Renewable Energy 169 (2021) 687–699

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Assessment of floating solar photovoltaics potential in existing hydropower reservoirs in Africa

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A R T I C L E I N F O

Article history:
Received 14 October 2020
Received in revised form
11 December 2020
Accepted 7 January 2021
Available online 11 January 2021

Keywords:
Floating PV
Floatovoltaics
Africa
Hydropower
Renewable energy
Evaporation reduction

A B S T R A C T

Africa is characterised by a very high solar potential, with a yearly sum of solar irradiation exceeding 2000 kWh/m^2. Many African countries are heavily dependent on hydropower, however, increasingly frequent droughts have been severely affecting hydropower generation in the last few decades. The installation of floating photovoltaics (FPV) in existing hydropower reservoirs, would provide solar electricity to help compensate hydropower production during dry periods and reduce evaporation losses while helping to sustainably satisfy the current and future energy needs of the fast-growing African population. This study provides a comprehensive analysis of the potential of FPV installation in Africa, by using highly accurate water surface data of the largest 146 hydropower reservoirs in the continent. In addition to the electricity production, evaporation savings and the potential extra hydroelectricity generated by these water savings are also estimated at reservoir level for four different cases and two types of floating structures. The results indicate that with a total coverage of less than 1%, the installed power capacity of existing hydropower plants can double and electricity output grow by 58%, producing an additional 46.04 TWh annually. In this case, the water savings could reach 743 million m^3/year, increasing the annual hydroelectricity generation by 170.64 GWh.

1. Introduction

Africa accounts for the lowest electricity access rate (54%) worldwide, which becomes significantly lower in Sub-Saharan Africa (47.7% compared to 96.5% in North Africa) [1], where the population also grows at an annual rate of 2.7% per year, significantly higher than in South Asia (1.2%) and Latin America (0.9%). This information shows the urgent need for new deployment of power infrastructure in Africa to compensate for the lack of energy access.

Hydropower is an important source of electricity in Africa, especially in eastern and southern Africa. For instance, 90% of the electricity generation in Ethiopia, Malawi, Mozambique, Namibia and Zambia comes from hydropower [2]. Africa is also the continent with the highest untapped technical hydropower potential. According to the International Hydropower Association [3], only 11% of the total technical potential has been developed. Although progress in deploying hydropower plants has been limited since 2010, hydropower is expected to grow rapidly in Sub-Saharan Africa. In 2019, almost 1 GW of additional hydropower became operational in Africa, reaching a total 37 GW of installed capacity and 138 TWh of electricity generation. Currently, more than 50 hydropower projects are under construction and are expected to add 15 GW of additional capacity by 2025. The compound annual growth is estimated to increase twofold and reach 9.7% over the period 2020–2025 [3].

However, water scarcity, is affecting many regions in the continent and in the last few years Africa has witnessed long and severe droughts, causing serious repercussions on hydroelectric generation [4,5]. Two-thirds of the continent is arid or semi-arid and future projections foresee longer and harsher droughts along with a decrease in river flow during dry season, caused by climate change [6]. Climate impacts can alter water resource availability, reduce hydro generation, due to erratic precipitation patterns, and increase risks. Moreover, higher temperatures are expected to increase evaporation loss and the average hydropower capacity factor is expected to decline by 1.4%–2.9% in the following decades. On a

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https://doi.org/10.1016/j.renene.2021.01.041
0960-1481/

Nomenclature

AC	alternating current
CAPP	Central African power pool
DC	direct current
EAPP	Eastern African power pool
EI	energy index
EP	electricity production
EQIC	equal installed capacity
EU	European Union
FPV	floating photovoltaics
GW	gigawatt
IC	installed capacity
kW	kilowatt
mcm	million cubic meters
MW	megawatt
NAPP	North African power pool
PR	performance ratio
PI	power index
PV	photovoltaic
SAPP	Southern African power pool
TWh	terawatt-hour
WAPP	West African power pool

regional level, certain African river basins are expected to be more affected than others and individual countries could see hydropower productivity drop by more than 10% [7].

In this context and considering climate targets, other low-carbon energy technologies such as PV need to be prioritised and deployed at large scales. Africa is the continent with the most abundant solar resources in the world. The vast majority of African countries have an excellent solar potential, with 85% of the continent totalling a yearly average solar irradiation exceeding 2000 kWh/m^2. In an attempt to put this into context, the yearly sum of solar irradiation in EU Member States ranges between 1100 and 2000 kWh/m^2, with the higher range occurring only in absolutely prime locations (e.g. Malta, Cyprus) [8]. Currently, Africa counts with a PV installed capacity of only 5 GW, less than 1% of the total capacity globally, which generated 6 TWh in 2018. However, IEA projections estimate an average future deployment of almost 15 GW per year, reaching 320 GW by 2040. This would make PV the largest electricity source in installed capacity in the continent, surpassing natural gas and hydropower [9].

Considering the increasing energy needs in Africa and its vast solar resources, this study presents the feasibility of an effective energy symbiosis between solar photovoltaics (PV) and hydropower through the development of Floating PV systems (FPV). FPV systems offer a noble solution to African hydropower reservoirs as they could rapidly ramp up installed power capacities through existing infrastructure and local expertise. Furthermore, FPV could compensate −at least partially-for the reduction of hydropower output during dry periods and reduce water loss from evaporation. In 2016, water loss due to evaporation in the African hydropower reservoirs accounted for 42 billion m^3, which represents more than 30 times the amount of water used to generate electricity by all the other energy technologies combined in the continent [10]. Bontempo et al. [37] compared four types of PV floating structures to obtain the evaporation savings using each one of them. For floaters that fully cover the area underneath them (thus reaching maximum evaporation savings), the results appear to be non-linear, obtaining for instance that 50% coverage of the reservoir surface area would reduce water consumption by 73%.

FPV systems have emerged as an alternative option to produce electricity bypassing the issues and challenges related to land use. Although land availability for renewable energy deployment is not currently a major challenge in the African context, FPV systems have additional advantages that are pertinent to Africa. Some of these are: efficiency increase compared to land-based systems due to the cooling effect of water; evaporation reduction; improvement of water quality by preventing algae growth; simpler installation and decommissioning than rooftop and ground-mounted systems; simpler cooling and tracking systems; less dust effect and an efficient complementarity with hydropower [11,12].

2. State-of-the art

The first commercial FPV installation of 175 kWp started operations in 2007 in the Far Niente Winery in California, with the main purpose of reducing evaporation in the irrigation tanks and provide additional energy. In the following years, the FPV cumulative installed capacity experienced an important growth, reaching 10 MWp in 2014 and 2.6 GWp by August 2020, with China controlling 73% of the total capacity and the rest mainly credited to Japan and Korea, followed by Europe [11,13,14]. In the next five years, FPV installation is expected to continue increasing with an average growth rate of above 20% [14]. While most of the projects so far are small in size (below 3 MWp), a number of large-scale projects also exists. The two largest plants, completed in 2018, are located in mining subsidence areas in China, with an installed capacity of 150 MWp each [11]. Sungrow and Ciel et Terre stand out as the top two FPV system providers, covering around 98% of the total installed capacity of FPV worldwide [15]. A recent report by the World Bank [11] concluded that with only 1% coverage of all the man-made reservoirs in the world, the potential capacity could reach 400 GWp. Covering 1% of these areas in Africa alone points to an estimate of 100GWp.

Hybrid systems combining hydropower with land-based PV systems have been widely addressed in the last decade. One of the main advantages of this type of systems is the easy access hydropower plants provide to the grid. Glasnovic et al. [16] presented the first analysis of a hybrid hydroelectric power plant using ground-based PV energy to pump water to an upper reservoir, which stores solar energy for later production of hydroelectricity. This concept provides flexibility to adjust to consumption needs and the results were positive when tested in Croatia. Several studies have also been performed in Africa proposing micro-hydro and PV hybrid systems for their application in rural areas such as Cameroon [17,18] and Ethiopia [19] among others.

A few years later, in 2013, a land-based PV plant was commissioned and connected to the pre-existing Longyangxia hydropower plant in China, creating the first large-scale commercial PV-hydro plant in operation, with a hydropower installed capacity of 1280 MW and a PV capacity of 850 MWp. In such complementary systems, PV is often referred to as virtual hydropower since it works as a backup hydropower unit. There are many advantages to this type of complementary systems. With its more stable and flexible operation, hydropower can compensate for the highly unstable and intermittent PV output, especially during the wet season when more water is available to run the turbines and/or winter when PV output is lower. In exchange, PV can complement hydropower by providing extra peak power load during dry periods when water levels are lower [20]. A similar complementarity can take place daily during day- and night-time operation and during peak hours, when hydropower can further contribute to the peak load thanks to the water saved during daylight hours [21]. Several studies on this complementary hybrid system have focused on optimising the size of the PV plant, for the short and long terms, with tests in Longyangxia [22–25]. Fang et al. [22] also performed a worldwide evaluation, demonstrating good potential for this type of system in central Africa, especially in the Congo river basin. The optimisation model of Ming et al. [23] for instance, obtained an increase of energy production of about 2% in the optimised scheduling of Longyangxia.

In the last few years, several studies have started analysing the use of FPV in hybrid systems with hydropower [26–30], however, the market is still in the early stages, with only a small system of 220 kWp installed in Portugal [11]. Silvério et al. [26] analysed the use of FPV with several hydropower plants in a river basin in Brazil, obtaining an energy gain of 73% and a capacity factor increase of 17% on average. It was also found that tilt angles have a high influence on the cost, making this technology sometimes unfeasible if tilt angles are selected based on maximum generation. Some studies at global level have also been performed. Cazzaniga et al. [29] analysed the 20 largest hydropower plants in the world. Assuming an FPV installed capacity equal to hydropower, the study obtained an increase in energy production of 15%–52% covering 3.5% of the reservoirs surface area. In the case of Africa, the analysis indicated that a coverage of 1.2% would produce an increase in electricity of 36%. Perez et al. [31] performed a similar study on the 128 largest hydropower reservoirs in the US, concluding that the same electricity generation obtained from hydropower could be obtained by covering 1.2% of the reservoirs surface area with FPV.

As previously mentioned, one of the benefits of FPV systems is the increase in energy efficiency compared to land-based PV systems, thanks to the cooling effect of water. Conclusions on this are very diverse, depending on the study. Choi et al. [32] obtained an average increase in efficiency of 11% in two projects in Korea; Rosa-Clot et al. [33] a gain of 10%; The World Bank [11] reported an increase between 5% and 10%, depending on the region; Sacramento et al. [34] 12.5% and Odeh et al. [35] and Krauter et al. [36], both using an active cooling system through a water veil applied to the surface of the FPV, obtained increases in efficiency of 4–10% and 10.3% respectively.

This study aims to provide a comprehensive assessment of the installation of FPV systems in the African hydropower reservoirs and their benefits from different perspectives. Its novelty lies on the fact that a highly accurate dataset of the largest hydropower reservoirs in the continent is used to estimate the FPV electricity output for different scenarios and with the highest possible accuracy at reservoir level. Additionally, the estimation of the evaporation savings and potential extra hydroelectricity production is also calculated for each of the reservoirs. Consequently, the study presents an original analysis that provides hard evidence of the benefits of FPV systems on hydroelectric stations' generation, a topic typically handled in a qualitative manner so far.

3. Data and methods

The methodology developed in this study uses a combination of satellite images and hydropower reservoir data to estimate the potential of FPV installation in the targeted hydropower reservoirs in Africa. The FPV energy output (subsection 4.2), the reduction of evaporation (subsection 4.3) and the consequent extra hydroelectric potential originated from the water savings (subsection 4.4) are obtained for four different cases and two types of floating structures.

3.1. Reservoir data

This study analyses the 146 largest operational hydropower reservoirs in Africa in 2016 with an installed capacity larger than 5 MW. It builds on and extends a database developed by the authors in an earlier study that used satellite data to profile reservoir areas and estimate their evaporation loss [10]. The database includes data such as location, area covered and evaporation loss, as well as information on the associated hydropower plants, such as installed capacity and annual electricity generation. The total reservoir surface area covered by the 146 hydropower reservoirs included in the study is 29,222 km^2.

3.2. FPV solar electricity output

The electricity generation of solar PV systems is location-dependent. The methodology used in this study to assess the potential FPV generation builds on a previous geospatial analysis of the energy output and reliability of PV system, described in detail in [8,38]. The mentioned methodology combines hourly solar radiation data from satellites (at 1 km^2 resolution), measured data on PV module performance and temperature and wind speed data from reanalysis. The model developed in [8,38] determines for each location and for different PV technologies (i.e.: crystalline silicon, CdTe and CIS thin films) the optimal inclination angle of the PV modules that provides the highest energy output for the whole year as well as the irradiation and electricity output in these conditions.

In the present study, the annual sum of solar irradiation at optimum inclination angle has been calculated from the aforementioned model [8,38] for each pixel (at 1 km^2 resolution) of the reservoirs, assuming polycrystalline silicon modules. The solar irradiation has been subsequently averaged for each of the reservoirs and used as input to obtain the annual electricity production from equation (1):

$$EP_{FPV} = A_{\mathrm{Res}} \cdot r_A \cdot I_{opt} \cdot y \cdot PR \cdot r_{\frac{AC}{DC}} \quad (1)$$

Where:

EP_{FPV}: annual electricity production (MWh/year)
A_{Res}: total area of the reservoir (m^2)
A_{FPV}: total reservoir' area covered with FPV (m^2)
r_A: ratio of reservoir area covered by FPV (A_{FPV}/A_{Res})
I_{opt}: annual sum of solar irradiation energy at optimal inclination angle averaged for the reservoir area (kWh/m^2)
y: PV area factor (kWp/m^2)
PR: system performance ratio
$r_{AC/DC}$: losses due to solar clipping

The study assumes PV modules with an area factor of 0.16 kWp/m^2; however, a final value of 0.1 kWp/m^2 has been considered in the calculations to account for a proper separation between rows, as to avoid shadowing and allow an adequate service area. The FPV coverage of the reservoir (r_A) is assigned according to the different scenarios presented later in 3.5. The performance ratio of the system (PR) introduces all system losses (due to cabling, inverters, conductive heat loss, etc.). The performance ratios of FPV have proved to be higher than those of ground-based PV systems due to the evaporative cooling effect [39]. In this study, a PR of 0.8 is assumed [11], which represents a conservative value compared to the range of 0.83–0.91 obtained in the SERIS test beds [39]. An inverter load ratio of 1.25 is applied to the FPV systems (a value typically used in commercial ground-based installations) [40,41]. A system with a DC-to-AC ratio greater than 1 produces more AC power in the mornings and evenings, obtaining a net benefit in terms of energy output. When solar PV generation is higher than the power the inverter can handle, energy curtailment, known as solar clipping, occurs. This typically happens during high peaks of solar irradiation (normally short periods around midday on sunny days) and it consequently accounts for 1% loss of the total annual generation, which according to industrial practice corresponds to the selected inverter load ratio of 1.25 [40,42,43].

3.3. Evaporation water savings

Water savings are calculated based on the evaporation rates obtained in Bontempo et al. [37] for four different types of floating structures. In the mentioned study, the evaporation rate from a body of water is obtained using two different evaporation numerical models (Penman and linear regression) as a function of the FPVs coverage of the reservoir (0%, 10%, 30%, 50%, 70% and 100%). The robustness of these models has been proved by comparison with experimental evaporation rates in the reservoir analysed using evaporimeters. In this study, a cubic spline interpolation function is applied to the percentages of evaporation savings resulting from Bontempo et al. [37] to interpolate the evaporation rates for each of the coverage values used in our study (r_A = 1%, 10% and 100%).

The present analysis considers two types of floaters included in Bontempo et al. [37] (the most commonly used in FPV applications): floaters that fully cover the surface underneath them and suspended systems. In the first case, the solar irradiation transmitted to the water is almost zero, since the panels installed on top of the floaters cover the entire surface, thus achieving the highest water savings. However, the disadvantage of this system is that it prevents PV panels from benefiting from the evaporative cooling effect of the water below, therefore no extra efficiency gain is expected. In the second type of floaters, consisting of a tubular structure to which the panels are attached, good ventilation and the evaporative cooling effect of the water allow the panels to operate at lower temperatures, which increase the efficiency of the panel. The downside in this case is lower evaporation savings.

3.4. Extra hydropower potential

Evaporation savings on reservoirs provide an additional quantity of stored water that can be utilised for electricity generation. The productivity of hydropower in Africa was estimated using country-level information for the period 2014–2019. Annual values of electricity generation and installed capacity collected for all African states during a five-year period [3] were used to obtain country-level capacity factors. Subsequently, due to the unavailability of power plant electricity output data, the average values of the capacity factors for 2014–2019 were calculated and applied to all the hydropower plants within each particular country to obtain the electricity output at power plant level.

The available open-access and proprietary databases (e.g. the World Electric Power Plants Database [44] and the Global Reservoir and Dam Database [45]) do not provide values of the hydraulic head of hydropower stations. The hydraulic height difference (head) is one of the two parameters that define the productivity of a station, with the other being the available water discharge. Accordingly, a thorough research was performed to collect this information from a wide range of sources (technical documents, corporate reports, country reports, reports of donors and investment banks, ministries and regional authorities).

Equation (2) describes the nominal power capacity (P) of a hydropower station:

$$P = n \cdot \rho \cdot g \cdot Q \cdot h \tag{2}$$

Where:

P: nominal power capacity of the station (W)
n: system efficiency
ρ: water density (1000 kg/m^3)
g: gravity acceleration (9.81 m/s^2)
Q: nominal water discharge of the turbine (m^3/s)
h: hydraulic head (m)

Since the nominal installed power, P, is known for all analysed stations, using Equation (2) and assuming an 85% of system efficiency for all the analysed stations, the nominal water discharge Q (m^3/s) of each station can be estimated.

Water savings from evaporation (see 3.3) can clearly prolong operation time of hydropower stations. With a total volume of water savings V (m^3), a station could operate at full power P for an additional number of hours equal to T (where $T = Q/V$). Assuming that all water savings are used for hydroelectric generation, the additional electricity generation will be $P*T$.

3.5. Scenarios of FPV reservoir coverage

The potential of FPV in the reservoirs analysed is evaluated for four different cases. Three of them consider a fixed percentage of coverage: full resource theoretical potential (100% coverage), 1% coverage and 10% coverage. The fourth case assumes the installation of an FPV system of the same installed AC capacity as that of the adjacent hydropower plant. Throughout the text, this case will be referred as EQIC (Equal Installed Capacity) for simplicity. This approach was suggested in [12,22,26] and enables FPV systems to fully utilise the existing electricity grid capacity of the power plant and feed the maximum possible solar electricity into the grid. Such scenario adapts to the specific characteristics of each hydropower station and maximises the solar output and opportunities of hybrid operations. More importantly, it does so with relatively low interventions and investments on grid infrastructure. This approach also sets an upper threshold for the FPV capacity and ensures that hydropower will be able to compensate for the power deficiency in case needed.

4. Results

4.1. Preliminary analysis: energy and power indices

The first step of the analysis evaluates the land footprint of FPV and existing hydropower installed capacity in the targeted African reservoirs. This includes the calculation of a power index, PI, (MW/m^2) and an electricity index, EI, (MWh/m^2) for both FPV and hydropower, which show the installed capacity and electricity generation per unit of reservoir surface, respectively. These indices are obtained for each of the reservoirs as:

PI_{FPV} = FPV peak installed capacity/area reservoir (KWp/m^2); (PI_{FPV} equals "y: PV area factor" defined as 0.1 kWp/m^2 in section 3.2)
PI_{hydro} = Hydropower installed capacity/area reservoir (KW/m^2)
EI_{FPV} = FPV electricity production/area reservoir (KWh/m^2) (calculated following Eq. (1))
EI_{hydro} = Hydropower electricity production/area reservoir (KWh/m^2)

Fig. 1 depicts the wide distribution of the PI_{FPV} and PI_{Hydro} ratios for the 146 reservoirs. Out of the 146 reservoirs analysed, 76% of them have a PI_{FPV} larger than the PI_{Hydro} with a median PI_{FPV}/PI_{hydro} value of 15.16. As for the electricity index, 72% of the reservoirs have an EI_{FPV} larger than the EI_{hydro}, with a median EI_{FPV}/EI_{hydro} value of 11.85. These results reflect the fact that FPV systems generally require less area compared to hydropower reservoirs, which are sometimes very large in terms of area per unit of installed capacity [29]. Exceptions to this are the run-of-river hydropower plants or those with large hydraulic heads and comparatively small reservoirs.

4.2. Installed capacity and electricity output of FPV deployment

This section presents the installed capacity and the electricity output for the four cases analysed: full theoretical FPV potential (100% coverage), 1% coverage, 10% coverage, and an installed FPV system capacity that equals the hydropower plant nominal power capacity (EQIC case).

The full resource FPV potential for electricity production (covering 100% of the reservoir area, total of 29,222 km^2) for the 146 analysed reservoirs would result in an almost 50-fold increase compared to the electricity currently produced by hydropower (from 105 TWh to 5293 TWh). The total installed capacity of FPV in this case would be 2922 GWp (more than 250 times the cumulative installed PV capacity of around 11 GWp at the end of 2020 [46]), in comparison to 28 GW of hydropower capacity currently installed. The deployment of the full FPV technical potential is not feasible, however, it provides an indication of the full existing potential in terms of water areas currently available for FPV installation in the continent. The results of the two other relatively more feasible cases, 1% and 10% of surface coverage, are summarised in Table 1 for the five African power pools: Central African Power Pool (CAPP), Eastern African Power Pool (EAPP), North African Power Pool (NAPP), Southern African Power Pool (SAPP) and West African Power Pool (WAPP). Madagascar and Mauritius are included in SAPP for visualization and aggregation purposes throughout the article,

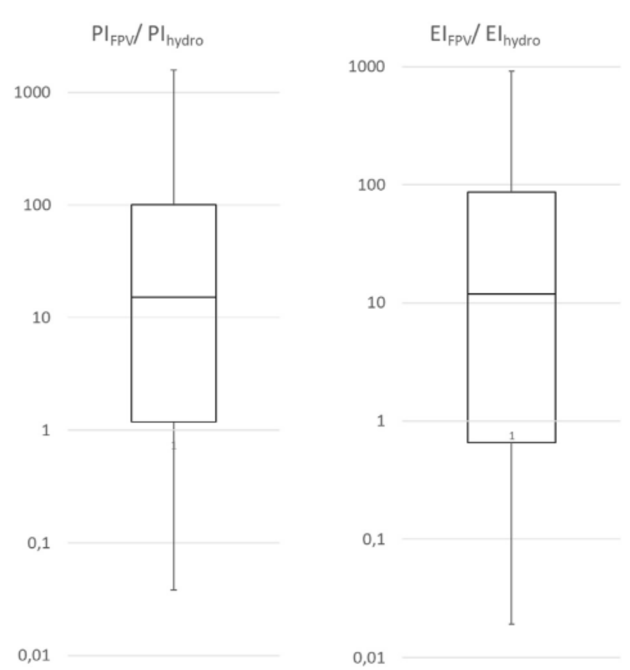

Fig. 1. Distribution of power (PI) index and energy (EI) index between FPV and hydropower for the 146 African hydropower reservoirs considered in the study (in logarithmic scale).

although they don't belong to any power pool yet. However they currently belong to the Southern Africa Development Corporation.

Fig. 2 presents the distribution of the A_{FPV}/A_{Res} ratio for the EQIC case for the 146 reservoirs, showing an FPV coverage median value of 8%. Out of the 146 reservoirs, 38 of them need more than 100% FPV coverage in order to equal the hydropower installed capacity, therefore these reservoirs are not considered further in the EQIC case analysis. The total annual electricity output with FPV installed in the remaining 108 reservoirs for the EQIC case is 46.04 TWh, covering an area of less than 1% with FPV and increasing the electricity output of hydropower by 58%.

The map in Fig. 3 shows the location of the reservoirs analysed in the EQIC case with information on the electricity output and coverage of the FPV plants installed. The size of the circles indicates the annual electricity output produced by each of the newly installed FPV plants and the colour classification represents the range of coverage (from white/light green to denote low FPV surface coverage to dark green for large FPV coverage). In this figure, it can be observed that all the large reservoirs require very small coverages (white/light green circles) to produce a significant amount of electricity with an equal installed capacity to that of the hydropower plant. As previously mentioned, this is due to the fact that PV technologies are more efficient than hydropower in large reservoirs in terms of surface productivity. Nevertheless, most of these very large reservoirs in Africa are also located in regions with very good solar radiation. For instance, in the Lagdo hydropower reservoir (Cameroon), due to the small energy and power indices of hydropower compared to FPV, an FPV coverage of 0.16% of the reservoir can increase the total electricity output by 35%, despite the particularly high hydropower capacity factor (71%). On the contrary, in tropical climate regions of central and western Africa, such as the region of the Congo River basin, there is a greater accumulation of reservoirs that require larger FPV coverage areas to match the hydropower installed capacity (darker green circles). Not only is this region covered by rainforest with a relatively lower solar irradiation, its reservoirs are also of smaller sizes.

Table 2 presents FPV installation values aggregated by power pool for the EQIC case while values at country level are summarised in Table 3.

The results at country level (Table 3) show that in 23 out of the 31 African countries analysed, the total area needed to cover with FPV to match the install capacity of the hydropower plants (doubling the installed capacity in the combined system) is less than 5%. In Burundi and Mauritius, the required FPV coverage reaches 15%, while Namibia represents the extreme case with an FPV coverage up to 85%, due to specific geomorphological characteristics of the single hydropower reservoir analysed in the country. The required FPV coverages for Tunisia, Algeria, Morocco and South Africa are fairly low, with values between 1% and 5% of the total reservoirs surface area. In Morocco and South Africa, the installation of FPV can generate as much electricity as the existing hydropower plants, while in Tunisia and Algeria the FPV production doubles the hydroelectricity generation. The hydropower capacity factors in these four countries are comparably lower than in other African nations, therefore the installation of FPV can provide additional benefits, due to the increase of the combined system capacity factors. Nevertheless, in countries with higher hydropower capacity factors, the installation of FPV can also be beneficial, increasing the electricity output by more than 50%, with an average coverage of around 4%. For instance, covering areas of 1% or less with FPV in Zambia, Mozambique and Ghana (where the largest hydropower reservoirs are located) can raise the hydroelectricity production by around 43%.

Table 1
Installed capacity (IC), annual electricity output (EP) and EP_{FPV}/EP_{Hydro} rates for the two cases: 1% and 10% surface coverage. Results aggregated by regional power pools.

			Hydropower		FPV 1% coverage			FPV 10% coverage		
Power pool	NR	A_{Res} (km^2)	IC_{Hydro} (MW)	EP_{Hydro} (GWh)	IC_{FPV} (MWp)	EP_{FPV} (GWh)	EP_{FPV}/EP_H	IC_{FPV} (MWp)	EP_{FPV} (GWh)	EP_{FPV}/EP_{Hydro}
CAPP	16	1094	2620	11,139	1094	1895	17%	10,936	18,953	170%
EAPP	34	8810	8682	32,420	8810	17,296	53%	88,104	172,960	533%
NAPP	30	485	1954	3031	485	858	28%	4846	8585	283%
SAPP	41	8334	10,080	40,592	8334	15,506	38%	83,343	155,060	382%
WAPP	25	10,500	5007	18,631	10,500	17,379	93%	104,996	173,793	933%
Total	146	29,222	28,343	105,813	29,222	52,935	50%	292,224	529,349	500%

NR: number of hydropower reservoirs included.
A_{Res}. Area: total reservoirs' area.
IC_{Hydro}: installed capacity of hydropower plants.
EP_{Hydro}: electricity production of hydropower plants.
IC_{FPV}: installed capacity of FPV plant.
EP_{FPV}: electricity production of FPV plants.

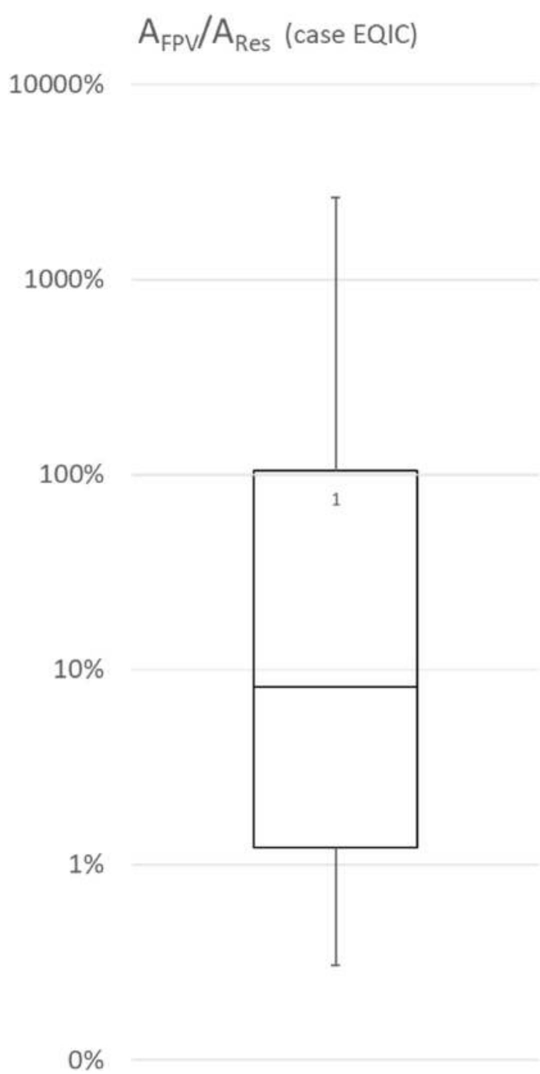

Fig. 2. Distribution of the ratio of FPV coverage versus hydropower areas for the selected 146 African hydropower reservoirs for the EQIC case (in logarithmic scale).

4.3. Evaporation savings

One of the main advantages of the installation of FPV is the reduction of evaporation in the hydropower reservoirs, a significant issue in Africa. Estimations of the total water loss through evaporation in the 146 analysed reservoirs results in 51,073 mcm per year [10]. In this study, two types of floaters are considered for the installation of the PV panel: floaters that cover fully the surface underneath (Type I) and suspended systems (Type II). In the first case considered (100% coverage) and according to Bontempo et al. [37], a floater Type I would save almost all the water lost, while a floater Type II would save 30,521 mcm (60% reduction). In the second case (1% coverage), the water savings would be 954 mcm (Type I) and 304 mcm (Type II) whereas in the third case (10% coverage), the water savings would be 93,539 mcm (Type I) and 3049mcm (Type II). For the EQIC case (108 reservoirs), a total of 743 mcm and 246 mcm of water savings could be achieved installing floaters Type I and Type II, respectively.

4.4. Additional potential hydroelectricity generation

The additional potential electricity that could be generated utilizing the water savings due to the installation of floating PV are estimated for the different scenarios. Table 4 and Table 5 summarise the results aggregated by power pool for both types of floaters and different coverages (1% and 10%). Additional 177 GWh and 1737 GWh could be obtained for the whole Africa using floaters Type I and covering 1% and 10% of the reservoir areas, respectively. For the floater Type II, the electricity generation decreases considerably due to the additional evaporation that occurs in this type of floaters compared to the Type I, declining to 56.6 GWh and 566.3 GWh for 1% and 10% coverages.

For the EQIC case, with a total coverage of 0.9%, the total additional hydroelectricity that could be obtained is 170 GWh (floater Type I) and 56 GWh (floater Type II). EAPP and SAPP are the most important contributors, caused mainly by Ethiopia, Mozambique, Egypt and Zambia producing 94 GWh all together with relatively small coverages, from 0.46% to 2.87%. The results at power pool level for this case are summarised in Table 6.

Fig. 4 and Fig. 5 present the location of the reservoirs analysed for the EQIC case for floater Type I and floater Type II, respectively. The size of the circles indicates the annual extra hydroelectricity as a result of the reduction of evaporation by the new installed FPV and the colour classification indicates the range of evaporation savings.

4.5. Validation: comparison with applications and similar analyses

This sub-section compares the estimations with evidence available in the academic and grey literature. The purpose is to evaluate the accuracy of the results in comparison with findings of similar studies and evidence from real world applications. At global-scale, the analysis in Farfan et al. [27] estimates that 25%

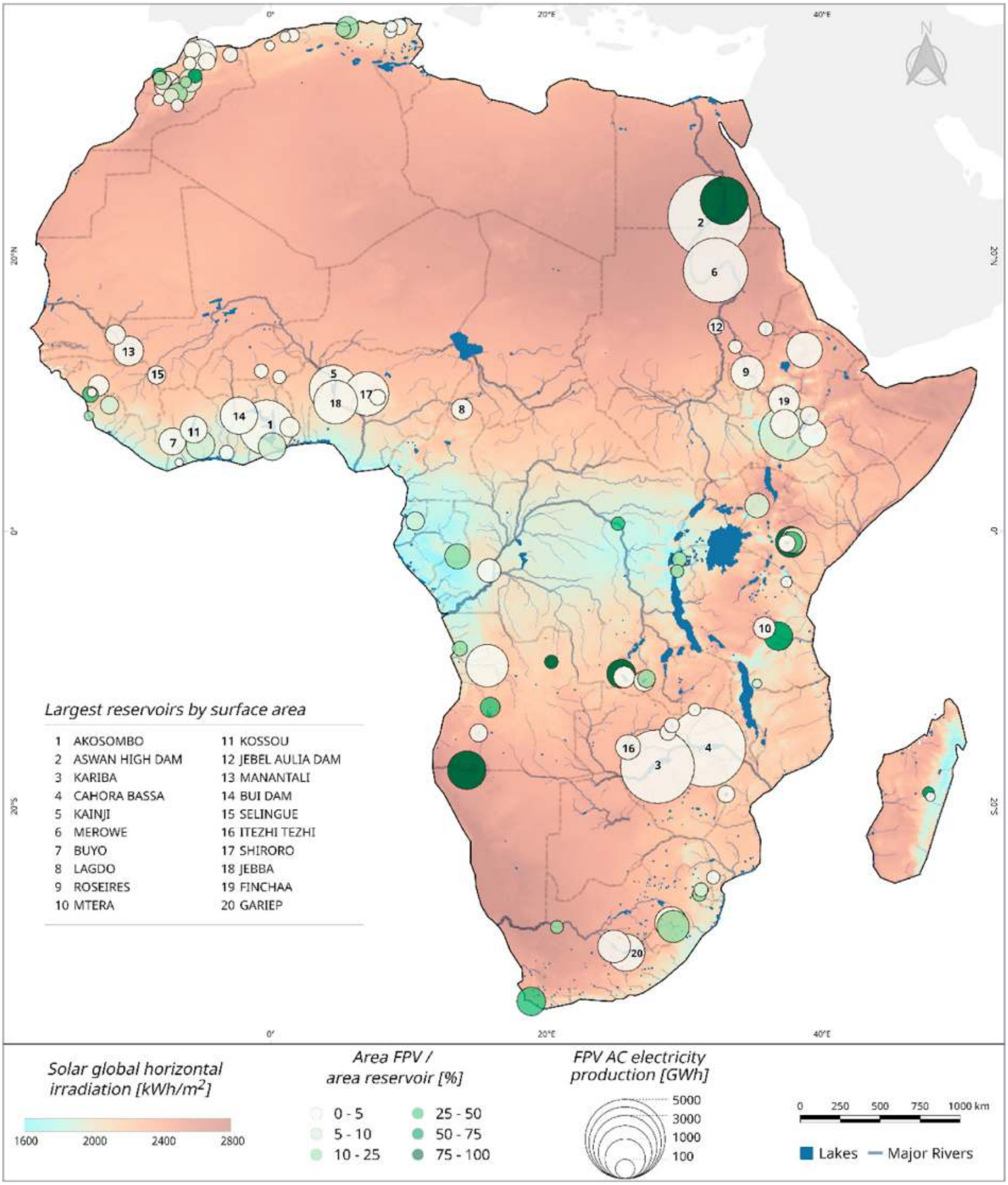

Fig. 3. Map indicating the reservoir location, FPV coverage and FPV annual electricity production for the EQIC case (FPV and hydropower equal installed capacity).

coverage of world's hydropower reservoir would result in at least 4400 GW of FPV with annual generation of 6270 TWh (1425 kWh/kW on average). It also anticipates 6.3% increase of water availability and 142.5 TWh of additional hydro generation. This is of the same order size but notably higher than the calculations presented in Tables 4 and 5, except from the case of WAPP for floater type I which, when adjusted to 25% coverage, results in 5.5% increase of available water resources.

A recent article [30] estimates the global potential for FPV in hydropower reservoirs to range between 3000 and 7600 GW (4251–10,616 TWh, respectively), depending on the coverage. This is equivalent to about 1400 kWh/kW, a value validated in field experiments and real-world applications [47]. Water resource conservation is also highlighted as a potential benefit with estimations linked to Lee et al. [30] and to a recent technical document on FPV [48], where the Colorado Energy Office provides a formula for the estimations of evaporation savings, however, it highlights the need to develop site-specific evaporative models to accurately calculate potential evaporation savings.

The World Bank presented a global assessment of FPV on man-

Table 2
Installed capacity, electricity output and area coverage at power pool level for hydropower and floating PV for the EQIC case.

Power pool	NR	A_{Res} (km^2)	IC_{Hydro} (MW)	A_{FPV} (km^2)	EP_{FPV} (GWh)	A_{FPV}/A_{Res}	EP_{FPV}/EP_{Hydro}
CAPP	9	1088	834	10.32	1675	0.9%	48%
EAPP	25	8808	7165	88.67	17,093	1.0%	63%
NAPP	25	481	1138	14.08	2483	2.9%	145%
SAPP	26	8312	6497	80.40	14,984	1.0%	52%
WAPP	23	10,498	4742	58.69	9810	0.6%	55%
Total	108	29,188	20,377	252.16	46,044	0.9%	58%

NR: number of hydropower reservoirs included.
A_{Res}. Area: total reservoirs' area.
IC_{Hydro}: installed capacity of hydropower plants.
A_{FPV}: Total reservoir' area covered with FPV.
EP_{FPV}: electricity production of FPV plants.
EP_{Hydro}: electricity production of hydropower plants.

Table 3
Installed capacity, electricity output and area coverage at country level for hydropower and floating PV for the EQIC case.

Countries	NR	A_{Res} (km^2)	IC(MW)	EP_{Hydro} (GWh)	A_{FPV} (km^2)	EP_{FPV} (GWh)	A_{FPV}/A_{Res}	EP_{FPV}/EP_{Hydro}
ALGERIA	5	36,5	152,0	146,1	1,88	303,5	5,15%	207,7%
ANGOLA	5	195,6	666,0	2550,1	8,24	1460,1	4,21%	57,3%
BURKINA FASO	2	353,8	33,4	105,0	0,41	72,5	0,12%	69,1%
BURUNDI	1	1,5	18,0	53,3	0,22	31,0	14,56%	58,1%
CAMEROON	1	607,9	80,0	497,8	0,99	173,6	0,16%	34,9%
CONGO	1	53,4	120,0	571,5	1,49	234,1	2,78%	41,0%
CONGO DEM REP	5	399,2	405,7	1349,1	5,02	873,9	1,26%	64,8%
COTE D'IVOIRE	5	1240,7	587,4	1905,3	7,27	1161,3	0,59%	61,0%
EGYPT	2	5248,4	2692,0	12,462,8	33,31	6801,4	0,63%	54,6%
ETHIOPIA	6	795,8	1848,4	5380,6	22,87	4239,2	2,87%	78,8%
GABON	2	27,7	228,4	1041,3	2,83	393,3	10,21%	37,8%
GHANA	3	6004,7	1605,8	7947,0	19,87	3285,2	0,33%	41,3%
GUINEA	3	108,1	110,7	388,2	1,37	234,0	1,27%	60,3%
KENYA	6	179,9	690,1	2714,2	8,54	1515,5	4,74%	55,8%
MADAGASCAR	2	26,4	15,3	74,4	0,19	31,1	0,72%	41,8%
MALI	3	826,8	315,0	1195,7	3,90	702,1	0,47%	58,7%
MAURITIUS	2	3,3	41,4	79,6	0,51	82,1	15,61%	103,2%
MOROCCO	17	405,5	930,3	1515,1	11,51	2064,6	2,84%	136,3%
MOZAMBIQUE	3	2390,8	2130,0	11,222,0	26,36	4917,8	1,10%	43,8%
NAMIBIA	1	5,2	353,0	1730,1	4,37	879,8	84,66%	50,9%
NIGERIA	4	1815,4	1968,4	5903,8	24,36	4104,9	1,34%	69,5%
RWANDA	1	3,3	28,0	79,6	0,35	50,3	10,63%	63,2%
SIERRA LEONE	2	10,1	56,0	133,1	0,69	112,2	6,91%	84,3%
SOUTH AFRICA	6	442,3	1303,2	1605,4	16,13	2975,9	3,65%	185,4%
SUDAN	5	1966,5	1591,6	5392,1	19,70	3840,7	1,00%	71,2%
ESWATINI	2	6,5	40,8	167,7	0,50	81,0	7,83%	48,3%
TANZANIA	4	612,6	297,2	1202,7	3,68	614,9	0,60%	51,1%
TOGO	1	138,8	65,6	133,6	0,81	137,7	0,58%	103,1%
TUNISIA	3	39,1	55,9	52,2	0,69	114,6	1,77%	219,4%
ZAMBIA	5	3379,8	1267,1	6823,8	15,68	2961,2	0,46%	43,4%
ZIMBABWE	1	1862,3	680,0	4686,3	8,42	1595,2	0,45%	34,0%

Table 4
Evaporation savings and extra hydroelectricity by power pool for 1% and 10% FPV coverage for floater type I.

FLOATER TYPE I			1% coverage			10% coverage		
Power pool	NR	WL (mcm)	Evap. Savings (mcm)	Add. Hydro (GWh)	Add. Hydro/EP_{Hydro}	Evap savings (mcm)	Add. Hydro (GWh)	Add. Hydro/EP_{Hydro}
CAPP	16	1820	34.00	4.0	0.04%	333	39.5	0.35%
EAPP	34	17,901	334.37	58.5	0.18%	3278	573.5	1.77%
NAPP	30	528	9.87	2.0	0.07%	97	19.4	0.64%
SAPP	41	14,161	264.51	71.0	0.17%	2593	696.2	1.72%
WAPP	25	16,663	311.24	41.7	0.22%	3051	408.5	2.19%
Total	146	51,074	953.98	177.2	0.17%	9353	1737.0	1.64%

NR: number of hydropower reservoirs included.
WL: water loss through evaporation in the hydropower reservoirs (without FPV installation).
Evap. Savings: water saved from evaporation due to the installation of FPV.
Add. Hydro: additional hydroelectricity that could be obtained utilizing the water savings.
EP_{Hydro}: electricity production of hydropower plants.

made reservoirs [11]. This increases the available area for FPV installation by more than 3 times. World Bank estimations are in line with the findings since the estimated power capacity and generation potentials are approximately three times higher than

Table 5
Evaporation savings and extra hydroelectricity by power pool region for 1% and 10% FPV coverage for floater type II.

FLOATER TYPE II			1% coverage			10% coverage		
Power pool	NR	WL (mcm)	Evap. Savings (mcm)	Add. Hydro (GWh)	Add. Hydro/EP_{Hydro}	Evap savings (mcm)	Add. Hydro (GWh)	Add. Hydro/EP_{Hydro}
CAPP	16	1820	10.86	1.3	0.01%	109	12.9	0.12%
EAPP	34	17,901	106.75	18.7	0.06%	1069	187.0	0.58%
NAPP	30	528	3.15	0.6	0.02%	32	6.3	0.21%
SAPP	41	14,161	84.45	22.7	0.06%	845	227	0.56%
WAPP	25	16,663	99.37	13.3	0.07%	995	133.2	0.71%
Total	146	51,074	304.58	56.6	0.05%	3049	566.3	0.54%

NR: number of hydropower reservoirs included.
WL: water loss through evaporation in the hydropower reservoirs.
Evap. Savings: water saved from evaporation due to the installation of FPV.
Add. Hydro: additional hydroelectricity that could be obtained utilizing the water savings.
EP_{Hydro}: electricity production of hydropower plants.

Table 6
Evaporation savings and extra hydroelectricity for floater type I and II aggregated by power pool for the EQIC case.

			Floater Type I			Floater Type II		
Power pool	NR	WL (mcm)	Evap. Savings (mcm)	Add. Hydro (GWh)	Add. Hydro/EP_{Hydro}	Evap savings (mcm)	Add. Hydro (GWh)	Add. Hydro/EP_{Hydro}
CAPP	9	1814	25.3	4.88	0.14%	9.2	2.01	0.06%
EAPP	25	17,898	281.0	69.47	0.25%	94.9	22.97	0.08%
NAPP	25	525	28.0	8.50	0.50%	9.1	2.79	0.16%
SAPP	27	14,131	237.3	64.98	0.22%	78.1	21.53	0.07%
WAPP	23	16,661	171.5	22.80	0.13%	54.9	7.30	0.04%
Total	109	51,029	743.1	170.64	0.22%	246.3	56.61	0.07%

NR: number of hydropower reservoirs included.
WL: water loss through evaporation in the hydropower reservoirs.
Evap. Savings: water saved from evaporation due to the installation of FPV.
Add. Hydro: additional hydroelectricity that could be obtained from the water savings.
EP_{Hydro}: electricity production of hydropower plants.

the values reported here.

5. Cost considerations of FPV systems

FPV applications typically involve higher costs than those for ground-mounted applications of similar size and location but lower than rooftop PV [49]. Higher FPV costs are due to higher soft costs, such as permitting-licensing costs and the generally higher cost of finance. Concerning labour costs, in the case of FPV, they can be higher due to the required specific expertise, but they are outbalanced by a more standardised installation process compared to ground-mounted systems. Moreover, the more complicated balance-of-system installation (boxes, inverters, cables and any other metallic supporting structures) also affects costs [50]. Operation and maintenance are important factors in the increased cost, both due to access to such equipment and maintenance needs. For instance, there are certain parts like anchoring and mooring that lie inside the water that are required to be inspected on a regular basis to ensure the plant's stability. For this reason, it is estimated that operation expenditures could rise up to 10% of the capital expenditures in the case of complicated conditions [51] compared to the typical 1.5% of land-based systems [52].

In the EU context, there is evidence that FPV costs are 20–25% higher than those of conventional systems [53]. In some cases, this is partially balanced by the avoided land acquisition costs, and in cases of high land value, FPV systems can even achieve better economic terms than the equivalent ground-mounted systems. Such is the case of a 10 MWp FPV plant in India that achieved an LCOE of EUR 0.022/kWh (25 years of operation), significantly lower than the equivalent land system in the area (EUR 0.035/kWh) [53]. In February 2020, a competitive tender in India reported the lowest CAPEX so far with a system cost of EUR 0.4/Wp for the 70MWp Kayamkulam II FPV plant. This is lower than the average values recorded in different countries in 2019 that range between EUR 0.7/Wp (low-cost systems in India) and EUR 2.5/Wp (high-cost systems in Japan) [49]. The relatively higher values are partly due to the fact that they refer to earlier projects but also to the water acquisition costs that they include. In the case of hydropower stations, such costs may be omitted.

As with every new technology application, FPV costs are expected to benefit from increased deployment rates (industrial learning and economies of scale). In 2019, FPV systems represented almost 1% of the total global solar PV demand, with future projections showing a 22% annual growth until 2024 [54]. This is also supported by the growing average size of FPV systems, which reached 5 MWp in 2019 from just above 1 MWp in 2017. The continuously increasing project size allows for economies of scale that yield lower installation costs. Some analysts claim that FPV plant sizes can be expanded to very large scales (several hundred of MWp) easier than land systems and achieve relatively lower costs soon. In order to support FPV market maturity and reduce costs, the EU supports research and innovation (R&I) projects to improve FPV technology, such as the FreShER project that started in late 2019 and aims to decrease the costs of mooring [55].

Assuming a CAPEX of EUR 0.4/Wp, the realisation of the EQIC case for the whole African continent (20.4 GWp of FPV) would require a total cost of EUR 8.15 billion. Two-thirds of the required investment would be directed towards EAPP (EUR 2.9 billion – 7.2GWp) and SAPP power pools (EUR 2.6 billion – 6.5GWp). The remaining deployment would mainly go to WAPP (EUR 1.9 billion – 4.7GWp), since NAPP and CAPP represent less than 10% of the available technical potential.

6. Discussion and conclusions

The present study provides an overview of the potential of FPV

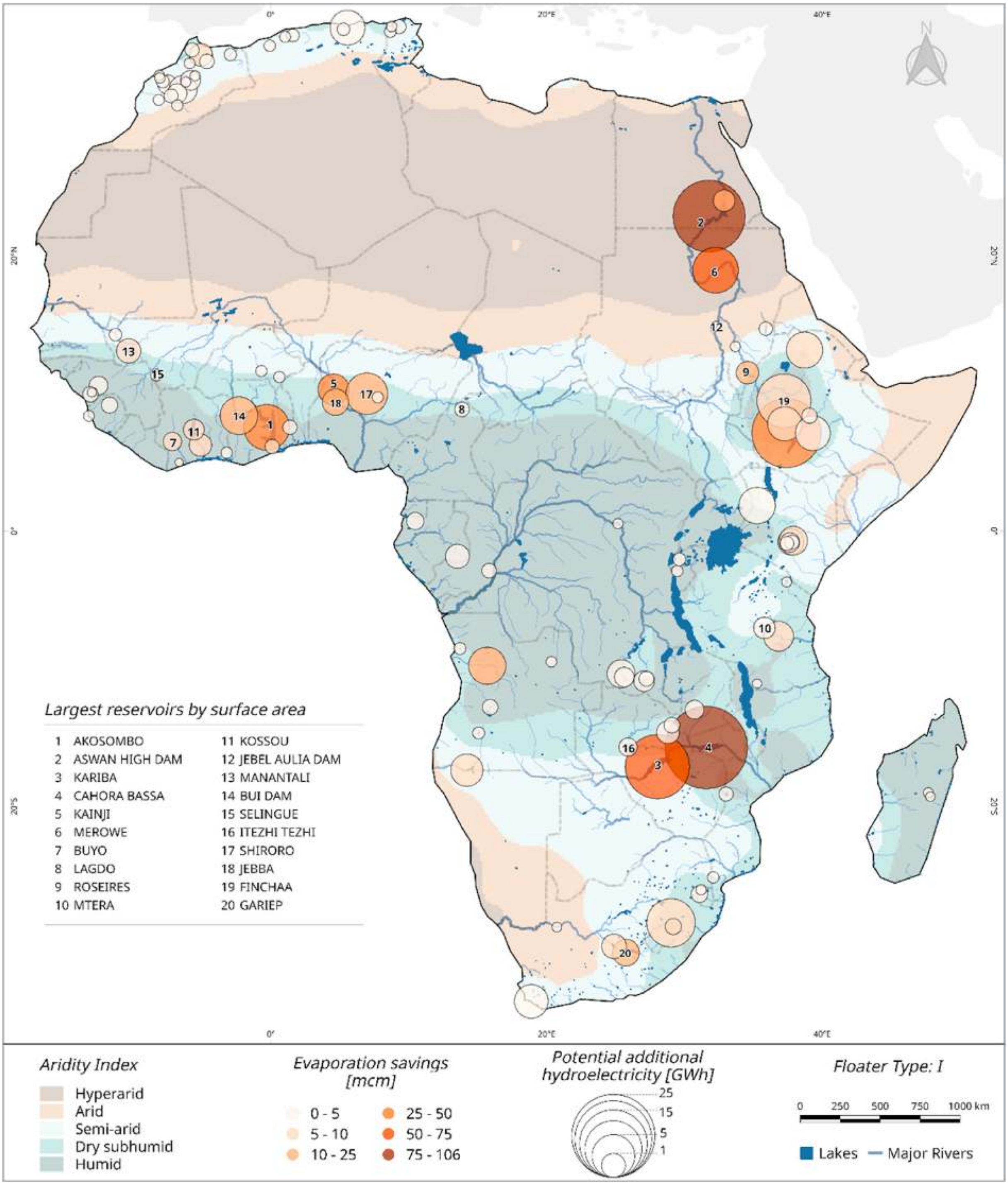

Fig. 4. Map indicating the reservoirs location with the potential additional hydroelectricity and evaporation savings for the EQIC case (FPV and hydropower equal installed capacity). Results forfloater type I.

in the 146 largest hydropower reservoirs in Africa. The main outputs of the study indicate that the total FPV resource potential (100% coverage) in terms of power capacity is estimated at 2922 GWp, more than 250 times the cumulative installed PV capacity at the end of 2020 [46]. This has to be compared with the 28 GW of pre-installed hydropower in Africa. The total electricity generated by full exploitation of the FPV technical potential (covering 100% of the 146 hydropower reservoirs) is 5293 TWh/year, 50 times more than the hydroelectricity currently produced in these reservoirs. For the EQIC case, in which the envisaged capacities of FPV equal the existing hydropower capacities (108 reservoirs considered), the results indicate that a total of 46 TWh/year can be obtained covering an area of less than 1% with FPV. This means an increase in electricity output of 58% compared to the existing hydropower generation.

Northern Africa countries and South Africa especially benefit from the installation of FPV, equalling the electricity produced by hydropower and even doubling it in some cases, with small FPV

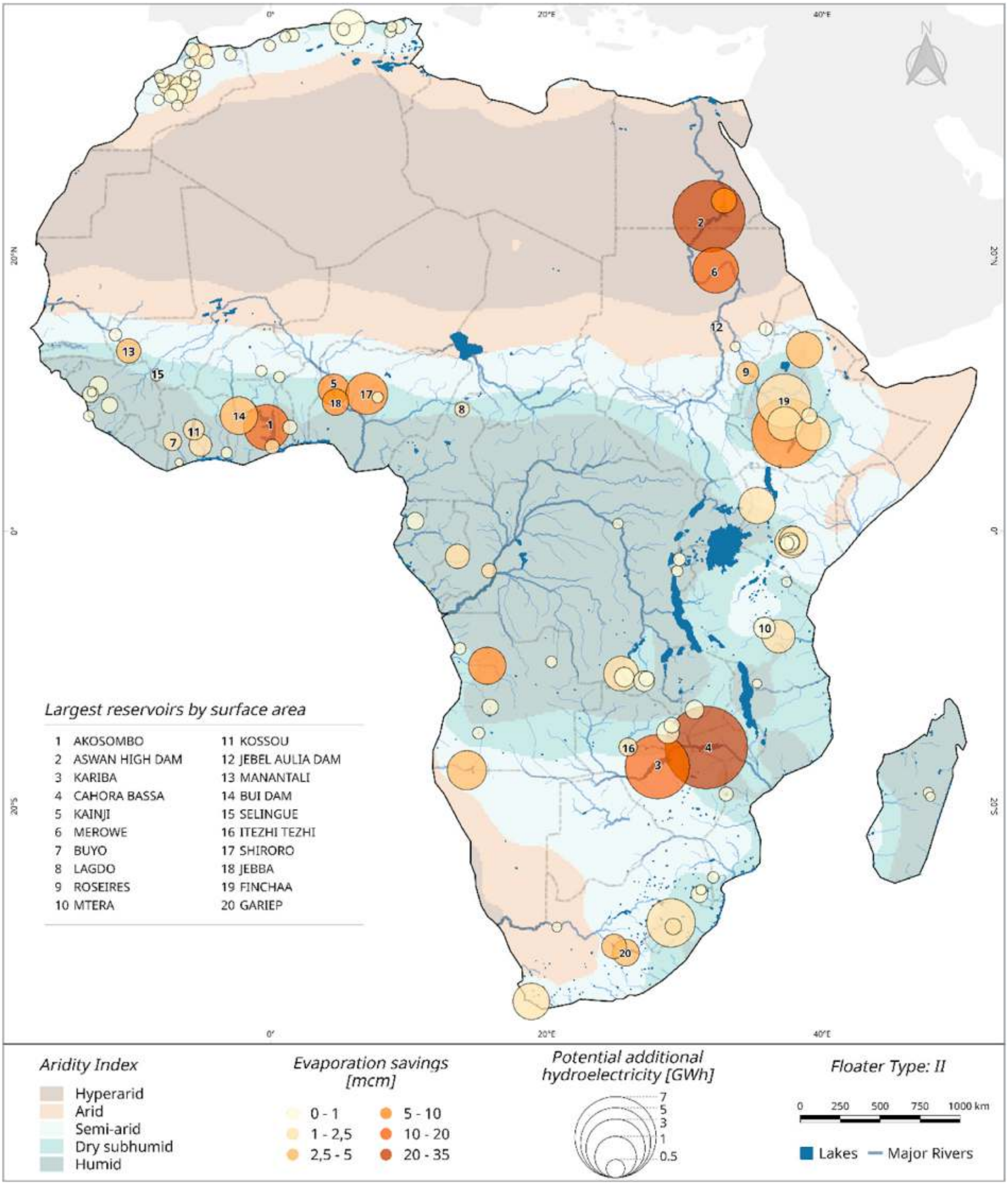

Fig. 5. Map indicating the reservoirs location with the potential additional hydroelectricity and evaporation savings for the EQIC case (FPV and hydropower equal installed capacity). Results forfloater type II.

coverages between 1% and 5% (for the EQIC case). This is due to the small hydropower productivity (capacity factors) in these countries, compared to other African nations, in combination with their good solar irradiation. The benefits of FPV installation in other African regions with higher hydropower capacity factors are also significant, increasing the electricity output by more than 50% with coverages of 4% on average (EQIC case).

With regards to evaporation savings and potential additional hydroelectricity production generated by these water savings, two floater types have been considered in the analysis - floaters fully covering the surface underneath them (floater Type I) and suspended systems (floater Type II). For the floater type I in the EQIC case, the water savings are maximised due to the limited evaporation occurring in the surface covered by FPV, resulting in 743 mcm of water saved and a potential additional hydroelectricity production of 170 GWh. Scientific research on the evaporation processes occurring with FPV are still in the early stages. A more detailed and region-specific analysis of the evaporation processes, including evaporation models that consider the local climate and the particular characteristics of the reservoirs, would further improve the results presented in this study.

The African continent is characterised by a high solar irradiation, with over 2000 kWh/m^2 on average in the reservoirs analysed across all regions. Despite the high dependence on hydropower in many African countries, the continent presents the highest untapped technical hydropower potential in the world, with only 11% developed [3]. While important efforts by the different governments continue to support the development of hydropower in the continent, the integration of FPV in the existing hydropower reservoirs would provide numerous benefits and additional advantages. FPV can complement hydropower production during the increasingly frequent dry periods in Africa while hydropower provides a more stable and flexible operation to the intermittent PV output. Additionally, the existing grid connection in hydropower reservoirs poses one of the greatest advantages that facilitates significantly the installation of FPV. In terms of cost, the decreasing prices of PV panels constitutes an important incentive for FPV installation as opposed to the observed raising prices of hydropower developments [56]. By reducing evaporation loss, FPV can also contribute to alleviate water scarcity in Africa, a serious problem that affects many regions in the continent with negative impacts on hydropower production.

An additional option for the hydropower and solar energy symbiosis is the installation of PV on the face of existing dams, which can be utilised in parallel with FPV to further increase clean electricity generation. An earlier analysis by the authors that focused on South Africa showed that the selection of prime locations for PV systems on the face of dams can be particularly advantageous and cost-efficient [57].

As a nascent, although fast-growing, technology, floating PV presents several challenges that need to be tackled and further investigated. Unknown environmental issues (e.g. algae growth, impact on the local fish food chain, ecosystems adaptation to changes in water temperature, etc.) and technical challenges such as bird fouling, electrical insulation, corrosion, mechanical wearing and anchoring and mooring systems need to be addressed in future developments.

With an excellent solar potential, the diversification of the energy portfolio in Africa is feasible and the introduction of FPV in the existing hydropower reservoirs can reduce risk and support the provision of reliable power services. This increases Africa's resilience to climate change and its ability to respond to extreme events without taking hard measures [7] and/or redesigning existing infrastructure.

Disclaimer

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.

CRediT authorship contribution statement

Rocio Gonzalez Sanchez: Methodology, Data curation, Investigation, Formal analysis, Writing - original draft. **Ioannis Kougias:** Conceptualization, Data curation, Methodology, Writing - original draft. **Magda Moner-Girona:** Conceptualization, Methodology, Data curation, Writing - review & editing. **Fernando Fahl:** Visualization, Data curation, Formal analysis. **Arnulf Jäger-Waldau:** Supervision, Methodology, Validation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank Ana Gracia Amillo, Barbara Realini and Nigel Taylor (Joint Research Center - European Commission) for providing valuable insights. The authors would also like to thank the Editor-in-chief and the anonymous reviewers for their comments which helped improve the quality of the manuscript.

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