that this finding is at odds with the New Policies Scenario of the IEA, which projects that by 2040 hydropower may account for 26% of electricity generation in SSA. Similar results are highlighted in Schwerhoff & Sy (2019), who compare results from Integrated Assessment Models (IAMs), finding that different sustainable energy supply pathways for Africa which are also compatible with the 2C climate target. Some scenarios determine a 100% switch to RE over the medium-run, provided sufficient transboundary transmission infrastructure is put into place.

Another significant aspect concerns the small-scale hydropower potential and its role for delivering electricity access to remote communities. Several technical assessments have been carried out for SSA (Korkovelos et al., 2018; Ebhota & Inambao, 2017; Kaunda et al., 2012), highlighting the significant potential (e.g., 9.9 GW in the Southern African Power Pool, and 5.7, 5.6, and 3.9 GW in the Central, Eastern, and Western African Power Pools, respectively). Least-cost techno-economic electrification models then show (Mentis et al., 2017b,a; Korkovelos et al., 2019) that these technologies can be the cheapest option to provide power to mini-grids in a number of settlements throughout SSA. Yet, little research has hitherto been performed to assess the reliability and vulnerability of such small-scale technologies to long-lived changes in the discharge or short-lived disruptions.

Finally, Szabó et al. (2016) show that in an array of settings the least-cost option for achieving electrification of local communities in SSA consists in transforming currently existing but non-powered dams into electricity-generating schemes. Overall the authors calculate a potential of 243 MW at a moderate cost of $365.7 million, which could supply nearly 4 million people with electricity.

3.2. Climate change impacts on hydropower

Table S2 (in the Supplementary material) reports and briefly summarises the main reviewed studies covering the projected impacts of climate change on hydropower in SSA. The literature can be classified among three key dimensions:

(a) the geographical scope, with 6 reviewed studies assessing the global scale, 5 papers examining broad African regions, and 14 contributions analysing specific river basins or countries; (b) the methodology, mostly including integrated electricity-hydrology model-based studies, and (c) the climate scenarios considered, with most studies assessing the RCP (Representative Concentration Pathways) and SRES (Special Report on Emissions Scenarios) scenarios.

Global or regional scale studies evaluating changes in global hydropower potential caused by potential changes in climate conditions include the following:

Hamududu & Killingtveit (2012) use an ensemble of simulations of regional patterns of runoff changes and found that on a global scale the absolute magnitude of change is projected to be small and positive (>+1%) for the hydropower system in operation today, but substantial heterogeneity exists. Most negatively affected SSA countries (in terms of percentage change of total currently operating hydropower output by 2050) include Mozambique (-9.5%), Namibia (-21.2%), South Africa (-11.6%), and Zimbabwe (-10.4%). Among countries potentially benefiting from climate change for hydropower generation, there figure Burundi (+13.1%), Rwanda (+15.1%), Uganda (+14.9%), and Tanzania (+12.9%).

Turner et al. (2017a) employ a coupled global hydrological and HPP (hydropower plant) model with downscaled, bias-corrected climate simulations (under RCPs 4.5 and 8.5), to explore consequent impacts on the power mix and associated emissions and investment costs using an integrated assessment model. They find significantly altered power sector CO_2 emissions in several hydropower-dependent regions and estimate the global 21st century investment necessary to compensate for deteriorated hydropower generation caused by climate change at \$1 trillion. For SSA, under the two RCP scenarios, they estimate an increase in the 0.07-0.13 EJ (exajoule) range in hydropower output in East Africa by 2100 with respect to today's level, coupled with a decrease in carbon dioxide emissions (up to 2.79 MtC/year) and in required energy investments (up to -\$72.6 billion), while for Southern and West Africa they find decreases in the hydro output of 0.01 and 0.03 EJ, respectively. These are associated with increase of 0.02-0.54 MtC/year on power sector emissions across the two regions, and a \$4.4-13.4 billion impact on cumulative power sector investments.

Turner et al. (2017b) further improve the model simulating HPP with a detailed dam model that accounts for plant specifications, storage dynamics, reservoir bathymetry and operations. They show that the inclusion of these features can have a non-trivial effect on the simulated response of the hydropower production to changes in climate factors. Here, results are expressed as the average country-level hydropower output change, considering A2 and B1 SRES scenarios and different models. The strongest negative change in hydropower output is found in West Africa: Togo (-14.4%), Ghana (-14.5%), Mali (-13.7%), Guinea (-12.9%), Côte d'Ivoire (-15.7%), Nigeria (-15.8%).

Van Vliet et al. (2016b) predict reductions in usable capacity for 61-74% of the hydropower plants and 81-86% of the thermoelectric power plants worldwide for 2040-2069. For the African continent, they highlight moderate declines (around -0.9%) in hydropower output by 2050 for both RCP 2.6 and 8.5, and more substantial declines (around -5.2-17.8%) in thermoelectric power if no adaptation measures are implemented.

Van Vliet et al. (2016c) carry out a multi-model assessment of global hydropower and cooling water discharge potential under RCP2.6 and RCP8.5 climate change scenario over five GCMs (general circulation models). For SSA they predict large increases of hydropower output (>20%) in Central Africa and considerable declines (<-20%) in North Africa and parts of Southern Africa.

Cervigni et al. (2015) present a comprehensive analysis of the future of water-related infrastructure (including both hydropower and irrigation in agriculture) under IPCC (Intergovernmental Panel on Climate Change)'s RCP warming scenarios. The authors focus on the question of how to design and build the essential infrastructure needed for Africa's development, while factoring in and addressing the challenge of climate resilience. The study covers seven major river basins (Congo, Niger, Nile, Orange, Senegal, Volta, and Zambezi) and all four of SSA's electric power pools (Central, Eastern, Southern, and Western). It is argued that failure to integrate climate change in power and water infrastructure could entail, in dry scenarios, losses of hydropower revenues in the 10-60% range with respect to a no-climate-change scenario (in part because the transmission lines and power trading agreements needed to bring the extra hydropower to the market could not be available). Threefold increases in consumer expenditure for backstop energy (e.g. diesel generation) are projected under the driest scenarios, with significant impact on infrastructure investment and future power mix configurations. Climate change is projected to have the largest impact on electricity consumer prices in the Southern African Power Pool, where transmission lines are limited and the percentage of hydropower in the total installed capacity is high. For instance, hydropower generation could decline by more than 60% in the Zambezi basin. On the other hand, an unexploited wetter climate (in terms of underdeveloped capacity) could imply forgone revenues of 20-140% *vis-à-vis* the baseline.

Cole et al. (2014) assemble an extensive spatial dataset for Africa from geographically based information on daily precipitation, soil conditions, power plants, and energy network grids. They find that while on average current plans for African dam building are well matched with river-flow predictions, in most countries a higher output variability would be witnessed, and a reduced hydropower production would still occur in some others, including Guinea, Mozambique, Sierra Leone and Niger.

Van Vliet et al. (2016a) quantify the impacts of drought episodes and warm years on hydroelectric and thermoelectric available capacity. They show that hydropower utilisation rates were on average reduced by 5.2% and thermoelectric power by 3.8% during drought years compared to the long-term average for 1981-2010, while during major drought years, hydropower showed declines in the 6.1-6.6% range and thermoelectric power in the 4.7-9% range. Among the global regions considered, they observe the highest interannual variability in utilisation rates of hydropower in Southern Africa (the only region of SSA considered in the study).

Besides global and continental-scale studies, many regional analyses have also been carried out. Sridharan et al. (2019) assess climate vulnerability of hydropower infrastructure in the Eastern African Power Pool. They find that failing to perform climate-resilient infrastructure investment (found to be a plan optimised for a slightly wetter climate compared to historical trends) can result in significant electricity price fluctuations, in particular in Uganda and Tanzania.

Stanzel et al. (2018) apply climate data of an array of Regional Climate Model simulations in a water balance model for the case of West Africa, based on RCP4.5 and RCP8.5 until 2065. The results show mixed trends, with median results of the model ensemble for the relative change in rivers' discharge in the range of ±5%. The ensemble agrees upon the significance of the results in a number of sub-regions, including stronger decreases in the north and east of West Africa and pronounced increases mainly in the southwest.

Kling et al. (2015) and Kling et al. (2014) assess future climate change impacts in the Zambezi basin - hosting three of the largest hydropower schemes in SSA, the Kariba (1470 MW), Cahora Bassa (2075 MW) and Kafue Gorge (990 MW) - for existing and planned major hydro plants, based on global climate model projections from the CMIP5. The authors refer to RCP4.5 and account for moderate economic growth to factor in changes in withdrawals for agricultural irrigation. They downscaled climate change signals at the stations to construct future time-series of precipitation and temperature at a number of sub-basins. Their results - characterised by significant uncertainty in future precipitation levels - show that by 2050 annual discharge could decrease by 20%, with sub-basin heterogeneity but diffuse negative changes. Such declining trends in discharge are predicted to worsen, with declines in the 40-55% range by the end of the century, posing a great risk for water resources management in the Zambezi basin. Runoff is found to be mostly sensible to changes in precipitation rather than in temperature, the former being however also the most uncertain variable.

Spalding-Fecher et al. (2016) also assess the vulnerability of hydropower production in the Zambezi River Basin to the impacts of climate change, but they include in the analysis more specific focus on irrigation development. Using the Water Evaluation and Planning (WEAP) tool, they find that for both existing (Cahora Bassa) and planned downstream schemes (Mphanda Nkuwa) prioritising irrigation demand over hydropower could severely compromise the plant's output and impair the feasibility or limit the cost-effectiveness of expansion plans. At the same time, the generation at upstream HPP (Karibe) is highly vulnerable to a drying climate, while new projects (Batoka Gorge) and expansions may not reach the production levels forecasted in feasibility studies.

Harrison & Whittington (2002) evaluate the relationship between climate change scenarios and the future technical and financial viability of hydro development. They elaborate on the case study of the not yet built 1,600 MW Batoka Gorge project on the Zambezi river, upstream of Lake Kariba. Their findings suggest that - under the examined climate change scenarios - significantly altered river flows and adverse power production and financial performance would occur (up to 19% of target production unmet, up to $3.8 million per month of forgone revenues and up to +$0.40 in unit cost of electricity) *vis-à-vis* a no-climate-change scenario.

Conway et al. (2017) rely on cluster analysis to define regions of coherent rainfall variability in East and Southern Africa to illustrate exposure to the risk of hydropower supply disruption of current and planned hydropower sites. The authors forecast substantial increases in the exploited capacity in the Nile and Zambezi river basins, and find that by 2030, 70% and 59% of the total hydropower installed capacity (including HPP currently planned or under constructions) would be located in a single cluster of rainfall variability (i.e., areas experiencing similar rainfall patterns) in EA and SA, respectively. According to the authors, unless robust power interconnection infrastructure is put into place, this would increase the risk of concurrent climate-related electricity supply disruption and power rationing in the two regions because dry years will negatively affect water storage at all reservoirs and their ability to subsequently refill.

Further regional or basin-level studies, heterogeneous in the methodology adopted, include the following: Beilfuss (2012) on the hydrological risks and consequences of climate change for Zambezi River Basin dams and Spalding-Fecher et al. (2016) on the vulnerability of hydropower production to the impacts of climate change and irrigation development in the same area; Boadi & Owusu (2017) on climate-induced hydro variability and disruptions in Ghana, and Kabo-Bah et al. (2016) on climate trends in the Volta River Basin and their potential impact on hydropower generation; Kizza et al. (2010) providing future hydropower scenarios under the influence of climate change for the riparian countries of the Lake Victoria Basin; Loisulie (2010) assessing the vulnerability of the Tanzanian hydropower production to extreme weather events; Oyerinde et al. (2016) estimating the projected impacts of increased GHG emissions on the Niger basin at the Kainji hydroelectric plant and implications for local power production; Bunyasi (2012) studying the case of the Seven Forks Project to assess the climate vulnerability of hydroelectric resources in Kenya; Mukheibir (2017) adopting a similar approach for large hydroelectricity schemes in Southern Africa. Uamusse et al. (2017) focusing on the case of Mozambique, where the Cahora Bassa dam provides an important share of the domestic power supply - in particular in the northern provinces - despite 65% of the total power generated at the dam being exported to South Africa, projecting a capacity reduction in all hydro plants in the country, with Cahora Bassa falling from the current 2,075 MW to 1,822 MW; and Karekezi et al. (2012) providing an assessment of the economic impact of recent droughts-induced hydropower capacity reduction and disruptions in the East and Horn of Africa region.

A comprehensive assessment shows that irrespective of large uncertainty in the projected change in precipitation levels and patterns, agreement is found over projections that East Africa could positively benefit from a warmer climate in terms of hydropower output, West and Southern Africa would be subject to negative impacts, while Central Africa is prone to be less affected. For all the predictive studies under examination it must be remarked that substantial uncertainties emerge when modelling the impacts of climate change on hydrological variables and hydropower output. These uncertainties regard both the magnitude of projected climate alterations (in particular for precipitations), and the degree of potential water abstraction from planned future upstream dams.

3.3. The impact of power generation on water availability

Power generation is itself a water-intensive activity in terms of both withdrawals (water removed from a source) and consumption (the volume withdrawn and not returned to the source due to evaporation or transport). The IEA (2016) estimates that, on a global scale, the power sector accounts for 10% of total water withdrawals and 3% of consumption, i.e., 88% of total water withdrawals and 36% of water consumption volumes of the energy sector. Fossil fuels are by far the most thirsty power generation sources, with 230 bcm (billion cubic meters) of water withdrawn worldwide for cooling purposes in 2014. However, withdrawals and actual consumption are largely variable across technologies and depend primarily on the cooling technology in question.

The effective water consumption of hydropower varies depending on technology type (e.g. reservoir vs. RoR plants), reservoir size, local climate, and total demand from all water users (IEA, 2016). Reservoirs serve as a major source of global energy storage, and a majority of the water withdrawn is returned to the river after passing through turbines. As a result, the amount consumed is highly site-specific. Nonetheless, this does not imply that water availability is neutral to hydropower, and vice versa. Short-lived droughts, as well as seasonality and long-term changes in water supply induced by climate change or other anthropogenic drivers can have a considerable impact on effective generation capacity.

Table S3 (in the Supplementary material) reports the reviewed studies (Mekonnen et al., 2015; Mekonnen & Hoekstra, 2012; Mouratiadou et al., 2016; Davies et al., 2013; Fricko et al., 2016; Meldrum et al., 2013; Bakken et al., 2017) on the impact of power generation - both from fossil fuels and hydropower - on water resources. The focus is on studies at the global or SSA scale, while we acknowledge but do not include similar studies on the UK (Byers et al., 2014), the US (Denooyer et al., 2016) and China (Zhang & Anadon, 2013).

The literature suggests that 96.4% of the consumptive water footprint of electricity and heat production in Africa stems from hydropower, with peaks of average 450,000 - 496,800 $l \cdot MWh^{-1}$ in hydropower-dependent countries (Mekonnen et al., 2015). To put the figures in perspective, the median water withdrawals from combined cycle once-through-cooled gas-fired plants stands at 43,100 $l \cdot MWh^{-1}$, and that of general once-through-cooled coal-fired plants is at 137,600 $l \cdot MWh^{-1}$, with a very similar value for steam gas-fired plants (Macknick et al., 2012). Concerning withdrawals (which include all water diverted) from its source, the figures stand at 669,600 $l \cdot MWh^{-1}$ at Cahora Bassa and at 2,239,000 $l \cdot MWh^{-1}$ at Lake Kariba (Mekonnen & Hoekstra, 2012).

3.4. Additional stressors for water availability

According to the UN (United Nations Population Division, 2017), the population of SSA is expected to reach the 2.75-5.5 billion range by 2100 from the current 1 billion, and hence to undergo a quasi threefold growth in the most conservative scenario. This means that - assuming constant per-capital withdrawals and efficiency in water use - consumption, industrial use and other withdrawals would increase. However, if this assumption is released, two effects will work in opposite directions: on the one hand the potential (by know-how, technology and infrastructure) to increase water use efficiency, which as of today is relatively low; on the other, the concrete chance that increasing development and well-being result in rising per-capita water demand, through both higher water use and increased consumption of products with large water footprints (such as meat). The link has been previously investigated by several studies, among which Buitenzorgy & Ancev (2013); Cole (2004); Floerke et al. (2013); Katz (2015); Duarte et al. (2014). Most assessments agree on an inverted-U shape statistical relationship between per-capita income and water use, with the estimated turning points found at income levels that have only been reached in the developed regions. Cole (2004) projects developing regions' (including SSA) per capita and total water use to increase in the coming decades, while they argue that the current extreme inefficiencies in use might be mitigated with sound policy and technological advances.

4. Data evidence results

Here, we investigate the historical evolution of hydropower capacity, generation, and capacity factors in hydropower-dependent countries, to understand the heterogeneity in the diversification trends observed. We also collect extensive information on capacity currently under construction or having secured finance, to understand how regional power mixes may evolve in the near future. Then, drawing from a long-run drought database, we evaluate if and to what extent the frequency and intensity of extreme events has evolved throughout the twentieth century. Lastly, we illustrate the potential evolution of hydropower under the downscaled CMIP5 climate projections under different warming scenarios to provide evidence of future potential stress on hydropower.

4.1. Diversification: trends and pathways

Fig. 4 and 5 plot the evolution of the share of hydropower over total capacity and generation, respectively, for the period between 1980 and 2015. The figures are reported for hydropower-dependent countries of SSA under examination. Here, both countries with a hydropower share > 50% of total generation, and further countries deemed potentially affected by the issues discussed in the paper are included. Countries are grouped by region (Central, East, West, Southern), so as to highlight the different trends of diversification that have been followed across neighbouring countries. Refer to Fig. S1a for a map showing the regional classification adopted in this paper.

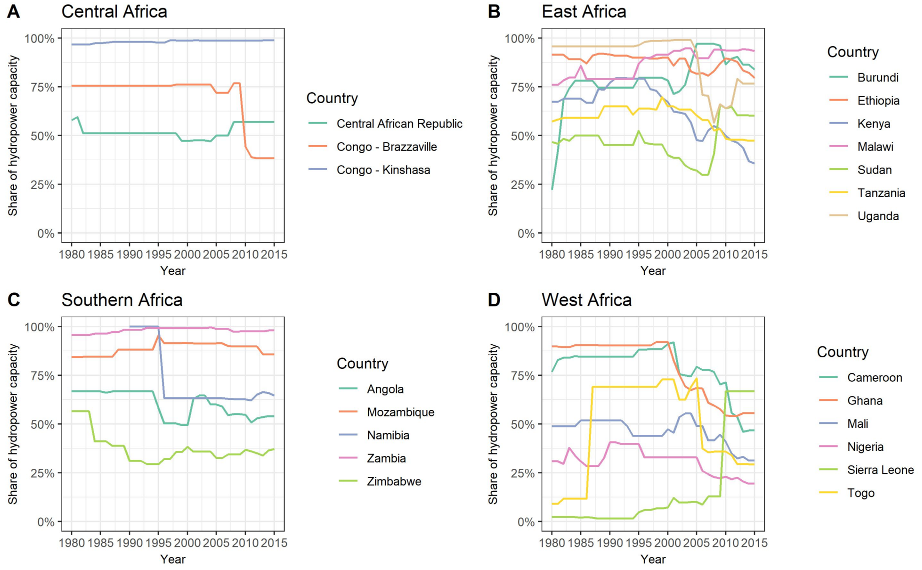


Figure 4: Evolution of share of hydropower over total capacity. Elaboration on data from (US EIA, 2017).

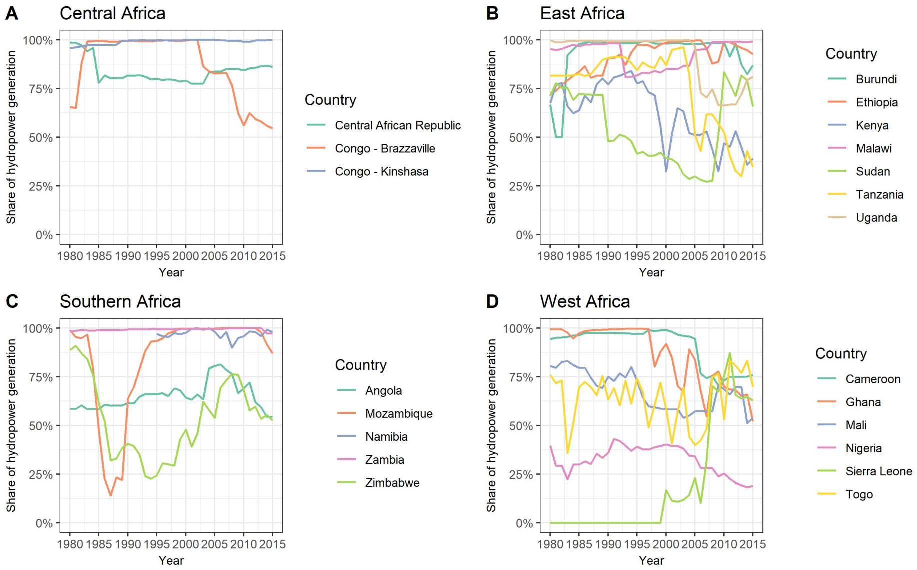


Figure 5: Evolution of share of hydropower over total generation. Elaboration on data from (US EIA, 2017).

The numbers on the share of hydropower generation show that only some countries have successfully pursued a diversification strategy over the last three decades. These include Tanzania (panel B), where hydropower fell from 95% in year 2000 to a low of 37% in 2015 thanks to the installation of 700 MW of gas-fired plants over the last decade; the Republic of Congo (panel A), where the delivery of a 300 MW gas-fired power plant in 2011 led to a temporary diversification (but further 1,600 MW of new hydropower capacity are planned); Ghana (panel D), where hydropower fell from a share of 80% in 2000 to around 50% in 2015. However, in the case of Ghana diversification via gas-fired capacity addition tells only part of the story for the reduction of the share of hydropower over total generation. Droughts and consequent water level reductions of Lake Volta over the last decade have in fact been significant contributors to the observed drop in hydro generation and consequent power supply issues experienced since (Boadi & Owusu, 2017), leading to deployment of emergency capacity.

This and analogous trends are detected when examining the trend in the national hydropower capacity factors reported in Fig. 6. Capacity factors are defined as the effective hydropower output over the total maximum theoretical output over a certain time period (here: yearly). Note that the dipping to a near-zero level in Mozambique between the early 1980s and the late 1990s is owing to the damaging of the dam during the civil war years,

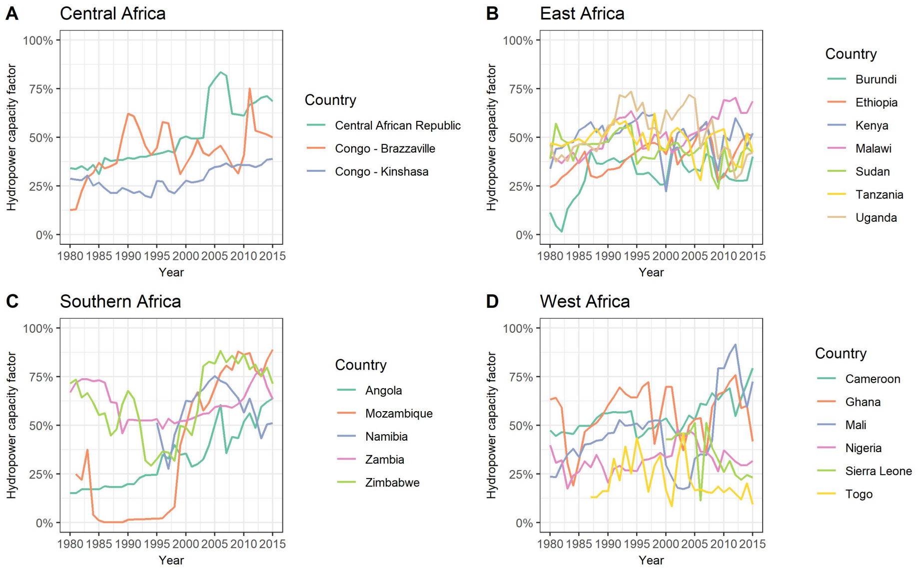
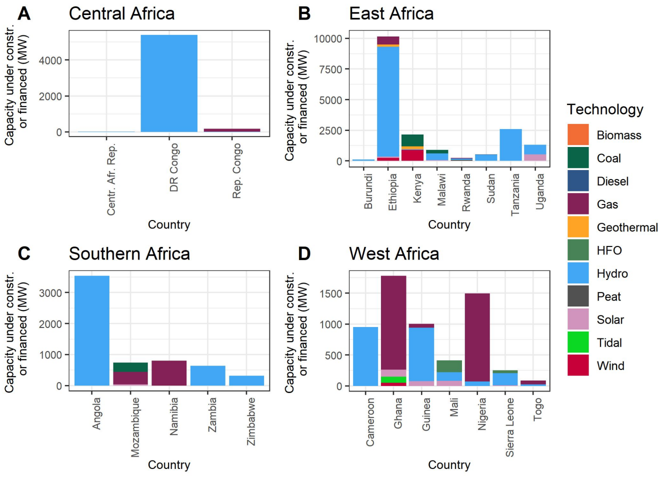
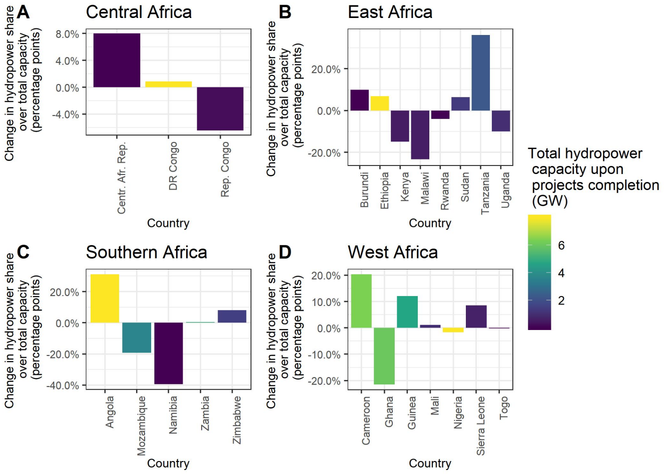


Figure 6: Evolution of hydropower capacity factors. Elaboration on data from (US EIA, 2017).

Fig. 7a shows the generation capacity currently under construction or for which financing has been already procured. The figures are clustered by region and technology. The figures exclude proposed or planned schemes which are still in the feasibility assessment or for which financing has not yet been secured. Information has been retrieved from (Cross-Border Information, 2017), as well as from an extensive screening of recently published African news reports. Fig. 7b shows the change in hydropower share over the total capacity that would result from the completion of those construction works (as compared to the current situation).



(a)



(b)

Figure 7: (a) Power generation capacity currently under construction or financed, by technology and region. (b) Change in the projected share of hydropower (in percentage points) in total capacity upon completion of the currently under construction/financed power plants. The colour shading indicates each technology and the total installed hydropower capacity in (a) and (b), respectively.

The figures reveal that the largest undergoing capacity additions are concentrated in a limited number of countries, and only in West Africa and partially in East Africa (mostly in Kenya) large-scale non-hydro expansions are undergoing. GW-scale hydropower capacity is being added in the DR Congo, Ethiopia, Tanzania, Angola, and Guinea. Gas-fired generation is the second technology by planned capacity, especially in Ghana, Nigeria, and Angola. However - crucially - a hydro-to-gas transition for baseload capacity would not be compatible with the Paris Agreement's goals over the long run. Countries with strong, RE-based diversification away from hydropower currently include Kenya (with a prominent role of geothermal and wind) and Uganda (with substantial solar PV capacity additions). While Ghana is implementing significant RE projects in solar PV, wind, and tidal power, the bulk of the planned capacity additions are based on gas.

Overall, in the short-run diversification - at least in terms of domestic installed capacity - will be strongest in Namibia (-39%), Malawi (-23%), Ghana (-21%), Mozambique (-19%), and Kenya (-15%), all countries which over the last years have been affected by drought-related outages. On the other hand, hydropower dependency will become stronger in Tanzania (+36%), Angola (+31%), Cameroon (+20%), Guinea (+12%), Burundi (+10%), Sierra Leone (+9%), the Central African Republic (+8%), and Zimbabwe (+8%).

4.2. Drought incidence

To assess the evolution of the incidence of drought events in the main river basins of SSA, we retrieved the World Resources Institute's major watersheds of the world shapefile (World Resources Institute, 2006) and extracted the monthly time-series of the average SPEI48 (Standardized Precipitation-Evaporation Index)(Beguera & Vicente-Serrano, 2017) over each of the nine major basins in terms of current installed hydropower capacity. Here, 48 denotes the scale of the index, in which dryness and wetness are defined as a function of the time scale over which water deficits accumulate. A long-term scale allows detecting long-lived, prolonged droughts, while short-term scales are better suited for droughts covering a limited period of time, such as the growing season in agricultural studies. The index is calibrated on precipitation and evapotranspiration data between 1950 and 2010. The 60-year calibration time-scale allows accounting for natural variability and seasonality and allows thus detecting anomalies. Refer to Fig. S1b for a map showing the location and extent of each basin. The data is then aggregated to produce: (i) counts of the number of drought months over 23-year periods (in order to have a consistent width across periods); (ii) counts of years that witnessed at least a drought month, and (iii) yearly average values for the SPEI48 (the classification of which is reported in Table S1). The metrics shed light on the frequency of extremes, and on the general trend in the average wetness/dryness level, respectively.

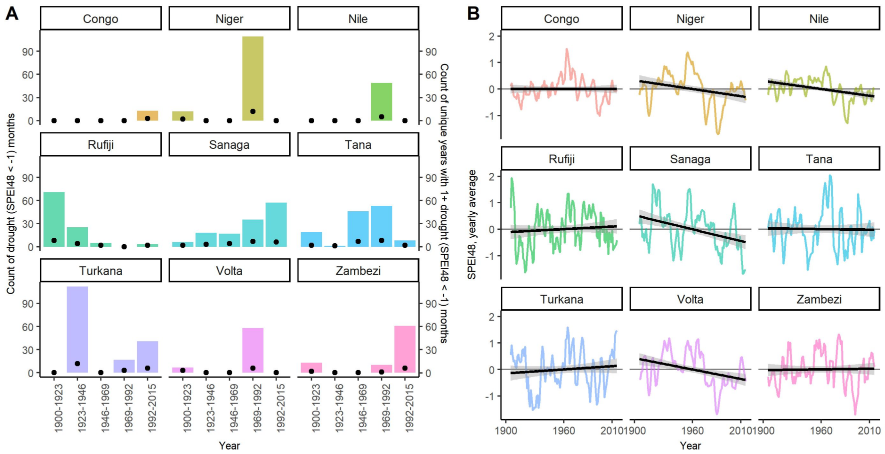


Figure 8: Historical representation of droughts in SSA rivers, (a) drought (SPEI48 ≤ -1) months per period (bars) and count of unique years with 1+ severe drought months (dots); (b) yearly average SPEI48. Elaboration on data from (Beguera & Vicente-Serrano, 2017), developed using monthly data from (University of East Anglia Climatic Research Unit (CRU) et al., 2017).

The results (Fig. 8) show that the frequency of drought months (here defined as months with a SPEI48 < -1) has changed heterogeneously across river basins during the twentieth century. The number of drought months seems to have been gradually growing in the Sanaga, Turkana, Volta, and Zambezi river basins, although many of these trends are not linear. Furthermore, the Congo, Niger, and Nile basins - previously only mildly affected by droughts - have experienced a very significant drought incidence in the last decades of the twentieth century. The only main exception is found for the Rufiji basin, where the incidence of droughts has declined during the past century. At the same time, the dots in Fig. 8a show the number of years in each 25-year period where at least 1 month of drought was experienced, giving a clearer picture on the frequency of droughts, besides their total duration. Again, this reveals non-linear, basin-specific trends. At the same time, the yearly average measured SPEI48 (Fig. 8b) has witnessed a robust decline, implying a drying of the local climate, in the Niger, Nile, Sanaga and Volta river basins, while statistically insignificant changes characterise all the remaining basins assessed.

4.3. Climate change projections

Further evidence to support the discussion of the results of the review is derived from downscaled CMIP5 (Coupled Model Intercomparison Project - phase 5) data for two RCP scenarios (2.6 and 8.5) from the IPCC (corresponding to 1.5 degree warming by 2100 and a business-as-usual trajectory, respectively). Data is averaged across the output of the 19 models in the CMIP5 consortium on country-level. Fig. 9 and 10 show the seasonal charts (i.e., the monthly profile) of the projected change in the mean precipitation and temperature across East, West, Central, and Southern Africa with respect to the historical mean of each specific month.

Concerning the projected shifts in the monthly profile of mean temperature (in °C) *vis-à-vis* a RCP 2.6 of mitigated climate change, an average increase of 3.5°C and up to 5°C by 2090 would occur across the different regions in a rather similar fashion (Fig. 9). The largest temperature increase would emerge after 2040 under a RCP 8.5 scenario. However, in countries that already have higher-than-average temperatures at the continent level, such as Congo, Sudan, Ghana, Togo and Mali, those changes might exert an ever stronger effect on evapotranspiration.

Predicted changes in the monthly profile of mean precipitations under the two RCPs (Fig. 10) provide instead a general picture of countries that could be more or less resilient to different degrees of warming in terms of water availability via direct rainfall. Trends are more heterogeneous than for temperature, and yet they show that in some regions (in particular in East and Central Africa) a larger change in radiative forcing could also have a wetting effect on the local climate with respect to a heavy abatement scenario. The most consistent declines in rainfall under unmitigated climate change are forecasted in Southern Africa, where rainfall could drop of up to $20mm/month$ in the wet season months (October to March) compared to the historical average in those months.

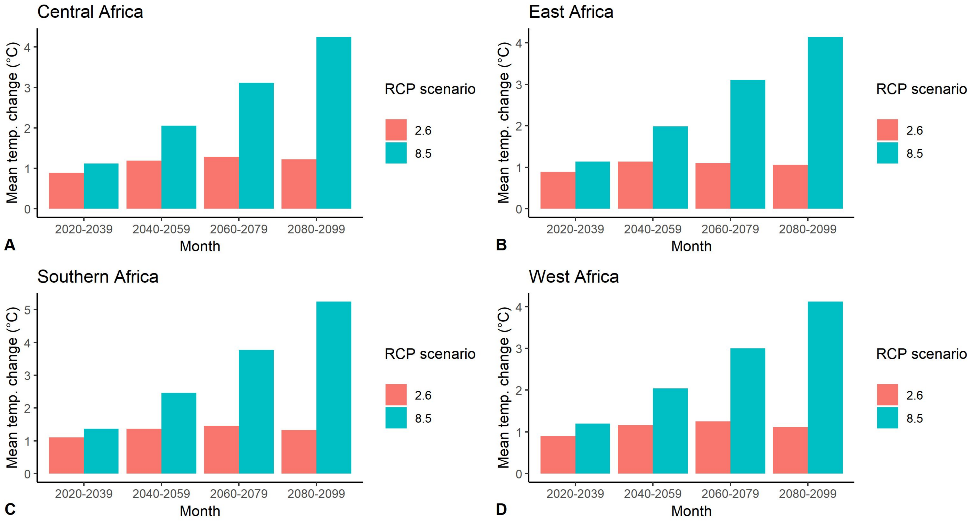


Figure 9: Seasonal plot of projected temperature change (compared to long-term historical averages) under two RCPs (CMIP-5 models median) over the 21st century for (A) Central Africa, (B) East Africa, (C) Southern Africa, and (D) West Africa. Elaboration on data from Taylor et al. (2012).

Finally, the annual severe drought likelihood change with respect to the average recorded between 1986-2005 describes the projected change in the likelihood

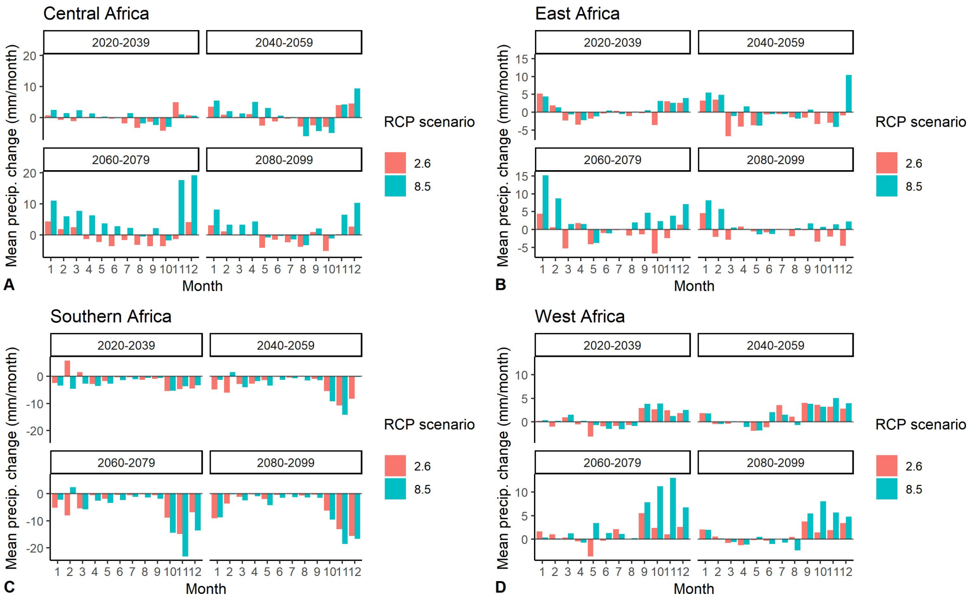


Figure 10: Seasonal plot of projected precipitations change under two RCPs (CMIP-5 models median) over the 21st century for (A) Central Africa, (B) East Africa, (C) Southern Africa, and (D) West Africa. A solid line is drawn at 0, to separate positive from negative change. Elaboration on data from Taylor et al. (2012).

of an extreme drought (defined as a SPEI < -2) to take place under the RCP scenarios 2.6 and 8.5 with respect to the historical incidence (Fig. 11). Irrespective of the predicted direction and magnitude of change in monthly precipitation patterns, in West, East, and Southern Africa RCP 8.5 is projected to lead to a consistently higher likelihood of extreme drought events to occur. While in East Africa the relative discrepancy between the predictions for two RCPs by 2100 is more limited (around +7.5%), in others the spread is substantial, and chiefly in Southern (+25%) and in West (+20%) Africa. Central Africa shows instead very little discrepancy in the probability of SPEI12 $<$ -2 periods to occur, and for the region the RCP2.6 results in an even slightly higher likelihood for severe drought incidence than RCP8.5.

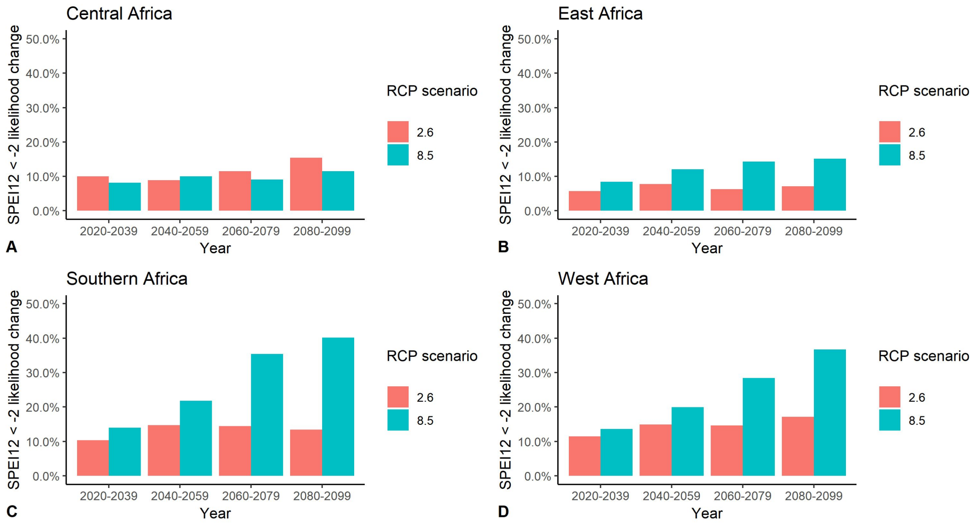


Figure 11: plot of projected severe drought (SPEI12 < -2) likelihood change change under two RCPs (CMIP-5 median) for (A) Central Africa, (B) East Africa, (C) Southern Africa, and (D) West Africa. Elaboration on data from Taylor et al. (2012).

5. Discussion

A large number of scenarios project hydropower as the main technology for procuring the on-grid capacity expansions helping to satisfy the growing demand for power in SSA, and achieving the SDG 7 of universal access to modern energy. HPP are deemed key assets thanks to the large untapped potential throughout SSA and the low running costs. Furthermore, international development institutions and national governments have been supporting hydropower thanks to its low carbon intensity. For instance, hydropower is considered eligible for the credits of the *Clean Development Mechanism (CDM)*, an emissions reduction program launched under the Kyoto Protocol (although life-cycle assessment studies have found instances where biogenic methane and carbon dioxide emissions stemming from artificial reservoir systems are significant (Zhang & Xu, 2015; Hertwich, 2013; Kumar & Sharma, 2012)).

Recently completed large schemes include the 250 MW Bujagali dam in Uganda, a 300 MW plant in Tekeze canyon in Ethiopia, and the 120 MW Djibloho dam in Equatorial Guinea. Significant expansion plans exist with different HPP under construction and massive projects proposed, such as the 39 GW Grand Inga Dam in DR Congo, expected to cost at least $50 billion and which has recently regained momentum (Financial Times, 2018). Other large ongoing or planned projects include the 6 GW Grand Renaissance dam on the Blue Nile river and the 1.8 GW Gibe III dam on the Omo river, both in Ethiopia, a 1.6 GW scheme on the Zambezi river basin between the Zambia-Zimbabwe border on the Batoka Gorge, and the 1.5 GW Mphanda Nkuwa project downstream of the Cahora Bassa reservoir in Mozambique.

As a result of those potential large-scale expansions, the climate-water-energy nexus is prone to become increasingly important in SSA. Water is a key node in development and economic growth dynamics of the continent owing to its strong interconnections it presents with a number of economic sectors, in particular where adaptive capacity is constrained. Climate change is expected to affect water availability for several end-uses, including hydropower and cooling in thermal power plants. Projected impacts (in particular those on precipitations and drought events occurrence) are, however, spatially and temporally heterogeneous and multiple sources of uncertainty exist at different scales as a consequence of modelling and parametric uncertainty (Arnell & Gosling, 2013; Schewe et al., 2014).

The results of our review show that the problem is highly basin-specific: some countries could face harsher issues due to structural long-run declines in generation potential (mostly in West and Southern Africa, although even within regions there can be large discrepancies between different river basins, see Stanzel et al. (2018)), while others (chiefly in East Africa) would benefit from increased yearly aggregate potential but also be more affected by extreme events, and some may not be substantially impacted. Changing seasonality patterns can also play an important role in the energy-water nexus, both in terms of streamflow and of electricity prices, and thus of revenue fluctuations (Gaudard et al., 2018). Therefore, dam planning must be careful and take into account the potential changes in river discharge and the increasing evapotranspiration trends among reservoirs as a result of a warmer climate (also depending on the global emission pathway followed in the coming decades).

Given the already high reliance on hydropower of a number of countries, risks of severe power disruptions (or of inter-sectoral competition for water resources) are likely to intensify if sound energy policy aimed at diversification, co-integration of different sources, and resilient and adaptive dam management (Kim et al., 2017) over multiple future scenarios is not implemented. In particular, hydropower generation is associated with the highest risks in countries where little alternative generation capacity is available and transboundary high-voltage transmission infrastructure for exchanging power is weakly developed. Combined, these could result in declining long-run hydro generation as well as in occasional outages in periods when multiple stressors overlap. This is particularly challenging in countries where the bulk of new base-load power additions will also be hydropower, which, if failing, may lead to substantial underprovision issues.

It is therefore crucial to design long-run strategies including power mix diversification for many SSA countries. Care must be taken in designing diversification pathways in the coming years: heavily expanding gas, coal, and diesel-fired plants - which could be considered less insecure than hydropower irrespective of resources price fluctuations - may set countries on a higher carbon-intensive pathway than those agreed in their Nationally Determined Contributions (NDCs). Different options exist, such as the possibility that part of the back-up stems from decentralised generation solutions (e.g. off-grid PV installed by grid-connected consumers), and planning power systems to integrate diverse zero-carbon sources (solar, wind, water, etc.) and technological advancements for balancing and storage. The success of these options depends on their strategic integration in the governmental energy planning. Energy security objectives and policy must be developed hand in hand with potential emissions mitigation and through the adoption of climate-resilient infrastructure and projects. Renewables can contribute to breaking the feedback loop between fossil fuels combustion, water withdrawal and consumption, and climate change, and in turn positively impact on water, food and energy supply, as well as boost economic growth prospects (refer to the framework presented in Fig. 3a). At the core of these linkages lie an integrated and effective energy and climate policy capable of recognising interdependencies, including those that will become stronger in the coming years

Multidisciplinary research plays an important role in quantifying potential climate change impacts on power generation security so as to provide policy makers with figures to inform their cost-benefit-analysis and infrastructure investment decisions (Frumhoff et al., 2015). Concerning the specific case of the impact of climate change and extremes on hydropower generation in SSA, both an analysis of energy, economic, and social impacts of short-lived extremes jeopardising generation in hydropower-dependent countries (e.g. Falchetta (2019)), and model-based research on long-term water supply under different energy, economic, climate, and demographic scenarios (e.g. Sridharan et al. (2019); Vinca et al. (2019)) are deemed of great significance. Ever more openly available, accurate, and standard-quality remotely-sensed and modelled river discharge data are likely to allow a new level of insight in this sense. Energy-climate-economy IAMs, and in particular regional-scale nexus-oriented ones, can provide additional insights. Their coupling with basin-level hydrological models under different potential futures could yield greater and more detailed information on water stress risks in different regions, and thus inform policy makers on the consideration of hydropower capacity expansion as well as on the climate-induced supply disruption risks.

5.1. Implementing hydropower in sub-Saharan Africa: the way forward

Recent years have witnessed a steep increase in the construction of hydropower dams, including in SSA (Zarfl et al., 2015). At the same time, the remaining techno-economical potential in the continent is large. An effective implementation of new schemes requires the adoption of a nexus approach (de Strasser et al., 2016), including within the modelling tools adopted by energy planners. These should be able to co-optimise energy-water-food systems at a transboundary scale in order to assess complementarities beyond the surroundings of the scheme being planned. This is crucial to avoid dam planning based only on energy-system optimisation, which can easily lead to strong impacts on livelihoods, the agriculture sector, and local livelihoods, which might render the overall project's cost-benefit-analysis negative. Transboundary planning thus requires to bring the energy planning dialogue at a regional scale, also because the technical hydropower potential is defined at the watershed, and not at the country level (de Souza et al., 2017).

Furthermore, moving to more flexible dam management strategies, where hydropower is not only a baseload technology but also a balancing solution for VRE integration, may be a very meaningful prospect for promoting a low-carbon energy development in parts of SSA (Sterl et al., 2019, 2018). This could prevent a significant share of the uptake of gas and coal-fired thermal plants. The approach could also reduce the need for very large-scale hydropower schemes (Deshmukh et al., 2018), which often are associated with substantial environmental and social impact.

Finally, as this review has highlighted, hydropower planning should necessarily account for the potential non-stationarity of runoff under different climate futures, and consider the incidence of disruptions or temporal as well as structural declines in the production.

6. Conclusion

This paper developed a nexus framework for the energy-water-land nexus in SSA, and carried out an extensive screening of the most recent literature on the projected impacts of climate change on hydropower. These have been linked to the issues that a significant number of countries largely or entirely depend on hydropower generation and currently have little back-up options available, implying risks for supply reliability. Evidence from the literature pointed at a number of key facts. First, the state-of-the-art on climate-induced risks for power supply - and in particular on hydropower generation - finds heterogeneity in projected trends across the SSA region, while it also identifies some consistent trends at the regional level. Irrespective of uncertainty in the expected change of precipitation levels and patterns, different studies that adopted different methodologies seem to be rather consistent in pointing out that countries in East Africa could positively benefit from a warmer climate in terms of its hydropower output, while West and Southern Africa would be subject to negative impacts. Central Africa would be the least affected sub-region in terms of precipitation change and drought incidence. However, the magnitude of these changes displays large uncertainty ranges, sometimes covering positive as well as negative changes.

An observation of the relevant data shows that only some countries have successfully pursued a resilience-building strategy to prevent hydropower disruptions over the last three decades. Even in those countries, power mix diversification was however hitherto mostly based on natural gas, such as in Tanzania, the Republic of Congo, and Ghana. Other countries, including Malawi, Zambia, DR Congo, and Namibia, have remained entirely dependent on hydropower. Some virtuous examples of non-hydro RE-based diversification exist, such as Kenya, where significant capacity in geothermal and wind has been and will be added. At the same time, capacity expansions under development will lead to an even higher dependency on hydropower in Tanzania, Angola, Cameroon and Guinea, at least in the short term. An assessment of the long-run evolution of the SPEI48 index reveals that hitherto the frequency of drought events and the general dryness have evolved non-linearly and heterogeneously across the major river basins of SSA. Nonetheless, some of the major basins (i.e., the Niger, Nile, Sanaga, and Volta) have witnessed a significant drying. Current and future strategic energy decisions will thus have a major impact on the resilience of energy systems in SSA. Countries - in particular those highly reliant on hydropower - should plan the mix of capacity additions accordingly and increase adaptive capacity under extremes to safeguard energy security. A missed diversification may hinder economic growth prospects. The adoption of nexus approaches and modelling tools able to consider sectoral and transboundary interdependencies in dam planning are recommended. Furthermore, new dam management paradigms in complementarity with a large penetration of VRE must be developed, as they allow for a greater balancing, supply security, and sustainability.

Data availability

The raw data on which the data analysis is based on are openly available, and the corresponding sources are cited in the article. The R code for figures and statistical replication, as well as the processed data can be accessed upon request to the corresponding author.

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Conflict of interest

Declarations of interest: none.

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