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AFRICAN RENEWABLE ELECTRICITY PROFILES FOR ENERGY MODELLING DATABASE: HYDROPOWER

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About IRENA

The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation, a centre of excellence, a repository of policy, technology, resource and financial knowledge, and a driver of action on the ground to advance the transformation of the global energy system. An intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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INTRODUCTION

Modelling exercises on power systems with potentially high penetration of renewable resources, most notably solar photovoltaic (PV), wind power and hydropower, require datasets on resource profiles at high resolution in space and time. Renewable power capacity expansion planning cannot be done reliably unless the modelling community can access resource profiles for solar PV, wind power and hydropower.

To accurately represent the contribution that modern renewable resources can make to electricity mixes in terms of installed capacity and power generation, such resource profiles must be included in capacity expansion models at high spatial and temporal resolution. Fortunately, various databases containing such datasets already exist for solar PV and wind power (also known as "variable renewables" or VRE), providing information on resource profiles both on diurnal and seasonal scales.

Such databases usually allow users to select locations by entering coordinates or selecting points on a map, and subsequently extract resource profiles for solar PV or wind power at various timescales. These profiles can then be used to represent solar and wind power technologies in energy modelling exercises.

While this process is well-established and common practice among energy system modellers to represent VRE, the same cannot be said for hydropower, even though this resource is typically subject to strong seasonalities, driven by rainfall patterns, snowmelt and other hydrological phenomena. Comprehensive databases of the seasonal availability of hydropower are currently not available to the community of power system modellers, which hampers research efforts to assess the spatiotemporal synergies between VRE and hydropower. Typically, to accurately represent the seasonality of hydropower, modellers therefore resort to measurements of river flow obtained from local measurements by utilities or researchers, or attempt to obtain historical data from hydropower plant operators. However, the former does not account for the design characteristics of hydropower plants (e.g. the design discharge or the water retention effects of reservoirs), whereas the latter can be a tedious process that may delay modelling efforts. While there exist detailed studies on hydropower availability at individual-country level, e.g. (Dalla Longa et al., 2018; van der Zwaan, Boccalon and Dalla Longa, 2018), databases at continental scales with plant-level detail remain lacking.

A consequence of this disparity in resource profile detail between hydropower on the one hand, and VRE on the other, and the unavailability of comprehensive databases on hydropower generation profiles in space and time, is that hydropower plants are often represented in relatively coarse manners and without the necessary spatiotemporal detail in power system models. For example, hydropower plants located on different rivers with varying seasonalities may be lumped together under a single technology in models, without taking each plant's specific design characteristics into account. This also makes it more difficult to model the potential effects of wet and dry years on electricity systems, since these effects may widely differ across adjacent river basins—or even within the same river basin, if the plants' technical characteristics are ignored.

In particular, the need for high-quality data on hydropower availability is strong for regions where (i) the share of hydropower in the electricity mix is high, (ii) there is a possibility for hydropower fleets to still expand considerably in the future, (iii) rainfall and river discharge exhibit high seasonal variability, and (iv) hydropower is subject to strong climate-related variability. Notably, all of these points apply across most of the African continent (Cole, Elliott and Strobl, 2014; Conway et al., 2017; Falchetta et al., 2019; Sterl et al., 2021a).

IRENA'S NEW HYDROPOWER DATABASE FOR AFRICA

To close this gap in resources available to the modelling community, IRENA released a new spatiotemporal data atlas, entitled *African Renewable Electricity Profiles for Energy Modelling (AfREP) – Hydro*, which covers all existing and several hundred committed, planned and potential future hydropower plants across the African continent. The database is accessible through IRENA's Global Atlas Platform (https://globalatlas.irena.org).

The AfREP-Hydro database, which is fully based on openly accessible information, contains hydropower plants' (i) geospatial references and the name of the associated river, (ii) status (existing, committed/planned, candidate), (iii) technical characteristics (e.g. installed capacity, volumetric size of storage, design discharge), and (iv) seasonal (month-by-month) availability profiles for hydrologically normal years as well as anomalously dry and wet years, taking into account current and future river damming infrastructure.

The AfREP-Hydro database will be kept up to date regularly. In its current form, it contains a total of plants across the West African Power Pool (WAPP), Central African Power Pool (CAPP), Eastern African Power Pool (EAPP), Southern African Power Pool (SAPP), the North African Power Pool (NAPP), and Madagascar. These plants can be further divided into existing (266), committed/planned (104), and candidate (263). "Candidate" plants include all those for which certain specific technical characteristics (notably to-be-installed capacity and geographical co-ordinates) are known, but no concrete information on planned date of entry into service, construction, or financing agreements are available. For all committed/planned plants, earliest assumed years of entry into service are also provided in the database.

The total capacity of all hydropower plants in the database amounts to 132 GW (24% existing, 25% committed/planned, 51% candidate). Figure 1 shows the division of the total capacity by power pool and by category. Clearly, the currently installed (existing) hydropower fleet is of comparable capacity across all power pools—but in some cases this only represents a fraction of the overall potential, whereas in others the potential is already nearly fully exploited.

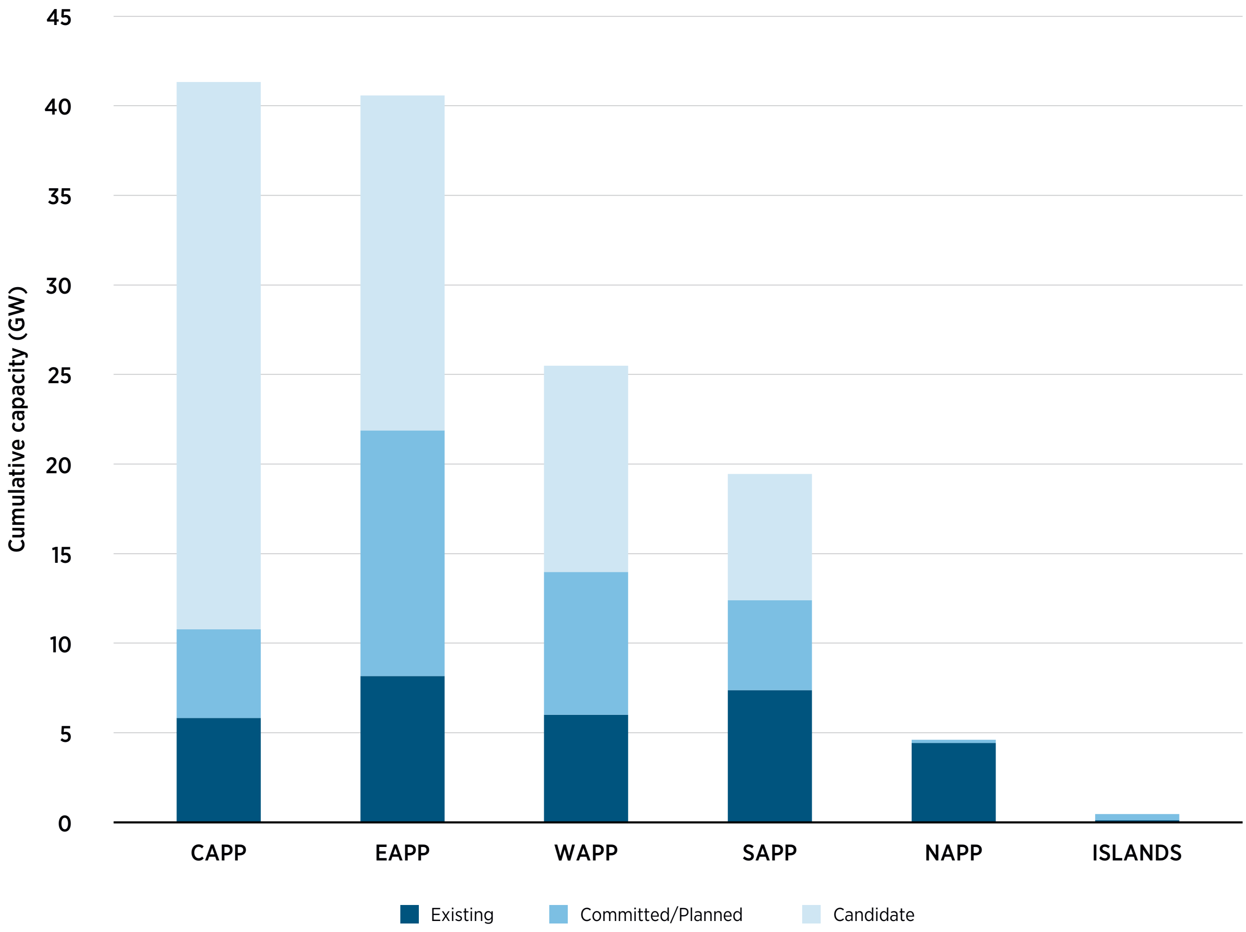
Data collection process

The data collected in the database was gathered from a range of publicly available sources. Globally, the consulted sources fall into one of three categories: (a) existing databases; (b) bespoke information on individual projects, e.g. from power utilities, sector ministry in the countries, environmental impact assessments, technical project sheets, scientific papers and other academic documents, such as master or PhD theses, etc.; and (c) online news articles.

The selection of data sources for inclusion in the AfREP-Hydro database happened strictly according to the hierarchy a-b-c. Sources from category (a) were used as the default; an overview of these sources is given in the Disclaimer to this brief. Wherever necessary, these sources were supplemented by data from categories (b) and (c) to consolidate and complete the required information.

Figure 1: Hydropower capacity by African region

The entries in the hydropower database are ordered by "existing", "committed", "planned" and "candidate" plants. This graph shows the division of hydropower capacity in these categories by power pool[1].



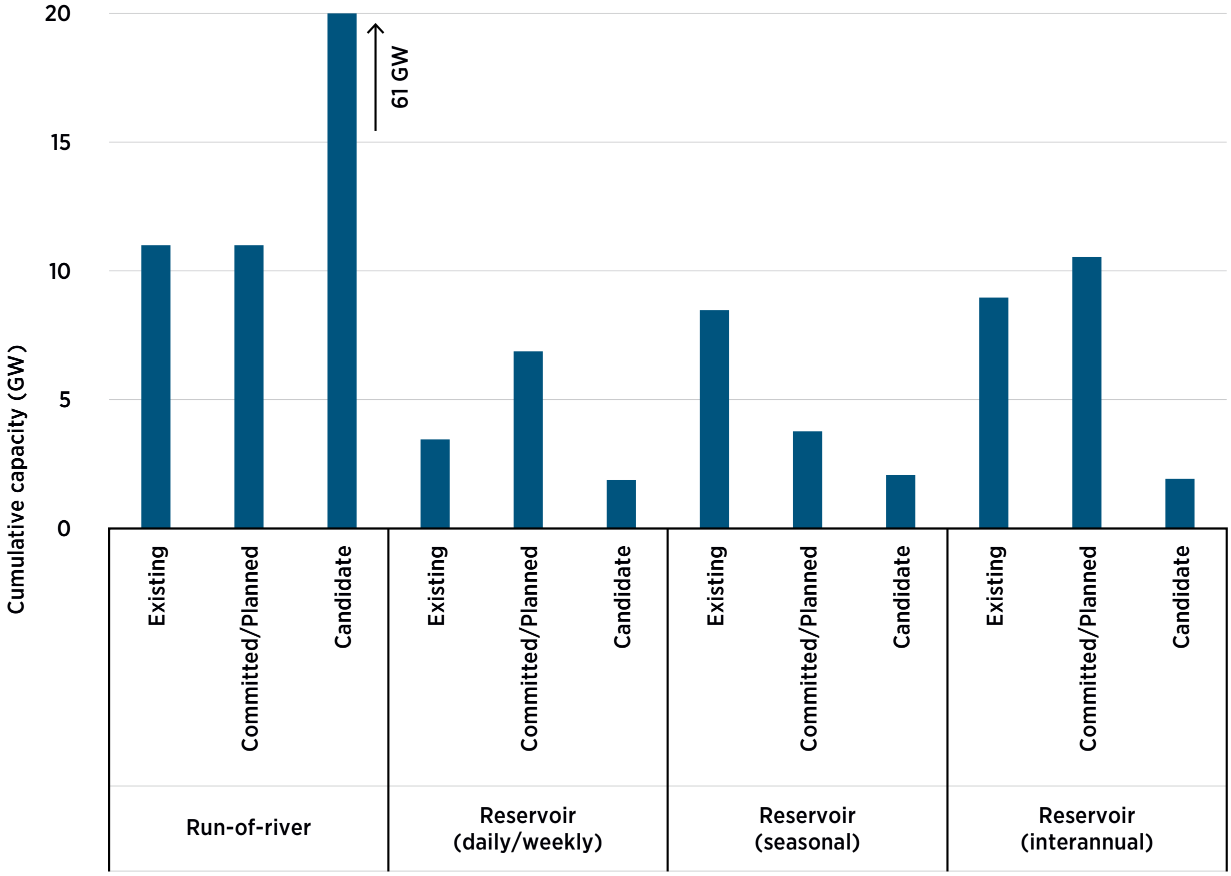
We note here that the existing, committed/planned, and candidate potential has been assessed based on concrete technical or conceptual information on the plants being available. The total theoretical potential of hydropower in Africa is therefore not limited to the 132 GW assessed here (for instance, a recent technical report estimated this at 553 GW (Pappis et al., 2019)). However, we deem these 132 GW to constitute the most useful subset of Africa's total theoretically exploitable hydropower potential for consideration in capacity expansion planning exercises.

The division of African hydropower projects by the size of their reservoir storage is shown in Figure 2. It is clear from this figure that existing and committed/planned hydropower capacity is dominated by the two extremes: most existing capacity is either for pure run-of-river projects, or for very large multi-annual reservoir storage projects. On the other hand, candidate projects appear to be mostly of run-of-river type, which would have the advantage of limiting the environmental impact of continued hydropower exploitation (Moran et al., 2018). However, we note that the lack of storage data for candidate plants may also simply result from the feasibility of storage schemes never having been assessed in detail for those sites.

1 Note that certain countries (Democratic Republic of the Congo, Angola, Burundi, Rwanda, Tanzania, Egypt, Libya) are part of more than one power pool; here, they have been allocated as follows – Egypt: NAPP; Democratic Republic of the Congo: CAPP; Angola: CAPP; Burundi: EAPP; Rwanda: EAPP; Tanzania: EAPP; Libya: n/a (no hydro).

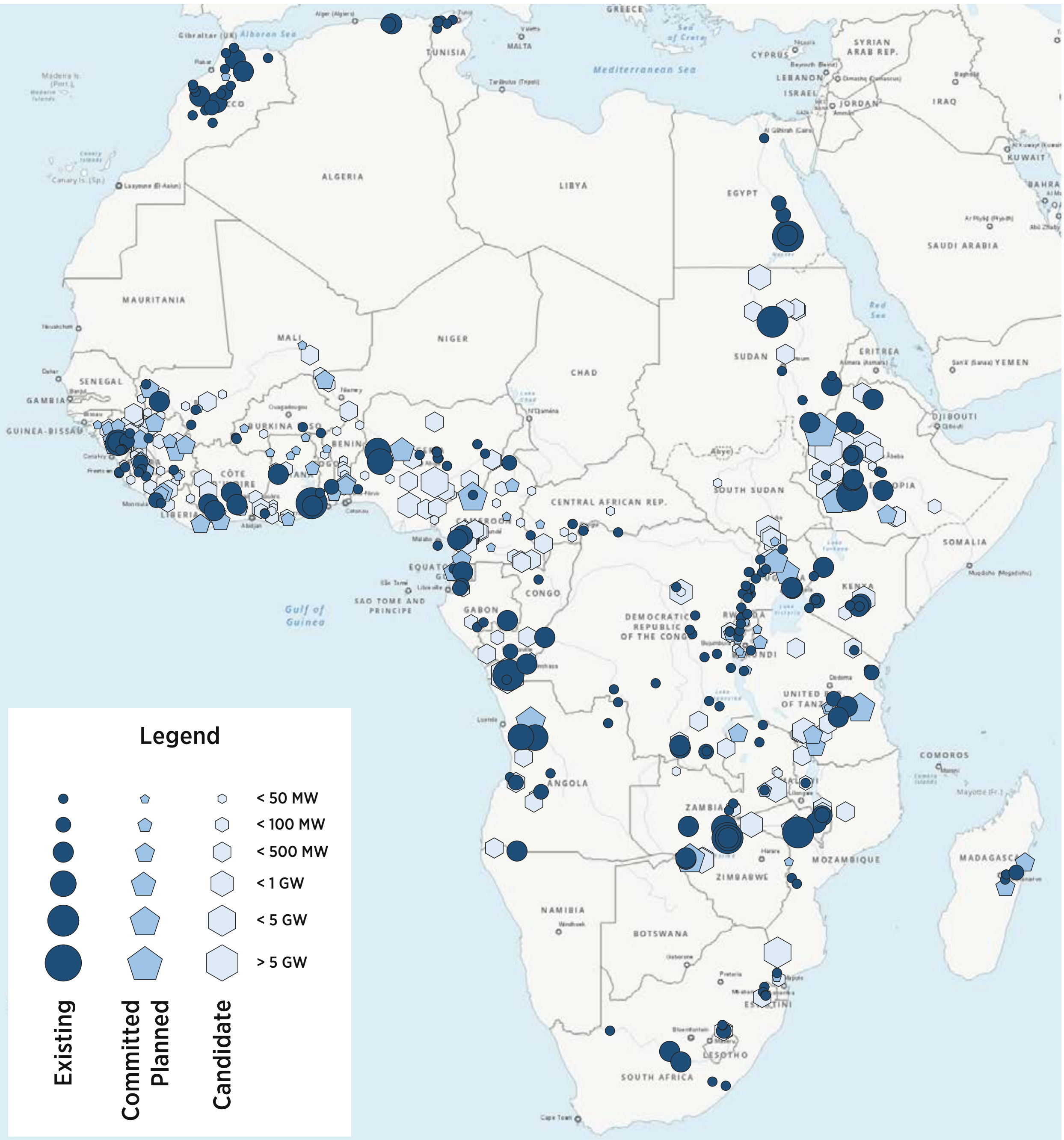
Figure 2: Storage and capacity of African hydropower

The cumulative capacity of hydropower plants with different storage sizes in each category: run-of-river (no storage), reservoir with daily/weekly (less than a month) storage, reservoir with seasonal (less than one year) storage, and reservoir with interannual (more than one year) storage.



The geographical distribution of hydropower plants of different sizes in all three categories is shown on the map in Figure 3.

Figure 3: The distribution of the hydropower plants in the database by country and by size (installed capacity) category.



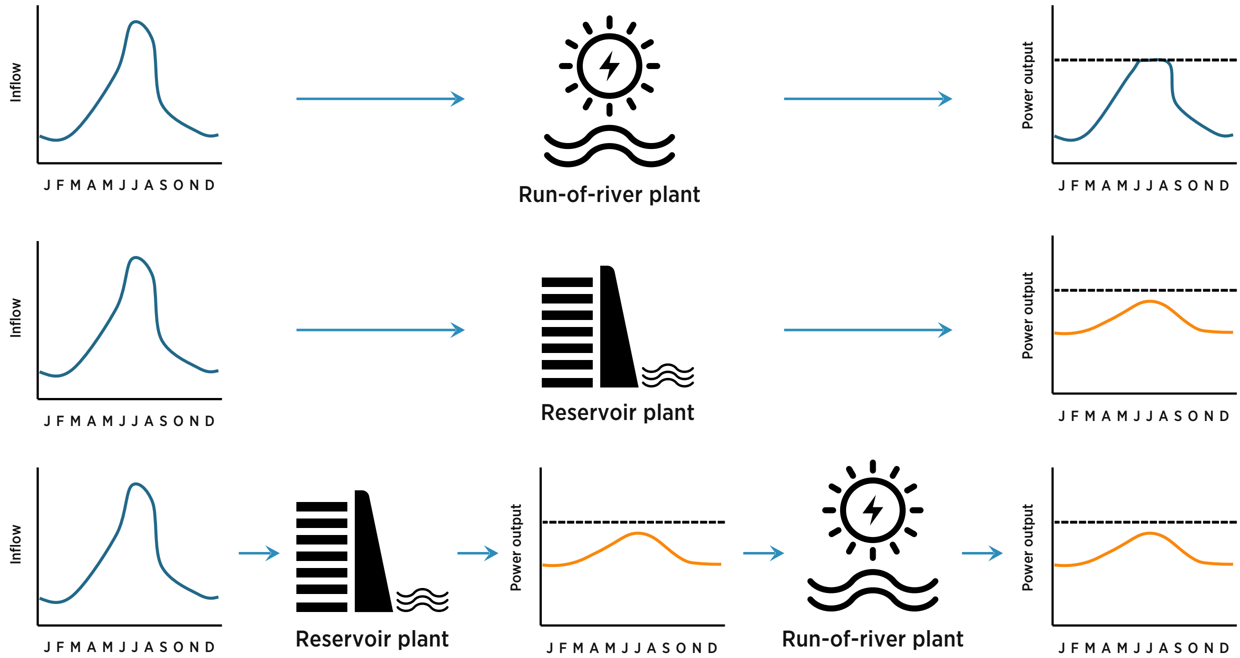
Note: The atlas covers plants with capacities between 90 kW and 11.5 GW.
Source: United Nations' Clear Map (plain web version).
Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

The hydropower availability profiles in the AfREP-Hydro database are calculated by accounting for various technical and configurational characteristics. Distinct calculations were performed for (i) run-of-river plants, (ii) reservoir storage plants, and (iii) plants forming part of a cascade. In each of these cases, the question is how the temporal inflow profiles of the rivers in question—which determine the temporal availability of water to be turbined by the hydropower plant—result in typical power output profiles of the hydropower plant, taking into account the plant's technical and design characteristics. The data thus reflects the combined effect on availability profiles of (i) design discharges, (ii) water storage effects in reservoir plants, based on the relative size of reservoir volume as compared to annual inflows, and (iii) the influence of upstream reservoir plants on downstream run-of-river plants.

Inflow profiles, in turn, are determined by the hydrology of the upstream basin, which is driven by the combined effects of rainfall, evapotranspiration, soil infiltration, topography, upstream man-made infrastructure (mainly other dams), extraction of water for irrigation, etc. These inflow profiles were obtained at monthly timescale from hydrological simulations with the SWAT+ (Soil and Water Assessment Tool) model covering the entire African continent, whose outcomes have been made available publicly and free of charge in a repository (Sterl and Chawanda, 2021).

Figure 4 schematically depicts the principal question answered by the database: How can a hydropower plant's seasonal power generation profile be determined from (a) the river inflow profile, reflecting, for example, the seasonal cycle of rainfall in a monsoonal climate, and (b) the technical characteristics of the hydropower plant? The specific ways of subsequently using this information in energy models is explained in more detail in the box "*Implications for energy modelling exercises*".

Figure 4: The objective of the AfREP-Hydro database is to provide seasonal hydropower availability profiles based on river inflow and hydropower plant characteristics. Three types of hydropower plant (configurations) are taken into account: run-of-river plants, reservoir plants, and cascades.



Run-of-river hydropower plants have no reservoirs to store water, and directly turbine the river flow. Typically, such plants are designed to produce at maximum power during several months of the year, meaning their design discharge should be exceeded during several months, not only during the very wettest month when river inflow is at its maximum (top row in Figure 4).

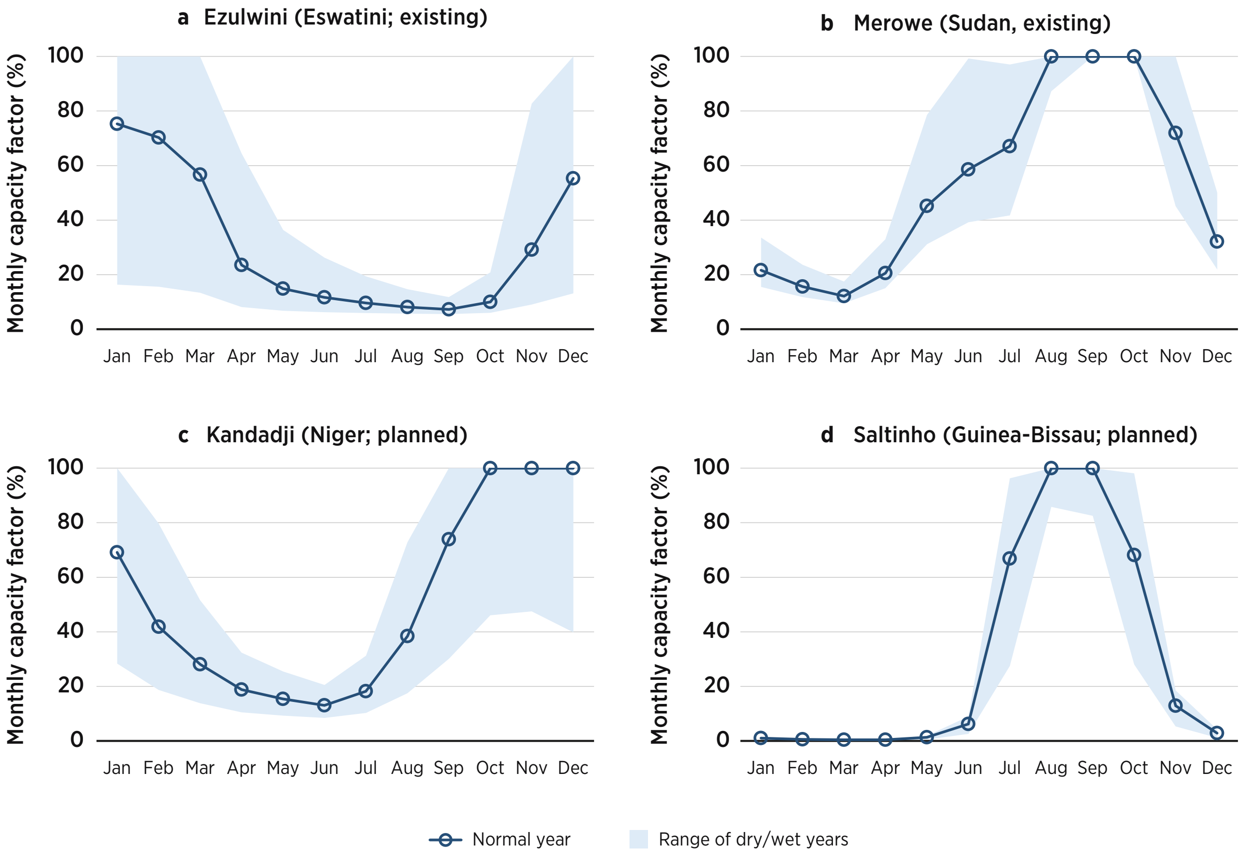
Reservoir hydropower plants, on the other hand, can store some of the inflow, thus mitigating inflow variability. For very small reservoirs, this may be limited to diurnal or intra-week variability; for medium-sized reservoirs, the storage may allow reducing the seasonality of the river flow to achieve a more stable year-round power generation. The very largest reservoirs (of which there are relatively few, given their typically profound environmental impact) may even mitigate interannual variability, and thus reduce the difference between dry and wet years. This effect has been taken into account in the database by comparing the storage volumes of the reservoirs with the inflow volumes, and subsequently adapting the profile by spreading the retainable component of inflow equally across the different seasons (middle row in Figure 4).

Cascaded hydropower configurations consist of a reservoir plant upstream, whose water releases are turbined by one or more run-of-river plants downstream. Effectively, these are cases where a single reservoir is shared by several hydropower plants in series (bottom row in Figure 4). Some existing run-of-river hydropower plants may become part of cascade systems in the future (if a reservoir plant is constructed upstream). The change in configurations of cascade systems has been taken into account in the AfREP-Hydro database based on estimated earliest years of entry into service of future plants. The provided profiles for a certain plant may thus change depending on the period considered.

Out of all 633 entries in the current version of the database, the required calculations to obtain seasonal hydropower plant availability profiles could be performed for 551 entries (87%).[2] For the other entries, the collected data is not yet comprehensive enough to allow the calculation. In the future, further updates of the database will allow the inclusion of more hydropower plants as well as the completion of seasonal profile calculations for the existing entries.

Four examples of hydropower availability profiles for plants in different climato-hydrological conditions and with different technical characteristics are provided in Figure 5. The characteristics of the shown plants are summarised in Table 1. It is clear that the seasonalities of hydropower generation differ greatly across climate zones and across different regions of the African continent. In addition, the difference between typical dry and very wet years is seen to be substantial, reflecting a challenge for African power systems that has been well-documented in literature (Conway et al., 2017; Wheeler et al., 2020).

Figure 5: Examples of seasonal hydropower availability profiles in the database. Shown are two existing plants: (a) Ezulwini and (b) Merowe, and two planned plants: (c) Kandadji and (d) Saltinho.



2 This was done using dedicated Python code available on GitHub (https://github.com/VUB-HYDR/2021_Sterl_etal_AHA).

Table 1: The characteristics of the four hydropower plants whose availability profiles, according to IRENA's African hydropower database, are shown in Figure 4.

Hydropower plant	Country	River	Power Pool	Reservoir (storage in days)	Köppen climate zone
(a) Ezulwini	Eswatini	Lusushwana	SAPP	Yes (~64 days)	CWa (Temperate, dry winter, hot summer)
(b) Kandadji	Niger	Niger	WAPP	Yes (~26 days)	BSh/BWh (semi-arid to arid, desert, hot)
(c) Merowe	Sudan	Nile	EAPP	Yes (~54 days)	BWh (arid, desert, hot)
(d) Saltinho	Guinea-Bissau	Rio Corubal	WAPP	No (run-of-river)	Aw (Tropical, savannah)

Implications for energy modelling exercises

The AfREP-Hydro database was created to serve the energy modelling community with detailed data to enable improved representation of the seasonal availability of individual hydropower plants, which goes beyond the typical state-of-the-art, especially for the African continent. The optimal way of importing such seasonal profiles into any energy planning tool or model will depend on the specificities of the software used (e.g. MESSAGE, LEAP, PLEXOS, TIMES family of models …). However, generally speaking, the profiles from the AfREP-Hydro database can be used and applied as follows in energy models:

For run-of-river plants, the profiles from AfREP-Hydro may be used as-is, given that such plants are not dispatchable and cannot be used to provide system flexibility. It should therefore be possible to use these profiles in the same way as one would use VRE resource profiles. This also applies to run-of-river plants in a cascade system.

For reservoir plants, for which it is desirable to model a certain flexibility of dispatch in power system models, the profiles denote constraints on seasonal availabilities, not fixed profiles (as would be the case for run-of-river plants). Reservoir storage plants can support load-following and VRE integration as constrained by maximum ramping rates, minimum stable loads and maximum discharge values. In such cases, models should be conceived such that reservoir storage plants are represented with a certain flexibility of dispatch, but with additional constraints on average seasonal profiles as provided by AfREP-Hydro. The specific modalities of including such constraints will be unique to each energy planning software.

CONCLUSION

IRENA's AfREP-Hydro database on African hydropower marks a strong case for improving the modelling of power systems across the African continent. By accounting in detail for the particular characteristics of individual hydropower plants as well as the hydroclimate-driven seasonality of river flow, it has the potential to become the go-to easy-to-access resource for the modelling community in all matters related to hydropower in Africa.

The availability of the AfREP-Hydro database will be of particular benefit to the assessment of spatiotemporal synergies between VRE and hydropower. This is of high importance in the context of power mix diversification through VRE in hydro-dominated systems in Africa (Falchetta et al., 2019), in the context of explicit hybrid project design such as through floating solar PV on reservoir surfaces (Gonzalez Sanchez et al., 2021), and in the context of integrated river basin-wide planning of future infrastructure (Conway et al., 2017). The database has already been used successfully in dedicated studies on smart and diversified renewable electricity portfolios in West Africa (Sterl et al., 2020), as well as in a recently proposed solution to the Grand Ethiopian Renaissance Dam conflict based on hydro-supported solar and wind power integration (Sterl et al., 2021b).

The data contained in the AfREP-Hydro database will be regularly updated and IRENA encourages experts in the field to get in touch and submit up-to-date (meta)data wherever relevant, such that the database can remain state-of-the-art. Aside from data updates, future improvements to the database could focus on including supplementary constraints on hydropower plant operation, e.g. the co-optimisation of power generation needs with current and future irrigation schemes, as well as the potential impacts that climate change may have on hydropower generation and potential on the African continent.

The latest release of the AfREP-Hydro database (v2.0) already includes a first iteration of climate change and land-use change scenarios. These will be analysed in more depth in the near future.

HOW TO ACCESS

IRENA's AfREP-Hydro database can be accessed through the HydroShare platform through the link https://www.hydroshare.org/resource/5e8ebdc3bfd24207852539ecf219d915.

A scientific treatise on the database can be found in (Sterl et al., 2021a).

A visualisation of the database contents can be accessed through IRENA's Global Atlas at https://globalatlas.irena.org/workspace. Users may click "*Layer*" and subsequently "*Get Data*", upon which a list will be shown containing the various datasets of the Global Atlas. Three of these datasets are based on the AfREP-Hydro database and labelled "*Africa – Seasonal hydropower availability [XXX]*". The three datasets represent, respectively, (i) the currently installed hydropower fleet, (ii) the hydropower fleet expected for 2030, and (iii) the hypothetical situation where all "candidate" hydropower plants in the database are constructed.

By clicking "*add to map*" the hydropower plants will be visualised geospatially. The user may subsequently select an area of the African continent (using *Shift+drag* on the map) from which to download data, by clicking "*download*". This latter step allows the user to obtain the numerical values representing month-by-month profiles of hydropower capacity factors in a comma-separated file.

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DISCLAIMER

Full disclaimer on sources

The African Hydropower Database was created using data from:

FAO's Aquastat: FAO. Geo-referenced Database on Dams: Africa. License: CC BY-NC-SA 3.0 IGO. Extracted from: www.fao.org/aquastat/en/databases/dams. Data of Access: 10-08-2020. No modifications were introduced to FAO's data. The data have been used in conjunction with data from other data providers for the creation of the African Hydropower Database. Data available subject to the Attribution-NonCommercial-ShareAlike 3.0 IGO Creative Commons license accessible here.

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