Water-Power nexus in African Power Pools – The Dispa-SET Africa model

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ABSTRACT

The operation and economic profitability of modern energy systems is constrained by the availability of renewable energy and water resources. Lower water availability due to climate change, higher demand and increased water consumption for non-energy and energy needs may cause problems in Africa. In most African power systems, hydropower is a dominant renewable energy resource, and interconnection capacities are usually limited or unreliable. This paper describes a new modelling framework for analysing the water-power nexus in the African Power Pools. This framework includes soft linking between two models: the LISFLOOD model is used to generate hydrological inputs and the Dispa-SET model is used for mid-term hydrothermal coordination and optimal unit commitment and power dispatch over the whole African continent. The results show a good agreement between the model outputs and the historical values, despite data-related limitations. Furthermore., the simulations provide hourly time series of electricity generation at the plant level in a robust way. It appears that some African power pools heavily rely on the availability of freshwater resources, while others are less dependent. In the long term, the dependence of the power system on water resources is likely to increase to meet the increasing electricity demand in Africa.

Key Words: African Power Pools, Water-Energy Nexus, Power Dispatch, Dispa-SET,

1. INTRODUCTION

Access to a stable and secure supply of energy is a fundamental driver of economic growth in Africa. More than two-thirds of the population, approximately 600 million people, especially in Sub-Saharan Africa, lacked access to electricity in 2016, and 850 million people had no access to clean cooking facilities such as natural gas, liquefied petroleum gas, electricity and biogas, or improved biomass cook stoves [1]. Africa's economic activity continues its growth. The economic growth is estimated at 3.4% in 2019 and is set to increase between 3.9 and 4.1% in 2021 [2]. A key point to support this growing demand is the presence of reliable and effective electricity infrastructure. To this end five regional power pools (regional cooperation entities aimed to developing a common power grid and a common market between their members) have been established in the last 20 years to improve generation capacity and allow cross-border trade.

Water-energy nexus refers all the interactions between the water and the energy sector. The combined effect of increased water consumption, for energy and non-energy purposes, with lower availability of water resources due to climate change, is expected to lead to monetary losses, power curtailments, temporary shut-downs and demand restrictions in power grids across the world [3]. Similar impacts of climate change on stability of power grid are assessed in [4] and vulnerability of electricity supply in US and European grids was analysed in [5] and [6]. The electricity demand in the all the African countries is expected to rise dramatically in the next decades and the entire generation capacity is projected to increase ten-fold by 2065 and consumption of water is expected to increase 7% by 2050 and hydropower, in most African energy systems, will continue to play a very important role, increasing its electricity production from 3 to 5 times in most of the power pools [7]. However, currently the energy systems, in most of the continent are characterized by their small sizes, the low electrification rates, the high shares of oil in the power generation mix, and the lack of significant power and gas interconnections [8].

Many initiatives such as The United Nation's Sustainable Energy for All[2] and Power Africa[3] focus on the sustainable development of African energy systems. Their aim is to electrify some 60 million homes and support the investment of 30 GW of clean power generation in the near future. Despite this, however, there is no coherent 'by country' and 'by region' set of scenarios besides the ones proposed by Taliotis et al. [9], nor an open energy system analysis platform that may be used to carry out a more detailed investigation of the proposed long term generation expansion scenarios.

[1] The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.
[2] https://www.seforall.org/
[3] https://www.usaid.gov/powerafrica

The purpose of this study is: a) to examine the potential for and relationship between current and future electricity situation and power trade between countries in the selected power pools and b) investigate the synergies between the water and energy sectors by assessing the hydropower potential. The goal is to refine similar previous studies, and notably the TEMBA model (The Electricity Model Base for Africa) [10], with a higher temporal resolution (8760 time periods per year) and a more detailed description of the power fleet second objective is the investigation of synergies between the water and energy sectors by assessing the hydro potential in the proposed region through several what if scenarios in regard to the availability of water for energy purposes in dry and wet seasons. This paper also identifies areas where grid extensions would be beneficial to the cost-optimal growth of the African electricity supply system. Cross border interconnections with Europe and other African power pools, despite their significant potential for the future [11], are out of the scope of this paper.

The main contributions of this study are as follows:

- An open-source unit commitment and optimal dispatch model covering the whole African continent
- A methodology for the analysis of the water-power nexus in Africa.
- A compilation of diverse data sources used for the integrated modelling of the five African Power Pools.
- The assessment of the hydro potential in the proposed regions through several what-if scenarios with regard to the availability of water for energy purposes in dry and wet seasons.
- The identification of grid bottlenecks and areas where grid extensions would be beneficial for the African electricity supply system.

2. METHODS

This section describes the different tools, techniques and methods used within this study. The proposed modelling framework heavily relies on publicly available information and data. Figure 1 provides an overview of this framework of its interrelationships with the input data. It comprises five main elements: data sources, model inputs, pre-processing, simulation, and calibration. The steps and data used for the calibration exercise are also indicated. The historically available input data, in the form of hourly time series, is complemented with the data from other tools and/or models, such as LISFLOOD, and/or annual reports or statistical databases. Because of relatively low data quality and availability at the continental level, some input are benchmarked at a country-level with historical data for 2018 retrieved from IEA, IRENA and IHA datasets as indicated on the right side of Figure 1. Through an iterative process, generator characteristics are calibrated (indicated with the red connections) to reproduce the 2018 context. These inputs include demand projections, costs, installed capacities (aggregated either per fuel or technology type), net transfer capacities (NTC) and energy flow limits between zones, demand profiles and annual generation. Four models are used to fulfil the objectives of this work:

- LISFLOOD[4] model - used for simulation and generation of multiannual hydro profiles;
- Dispa-SET Side Tools package[5] – used as the data translation and calibration model between the publicly available datasets and LISFLOOD outputs, and the Dispa-SET[6] input database;
- The Dispa-SET mid-term hydro-thermal scheduling (MTS) module - used for the pre-allocation of large storage units (horizon length of 365 days), and
- The Dispa-SET UCM module - used to optimize the short-term (horizon length of 4 days) unit commitment and power dispatch in considered zones (countries).

The input data was collected from "best" publicly available sources. In some cases, the data was complemented or corrected using more detailed dataset (e.g. relative to a single country or to a single river basin). All data is openly available under the FAIR Guiding Principles for scientific data management and stewardship allowing users to modify or recreate the model in other simulation environments [12]. The data processing workflow is also thoroughly documented and is provided as electronic annex of this paper.

[4] https://github.com/ec-jrc/lisflood-code
[5] https://github.com/MPavicevic/DispaSET-SideTools
[6] http://www.dispaset.eu

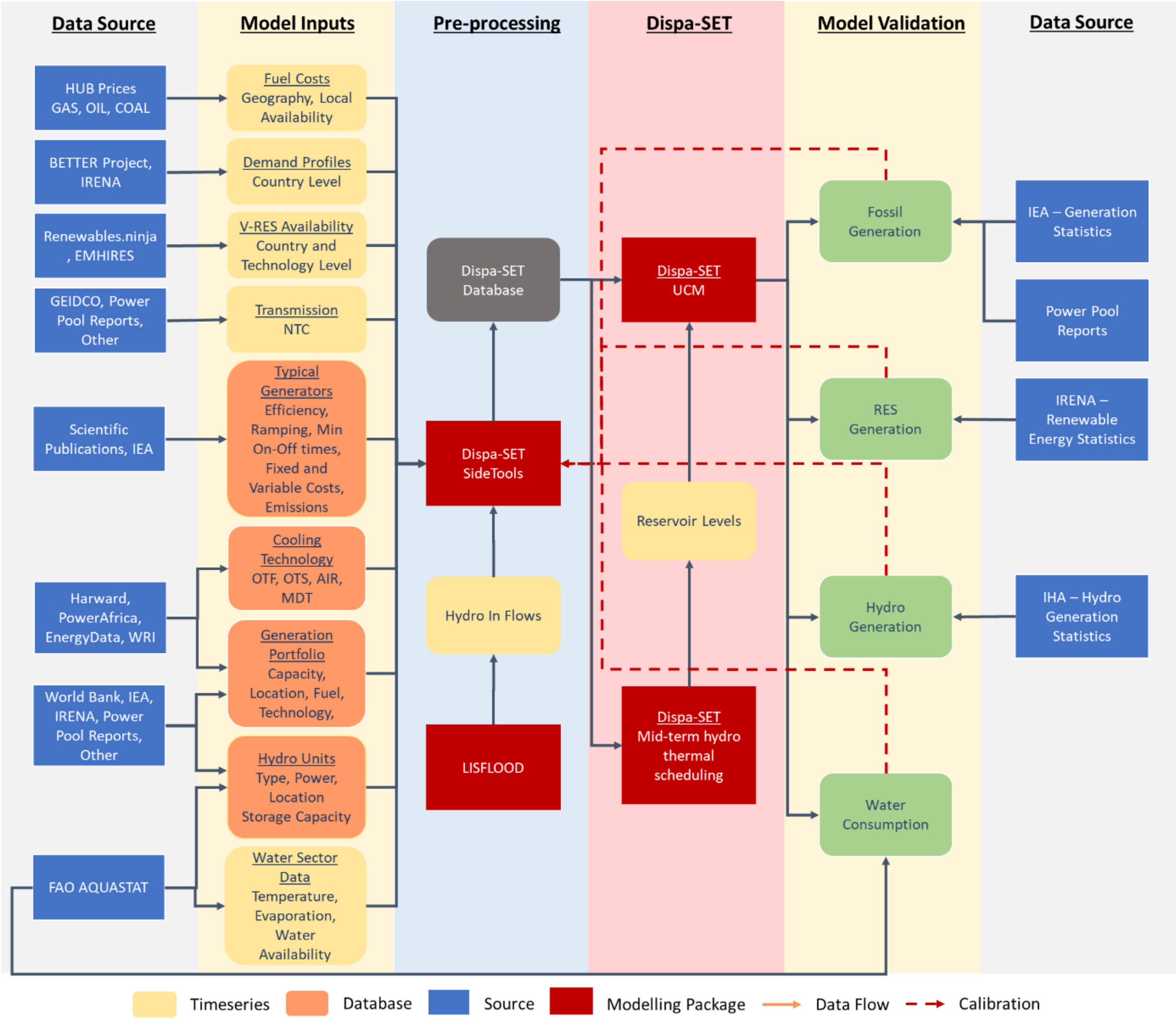

Figure 1 Flow chart visualizing the different steps for the modelling framework within this study.

2.1. Computation of hydro dam inflows and run-of-river availability factors

Hydropower inflows in m^3/s are computed using a standard LISFLOOD model [13] setup for a particular river basin and particular geographical location. This setup includes a three-layer simulation of soil-water balance, flow of subsurface and groundwater, routing of surface runoff to the nearest river channel and routing of the channel flow. Besides, snow melt, infiltration, interception of rainfall, leaf drainage, evaporation and water uptake by vegetation, surface runoff, preferential flow (bypass of soil layer), exchange of soil moisture between the two soil layers and drainage to the groundwater, sub-surface and groundwater flow, and flow through river channels are considered [14]. LISFLOOD outputs usually generate relatively high water availabilities (WA) for energy needs only and for the considered location. In order to assess the share of WA for hydropower generation, technological features, such as nominal head, maximum power capacity, volume and surface area of the reservoirs, as well as satellite-based data such as average, minimal and maximal daily air temperatures and daily solar irradiation, need to be properly assessed. Evapotranspiration is calculated for each unit and geographical location, as proposed by [15]. They are then subtracted from the LISFLOOD outputs.

For some hydro units, the computed inflows (potential energy in accumulation reservoirs behind the dams, in MWh) are orders of magnitude higher than the historical generation. This is due to the limited quality of the input data and to inaccuracies in the definition of the catchment basins for these units. To remediate this, parameters such as hourly availability factors for hydro run-of-river (HROR) units and capacity factors for hydro dams (HDAM) and pumped storage (HPHS) units are corrected using an iterative two-stage calibration method (Figure 2).

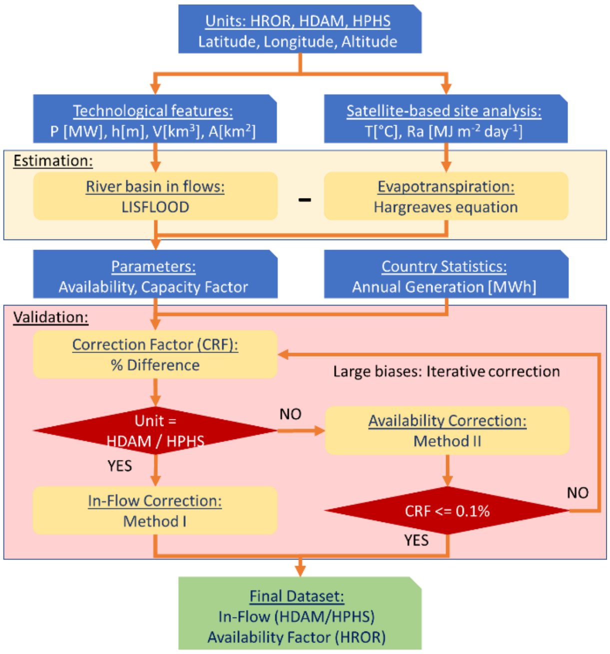

Figure 2 Flow chart visualizing the generation of availability factors time series for run-of-river (HROR) and scaled inflows time series for hydropower dam (HDAM) units.

The first iteration computes the difference between annual generation and computed inflows. Based on the unit type, one of the two scaling methods is selected. For HDAM and HPHS units, inflows are scaled proportionally to match the yearly output. It is assumed that spillage is low and can be neglected thanks to large storage reservoirs usually representing several hundreds of hours of full load capacity. In the case of HROR units, a second method is applied to account for the lost energy due to spillage. This typically occurs when inflows are higher than the design flow rate of the turbine. The following iterative five step methodology is introduced:

$$\begin{aligned}
&\text{I)} \quad InFlow_{u,i} = InFlow_{u,i} \cdot (1 + Correction_u) \\
&\text{II)} \quad Spill_{u,i} = InFlow_{u,i} - PowerCapacity_u \\
&\text{III)} \quad Spill_{u,i}(Spill_{u,i} < 0) = 0 \\
&\text{IV)} \quad InFlow_{u,i} = InFlow_{u,i} - Spill_{u,i} \\
&\text{V)} \quad Correction_u = \frac{HistoricGeneration_u - \sum_{i=1}^{i=n} InFlow_{u,i}}{\sum_{i=1}^{i=n} InFlow_{u,i}}
\end{aligned} \qquad (1)$$

these inflows are scaled to match the yearly output, and spillage recomputed using the given inflows. If the newly computed HROR is close to the historical values, the iteration stops, otherwise new correction factors are applied to the initial inflows and the next iteration starts.

2.2. Fuel price forecasts

Variability of fuel prices is estimated based on a fingerprinting algorithm. This type of algorithm maps large data (in this case: geography, local production and transportation and resource availability) to a much shorter sequence of information, referred to as "fingerprint", used to determine a value of interest (in this case: fuel price). While fingerprints may identify the original data, the original data cannot be derived from its fingerprint. For each fuel type, one fingerprint per category is used to increase or decrease the final fuel price, as proposed in [16]. In each zone, one fingerprint is defined by the: local fuel production (yes/no) and means of transportation (rail, truck and/or ship or through international pipelines), access to a major sea port (yes/no), and local resource availability (biomass, and peat scarcity/availability). A summary of the proposed algorithm is presented in Figure 3.

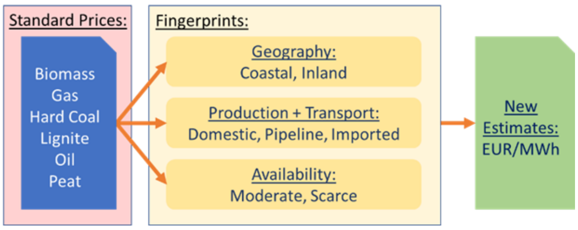

Figure 3 Fuel price estimation based on three fingerprints: geography, fuel production and availability.

2.3. Power system model

The central point of this study is the computation of optimal operation of power generation fleet in several interconnected power pools. This is achieved using the open-source Dispa-SET model, a cross sectoral unit commitment and power dispatch model [17]. As indicated in Figure 1, optimization in Dispa-SET is split into two stages: a hydro-thermal mid-term scheduling and a classical unit commitment (UCM) and power dispatch stage. Both stages use the same input dataset, pre-processed and created by the intermediate Dispa-SET side tools package, as described in the previous sections. The short-term Dispa-SET UCM module optimizes the power dispatch of individual generator units, energy flows between interconnected zones, variable renewable energy source (VRES) curtailment, shed load, carbon emissions, interactions between water and energy sector, shadow prices, water values etc. It is expressed as a MILP problem and integrates diverse clustering techniques and a rolling horizon optimization to ensure computational tractability [18]. The model outputs are then analysed, and relevant water-energy nexus metrics are computed. A detailed formulation of the Dispa-SET model is out of the scope of this paper. All relevant equations and constraints can be found in [19], and detailed description of the clustering approaches is further discussed here [18]. The main constraints of the model are as follows:

- Technical limits on minimum and maximum power generation for individual units,
- Multiple storage technologies (hydro, thermal, etc.)
- Ramping limits, start-up and shut down times and minimum on and off times,
- Non-dispatchable units (e.g. wind turbines (WTON), solar photovoltaics (PHOT), hydro run-of-river (HROR), etc.)
- VRES Curtailment,
- Shed load as the main measure of the adequacy of the system,
- Up and down reserve requirements (spinning and non-spinning),
- Detailed representation of fixed and variable costs
- Multiple nodes with constrained interconnection capacities (congestion management)

In the following chapters, the equations relevant for this study are presented and discussed in more detail.

1.1.1. Objective function

The objective function of the Dispa-SET model can be summarized as follows:

$$\text{Min}\, TotalSystemCost = \sum_{\forall u,i} \left(\begin{array}{c} CostStartUp_{i,u} + CostShutDown_{i,u} + \\ CostFixed_{u} \cdot Committed_{i,u} + \\ CostVariable_{i,u} \cdot Power_{i,u} + \\ CostRampUp_{i,u} + CostRampDown_{i,u} + \\ PriceTransmission_{i,l} \cdot Flow_{i,l} + \\ \sum_{n} \left(CostLoadShedding_{i,n} \cdot ShedLoad_{i,n} \right) + \\ VOLL_{Power} \cdot \left(LL_{MaxPower,i,n} + LL_{MinPower,i,n} \right) + \\ VOLL_{Reserve} \cdot \left(LL_{2U,i,n} + LL_{2D,i,n} + LL_{3U,i,n} \right) + \\ VOLL_{Ramp} \cdot \left(LL_{RampUp,u,i} + LL_{RampDown,u,i} \right) \end{array} \right) \tag{2}$$

Here $TotalSystemCost$, in EUR, are defined as the sum of different cost items such as: start-up and shut-down, fixed, variable, ramping, transmission-related and load shedding (voluntary and involuntary) over the optimization period.

1.1.2. Demand balance

The main constraint to be met is the power supply-demand balance, for each period and each zone, in the day-ahead market as proposed in the following equation:

$$\begin{aligned} \sum_{u} \left(\text{Power}_{u,i} \cdot Location_{u,n} \right) + \sum_{l} \left(\text{Flow}_{l,i} \cdot LineNode_{l,n} \right) = Demand_{DA,n,h} \\ + \sum_{r} \left(\text{StorageInput}_{s,h} \cdot Location_{s,n} \right) - ShedLoad_{n,i} - LL_{MaxPower_{n,i}} \\ + LL_{MinPower_{n,i}} \end{aligned} \tag{3}$$

According to this restriction, the sum of the power generated by all the units present in the node (including the power generated by the storage units), the power injected from neighbouring nodes, and the curtailed power from intermittent sources is equal to the day ahead load in that node and power consumed for energy storage, minus the shed load.

2.3.1. Hydro-thermal mid-term scheduling

Hydro-thermal mid-term scheduling (MTS) is a submodule of the Dispa-SET library. It provides a relaxed (LP) version of the classical and highly detailed MILP formulation of the unit commitment and power dispatch problem. Constraints linked to power plant cycling such as start-up and shut-down time, ramping rates, minimum up and down time, must run power and unit commitment are neglected. This enables a more efficient computation of the optimal (instead of exogenously supplied) reservoir levels which are then used as minimum level constraints in the UCM module. In the latter, the problem is split into smaller optimization problems that are run recursively throughout the year. The initial values of the optimization for any given day are the final values of the optimization of the previous day. A look-ahead period is included and then discarded to avoid issues linked to the end of the optimization period such as starting low cost but non-flexible power plants. This optimal hydro allocation is particularly relevant for the analysis of the water-energy nexus, where availability of water resources for energy needs is crucial for the operation of the power generators.

2.3.2. Power system indicators

The following indicators are computed from the model output:

- **Shadow prices** are computed for each hour and for each zone. The shadow price of electricity is the dual value of the energy balance equation. It can be interpreted as the clearing price of an ideal wholesale market.
- The need for **load shedding** highlights the inadequacy of the system. It is defined as the demand of the system that must be reduced to match the available supply [17]. A maximum value of the load shedding capacity is defined for each simulated country using the generic formula as described in [20].
- **VRES curtailment** refers to the intentional reduction of renewable generation. The total curtailed energy computed as a share of total available VRES generation and reflects the lack of flexibility in the system.
- The **carbon footprint** is computed using the standard emission factors for different fuel and technology combinations, as proposed in [21]. These emissions relate to emissions from power generation and operation of thermal units only (life cycle emissions are not considered) and are disaggregated on per unit level.

2.4. Water stress indicators

Water stress levels caused by the power generators are hugely influenced by the type of cooling technologies.

2.4.1. Cooling systems

Despite the use of multiple data sources, more than 30% of the units were left with unidentified cooling technology. In order to fill this gap, a cooling system selection matrix based on different fuel and technology (open cycle gas turbines – GTUR, combined cycle gas turbines – COMC, internal combustion – ICEN and steam turbines - STUR) combinations was applied (Table 1). This matrix is based on previous work from Macknick et al. [22] in the United States, Fernandez-Blanco et al. [3] in the Iberian peninsula, and Pappis et al. [23] for several African countries.

Table 1 Cooling system allocation algorithm for power plants where cooling type is not known. Values in the table indicate installed power plant capacities (MW).

Fuel	Id	Cooling	GTUR	STUR	ICEN	COMC
Biogas, Biomass, Straw, Wood, etc.	**BIO**	**AIR**	< 15	< 15	< 15	< 15
Geothermal	**GEO**	**MDT**	>= 15	>= 15	>= 15	>= 15
Hard Coal, Anthracite,		**AIR**	----	< 200	----	----
Bituminous Coal, Coke,	**HRD**	**MDT**	----	200-450	----	----
Steam Coal, etc.		**OTS**	----	>= 450	----	----
Natural Gas, Butane,		**AIR**	> 0	----	< 15	200-250
Methane, Propane, Liquified	**GAS**	**MDT**	----	< 20	----	> 0
and Synthetic Natural Gas		**OTS**	----	>= 20	>= 15	180-720
Crude Oil, Diesel, Fuel Oil,		**AIR**	> 0	< 15	> 0	< 15
Jet Fuel, Kerosene, Light Fuel	**OIL**	**MDT**	----	>= 720	----	>= 720
Liquefied Propane Gas, Methanol, Naphtha		**OTS**	----	15-720	----	15-720
Peat Moss	**PEA**	**MDT**	> 0	> 0	----	----

2.4.2. Water exploitation indicators

The water exploitation index (WEI) is an indicator of water stress, relating water uses (in this study this refers to water needs for energy sector only) to water availability (WA) as proposed by [24]. Within this study, several indicators of water use are defined:

- **Water withdrawal** (WW) is abstraction of water for an economic activity. Literature also refers to it as gross water abstraction or withdrawal [22].
- **Water consumption** (WC) is defined as the portion of water not being returned to the original water source after being withdrawn. WC occurs when water evaporates into the atmosphere or diverted for other usages. WC is also commonly referred to as net water abstraction or blue water footprint [22].
  Absolute water exploitation index (WEI^{Abs}) refers to the ratio of WW over WA. It can be any positive number, but normal range is between 0-5. Values above 1 do not indicate that more water is being withdrawn than potentially available because same water can be withdrawn multiple times along the supply chain (i.e. two hydro dams operating as a cascade on the same river are withdrawing same water two or more times).

$$WEI^{Abs} = \frac{WW}{WA_{Int} + WA_{Ext}} \quad (4)$$

- **Absolute internal water exploitation index** (WEI_{Int}^{Abs}) stands for all water abstractions (withdrawals) expressed as a ratio of the internally (local) available water.

$$WEI_{Int}^{Abs} = \frac{WW}{WA_{Int}} \quad (5)$$

- **Consumptive water exploitation index** (WEI^{+}) stands for WC over WA. It typically ranges between 0 and 1, but values above 1are also possible in extreme cases. Values above 0.2 are considered as critical in terms of water scarcity.

$$WEI^{+} = \frac{WC}{WA_{Int} + WA_{Ext}} \quad (6)$$

- **Internal consumptive water exploitation index** (WEI_{Int}^{+}) stands for WC expressed as a ratio of internally (local) available water.

$$WEI_{Int}^{+} = \frac{WW}{WA_{Int}} \quad (7)$$

These indicators are computed per country and per power pool.

3. THE AFRICAN POWER SYSTEM

3.1. African Power Pools

The geographical overview of African power pools within this study is presented in Figure 4. This is an extension of previous works done by the same group of authors, including a two separate models for the West African Power Pool (WAPP) [8], Southern African Power Pool (SAPP) [25], and another model covering the Central, Eastern and North Power Pools [26,27].

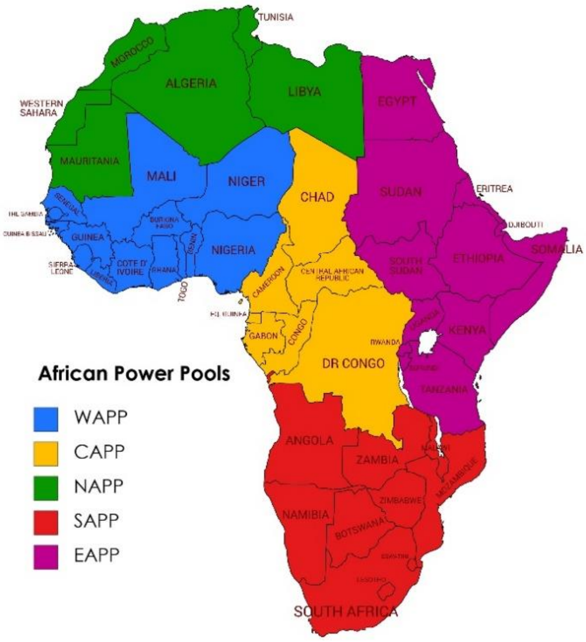

Figure 4 Classification of African Power Pools (The same colour code is used for individual power pools throughout the paper).

3.2. Scenarios

In order to evaluate the potential flexibility originating from the water-energy nexus in the African power pools, two scenarios are defined: the Baseline scenario referring to the power system from year 2018 and a High interconnections scenario referring to the short term expansion of the African power grid. Each scenario includes a detailed sensitivity analysis in which the power system is simulated over 39 weather years. For each weather year, different hydrological conditions are simulated.

3.2.1. Baseline

The Baseline scenario corresponds to the year 2018 and is run for the 39 weather years. NTCs between neighbouring power pools and NTCs between individual countries within the power pools are constrained by the existing power grid. Several countries (Central African Republic in CAPP, Eritrea and Somalia in EAPP and Gambia, Guinea, Guinea-Bissau, Liberia, Niger and Sierra Leone in WAPP) that do not share any cross border lines with the neighbouring countries are simulated in isolation. Although the results from this study are grouped by power pool, the simulations are carried out at the country level.

3.2.2. High Interconnections

The High Interconnections is the potential short-term grid expansion what if scenario. The main idea is to analyse the impact of planned grid expansion projects for the year 2025. The input data is obtained from the projects currently in development and from studies and reports from individual power pools and national regulatory agencies.

4. INPUTS

4.1. Hydrology

The availability of water resources for hydropower generation shows a strong inter-annual variability, as presented in Figure 5. For some regions, the range of the water inflow variations within the year is particularly wide, as for example for CAPP, where the share renewables range from 50.7% (in 1983) to 77.6% (in 1988).

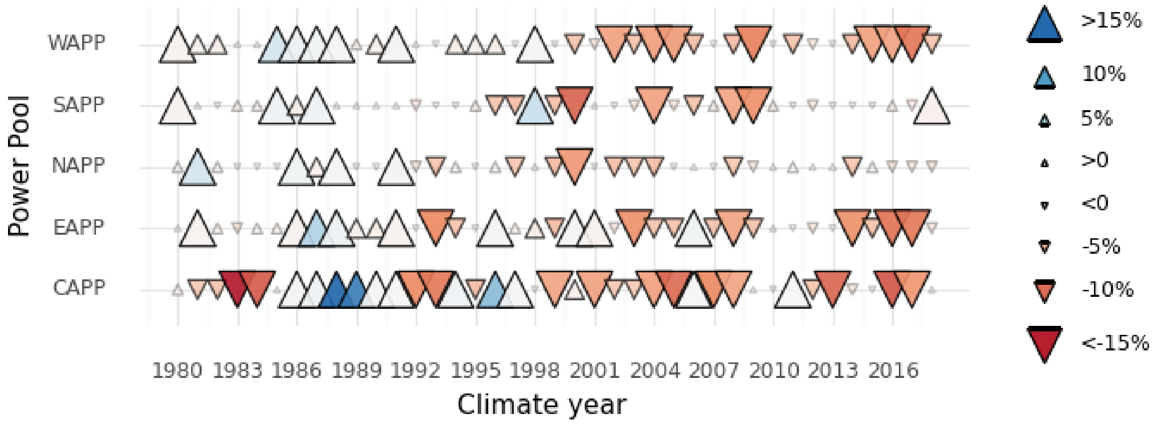

Figure 5 Annual variability (percentage deviation from the mean) of daily inflow in the 39 climate years for the considered power pools. The size of the triangles indicates the inter-annual variability, the direction of the rectangles highlights the increase or decrease compared to the mean and colour indicates the intra-annual (seasonal) variability within the individual power pools.

4.2. Capacity Mix

The total generating capacity of the African power pools sums up to 30.5 GW as shown in Table 2. Most values are based on the year 2018, but due to limited data availability, in some countries, latest known values were used instead. The sources for thermal power plant capacities are the "World Electric Power Plants Database" [28], the "African Energy Portal" [29], the "Global Power Plant Database" [30], Renewable Energy Statistics" [31], IEA [32] and IHA [33].

The largest share of installed generation capacity, around 76% (165.7 GW), corresponds to the thermal power plants (OIL, GAS and HRD). The second largest share of around 16% (35.8 GW) corresponds to hydro generators, and only 5% (11.6 GW) of the total installed capacity corresponds to variable renewables such as wind (WIN) and solar (SUN). The share of other renewable sources, such as bio-based fuels (BIO) and geothermal (GEO), corresponds to only 1% (2.8 GW). Situation across different power pools is however diverse, as shown in Figure 6.

Table 2 Installed capacity in individual power pools and Africa as a whole grouped by the generation type (installed capacities are expressed in MW)

	Total	BIO	GEO	PEA	OIL	GAS	HRD	NUC	WAT	SUN	WIN
CAPP	6 749	12	0	0	975	1 433	0	0	4 293	35	1
EAPP	74 273	928	793	15	9 052	49 323	0	0	11 170	1 182	1 810
NAPP	46 118	2	0	0	5 253	31 343	4 315	0	2 272	1 322	1 611
SAPP	70 669	916	0	0	5 596	2 457	42 064	1 930	12 436	3 171	2 099
WAPP	20 156	166	0	0	5 089	8 086	746	0	5 670	395	4
Africa	217 964	2 024	793	15	25 964	92 643	47 124	1 930	35 841	6 105	5 525

Three hydro technologies are considered: reservoir-based hydropower without pumping capability (HDAM) totalling 24 599 MW, pumping hydropower (HPHS) totalling 3 388 MW and run-of-river totalling (HROR) 7 852 MW. This study also distinguishes two solar power technologies, namely the solar PV (PHOT) totalling 5 129 MW and concentrated solar power (SCSP) totalling 976 MW, and two wind technologies: onshore wind (WTON) and offshore wind (WTOF).

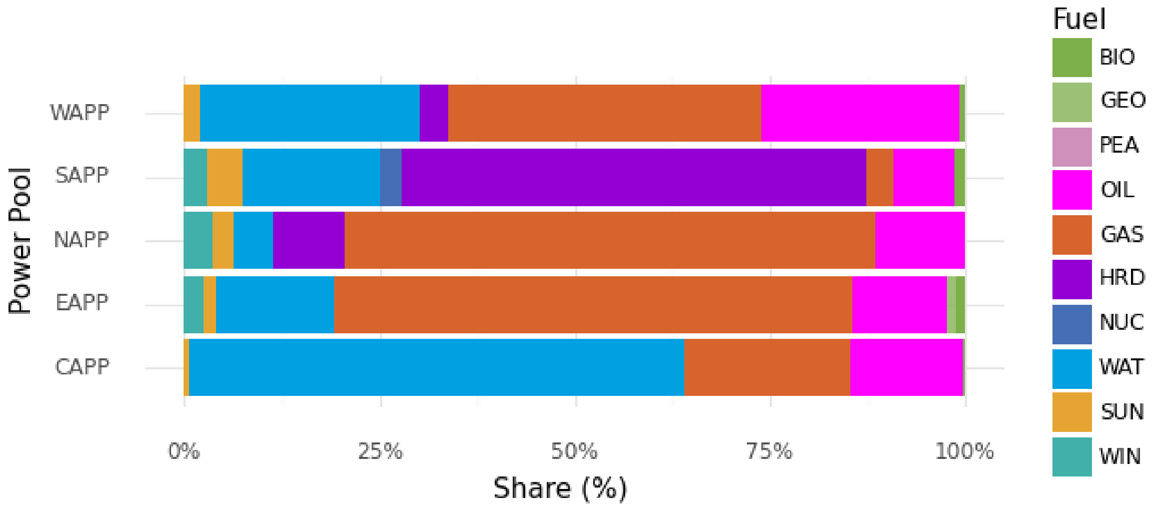

Figure 6 Share of capacity by power generation type in the analysed power pools.

4.3. Storage capacities

There are three main storage technologies: HDAM, HPHS and SCSP Their capacities are provided in Figure 7. HDAM units allow the delay of the use of the water to generate electricity later (from hours to months), HPHS gives the possibility to store the surplus of electricity (generally during low-demand periods) and SCSP power plants can usually store energy in the form of sensible heat (in molten salts) with 8 to 15 hours of storage. The main reason for this is the fact that most hydropower plants are either HROR or HDAM with limited storage capacity.

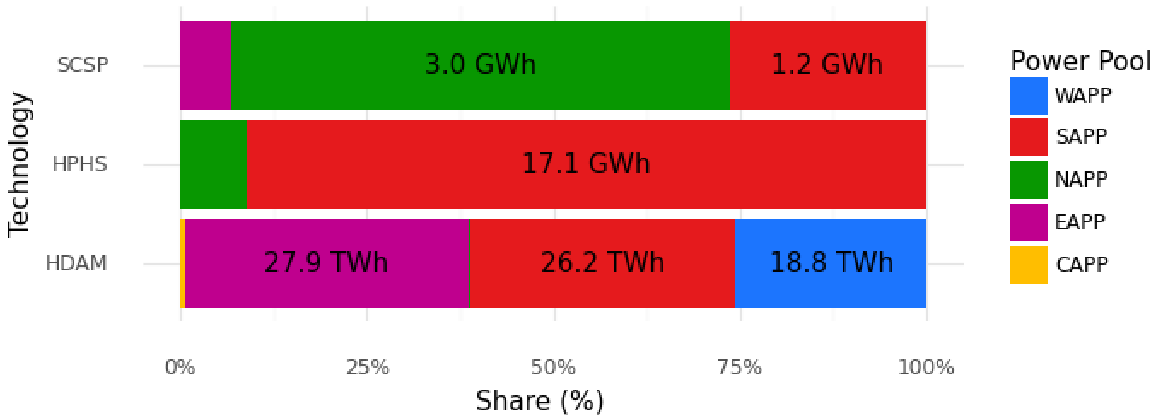

Figure 7 Maximum amount of storable electricity for each technology (hydro dams, pumped storage and concentrated solar power).

4.4. Power grid and cross-border interconnections

The existing grid infrastructure in sub-Saharan countries is relatively weak. Countries such as Central African Republic and South Sudan experience system-wide outages for up to 10 hours per day [34]. A better situation is observed in NAPP and SAPP, where more than 97% and 87% of the population has access to electricity respectively and national grids are modernized. NAPP and SAPP are also the most interconnected power pools, followed by EAPP, where Eritrea and Somalia [35] do not share any cross-border lines, and CAPP where Central African Republic [36], Chad [37] and most of the Democratic Republic of the Congo are isolated from the main grid. Nevertheless, several interconnection projects such as Kenya-Ethiopia [38], Kenya-Tanzania-Uganda [39], Rwanda and Democratic Republic of the Congo [40] and strengthening of the WAPP power grid [41] are already under construction. Total existing and planned NTC's between different power pools are shown in Figure 8.

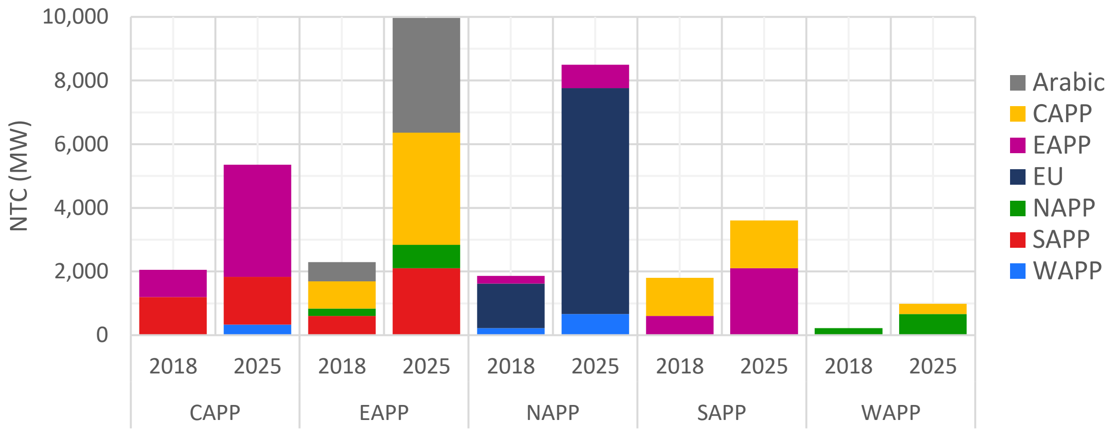

Figure 8 Total NTC (stacked columns) and NTC between different power pools (colour). Year 2018 represents historical NTCs, while year 2025 represents planned short-term grid expansion according to existing grid extension plans.

4.5. Fuel Prices

A summary of the fuel prices is presented in Figure 9. Variability of the prices across different countries and power pools is based on the proposed price adjustment algorithm, taking into the account the influence of resource availability, fuel supply network and geographical location. The marginal price of VRES, geothermal and hydro are assumed to be zero.

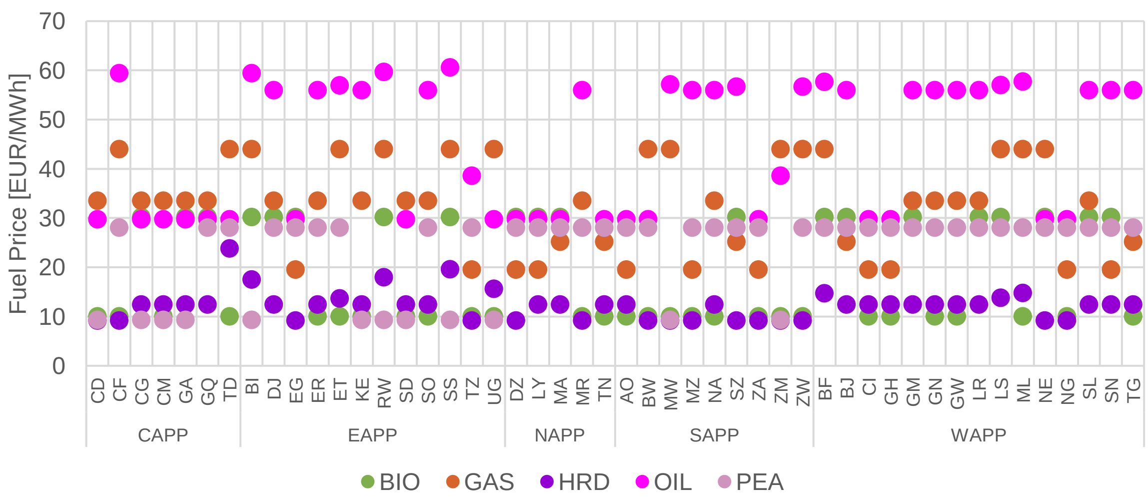

Figure 9 Summary of the fuel prices across all analysed countries (two letter country codes – iso2) and all five power pools.

5. RESULTS

This section shows how each power pool reacts to the wide range of climate conditions (mainly hydropower inflows). The simulations from both scenarios, and over the 39 weather years, produce outputs in form of a hourly time series describing the state of the power system (commitment status of individual units or clusters of units, costs of dispatching them etc.).

5.1. Energy Mix

The simulation results indicate that the share of renewable power generation varies between 14.8% (weather year 2017) and 21.9% (weather year 1987). The average annual generation from renewable sources is 156.3 TWh (deviation range is between 81% and 110%. Figure 10 shows the energy mix for the 39 weather years. Among the analysed power pools, the CAPP shows the widest variation, between 50.7% and 77.6%. In most power pools the largest portion of variability is caused by hydropower, while in NAPP, it is caused by wind and solar generation.

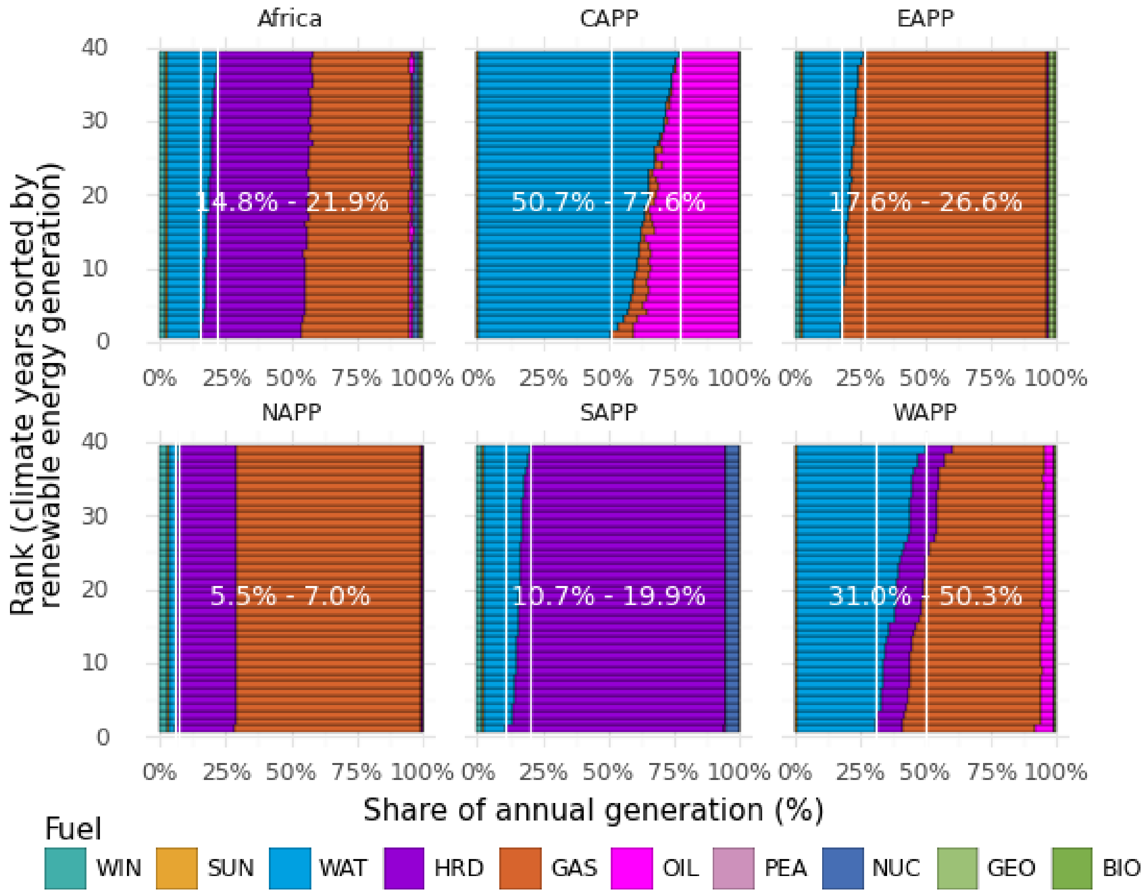

Figure 10 Generation mix and share of renewables for the considered climate years. White lines indicate minimum and maximum shares of renewable generation in individual power pools and Africa as a whole. Climate years are ordered by the share of renewable generation.

5.2. Hydro Generation

On average, about one fifth of the electricity comes from the hydropower. Figure 11 illustrates the hydropower generation in all the power pools and different weather years. For run-of-river technologies the largest variability (standard deviation of 27%) is observed in CAPP while hydro storage technologies, the largest variability (standard deviation of 29%,) is observed in SAPP. Total generation form storage and pumping units at the continental scale exceeds that of run-of-river units by a factor of five. CAPP is the only power pool where run-of-river is the dominant hydro technology.

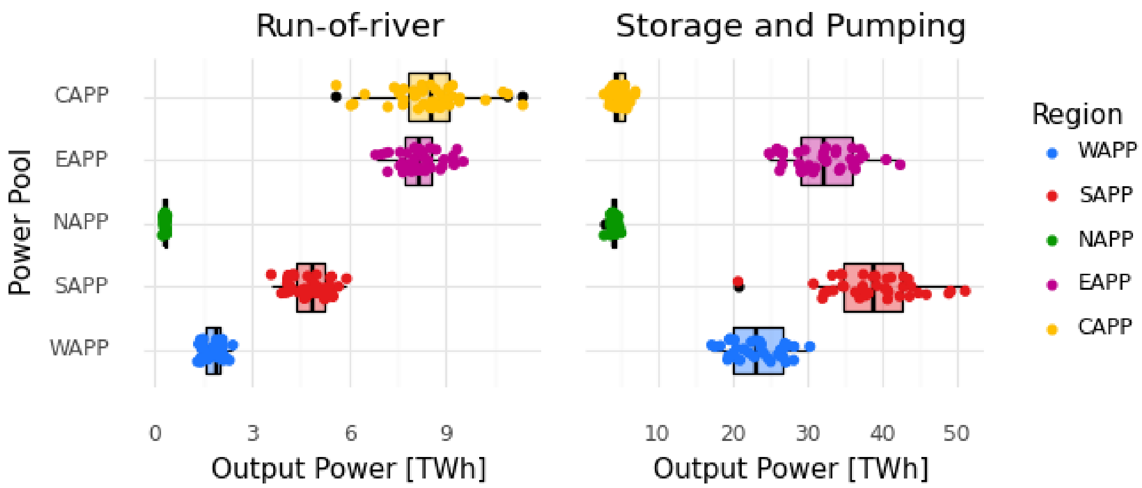

Figure 11 Hydropower generation for run-of-river and storage/pumping for all power pools and climate years. The box shows the range between the 25th and the 75th percentile of the generation for all the climate years considered.

5.3. CO_2 emissions and generation costs

The variability of renewable energy generation, due to water availability, also has an impact on CO_2 emissions and generation costs. The observed range for the CO_2 intensity ranges between 434 - 473 kg_{CO2}/MWh for weather years 1987 and 2017 in the Baseline scenario as shown in Figure 12. The largest CO_2 intensity is observed in SAPP (between 589-659 kg_{CO2}/MWh in Baseline and 596-653 kg_{CO2}/MWh in High Interconnections scenario) and the lowest in CAPP (between 139-303 kg_{CO2}/MWh in Baseline and 38-228 kg_{CO2}/MWh in High interconnections scenario). The average generation cost on the continental scale ranges between 23.23-25.69 EUR/MWh for weather years 1987 and 2000 in the Baseline and 22.03-24.09 EUR/MWh for weather years 1987 and 2017 in the High interconnections scenario.

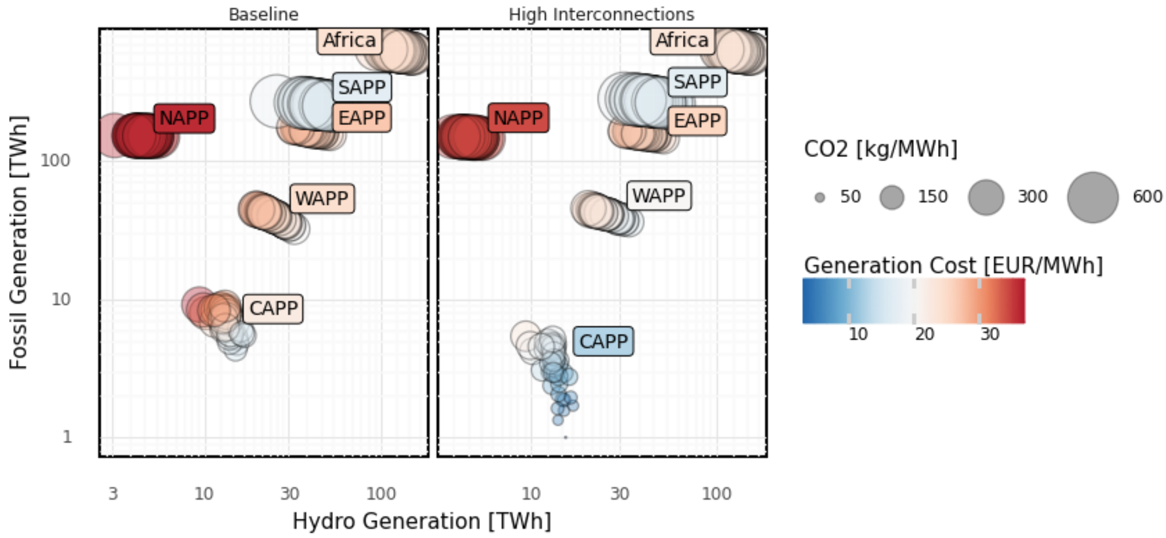

Figure 12 Generation from hydro and fossil units in both scenarios and for all climate years and all power pools. The size and the colour of the bubbles show the fuel cost and the carbon intensity for the specific climate year. Axes are presented in logarithmic scale in order to increase the readability of the plot.

5.4. Power System Adequacy

5.4.1. Curtailment and Shed Load

Load shedding and curtailment can be considered as good indicators of system adequacy and flexibility, respectively. At the continental scale, the median curtailment from the 39 weather years equals 4.49 TWh in Baseline and 3.08 TWh in the High interconnections scenario. The largest curtailment levels are observed in CAPP (up to 30% in both scenarios) while there is almost no curtailment recorded in NAPP. The need to shed load is observed in all power pools at the exception of SAPP. In the Baseline scenario the supply and demand balance cannot be guaranteed in Central African Republic, Gabon, South Sudan, Somalia, Guinea Bissau, Democratic Republic of Congo and Libya. The High interconnections scenario does, however, resolve the unbalance and suppresses most of the observed shed load. The dependency of VRES curtailment and load shedding versus power output from hydro and fossil units is presented in Figure 13.

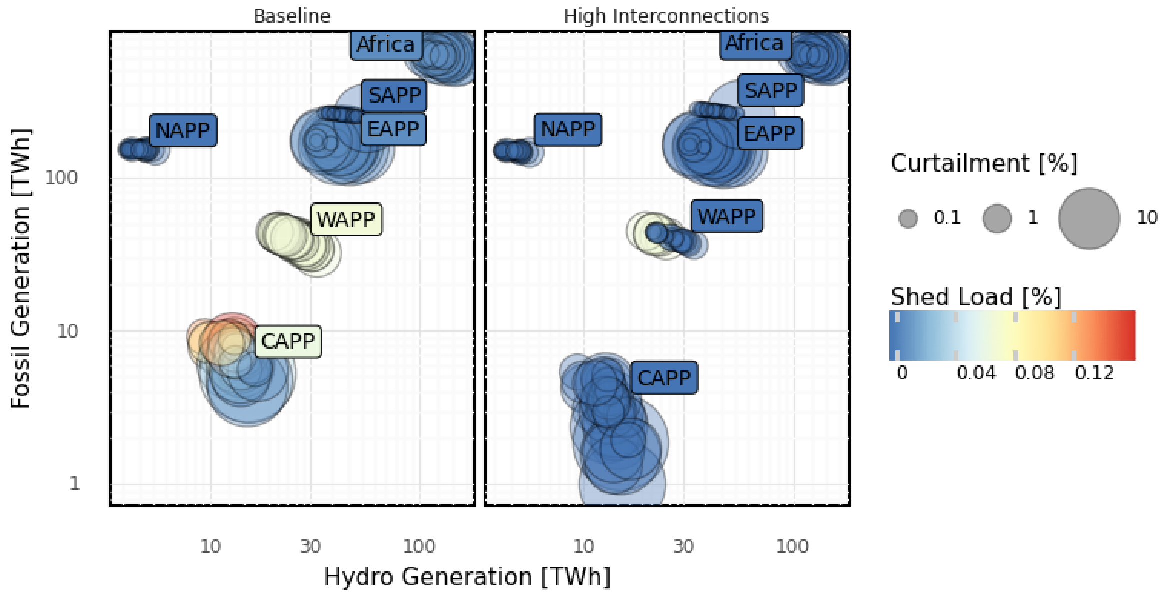

Figure 13 Generation from hydro and fossil units in both scenarios and for all climate years and all power pools.

5.4.2. Power feed and congestion

The energy produced in each zone and transfers between them are presented in Figure 14. In both scenarios South Africa, Zambia, Zimbabwe, Ethiopia, Kenya, Nigeria, and Ghana have important capacities and are net exporters. It is noteworthy that the lack of intra-regional cross border interconnections, especially in WAPP and CAPP, is significant cause of suboptimal dispatch.

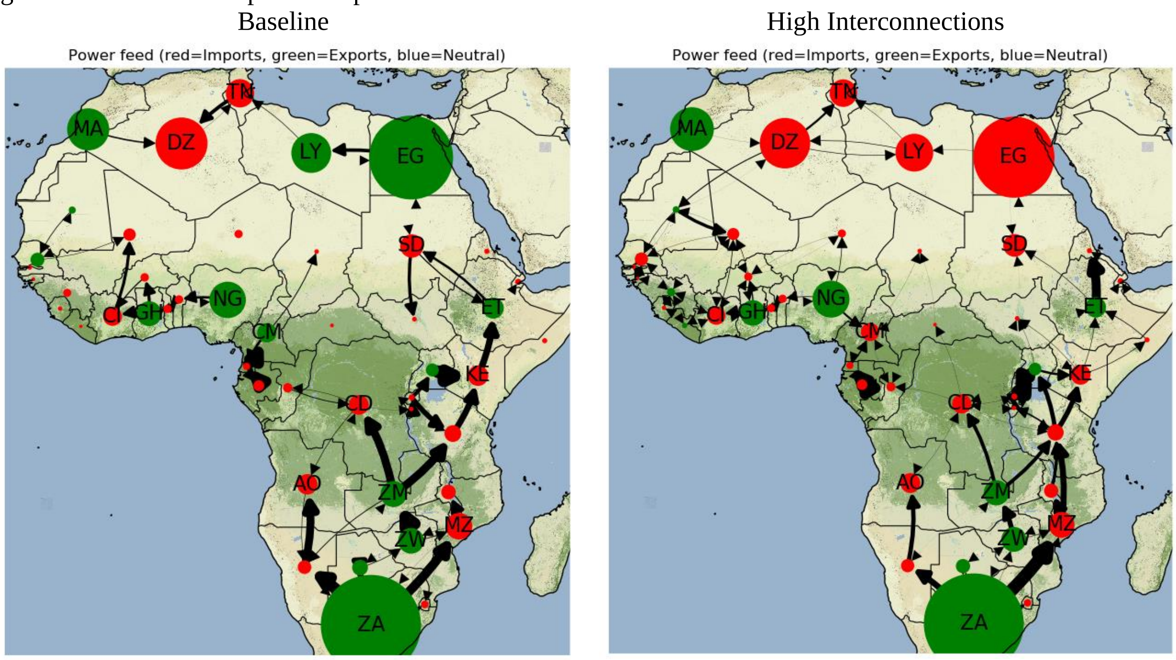

Figure 14 Power feed in African countries in both scenarios for the calibrated weather year (2018). The bubble size indicates the total annual demand. Colour code indicates that a particular country is either importing (red) or exporting (green) electricity to its neighbours. Size of the arrows indicates the amount of energy being transferred.

For example, Guinea does not share any interconnections with its southern neighbours which leads to an underuse of hydro dams balancing potential in the region. In the High interconnections scenario, new cross border capacities allow unlocking part of this potential to more uniform shadow prices, reduced VRES curtailment and load shedding and lower CO_2 emissions. Limited interconnections in the Baseline scenario result in highly congested lines from SAPP to Tanzania. This is only marginally reduced in the High interconnections scenario, despite the new NTC additions. The cross-border congestion is presented in Figure 15. Overall, in the fully interconnected grid, flows from north to south and to some extent from east to west are made possible.

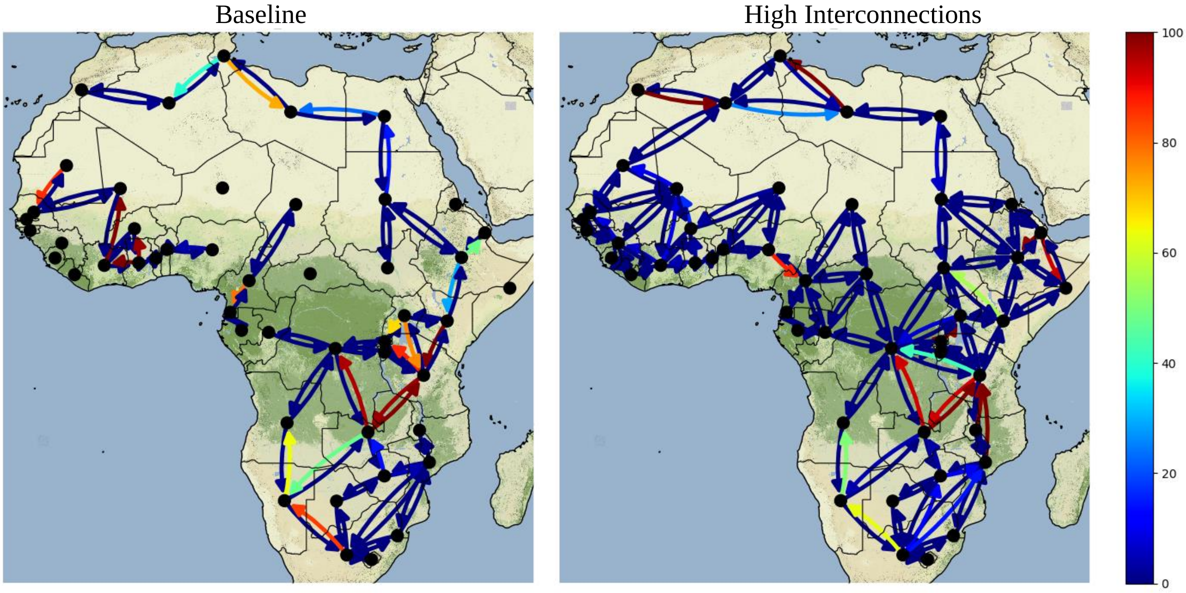

Figure 15 Congestion in the cross-border interconnection lines. The colour gradient indicates the proportion of congested hours in the year.

Figure 16 shows the range of average weekly net power flows in individual power pools. In the Baseline scenario SAPP is the only African power pool that exports electricity in the 39 weather years. In the High interconnections scenario, the net exports of SAPP are even higher. The main difference is observed in EAPP, which becomes a net exporter. In the Baseline scenario the highest congestion is observed between EAPP and NAPP (97%), and EAPP and SAPP (99%). In the High interconnections scenario, congestion between EAPP and NAPP (92%), and EAPP and SAPP (93%) is reduced, while the newly established link between CAPP and WAPP is highly congested (96%).

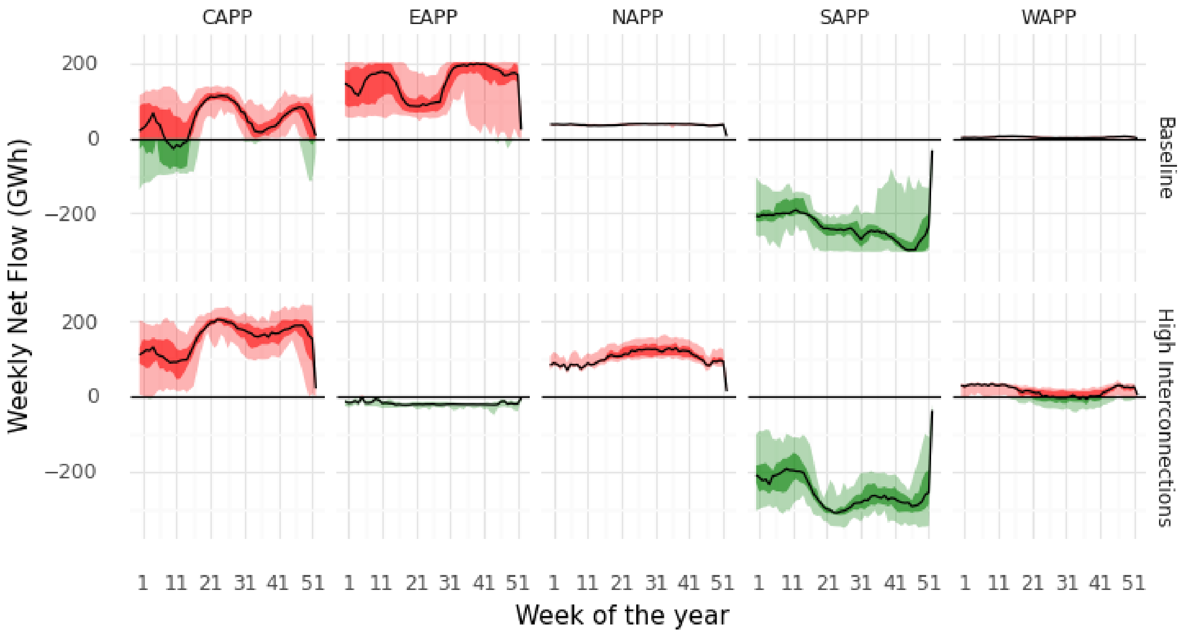

Figure 16 Average weekly net power flow between power pools. Colour transparency indicates 25th and 75th percentiles in different weather years. Red indicates net importing and green indicates net exporting power pools.

5.5. Water stress

5.5.1. Water withdrawal and consumption

An important impact of electricity generation is the freshwater consumption linked to the operation of power plants. The annual need of fresh water (excluding sea and polluted water) for cooling purposes (gas, oil, nuclear, coal, biomass, waste, peat etc.) is computed for the considered weather years according to the methodology presented in section xx. A summary of water consumption and water withdrawals for thermal power plants, in relation to the average annual inflows and generation costs is shown in Figure 17. The difference between different power pools is due to different energy mixes and to different weather conditions. As expected, power pools with the highest variability (i.e. the difference between the minimum and maximum use of freshwater) are the regions with highest shares of renewables (wind. solar and hydro). The highest average WC of 1.13 m^3/MWh of total electricity generation is observed in SAPP because of harsh climate conditions, low water availability, high total demand and most water intensive technology mix, and the lowest of 0.006 m^3/MWh in CAPP due. The highest average WW of 43.54 m^3/MWh is observed in NAPP because of largest share of once through cooling systems and the lowest of 0.55 m^3/MWh in CAPP. The average WC on continental scale ranges between 0.69-0.77 m^3/MWh, while WW range between 17.52-19.29 m^3/MWh. When compared to values computed for the European power pools [42] this is relatively low.

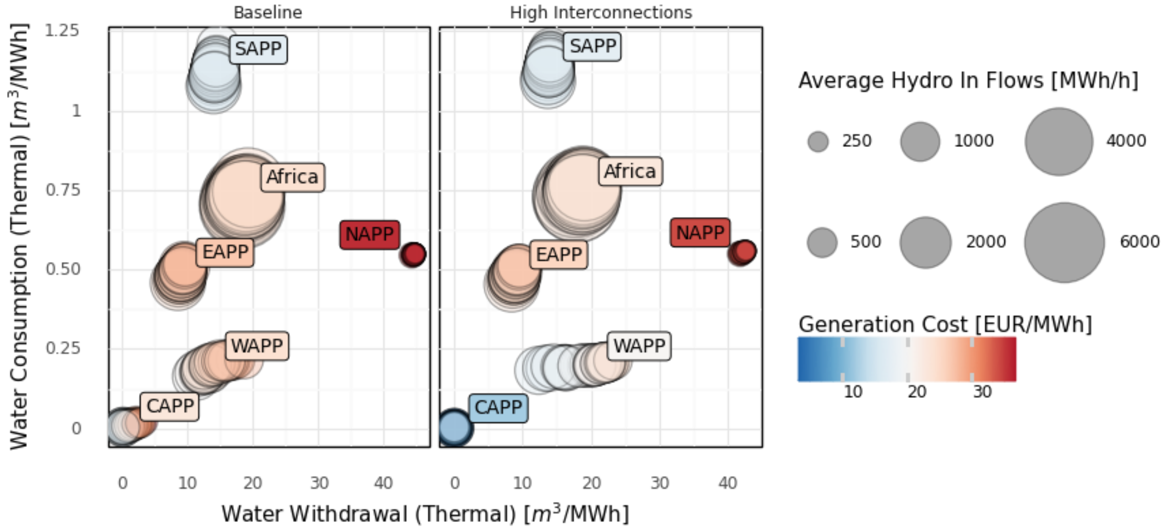

Figure 17 Water withdrawal and water consumption for thermal generation purposes in both scenarios, for all weather years and all power pools (colour coded).

5.5.2. Absolute water exploitation index

As previously defined, absolute WEI stand for all WC and WW used for power generation (including thermal generation and water evaporation in hydro reservoirs). A proper calculation of absolute WEI is challenge, because of the lack of proper data or large number of external variables impacting the consumption. For example, multipurpose dams (which are quite common in Africa) are used for power generation, irrigation, tourism and recreation, drinking water supply, flood control, navigation etc. Water levels in certain reservoirs must therefore be kept within certain non-energy related bounds. Water evaporation caused by those activities should also subtracted when calculating WEI, as proposed in [43]. This is also further clarified in [44] where water consumption allocation factors of hydropower units based on the number of economic benefits are defined for different power capacity ranges. The same principles were also applied for calculation of absolute WEI in this study. A summary of the WEI expressed as internal and total (internal and external) freshwater resources is presented in Figure 18. Dependency on external freshwater resources is particularly visible in East Africa, where most countries, including Egypt and Sudan, largely depend on the fresh water from the Nile river. These two countries are the only ones consuming more water then locally available (on average nearly 5.2 times as much in Egypt and 6.4 in Sudan) and withdrawing above critical threshold of 5 withdrawals of the same water resource (131.9 times in Egypt and 20.9 times in Sudan). The only other country withdrawing locally available freshwater resources above the critical threshold is Morocco from NAPP, with an average 52.3 times higher than the threshold. In terms of total availability of freshwater resources, Sudan has the highest average WEI+ of 0.52 (ranging between 0.39 and 0.88). The only other African country consuming more fresh water than the proposed threshold of 0.2 [24] is Ghana in WAPP. is Ghana in WAPP. Although WEI^+ of Ghana (0.17) is in average below the threshold, a maximum WEI^+ of 0.25 can be reached in certain climate years. As expected, the difference between both scenarios is low, the largest impact being observed in WAPP and CAPP, the only two power pools with limited interconnections between the member states.

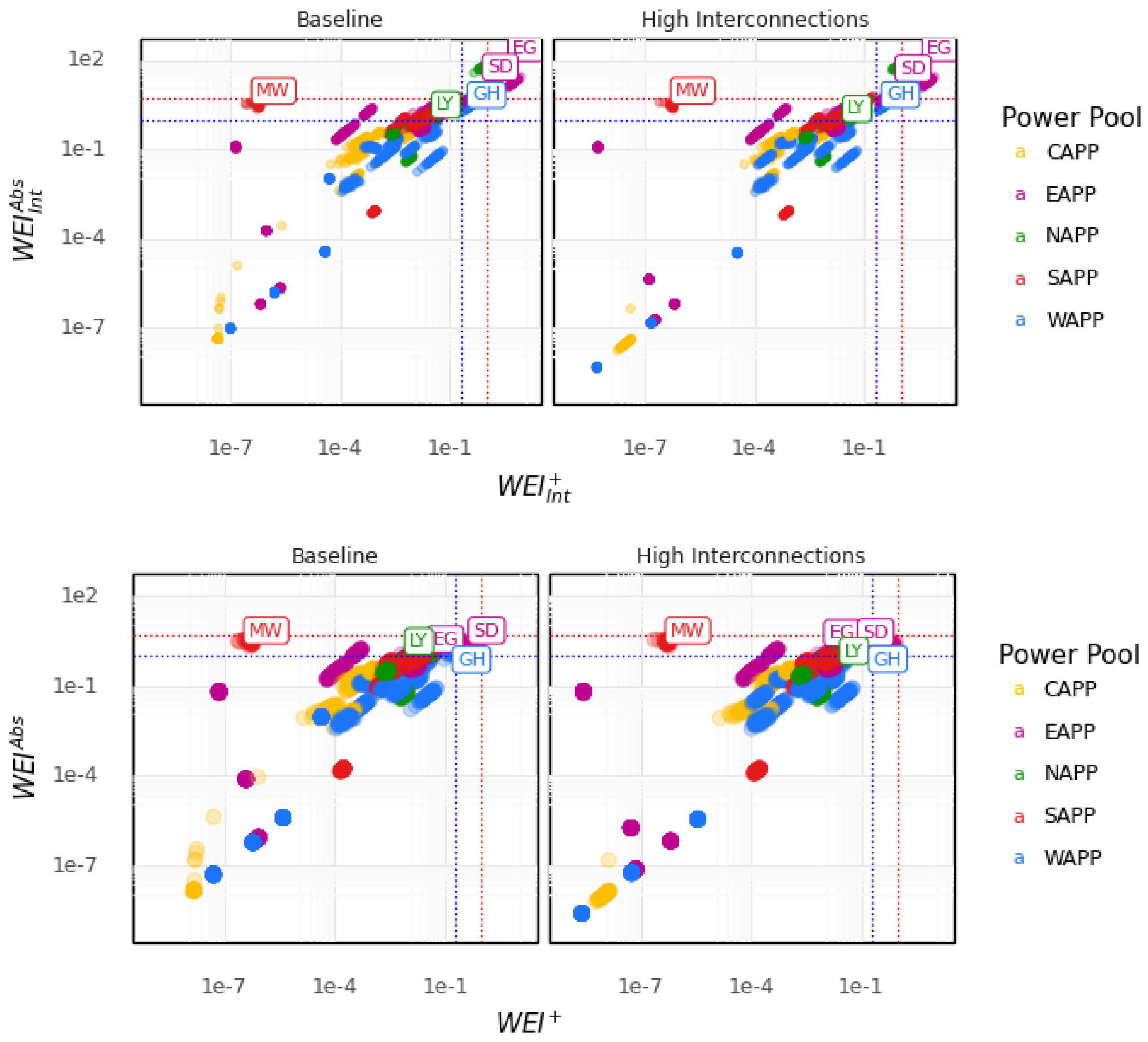

Figure 18 Absolute water exploitation index for the 48 African countries and for the 39 weather years. Upper two charts show WEI in terms of internal water resources while lower two show the WEI in terms of total (internal and external) water resources. The colour codes indicate countries belonging to individual power pools. Blue lines indicate acceptable WEI values (0.2 for WC and 1 for WW) and red lines indicate critical WEI values (1 for WC and 5 for WW).

5.5.3. Thermal only water exploitation index

WEI of thermal units only is analysed in this section. These calculations are more representative as there are no other activities, besides water abstractions for power generation, included. The correlation between WEI^{abs} and WEI^{+} in terms of internal and total (internal and external) freshwater resources is presented in Figure 19. Similar patterns as before are observed, however all countries are within consumption bounds. Excessive water withdrawals in terms internal freshwater availability is only observed in Morocco (on average water is withdrawn 7.3 times). There are three other countries whose withdrawals are still above the proposed WW threshold. Libya in NAPP (on average water is withdrawn 1.13 times), Egypt in EAPP (on average water is withdrawn 1.99 times) and Malawi in SAPP (on average water is withdrawn 3.2 times). In terms of total (internal and external) freshwater resources Malawi and Libya, two countries depending on internal freshwater resources only, are the only countries above the proposed WW threshold (3.2 and 1.13 times respectively). Compared to the absolute WEI, difference between scenarios in WEI of thermal only units is more pronounced. For example, in Libya WW in High interconnections scenario are reduced by 11.8% (down to 1.01), while in most CAPP countries WW fell significantly (as much as 75% in Chad and Central African Republic). This reduction can be directly contributed to the reduced operation of the local (expensive and mostly OIL fired) backup thermal units, due to increased inflows from the SAPP. As the total annual demand between SAPP and CAPP differs by two orders of magnitude, increase of WW and WC in SAPP countries is negligible.

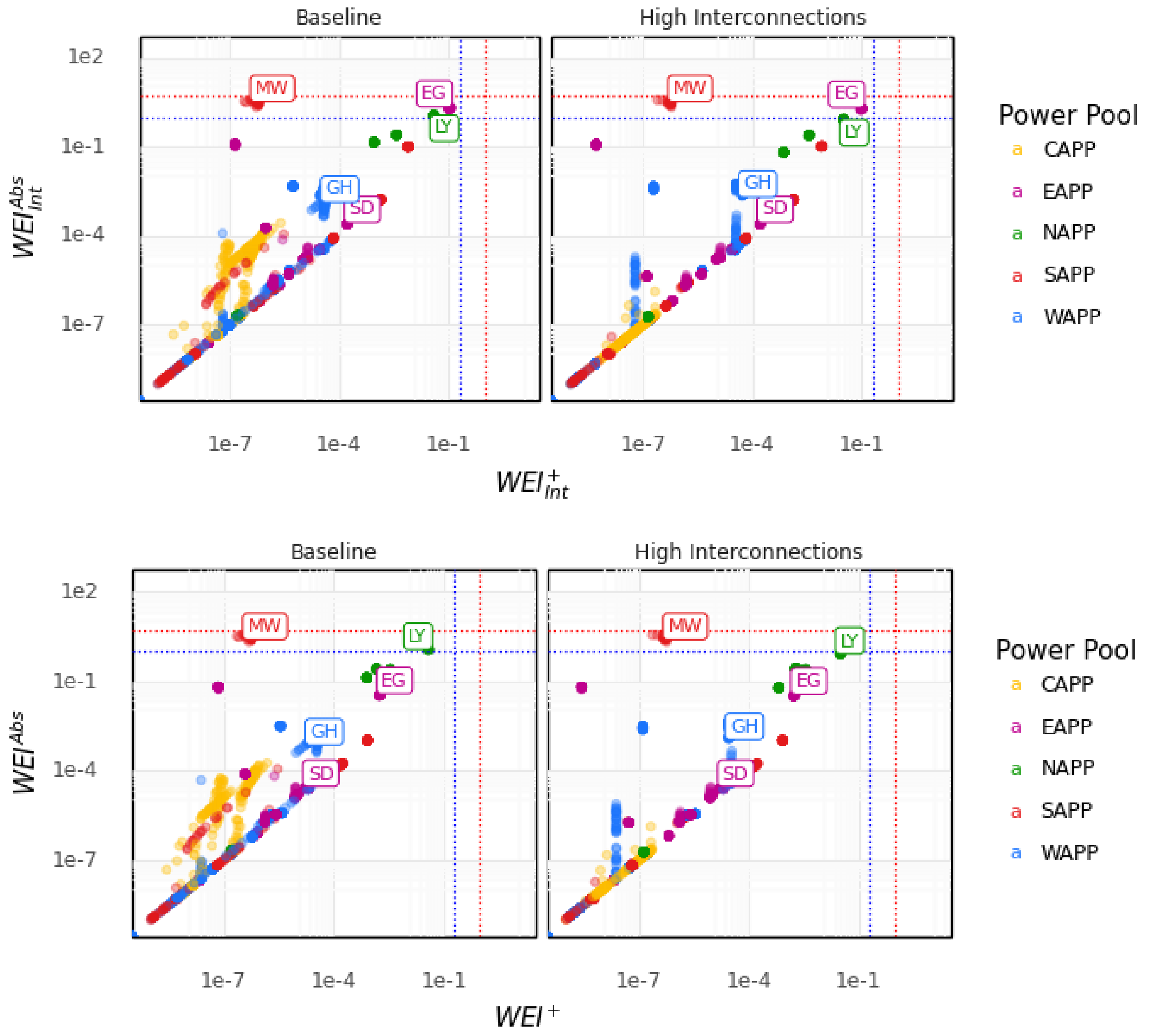

Figure 19 Water exploitation index of thermal units only for the 48 African countries and for the 39 weather years. Upper two charts show WEI in terms of internal water resources while lower two show the WEI in terms of total (internal and external) water resources. The colour codes indicate countries belonging to individual power pools. Blue lines indicate acceptable WEI values (0.2 for WC and 1 for WW) and red lines indicate critical WEI values (1 for WC and 5 for WW).

6. CONCLUSION

In this study, a detailed power system modelling framework is presented for the African continent and applied to assess the induced water stress. The proposed model is an open source unit commitment and power dispatch model with one node per African country. All large-scale operating generation units are reviewed and parametrized using different data sources. The modelling framework is then calibrated with historical data from 2018. Two scenarios are defined to assess the effects of the short-term expansion of the African power grid in the five African power pools. 39 weather years are considered to strengthen the results and provide insights regarding the effect of weather variability.

The results indicate that the system adequacy is insufficient in various countries: significant amounts of load shedding are required in several isolated or poorly interconnected countries in the five power pools. Interestingly, increasing the interconnection capacities reveals to be a relevant solution, which brings the requirements for load shedding to almost zero. Increased interconnections also reduce VRES curtailment, thus increasing the overall flexibility of the system, and the marginal prices inside individual power pools and in some cases between two neighbouring power pools become more uniform. Congestion in several major cross border lines is however observed in all scenarios, because of the limited transfer capacities from North to South, East to West and vice versa.

The analysis of the water energy nexus indicators reveals that that the water stress induced by power generation activities is problematic in some power pools. Water consumption from power plants exceeds maximum 0.2 times the water availability in several countries. A particularly vulnerable country is Sudan, with water withdrawals up to 6.4 times the water availability and total water consumption of 0.52 times the water availability. Highest internal freshwater abstraction among all analysed weather years of 160.1 is recorded in Egypt, a country with excessive dependency on external freshwater resources from the Nile river. Despite this, the current exploitation of water resources for power generation remains acceptable in the majority of African countries. It is important to note that Africa is currently undergoing a rapid growth in electricity demand, which will most likely impact the previous conclusion.

In future works, the model will be used as a reference model to assess a various scenarios regarding the further development of African energy systems and their environmental impacts. For example, advanced analyses of increased demands levels together with the further deployment the grid and of variable renewable energy sources is made possible by the proposed model, which is released under an open license[7] and will therefore benefit the entire scientific community.

ACKNOWLEDGEMENT

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NOMENCLATURE

Abbreviations	Description	Unit
AF	Availability factor	[-]
BIO	Biomass and biogas	[-]
CHP	Combined heat and power	[-]
COMC	Combined cycle	[-]
SCSP	Concentrated solar power	[-]
GAS	Gas	[-]
GEO	Geothermal	[-]
GTUR	Gas turbine	[-]
HDAM	Hydro dam (turbine)	[-]
HPHS	Pumped hydro (pumped / turbine)	[-]
HRD	Hard coal	[-]
HROR	Hydro run-of-river	[-]
ICEN	Internal combustion engine	[-]
LIG	Lignite	[-]
LL	Lost Load	[-]
MILP	Mixed integer linear programming	[-]
MTS	Mid-term scheduling	[-]
NTC	Net transfer capacity	[-]
NUC	Nuclear	[-]
OIL	Oil	[-]
OTH	Other energy carriers including electric vehicles	[-]
PHOT	Photovoltaics	[-]
RES	Renewable energy sources	[-]
STUR	Steam turbine	[-]
SUN	Solar	[-]
TSO	Transmission System Operator	[-]
UCM	Unit-commitment and power dispatch models	[-]
VRES	Variable energy sources	[-]
WAT	Hydro	[-]
WIN	Wind	[-]

Sets	Description	Unit

[7] 10.5281/zenodo.4321628

i	Time step in the current optimization horizon	[-]
l	Transmission lines between nodes	[-]
n	Zones	[-]
$p2h$	P2HT units	[-]
u	Units	[-]
Parameters	Description	Unit
$CostFixed_u$	Fixed costs	[EUR/h]
$CostLoadShedding_{i,n}$	Shedding costs	[EUR/MWh]
$CostRampDown_{i,u}$	Ramp-down costs	[EUR/MW]
$CostRampUp_{i,u}$	Ramp-up costs	[EUR/MW]
$CostShutDown_{i,u}$	Shut-down costs for one unit	[EUR/u]
$CostStartUp_{i,u}$	Start-up costs for one un	[EUR/u]
$CostVariable_{i,u}$	Variable costs	[EUR/MWh]
$Demand_{DA,n,h}$	Hourly demand in each zone	[MW]
$LineNode_{l,n}$	Line-zone incidence matrix {-1,+1}	[-]
$LoadShedding_n$	Maximum value of load shedding	[MW]
$Location_{u,n}$	Location {binary: 1 u located in n}	[-]
$PriceTransmission_{i,l}$	Price of transmission between zones	[EUR/MWh]
$StorageInput_{s,h}$	Charging input for storage units	[-]
$Technology_u$	Technology type	[-]
$VOLL_{Power}$	Value of lost load due to power output	[EUR/MWh]
$VOLL_{Ramp}$	Value of lost load due to ramping	[EUR/MWh]
$VOLL_{Reserve}$	Value of lost load due to lack of reserve capacities	[EUR/MWh]
Variables	Description	Unit
$Flow_{i,l}$	Flow through lines	[MW]
$LL_{2D,i,n}$	Deficit in reserve down	[MW]
$LL_{2U,i,n}$	Deficit in reserve up	[MW]
$LL_{3U,i,n}$	Deficit in reserve up - non spinning	[MW]
$LL_{MaxPower,i,n}$	Deficit in terms of maximum power	[MW]
$LL_{MinPower,i,n}$	Power exceeding the demand	[MW]
$LL_{RampDown,u,i}$	Deficit in terms of ramping down for each plant	[MW]
$LL_{RampUp,u,i}$	Deficit in terms of ramping up for each plant	[MW]
$Power_{i,u}$	Power output	[MW]
$ShedLoad_{i,n}$	Shed load	[MW]
$TotalSystemCost$	Total system cost	[EUR]
Integer variables	Description	Unit
$Committed_{i,u}$	Committed status of unit at hour h {1 0} or integer	[-]

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