Data-driven appraisal of renewable energy potentials for sustainable freshwater production in Africa

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Abstract

Clean water scarcity plagues several hundred million people worldwide, representing a major global problem. Nearly half of the total population lacking access to safe, drinkable water lives in Africa. Nonetheless, the African continent has a remarkable yet untapped potential in terms of renewable energy production, which may serve to produce clean water from contaminated or salty resources and for water extraction and distribution. In this view, the analysis of possible scenarios relies on data-driven approaches due to the scale of the problem and general lack of comprehensive, direct on-site experience. In this work, we aim to systematically review and map the renewable potentials against the freshwater shortage in Africa to gain insight on perspective possible policies and provide a readily usable and well-structured framework and database for further analyses. All reported datasets are critically discussed, organized in tables, and classified by a few metadata to facilitate their usability in further analyses. The accompanying discussion focuses on regions that, in the near future, are expected to significantly exploit their renewable energy potentials and on the reasons at the basis of the local water shortage, including technological and distribution problems.

Keywords: Renewable energy, Sustainable freshwater, Big data, Energy policies, Water, Water-energy nexus, Africa

1. Introduction

During the last years, the African continent has experienced the highest global population and economic growth. The total number of African inhabitants is estimated to further grow in the future, bringing the population from 1.3 billion people in 2019 to 1.7, 2.5 and 3.3 billion in 2030, 2050, and 2070, respectively [1]. According to real Gross Domestic Product data (constant 2010 US$), among the 20 fastest growing countries in the years 2010–2018, 7 are located in the Sub-Saharan region: Ethiopia 108.1%, Rwanda 73.4%, Ivory Coast 70.5%, Ghana 67.2%, Tanzania 63.8%, Democratic Republic of the Congo 63.2%, and Mozambique 62.5% [2]. The drawback associated with this rapid development is that it accentuates two major problems for Africa: the lack of electrification, as approximately 62% of population lives without electricity [3], and the clean water scarcity, as over 40% of Africans live in arid regions [4].

Due to the lack of proper electrification, the African energy demand only accounts for 3% of the global electricity production [5], while the African continent accounts for approximately 17% of the world population [1]. As an example of this imbalance, in 2017 Germany consumed approximately 648 TWh [5], that is approximately 79% of the whole African consumption, which was approximately 817 TWh [5]. With the aim of improving quality of life and promoting economic growth, many countries have undertaken a set of national and international projects to increase the electrification rate [3]. Power pool agreements (Fig. 1) are now playing a pivotal role in these challenging projects.

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Owing to these new policies and expected population growth, an exponential increase of the African energy output is forecast, from around 817 TWh in 2017 to 2200–2600 TWh in 2040 [3, 5].

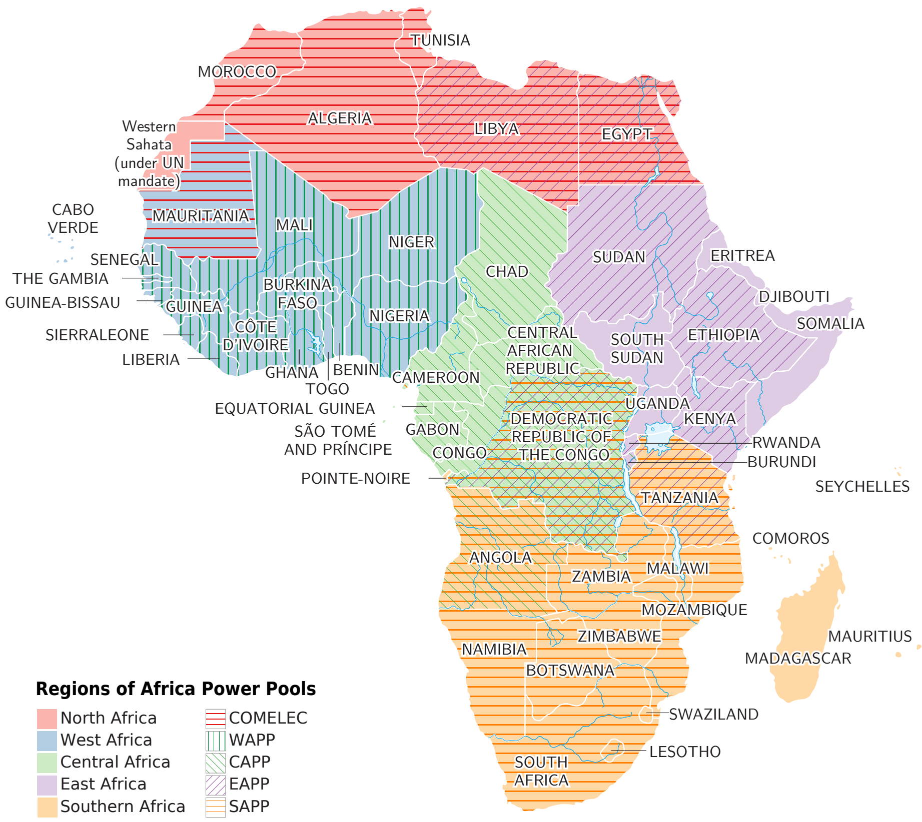


Figure 1: Regions of Africa and power pool agreements.

The second problem exacerbated by rapid development and population growth in Africa is the clean water scarcity. Several previous works have discussed water scarcity and its consequences in Africa at both regional [9–16] and continental [17–22] scales. At the time of writing, a stable supply of drinkable water is not guaranteed to 319 million people in Sub-Saharan Africa, and the Millennium Development Goals related to sanitation have not been met by any Sub-Saharan African country [23]. In subsequent years, as reported by the projections of the *World Resources*

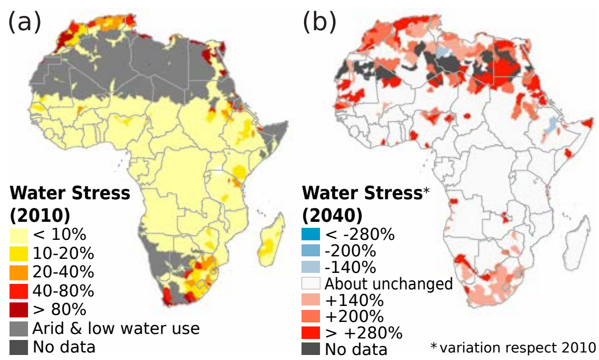


Figure 2: Current and projected water stress index in Africa (source: WRI Aqueduct [6], accessed on March 2020): (a) Baseline water stress index (2010); (b) Index variation in the projection for year 2040 using the halfway scenario called "Business as usual."

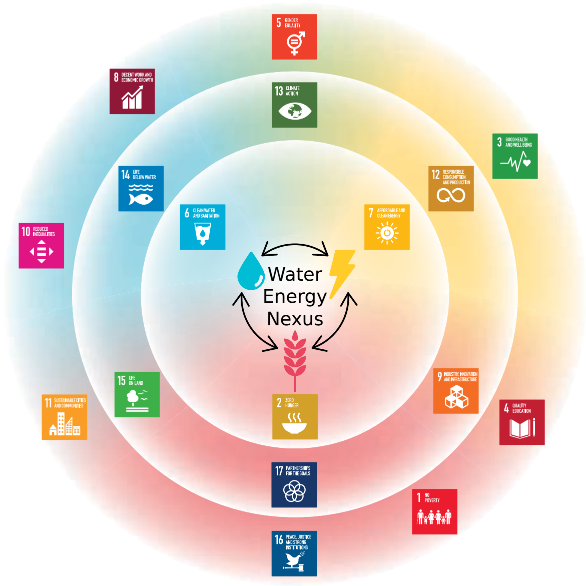


Figure 3: The Water-Energy Nexus's role and its impact on the United Nations Sustainable Development Goals (SDGs) [7]. Image inspired by Liu, J., Hull, V., Godfray, H.C.J. *et al.* "Nexus approaches to global sustainable development" [8].

Institute (see Fig. 2), this scenario is expected to worsen, mainly due to the rapid climate change. As we discuss in the next section, water scarcity can be either due to the lack of the primary resource itself or to the lack of infrastructure and energy for extraction and distribution (pumping) and disinfection.

Considering the scenario outlined above and the new global policies for mitigating climate change and pursuing a sustainable green economy, a significant role will be played by renewable resources in the near-future energy development of Africa. The continent has indeed an outstanding potential in terms of renewable energies, whose proper exploitation would help sustainable development [24, 25], and freshwater production [26, 27]. To this latter purpose, several technologies using thermal and electrical energy are available, see e.g., [28–32]. The proposed analysis is meant to be particularly meaningful in the context of the United Nations Sustainable Development Goals [7], where it may be directly contextualized within the goals: 1) No Poverty: Access to basic human needs of health, education, and sanitation; 2) Zero Hunger: Providing food and humanitarian relief, establishing sustainable food production; 6) Clean Water and Sanitation: Improving access for billions of people who lack these basic facilities; 7) Affordable and Clean Energy: Access to renewable, safe and widely available energy sources for all; 13) Climate Action: Regulating and reducing emissions and promoting renewable energy (see Fig. 3). Generally, there are also indirect implications associated with these goals: 9) Industry, Innovation, and Infrastructure: Generating employment and income through innovation; 10) Reduced Inequalities: Reducing income and other inequalities, within and between countries; 11) Sustainable Cities and Communities: Making cities safe, inclusive, resilient and sustainable; 12) Responsible Consumption and Production: Reversing current consumption trends and promoting a more sustainable future. However, the connection with this latter second set of goals is indirect and should necessarily pass (local) social and economic policies; thus, we just mention them as perspective potential implications of the presented analysis.

This work aims to critically review and map the renewable energy potentials against the freshwater shortage in Africa to gain insight regarding possible water–energy policies and provide a well-structured and data-oriented framework for further analyses. To this end, we first map and discuss the freshwater shortage in Africa. We demonstrate that this problem, worsened by the arid climate in some areas, is not only due to the lack of available water resources but is also related to the missing facilities and infrastructures to distribute clean water. In the second part of the paper, an extensive review of the available datasets and tools for the assessment of renewable energy potentials and their exploitation in Africa is carried out. This analysis focused on regions that are expected to exploit their renewable energy potential to a greater extent in the near future. All references to available datasets for water and energy are reported in ready-to-use tables and classified by a few metadata in the appendix to facilitate their usability in future

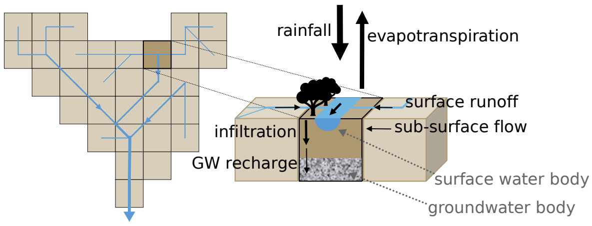


Figure 4: Scheme of the most important water fluxes (represented through arrows) and storages (represented through boxes) within each grid cell. This scheme was adapted from [33].

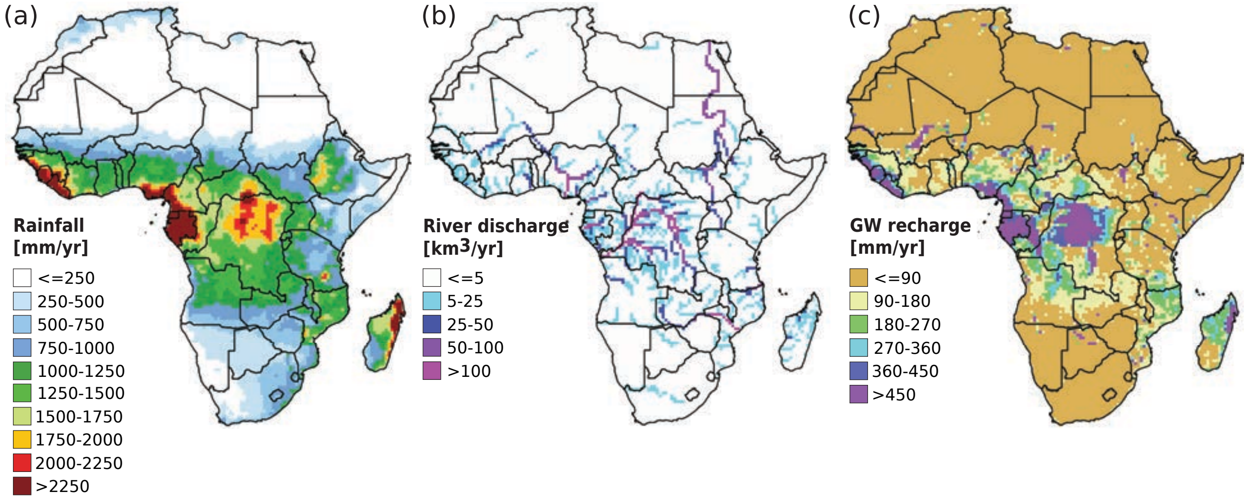


Figure 5: Gridded long-term water availability over the period 1987–2013: (a) annual rainfall, (b) annual river discharge, and (c) annual groundwater (GW) recharge. Data were derived from the WATERGAP model, version 2.2c [33].

analyses.

2. Water availability in Africa

2.1. Water availability mapping

Water is a naturally circulating resource that continually renews through rainfall [34], despite periods of stock in natural and artificial reservoirs. Figure 4 shows the most important flows (e.g., rainfall, runoff) and natural storages (e.g., canopy, groundwater) of the hydrological cycle happening in a grid cell. The amount of rainfall that reaches the soil partially penetrates in the root zone level, hence becoming available for evaporation and transpiration processes, and partly generates runoff. Infiltrated-rainfall can deeply infiltrate and recharge the groundwater storage (triggering groundwater recharge). Importantly, the grid cell is not isolated from other surrounding cells as it belongs to a network where water flows from upstream to downstream cells, both over the surface (*i.e.*, surface runoff) and as sub-surface flows (*i.e.*, base flows and groundwater flows). The volume of water flowing in the unit time through the river channel is the river discharge.

The renewable freshwater resources become available for human use under three main water sources: rainfall, river discharge, and groundwater recharge (Figure 5). Across African nations, freshwater resources, measured on an average year, exhibit significant spatial heterogeneity. The values shown in Figure 5 have been obtained as long-term averages (over the period 1987–2013) of the annual water availability on a 30' x 30' grid (*i.e.*, each grid cell has an area of 50 x 50 km^2 at the equator). Elaborations have been carried out using the outputs of the WATERGAP model, version 2.2c [33].

Locations close to the equator exhibit larger annual availability, with rainfall amounts exceeding 2000 mm/yr (e.g., in southern Nigeria, Congo, Liberia, Sierra Leone); as the distance to the equator increases, rainfall tends to decrease, falling under 200 mm/yr (e.g., Northern countries, Namibia, and South Africa). This is also demonstrated in Fig. 6, where the average precipitation across the latitude is represented. Rainfall recharges both surface and ground water bodies depending on soil properties (e.g., texture and field capacity), climatic conditions (e.g., humidity, evaporation, and transpiration rate), and sub-surface interactions between rivers and aquifers (Fig. 4). The largest values of river discharge are observed along the Congo, Zambezi, Nile, and Niger rivers (see Fig. 5b). Groundwater recharge exhibits spatial patterns similar to those of rainfall, with largest recharges occurring in tropical Africa where aquifers are mostly shallow (e.g., around 5–25 meters below the ground, according to [35]).

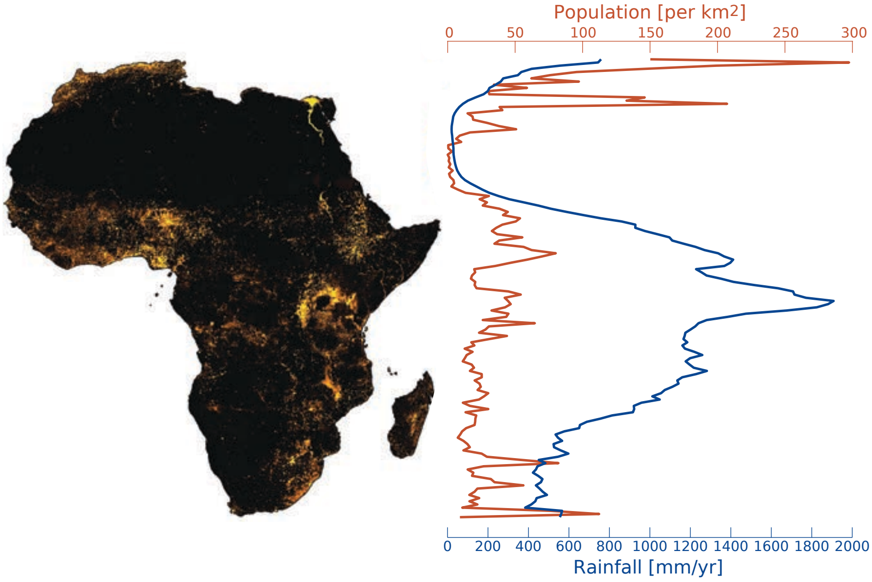


Figure 6: Analysis by latitude of the spatial distribution of population density (*i.e.*, inhabitants per square kilometer) and average rainfall across Africa (measured in millimeter per year). The map on the left side shows the population density in each grid cell: the black to yellow pixels show increasing population density. Population data are provided by `https://gadm.org/`, rainfall data are sourced from [33].

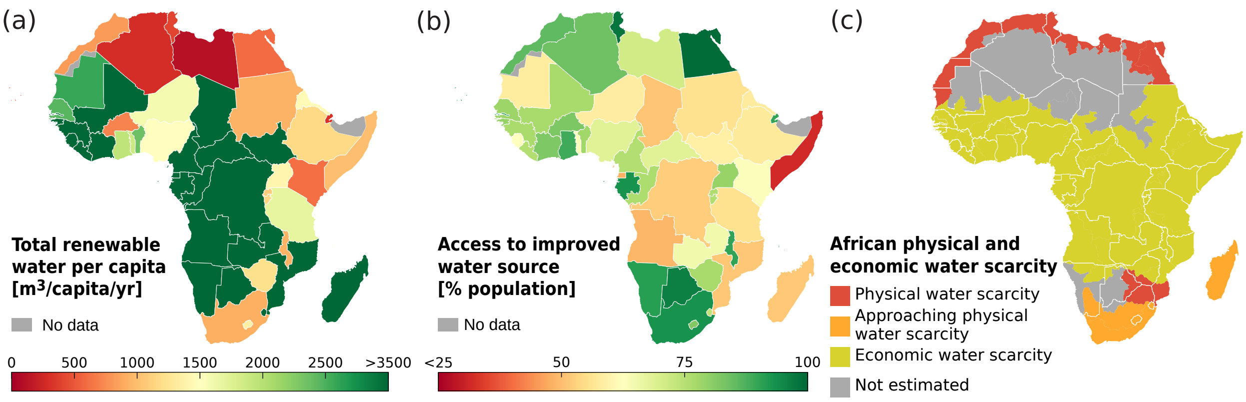


Figure 7: Clean water issues in Africa: (a) Renewable water resource available per person on average: latest data available, 2017 (data: AQUASTAT Main Database by FAO [36]); (b) Share of population with access to safe drinking water: latest data available, 2015 (data: AQUASTAT Main Database by FAO [36]); (c) Map elaborated by the Institute of International Water Management [37], which identifies different areas according to water availability and demand. *Physical water scarcity*: identify zones where the water demand for agriculture, industries, or domestic purposes comprises more than 75% of river water, considering only water availability and consumption. Arid areas do not imply water-scarcity. *Approaching physical water scarcity*: regions that are expected to experience physical water scarcity soon as residents are using over 60% of river flow. *Economic water scarcity*: areas where the withdrawn water for human purpose does not reach 25% of the total available river water, but limited water access is observed. These areas may have significant water availability but economic and social capacities limit their exploitation.

Although equatorial locations exhibit more abundant water availability than Northern and Southern African regions (see Fig. 5), the population density by latitude shows a different pattern (Fig. 6). The highest densities are located in the North of the continent with values reaching 300 inhabitants per square kilometer at the latitude of major cities (among others Algiers, Cairo). In the Sub-Saharan Africa densities are generally below 50 inhabitants per square kilometer, despite two peaks in correspondence of Johannesburg and Cape Town.

Locations with higher population density have generally access to improved water sources (note that here the term "improved water" follows the definition given by the UN, which includes water from home plumbing plus other improved water sources, such as standpipes or public drinking fountains, boreholes or tube wells, protected springs or dug wells, and collection of rainwater [40]), but the total renewable water per-capita is often below 1000 m^3/yr, which is the threshold defined by the UN as indicating "physical water scarcity" (Fig. 7a,b). While these locations experience physical water scarcity (Fig. 7c), some countries in Central Africa (e.g., Angola, Democratic Republic of Congo, and Tanzania) must cope with economic water scarcity due to the lack of proper infrastructures. This implies that many countries have more than half of the population without access to clean water sources, implying higher mortality and diffuse economic water scarcity (Fig. 7b).

According to the Food and Agricultural Organization [39], agriculture uses most freshwater resources in Africa with a prevalence larger than 90% (e.g., in Egypt, Sudan, and Mali) with respect to other sectors. Only in a few countries (e.g., in Liberia, Democratic Republic of Congo, and Congo) agriculture contributes to less than 10% to the freshwater use. In these regions, most agriculture relies upon rainfall along the cropping period, as surface and ground

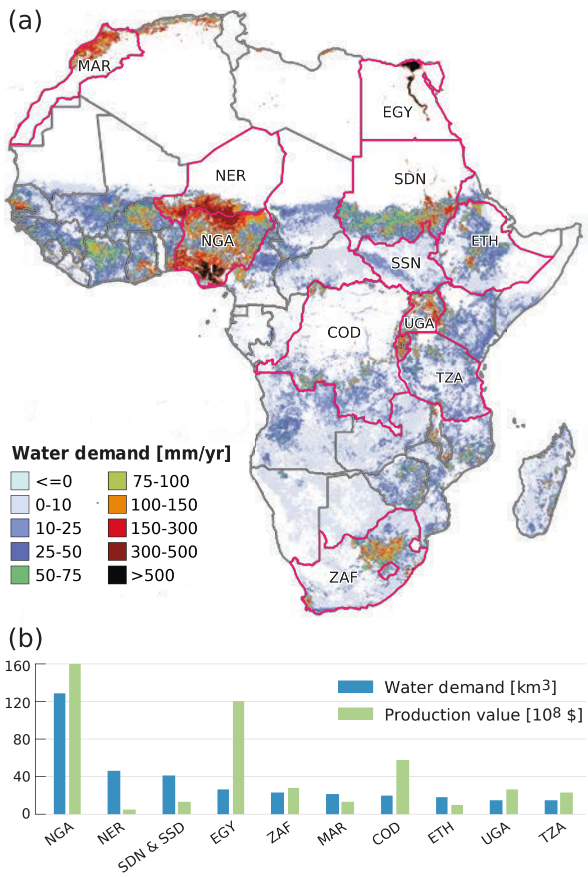


Figure 8: Annual water demand of agriculture. (a) Map of green (i.e., soil-infiltrated rainfall) plus blue (i.e., irrigation water) water demand for crop production in year 2000 [mm/yr]. Water demand is shown as the ratio between the total water volume required by crops' growth in a year and the cell area. (b) National water demand and economic value associated with the agricultural production for the top-10 countries selected for their water demand. Water demand is sourced by [38], and production values are derived from [39].

water resources are less accessible. As a consequence, farmers are exposed to climate variability [41] and extreme events [42], which impact food security, compromise price stability, and increase susceptibility to droughts.

Given that agriculture acts as a driver of freshwater resources depletion, Fig. 8a shows the average annual water demand of agriculture, namely the water required by crops for the evapotranspiration process throughout the cropping season. Water demand measures the amount of water from rainfall (*green water* [43]) and irrigation (*blue water* [44]) that is provided to crops throughout the growing period. The values shown in Fig. 8 are for the year 2000, which is the most complete year in terms of agricultural database availability. The data were evaluated following the approach by [38, 44] in which a daily soil-water balance model is used. We observed that the largest (green plus blue) water demands are located in Northern Africa and in the Sub-Saharan belt; in particular, Nigeria, Niger, Sudan, and South Sudan show the largest annual water demand (Fig. 8b). Instances of high water demand were also found in South Africa, Uganda, and Ethiopia. According to the FAO [39], Nigeria, Egypt, and the Democratic Republic of Congo have the largest agricultural-production value (over 10 billion dollars), although Egypt uses much less water than Nigeria owing to its advanced and efficient water management systems [38]. On average, Egypt requires 2 m^3 of water to produce one dollar of products while Nigeria needs 8 m^3. Importantly, over 70% of Egyptian water demand relies on surface water bodies, which leads to issues in terms of availability as the Nile is a controversial trans-boundary river. Niger and Sudan and South Sudan have the lowest water use efficiency with 97 m^3 of water required to make one dollar of agricultural products in Niger and 33 m^3 in Sudan and South Sudan.

Most agricultural production relies on rainfall to meet the water demand. However, few locations can exploit surface and ground (blue) water bodies owing to a lack of proper infrastructures that transports water toward cultivated areas (Fig. 9). Most areas equipped for irrigation are located in the North, specifically along the Nile river. However, locally generated runoff in these areas (measured as the outflow from the cell minus inflow to the cell along the drainage network, Fig. 4) is much smaller than that available in the equatorial zone.

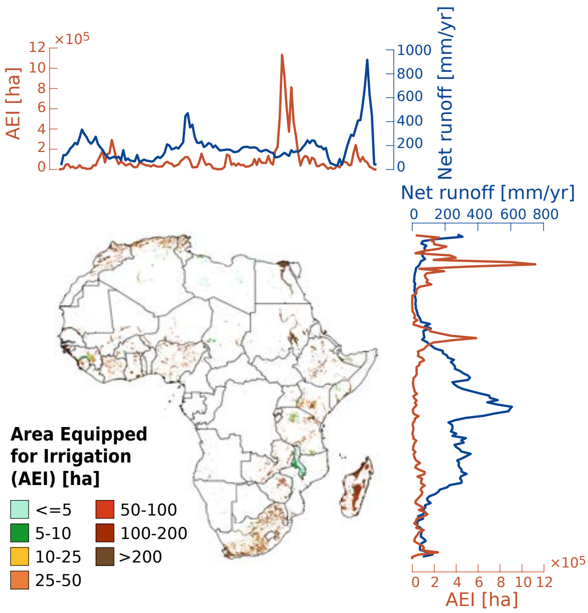


Figure 9: Analysis by longitude and latitude of the spatial distribution of locally generated runoff [mm/yr] compared to the area equipped for irrigation (AEI) [ha]. The map depicts the spatial distribution of the AEI at the cell level. The locally generated runoff has been provided by [33], the AEI is available from [45].

Sub-Saharan African countries have sparsely cultivated areas, and irrigated fields are often smaller than 10 hectares. For this region, over 70% of the total food calories are produced by local smallholder farmers (*i.e.*, cultivating less than 5 hectares per household) [46]. This suggests the importance of developing infrastructure for water withdrawal. In particular, the longitudinal analysis makes clear a significant inequality between the capacity of the Eastern countries to exploit the Nile river discharge through proper irrigation systems and the lack of infrastructures in the Western countries to exploit, for example, the discharge of the Congo river.

Overall, the integrated framework shown in Figures 5, 8, and 9 sheds light on the potential of expanding current agricultural production through new cultivated areas with proper infrastructures for irrigation, especially where the locally generated runoff is large without compromising the environmental flow and the downstream flow toward the other cells of the drainage network. Improved water management is a key driver for production boosting, for example, through the yield gap closure. There are many locations across the African territory where the actual crop yield falls below the potential value due to water stress conditions occurring along the cropping period. It is noteworthy that, according to the 2000 dataset on the areas equipped for irrigation [45], groundwater sources are notably underutilized, despite the potential for sustainable use by taking advantage of the rainfall-generated recharge (Fig. 5). Nearly 80% of AEI obtain water from surface water bodies [45].

3. Renewable energy potentials in Africa

Considering the aforementioned water availability mapping, we report an accurate analysis of the renewable energy potentials throughout the continent in this section, which may help sustainable freshwater production via extraction and distribution especially in those areas affected by economic water scarcity.

3.1. Overview

Similarly to other emerging economies, development in many African nations is supported primarily by fossil resources (Fig. 10) and, although the African continent exhibits significant potential in terms of renewable sources, African nations still account for 18% of global electricity production [47], which has remained constant with respect to the growth in electric energy demand over the last years. In fact, renewable energy sources do not currently play an important role due to the lack of integration between different electricity markets throughout the continent. Northern Africa is highly dependent on gas and oil, Southern Africa on coal, and the remaining parts of Sub-Saharan Africa rely on a mix of oil, gas, and hydroelectric generation, as shown in Fig. 11. Notably, Southern Africa represents approximately one-third of the power generation market; however, energy policies have recently begun to stimulate energy production from renewable sources [48]. The majority of the remaining demand is located in Northern Africa.

In the Sub-Saharan area, where renewable sources have the potential to fulfil the majority of the energy demand, the electric market is very underdeveloped. Indeed, a reduced fraction of the population can have access to electrical energy (see Fig. 12), and the transmission lines are not sufficiently robust to transport large amounts of power [49]. The actual scenario of the renewable energy sector shows extensive use of hydropower resources (see Fig. 13), which currently exploits only 7% of the enormous potential in Africa [50]. Other current renewable contributions come from bio-energy resources, mainly from agricultural wastes like sugar industry scraps in East Africa, and wood in rural areas [51]. Wind and solar sources are underused due to relatively high cost, grid inadequacy, and absence of regulations and financial support [48, 49, 51]; yet, they are expected to have a crucial role in the short-term future.

Owing to new global policies, significant attention on climate change mitigation and sustainable development, and the falling prices of clean technologies, renewable resources are forecast to increase their market share. According to the projections presented in Fig. 10, renewable resources will reach 35–38% market share in 2040. Many ambitious projects are being planned or are under construction throughout the continent (see Tab. 1 and Fig. 11); in addition to hydropower, the largest capacity plants will exploit solar and wind power. The small size and flexibility of solar technologies, especially photovoltaics (PVs), are crucial for increasing access to electricity for the low-income population [54]. These technologies, when adopted under proper regulation in terms of environmental impact and perspective disposal [55, 56], can be used with the support of batteries or other energy storage systems in the stand-alone layout, which is particularly suitable and effective for rural and remote areas [49].

Notice that these technologies for renewable energy conversion, storage, and transportation all require freshwater for their manufacture, installation, and operation. Such water requirements are typically referred to as "virtual water" or "water footprint" [57], allowing for the nontrivial optimization between carbon emissions and water consumption in the energy sector [58]. While the water footprint of power generation based on fossil fuels has been widely analyzed [59, 60], concerns have been raised regarding the water needs of the renewable energy development [61, 62]. Several methodologies have been proposed to quantify the water footprint of these technologies, aiming to assess the real sustainability of renewable sources of energy [63–66], e.g., PV [67], biomass [68], hydropower [69, 70] or wind ones [71]. Estimates indicate that the water footprint of renewable power technologies could be reduced by shifting to

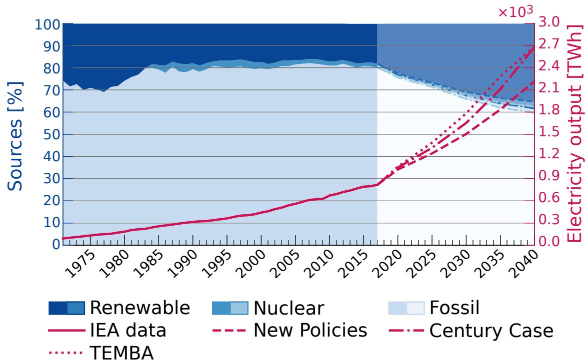


Figure 10: Electricity output from 1971 to 2017 in solid red line (right axis), and the relative electricity generation mix percentage in blues stacked areas (left axis), dividing the energy sources into three main categories: Renewable (dark blue), Nuclear (blue) and Fossil (light blue) (source: IEA (2019) World Energy Balances [5] and IEA (2019) Headline global energy data [47]). The Africa electricity output projection from 2017 to 2040 was computed according to three scenarios. *New Policies Scenario* (dashed line): IEA projection based on existing policies and measures, which cautiously considers plans announced in mid-2014 [3]. *African Century Case* (dash-dotted line): IEA optimistic projection in which rapid power sector growth is assumed ($450 billion additional investments), as is the acceleration of the electricity access process, specifically in rural areas [3]. *TEMBA model* (dotted line): proposed by KTH Royal Institute of Technology, it is similar to other projections because it accounts for both actual and future plants, the electricity generation mix, and power purchase agreements. The main difference is the focus on the energy trade between African countries to improve energy generation; furthermore, the model allows for interconnection investments and trades between neighboring countries after 2025 [52].

greater contributions of PV, wind, and geothermal energy [72]. Recently, the water footprint of freshwater use in the energy sector specifically dedicated to African countries has been reported in the literature [73, 74]. A virtual water trade network coupling the virtual water demand for various power technologies with international energy trade data could facilitate a more holistic approach to global water resource management [75].

3.2. Solar power

Solar energy is a key sustainable energy source, as it is immediately accessible in urban environments. In 2017, approximately 55% of the global population resided in urban areas [78]; such urban populations require extremely high energy quantities. Moreover, the urban residents in developing countries are expected to have a tremendous increase in the next few decades [77]. In Africa, a 1% increment in urbanization leads to a 14% increment in coal consumption, which corresponds to an increase in air pollution and emissions of greenhouse gases and thus a contribution to the global warming [77]. Solar energy is a pivotal resource for reducing the impact of fossil fuel consumption and improving the living quality in urban areas, and Africa has quite an extraordinary solar potential which can be exploited for electric and thermal energy production via solar PVs and solar-to-thermal energy conversion, respectively [79–81]. Both technologies are scalable and suitable for energy conversion, from household scale and community levels to the industrial and country scale, also using concentrated solar power (CSP) [77].

In Africa, potential solar power surmounts the forecasted demand of energy by orders of magnitude; hence, in this continent, even small countries can cover their local electricity and thermal energy demand by exploiting solar sources. This is particularly evident in the North, East, and South Africa regions, which are characterized by dry climates with high average temperatures, as shown in Fig. B2 in the Appendix. The East African Community region presents among the highest potentials in terms of solar power at a global level [82]. Kenya and Tanzania are a clear example of how, in East Africa, solar energy can push the country development and increase electricity access through stand-alone systems [83]. However, both PV and CSP potentials do not depend exclusively on the solar irradiation but also on other factors [84, 85] that can discriminate which technology is more convenient. In particular, M.-L. Barry *et al.* found thirteen factors to be considered opportunely for the selection of the most suitable renewable technology in an African region [86]. Other works produced a GIS-based analysis combining factors as theoretical, geographical, technical, and eventually economic potentials, see [87–89] and the tools based on multiple criteria for renewable-energy planning and deployment (MapRE) developed by IRENA and Berkeley University [90, 91].

Table 1: Capacity [MW] of the main future renewable energy plants by resource type (Source: African Development Bank [53]).

	Country	Name	Capacity	Status
Hydro	Congo, Dem. Rep.	Grand Inga Power Station	39000	Planned
	Ethiopia	Grand Ethiopian Renaissance Plant	6000	Under Constr.
	Congo, Dem. Rep.	Inga III Power Station	4800	Under Constr.
Wind	Kenya	Meru Wind Power Station	400	Planned
	Kenya	Lake Turkana Wind Power Station	300	Under Constr.
	Ghana	Ayitepa Power Plant	225	Planned
Solar	Ghana	The Nzema Project	155	Planned
	Nigeria	Ganjuwa LGA Power Plant	135	Planned
	Uganda	Uganda Solar Power Station I	125	Under Constr.
Biomass	Ivory Coast	Bondoukou BioKala Power Plant	40	Planned
	Ivory Coast	Aboisso Biomasse Power Plant	18.3	Planned
	Senegal	Ross-Bethio Power Plant	15	Planned
Geoth.	Kenya	Olkaria V Geothermal Power Station	140	Under Constr.
	Kenya	Akiira One Geothermal Power Station	70	Planned
	Rwanda	Symbion Thermal Power Station	50	Under Constr.

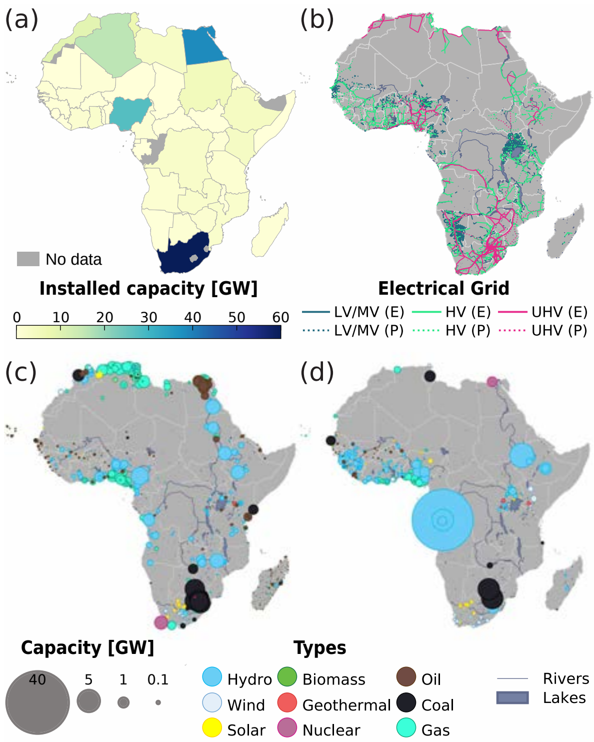


Figure 11: Current and future electrical infrastructure in Africa: (a) Installed capacity (February 2017, data: African Development Bank [53]); (b) Electricity transmission and distribution grid existing (E) and planned (P). Voltage levels are LV/MV (Low and Medium Voltage, < 35 kV), HV (High Voltage, > 35 kV but < 230 kV), and UHV (Ultra High Voltage, > 230 kV), as defined by the standard IEC-60038 [76] (September 2017, World Bank [2], which is available under CC BY 4.0 license); (c) African power plants in operation (data: African Development Bank [53]); and (d) African power plants under construction & planned (data: African Development Bank [53]).

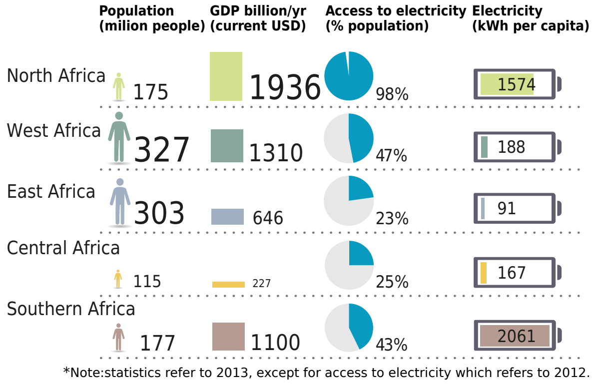


Figure 12: Access to electricity in African regions (data refers to 2012). Source: p.9, Africa 2030: Roadmap for a Renewable Energy Future [77]. Copyright IRENA 2015.

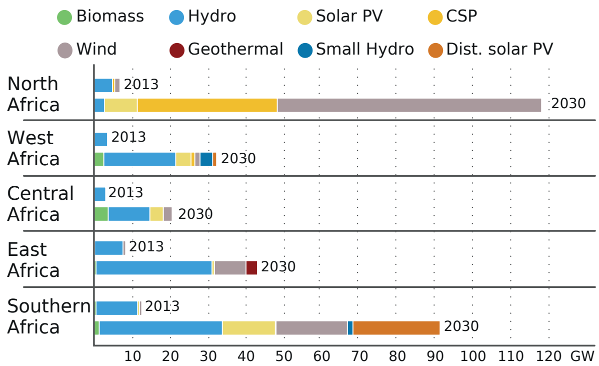


Figure 13: Predicted capacity development for African renewable scenario in 2030. Source: p.39 Africa 2030: Roadmap for a Renewable Energy Future [77]. Copyright IRENA 2015.

3.2.1. Photovoltaic technologies

Photovoltaic solar panels convert direct and diffuse components of solar radiation into electric power; thus, they can be opportunely installed and exploited in areas where direct radiation may be reduced. The most widely available PV technologies rely on crystalline Silicon (C-Si) with flat-plate panels, thin-film technology, or concentrated solutions (CPV). Currently, crystalline silicon PVs are the mostly widely adopted type, with a 92% of the global market share [96]. PV panels are among the most expensive components in the system and, despite prices having been reduced in the last several years, the overall production cost of electricity still represents a limiting factor towards a wider exploitation of PV systems. It should indeed be considered that in Africa, particularly in the sub-Saharan region, nearly 60% of the population lives in poor rural areas with no access to the electrical power grid. In these areas, the distribution of the population is sparse, which implies technological and economic limits to the development of a capillary infrastructure for electricity distribution. Therefore, off-grid solutions may represent an alternative; however, the scarce economic possibilities for investing in modern energy solutions is very limiting and requires proper economic and social development policies [97]. The currently installed units are distributed between utility-scale systems (grid-connected in those areas where the infrastructure is available) and solar home systems, being prevailing the former in terms of overall installed capacity and the latter in terms of number installed of systems. Regarding the distribution of the conversion technologies, precise data is very difficult to retrieve, due to the lack of accurate tracking and monitoring tools for the installed PV components [98]. Finally, another critical aspect limiting a wider exploitation of PV systems relates to the intermittency of the primary solar resource and to the necessity to provide continuity to the varying demand. To this, electrical energy storage systems are crucial assets [99, 100]; however, their high capital and operation costs still represent a bottleneck limiting their utilization.

The PV potential for the whole African continent has been studied in Ref. [89], and results are reported in Fig. 14a.

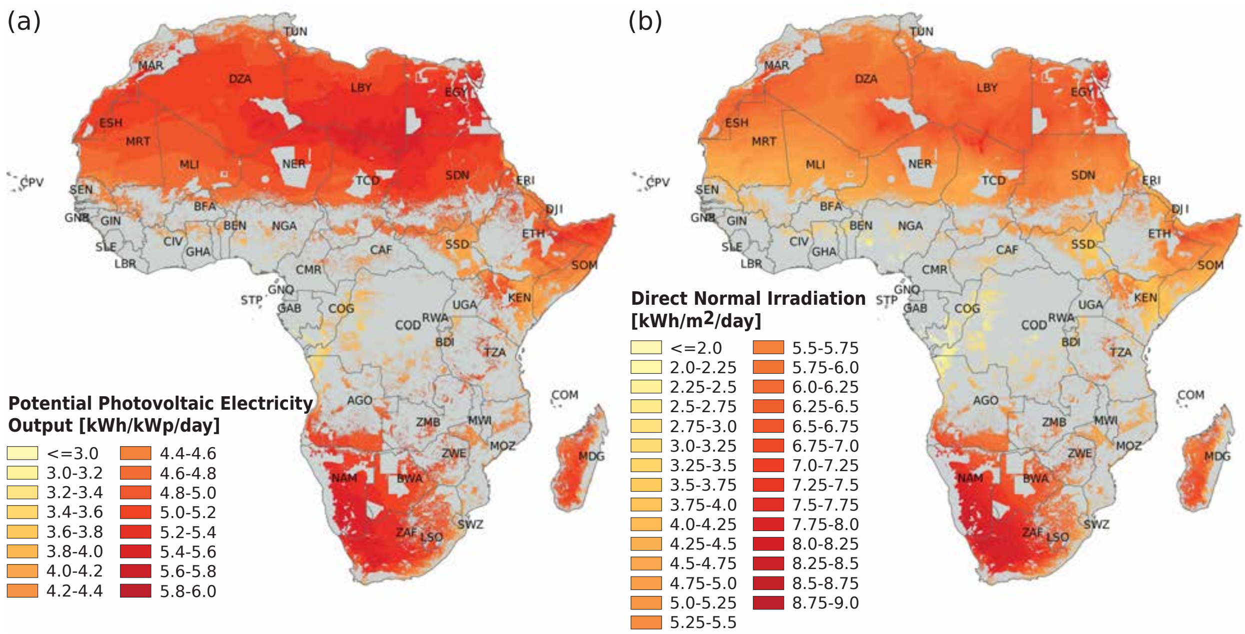


Figure 14: Overview of (a) the PV potential (kWh produced per each peak of kW installed, per day) and (b) direct normal solar irradiation in Africa computed with the method proposed in Ref. [89], using the data from Refs. [92–95]. For completeness, the map of diffuse horizontal solar irradiation is reported in the Appendix (Fig. B1).

As it is possible to notice from the potential distribution, the African region with the highest potential is the Eastern one, particularly Ethiopia and Somalia (maximum values of 2500 kWh per square meter per year). As the figure shows, PV technologies have a great estimated potential, and the rapid development in panel technology and further reduction of prices (at an average of approximately 1.5 USD/W in 2019 for the utility-scale setup [98]) create positive expectations towards an increase in PV electricity exploitation.

3.2.2. Solar thermal technologies

CSP is a particularly interesting renewable technology, especially in relation to medium-to-large scale plants; thus, owing to the current policies, it has a high potential for use in a sustainable pathway [103]. In the concentrated technology, CSP are employed to harvest solar light and transform it first into thermal energy, which is in turn used to generate electric power via turbines using gas or vapor or Stirling engines. The overall system for electricity production relies then on a two-stage logic for the conversion of the primary resource, and high temperatures are required to empower the conventional stage of the power cycle. Therefore, CSP devices are best suited to be exploited where a consistent Direct Normal Irradiance (DNI) is available. The potential of this latter resource throughout the African continent is reported in Fig. 14b. The data show that the highest potential for CSP plants locates between 20 south and 40 north latitude degrees. The leading technologies available for CSP installations are mainly four: Fresnel and parabolic troughs [104–107]; solar towers [104, 105, 108]; linear Fresnel systems [104, 105]; dish-Stirling systems or parabolic dishes [104, 105, 109]. For the sake of completeness, the map of the diffuse horizontal irradiation throughout the African continent is reported in the Appendix (Fig. B1). Similar to PV energy potential, an analysis of CSP energy potential was presented in IRENA and KTH works [89]. Distinct from the PV case, these studies highlighted that CSP technologies are reasonably applicable in the Northern Africa region, where desert areas are located. Regarding Eastern Africa, the country that could best exploit this technology is Somalia. A comparison of PV and CSP solar technologies in terms of economic potential can be found in Köberle *et al.* [102].

Similarly to PVs, the intermittency of solar resources can be mitigated via thermal energy storage [110–112]. Owing to thermal energy storage, which allows continuous operation, and to a co-generation layout, which increases the overall efficiency, the CSP is considered the most profitable solution in several African regions, such as the Saharan region [102]. According to the latter study, the CSP cost is expected to exhibit a more rapid decline in the short term;

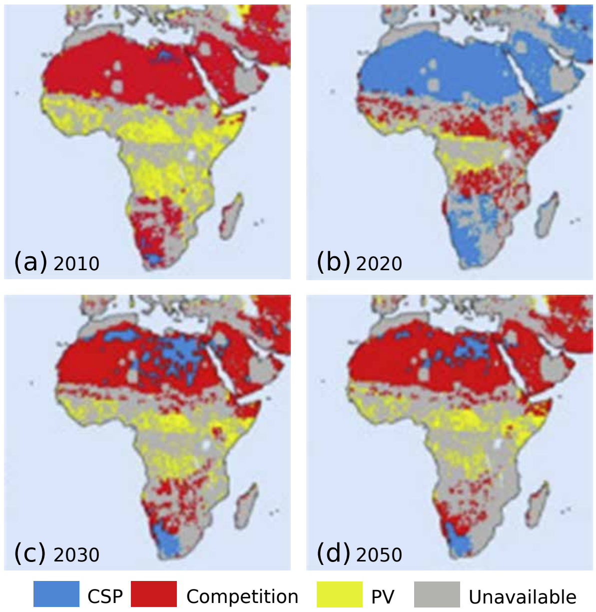


Figure 15: CSP vs. PV technology comparison based on the relative Cost of Energy (COE) [101, 102], according to the model published by Köberle *et al.* [102]. The red areas (competition) indicate where the difference between the cost of the two technologies is less than 10%; while blue (CSP) and yellow (PV) areas show where one of the two technologies is less expensive. Panels a, b, c, and d show the time evolution of the economic model: in the medium term, the CSP exhibits a faster reduction in the cost of electricity because it is a less mature technology and remains in the initial stage of the learning curve [101, 102], which translates into CSP advantage in high Direct Normal Irradiance (DNI) areas around 2020. In the long term, the PV exhibits a slower but continuous cost reduction and will overtake the CSP in some areas. (Image reprinted from Köberle *et al.* [102, p.748] with permission from Elsevier).

whereas, considering a longer perspective, the difference in terms of profitability between the two solar technologies should be less than 10% in most of Africa (see Fig. 15).

3.3. Wind power

For wind power generation, windmills are employed to transform the kinetic energy of air into mechanical and electric power. The first turbines for wind-based power generation were introduced in the early 20th century; since then, this technology has undergone gradual but substantial improvements. Since the end of the 1990s, wind energy has been considered a key resource in the renewable mix for sustainable development [113, 114]. Then, the pivotal challenge for industrial windmills manufacturers consists in the design and realization of always more efficient and cost-effective turbines, in order to lower the energy production costs [115]. Such conversion technologies typically apply to mechanical power and electricity production, and to wind pumps for water [116].

In Africa, the potential energy from wind source exceeds the current energy demand by several orders of magnitude. Nevertheless, wind power is still widely under-exploited: it is estimated that, from 864.2 TWh of worldwide wind energy generation in 2015, only 6.9 TWh were produced in Africa [118], namely less than 1% of the total energy demand throughout the continent. In Fig. 16, it is possible to appreciate that this capacity is outstanding, even though not uniformly distributed in the continent [89]. Particularly abundant wind resources are especially located in the countries in the North regions of Africa, in the East (Kenya, Sudan, Somalia, Uganda, Djibouti, Ethiopia) and South (South Africa, Tanzania, Lesotho, Malawi and Zambia), and in Niger in Western Africa [77].

Regarding Eastern Africa, Kenya and Tanzania may be potentially suitable sites for large-scale installations. Kenya represents indeed the country with the most important potential in Africa [119]. The districts of Turkana together with that of Marsabit, located in the north-west of the country, have an estimated potential which may exceed 1 GW for grid-connected systems [119]. Promising resources are also envisioned for the Rift Valley area in Tanzania, particularly in the islands (Pemba, Zanzibar, and Mafia), Makambako (Iringa), and Kititimo (Singida) [82].

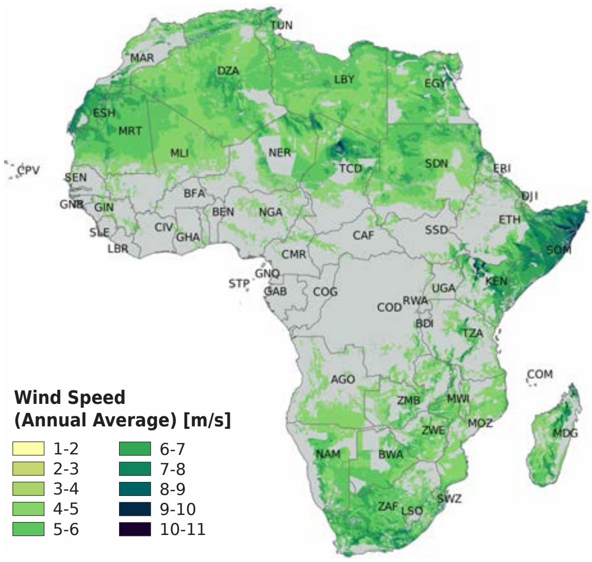


Figure 16: Overview of wind potential in Africa. Map from Ref. [89] (Copyright IRENA 2014) using the data in Ref. [117].

3.3.1. On-shore wind power production

Different methods have been proposed to evaluate on-shore (land) wind energy potential, and all methods consider factors that can be grouped into four categories [120]: *theoretical potential*, the total amount of wind energy potentially available; *geographical potential*, the total amount of wind energy that could be obtained from the fraction of land area suitable for a wind farm; *technical potential*, the remaining wind energy after subtracting all the losses occurring in the energy conversion process; *economic potential*, and the fraction of energy actually exploitable after that all the costs related to production, renewable energy subsidies, and grid connection cost have been considered.

Considering the first two factors, the total wind energy potentially available in Africa is approximately 460 PWh/year [89], being roughly 37% from Eastern Africa, which is the region with the highest wind potential (see Fig. 16). If the other two factors are introduced and a cut-off cost of 0.14 USD/kWh is considered (equivalent to a capacity factor, namely the average power generated with respect to the nominal turbine size, of 23% in Africa), the total technical-economic energy potential is up to 27 PWh/year [121], *i.e.* 35 times the African electricity consumption in 2015.

The current size of projects involving wind power production in Africa is typically smaller than 150 MW. Nevertheless, an increase in the size of the perspective projects is envisioned to reach 300–700 MW, although these projects are still in the planning or construction stages [119]. In general, the very low cost of electricity production via wind energy conversion (e.g., around 0.05 to 0.13 USD/kWh in Africa in 2016) can act as a driver for further promotion of the exploitation of wind resources for electricity production in the near future [122].

3.3.2. Off-shore wind power production

Off-shore wind turbine technology is a relatively recent wind power innovation, where wind towers are built far from the mainland [123, 124]. The benefit is twofold, namely higher wind speeds and reduced visual impact and noise. The cost required for building off-shore generators is higher with respect to on-shore ones: according to the 2016 IRENA estimations, the Levelized Cost of Energy (LCOE) of off-shore wind plants was approximately 0.14 USD/kWh, ranging between 0.13 to 0.23 USD/kWh [122]. This technology is exploited mainly in advanced economies, such as United Kingdom, Germany, China, and Denmark, being in the first two previous countries installed 65% of the global cumulative capacity in 2017 [125]. In developing countries, the advantages and potential of this technology are currently hindered by the high cost and lack of infrastructures [126].

Table 2: Current and perspective capacity of renewable energy in Africa. CAP is the capacity [GW], %TOT is percent share of the total capacity (including the non-renewable sources of energy), %RE is percent share of the renewable capacity. The "Perspective overall" column reports the summation between the operational plants, the under construction, and planned ones, showing the possible future power generation landscape. Source: African Development Bank, 2017 data [53].

	Operational			**Under construction**			**Planned**			**Perspective overall**		
	CAP	%TOT	%RE	CAP	%TOT	%RE	CAP	%TOT	%RE	CAP	%TOT	%RE
Hydro	37.06	20.8	87.8	17.57	54.6	86.5	53.24	74.2	95.6	107.9	38.2	91.2
Wind	2.68	1.5	6.3	1.39	4.3	6.8	1.14	1.6	2.0	5.20	1.8	4.4
Solar	1.82	1.0	4.3	1.18	3.7	5.8	1.01	1.4	1.8	4	1.4	3.4
Geo	0.57	0.32	1.35	0.19	0.59	0.93	0.22	0.31	0.39	0.98	0.35	0.83
Biomass	0.08	0.04	0.19	-	-	-	0.11	0.15	0.19	0.18	0.07	0.16
Total	42.2	23.7	100	20.32	63.1	100	55.72	77.6	100	118.2	41.9	100

3.4. Hydroelectric power

Hydropower is currently the main source of clean energy in Africa. In 2015, 122 TWh were generated from hydropower plants in the whole continent [127], providing approximately 16% of the total electricity output. Nevertheless, at the moment, only a small fraction of the promising hydropower potential of the African continent is exploited. It is estimated that a total technical potential of 2880 TWh/year with a cost of energy lower than 0.5 USD/kWh [128], which is more than three times the actual electricity demand, but only a 5% is currently deployed. Moreover, 770 TWh/year could be potentially exploited at a cost lower than 0.1 USD/kWh with a reduced environmental impact [128]. Among the African rivers, the Congo has the highest water discharge amount, and most of its potential remains under-exploited; the Nile, Zambezi, and Niger rivers have the second-highest water discharge amounts [77]. An interesting overview of this potential is reported in Ref. [128], where the largest basins in Africa, including the existing use and the remaining potential, are analyzed together with the geographical location of the current and new potential hydropower plants.

According to the magnitude of resource, different setups for hydropower plants can be adopted [129]. Large hydropower plants come generally combined with a storage dam, whose environmental and social impact is a subject of debate [130, 131], and are employed for generating grid electricity. Instead, dams may or may not be present in case of hydropower plants with smaller sizes (from 1 to 10 MW capacity), while mini- (from 100 to 1000 kW) or micro-hydro (from 5 to 100 kW) could provide distributed electricity to areas not connected to the grid. At present, the installed hydropower capacity of the African continent is approximately 37 GW, with an electricity market share of 21% (see Tab. 2); however, in 25 countries, mostly located in the sub-Saharan region, the hydropower contribution to electricity generation is more than 50% [132]. Thanks to the abundance of resources and the maturity of this technology, hydropower represents the cheapest technology for renewable electricity generation at the utility-scale [77]. Table 2 indeed shows that more than half of the power plants under construction is hydro-electric, and the percentage increases to 75% for the plants planned in the near future. An interesting example is the Grand Inga project in Congo, which is planned for up to 42 GW capacity [133] and, once completed, would be the largest hydro facility in the world, with a nearly double capacity with respect to the Three Gorges Dam in China [134].

In East Africa, a potential capacity of 13.4 GW is estimated for large-scale hydroelectric plants; however, only 16% is currently exploited (see Fig. 17). More than half of this potential pertains to Tanzania and Kenya (4.8 GW and 4.5 GW, respectively), followed by Uganda and Burundi (2.0 GW and 1.7 GW, respectively). In these regions, the low currently access to electricity implies that large hydropower facilities can satisfy a significant part of their electricity demand. In some extreme cases, such as Burundi, hydropower now represents 95% of the country total electricity generation [82]. On the other hand, small-hydro power can play a key role in developing a more distributed electricity access throughout the region [82, 135].

To conclude the analysis of hydroelectric resources, we must keep in mind that these power production plants can lead to critical geopolitical, environmental, and socio-economic issues: because basins of the main rivers in Africa can include two or more states, the exploitation of the watercourse by one of the countries can lead to tension and conflicts with the downstream countries [136].

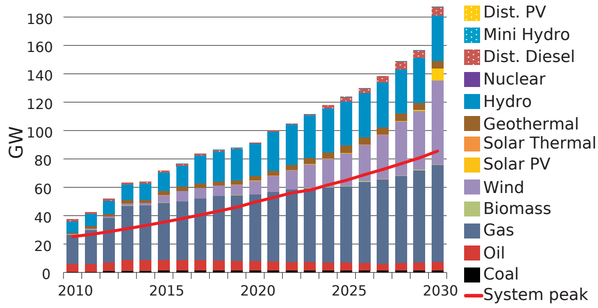


Figure 17: East Africa installation capacity mix projection from 2010 to 2030: in 2030, approximately half of the currently installed capacity in the region will be retired. It follows that, to meet the future electricity demand between 2010 and 2030, an additional capacity of 170 GW will be required. Under the IRENA renewable-promotion scenario, the total installed capacity in 2030 (~ 190 GW) for renewable technologies will be covered by more than 100 GW, being more than half from wind power (60 GW), 30 GW from hydro, 8 GW from solar PV and 5 GW from geothermal [137]. Copyright IRENA 2015.

3.5. Geothermal power

The use of geothermal energy as a source of electricity is particularly relevant in the eastern and southern regions of Africa. The continent potential is estimated to be 15.8 GW, being mostly localized in the Rift Valley from Djibouti to Mozambique. The following geothermal electrical power potentials have been estimated: 300 MW in Rwanda, 450 MW in Uganda, 7–10 GW in Kenya, and 5 GW in Tanzania (no estimations are available for Burundi, to date). In 2014, Kenya was the only country in the Eastern African Community with geothermal power plants, with an operational capacity of 597 MW increased to 607 MW in late 2015 [82]. The Kenyan power generation from geothermal sources was reported for the first time to be more than half of the national production of electricity in December 2014. Along this line, nearly 3 GW of additional geothermal power production plants have been planned in Kenya. Ethiopia and Tanzania are also developing geothermal power plants, aiming to achieve a 640 MW capacity in 2018. Geothermal plants require large initial investments, mainly due to engineering, procurement, and building costs [77].

3.6. Biomass power

Biomass can be directly used as a solid fuel or processed to obtain biogas or liquid biofuel and then employed to generate electricity or other forms of power [138]. Biomass can be defined as a renewable source of energy if exploited in a sustainable way, and it may also come as byproduct or residue from multiple processes. Agricultural activities generate biomass residues at various stages, for instance crop harvesting residues such as cassava stalk, maize stover, or wheat straw. Animal farms also typically produce biomass that can be re-used for energy purposes, such as manure or manure-bedding materials mixtures. Forestry can provide wood logging residuals, namely the remainders of trees after obtaining industrial wood fuel and roundwood. Rice husk and sugarcane bagasse from agri-food processing plants, and wood processing residues, bark, sawdust and cuttings from sawmills and furniture production facilities can be employed as biomass as well. Finally, the organic fraction of municipal waste also represents a widely employed biomass source.

It has been estimated that African agro-processing and crop harvesting biomass residues will have an energy potential of around 4.2 EJ in 2030, with 40% of this resource being localized in West Africa. The estimated energy potential from animal residues is approximately 1.1 EJ/year, whereas that from wood residues/wastes is approximately 1.5 EJ/year. The central regions of Africa show the lowest wood residue/waste potential, while the north ones the highest (40% of the overall amount) [139]. Because the cost of collecting and transporting biomass residues is a major factor affecting the economic feasibility of their energy exploitation, it is preferable to convert *in loco* biomass into final energy forms or fuels as much as possible before utilization [140]. Notably, bioenergy technologies may be also cost-effective solutions to mitigate the environmental impact of biomass waste and residues (e.g., the organic fraction of municipal waste or sewer) [77].

3.7. Configurations for renewable energy production

The poor access to electricity and weakness of the grid are among the most important obstacles to Africa development [142]. IEA estimated that 48% of the whole African population was lacking access to electricity in 2016

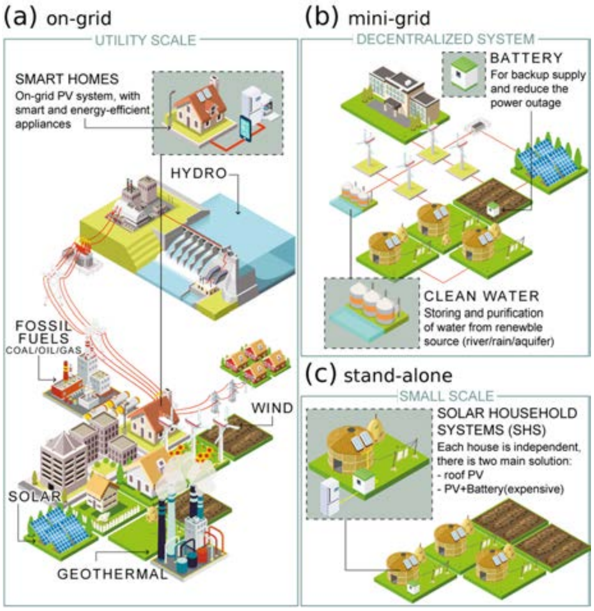


Figure 18: Infographic of the three renewable energy production layouts, namely (a) on-grid, (b) mini-grid, and (c) stand-alone (see Section 3.7). Picture re-elaborated from Ref. [141, p.19].

[143]. The majority of these people was located in the sub-Saharan region, where 80% of the African population lived but only one-fourth of the African electricity was generated and consumed [143, 144]. In addition, the current grid shows an alarming instability, as proved by the frequent power outages in the region (approximately 6.3 times per month, with an average duration of 2.8 hours), which is much larger if compared with high-income countries, where the frequency and duration of blackouts are approximately 0.4 per month and 30 minutes each, respectively [49]. In the mid-term, solutions to these problems may including the following: stand-alone and mini-grid layouts to quickly improve access to electricity, especially in rural zones; a heterogeneous generation mix; and electricity trade between countries. Currently, power trades between neighboring countries comprise only 8% of the electricity production [118]; however, this trend is estimated to rise in the next years, thanks to different power pool agreements that should increase the energy generation and improve the grid [145–148].

3.7.1. Grid connected (on-grid)

The term "on-grid" or "grid-connected" refers to the most common setup for energy generation and transport, that is, electrical plants and users connected via a complex electrical grid, as shown in Fig. 18a. In the case of several electrical sources, layout is suitable to manage complex generation mixes, thus guaranteeing a continuous supply of electricity. Renewable energy sites in Africa are often located far from areas where the energy needs are concentrated; thus, the cost of new transmission lines sometimes hinders the feasibility of new sites [49, 149]. According to the IRENA agency, the energy demand in Africa is estimated to require investments of USD 25 billion per year for transmission and distribution lines [77]. Such energy infrastructure is therefore critical for African countries, and a key role is played by power pool agreements (Fig. 1). An example of this strategy is the Inga project, where the collaboration between Central and Southern Africa power pools is crucial for project development [150].

Centralized (utility scale) on-grid systems can significantly reduce the cost of energy from renewable sources because no batteries or other storage systems would be required. Owing to the possibility to reintroduce the unused energy, countries can adopt a feed-in tariff (FIT), stimulating the renewable energy market, which could decrease the energy cost for households [48, 49]. For example, the energy cost saving would be approximately 70% in South Africa with the actual FIT of 0.046 USD/kWh [151]. To conclude, on-grid systems coupled with the most advanced technologies for renewable energy generation and storage can produce what is called "smart-grid," where a digital connection system is used to detect and react to local energy consumption (and production) [152]. This would allow

African countries to leapfrog “traditional” transmission systems, thereby accelerating and improving electrification development and generation mix [153].

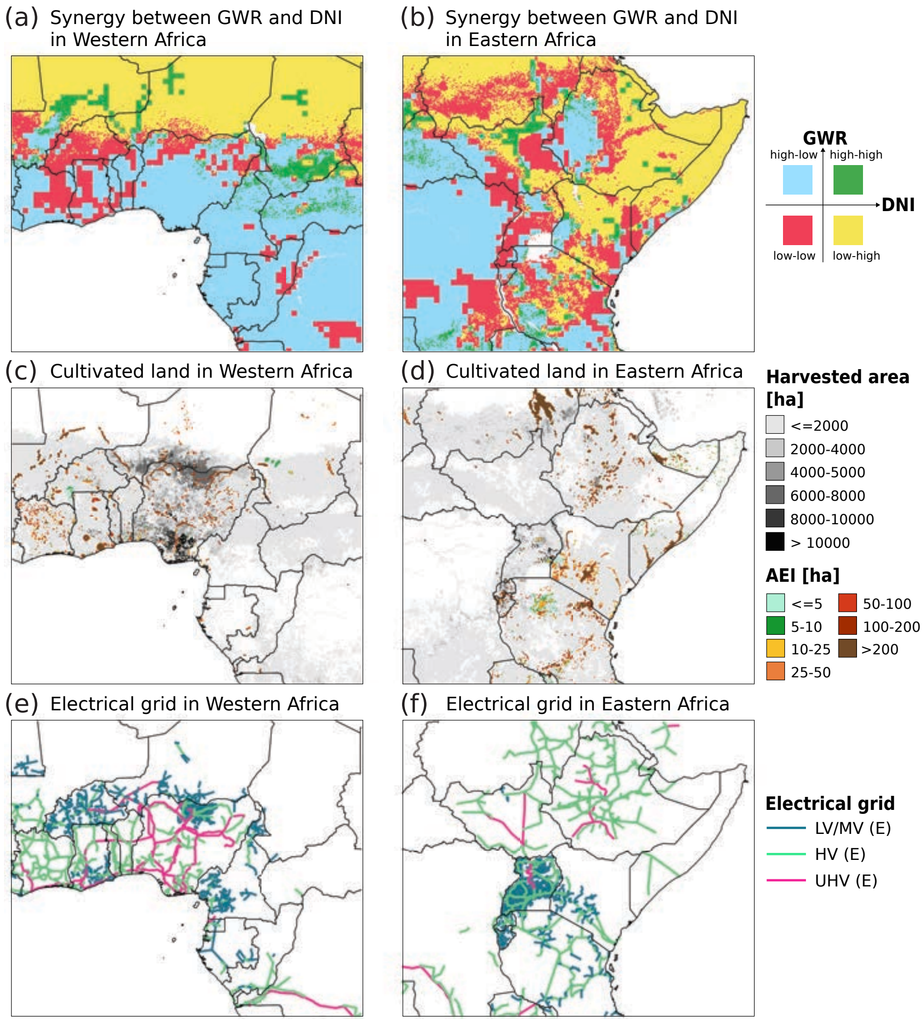


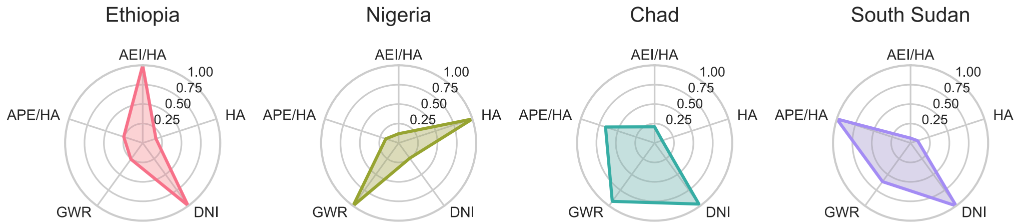
Figure 19: A schematic representation of the water and energy nexus in two African regions. The potential synergy between renewable groundwater and renewable energy is reported for (a) Western and (b) Eastern Africa. Pixel colors are representative of the potential synergy between water and energy. Ground water recharge (GWR) is termed “high” when it exceeds 90 mm/yr and “low” otherwise; direct net solar irradiation is termed “high” when it exceeds 4 kWh/m^2/d and “low” otherwise. Current harvested areas and area equipped for irrigation (AEI) in (c) Western and (d) Eastern Africa. Electricity transmission and distribution grid currently existing in (e) Western and (f) Eastern Africa.

3.7.2. Mini-grid and stand-alone (off-grid)

When using the term “off-grid,” we refer to all systems disconnected from public electricity transmission networks. Such systems can be divided into two subgroups: mini-grid and stand-alone.

The term “mini-grid” refers to a layout in which small power generators, energy storage systems, and users are interconnected through a distribution line to constitute an independent and totally self-sufficient system, with a total power production between 10 kW and 10 MW [154–157], as shown in Fig. 18b. This layout allows also to generate energy from different sources, like PV, small-hydro, wind turbines and biomass-based plants [77]. Thanks to the generation mix and distribution line, the mini-grid has many advantages with respect to the stand-alone configuration, since such a mix reduces the total price of electricity and can meet the typical domestic demand and that of other activities, such agriculture, commercial activities, and public services such as schools and hospitals [158].

The term “stand-alone” denotes a strategy of energy generation and optional storage, which is totally independent from the main distribution lines. This approach is typically used for small-size generation, e.g., to supply households or small industrial activities, as shown in Fig. 18c. This solution serves a key role in improving the availability of electricity in rural zones, where the energy demand is between 250 and 500 kWh/year per household [159]. PV technology is predominantly used in this configuration due to its simple layout, low operational costs, and flexibility. For example, possible applications are solar chargers for mobile phone, sun-powered lanterns, and Solar Home System (SHS) [154], with or without battery [49]. Kenya and Tanzania have developed their own internal market for small PV products, showing that this type of technology brings benefits also in the social and economic fabric of the country [83].



scale factor	
DNI [kWh/m^2/day]	2.56
GWR [mm/yr]	217.93
HA [ha/km^2]	36
AEI/HA [%]	5.86
APE/HA [%]	14.46

Figure 20: Insight on the outcome of the proposed analysis (see Fig. 19) for four different African countries, namely: Ethiopia, Nigeria, Chad and South Sudan. The reported quantities are: direct normal solar irradiation (DNI), ground water recharge (GWR), current harvested areas (HA), current area equipped for irrigation (AEI) and area that can be potentially equipped for irrigation (APE). The units and the scale factors used for the representation are reported in the table on the right. Note that, the AEI and APE are reported as percentages with respect to HA.

4. Sample analysis using the water-energy datasets

An example of potential results with an integrated dataset is reported in Fig. 19, with specific reference to two macro-areas in Eastern and Western Africa. We first locate places where potential water and renewable-energy availability are both high (i.e., green pixels). For the purpose of this example, we concentrate our attention on groundwater availability and direct normal solar irradiation only; however, this type of analysis may be extended to other sources of freshwater and renewable energy. Groundwater withdrawal is sustainable only when it does not exceed natural recharge: we therefore use groundwater recharge as a proxy of groundwater availability (see Fig. 5). For the purpose of this example, groundwater availability is divided into two classes, and it is termed “high” when recharge exceeds 90 mm/y and “low” otherwise. Analogously, direct normal solar irradiation (see Fig. 14) is termed “high” when it exceeds 4 kWh/m^2/d and “low” otherwise. Places where both resources are largely available can be clearly spotted in Fig. 19(a) and Fig. 19(b). However, places where water and energy are abundant do not necessarily correspond to places where agriculture could be intensified because issues such as a lack of fertile soils or available electrical infrastructure may inhibit water pumping from groundwater resources. Thus, future research should also consider where the harvested areas are, whether these areas are already equipped for irrigation (Fig. 19c and Fig. 19d), and whether the existing electricity transmission and distribution grid is sufficiently dense (Fig. 19e and Fig. 19f). Specific places naturally emerge as foci for agricultural intensification, including South Sudan, Western and Central Kenya, and locations across Tanzania. In other places, the potential is high but investments in irrigation (e.g., in South Sudan, North-East Uganda) or electrical infrastructure (e.g., in Mali, Western Niger) are required.

Figure 20 provides an insight on the outcome of the analysis for four different representative countries, namely: Ethiopia, Nigeria, Chad and South Sudan. The reported quantities are: direct normal solar irradiation (DNI), ground water recharge (GWR), current harvested areas (HA), current area equipped for irrigation (AEI) and area that can be potentially equipped for irrigation (APE). Note that all these quantities have been extracted from the data in Fig. 19. In particular, the aggregated values have been obtained as an average among the pixels which are identified as current suitable areas for agriculture (HA). The APE index, obtained as the intersection between the water-energy synergy maps (Figure 19a,b) and the current rainfed harvested areas (Figure 19c,d, grey pixels), represents the potential gain of solar-energy driven irrigation area for the country. Ethiopia, for example, has much higher solar potential than Nigeria; yet, it has lower groundwater availability. Moreover, Ethiopia has a larger fraction of cultivated area which is already equipped for irrigation. On the other hand, Nigeria has a little area fraction already equipped for irrigation, and limited solar resource to potentially increase the APE. Chad has a remarkable potential of groundwater and solar resource; then, it has better potential in terms of APE. Finally, South Sudan has the highest potential in terms of relative APE enhancement. Even though, it has lower groundwater resources than Chad.

This example is limited to considering only few renewable energy and water sources, while a more complex framework would be needed to simultaneously consider many sources of energy and water. Moreover, quantitative methods are required to identify the locations with sufficient resources and infrastructure availability more objectively. In addition to these data, previous studies have provided useful tools and code that may promote the combination of various GIS data and aid in the decision-making process for where and how investing in developing countries, such as open-source projects OnSSET [160] and FREEWAT [161]. Furthermore, the fast Machine Learning methodology spreading as a tool for processing a huge set of data opens new perspectives, which may help the Sub-Saharan region meet the Sustainable Development Goals, as desired by the initiative Machine Learning for the Developing World (ML4D) [162]. The application of this technique already shows some encouraging results in using different geographical data, for instance, extract land coverage from satellite images [163–165], predicting the water demand and quality [166, 167], understand social-economics evolutions [168–170], and public health control [171–173].

5. Conclusions

Due to significant population growth and economic expansion occurring within the African continent, which is anticipated to continue over the next decades, serious problems are expected with a strongly increasing energy demand and clean water scarcity. Nonetheless, Africa has an outstanding potential of renewable sources of energy, which can help serving sustainable development and freshwater production. Energy policies must be properly designed to target the best solutions for energy conversion, distribution, and utilization.

In this work, we have provided a critical review of the renewable energy potentials against the freshwater shortage and availability (split into rainfall, river discharge, and groundwater recharge) in Africa to promote the development of a comprehensive data collection supporting water–energy policy makers. A detailed mapping of water availability throughout the continent elucidated reasons influencing the widespread lack of access to useable water.

Our analysis has shown that, although the water availability in most African regions is above the "physical water scarcity" threshold defined by the UN, the lack of infrastructure causes more than half of the population to go without access to clean water sources. These areas therefore suffer an "economic water scarcity, " which also prevent farmers from obtaining a stable and sufficient food production with important impacts on the food security. All these territories may particularly benefit from renewable sources of energy, e.g., solar and wind ones, for water extraction and pumping for distribution. On the other hand, in those regions suffering actual lack of clean water, such as coastal regions, sustainable desalination technologies may be particularly beneficial. In perspective, the lowering price of technologies for energy conversion [82] may also pave the way towards the concurrent use of soil for agricultural purposes and PV installations, such as agrivoltaic solutions [174–176], which would allow an optimized and a more sustainable use and preservation of the territory.

Areas experiencing "physical water scarcity" may obtain greater benefits from the introduction of renewable energy-driven desalination technologies [177]. Although desalination is a good option for mitigating physical freshwater scarcity, it remains an energy intensive process [178]. Renewable sources of energy have been studied to improve the energy sustainability of conventional desalination and water treatment technologies [179, 180]. Photovoltaic and wind power generation have been proposed to supply electricity with reverse osmosis or electrodialysis desalination systems [181], whereas solar thermal and waste heat recovery to power evaporation-driven distillers (e.g., multi-stage flash distillation, multiple-effect distillation, membrane distillation) [182]. Lately, new passive approaches to desalination (relying on spontaneous phenomena, e.g., capillarity and transpiration) have been proposed, being mainly based on solar thermal distillation [183–185]. These passive technologies are typically realized by inexpensive materials thus requiring low capital and maintenance, being perfectly suitable for small-scale installations in off-grid areas [28, 186–190].

The most relevant datasets for renewable potentials and water mapping have been organized in tables and reported in the Appendix to this document (Tab. A1 and A2). These tables are meant to provide a systematic basis for further data-driven analysis and, in perspective, towards a detailed policy design for water and energy at the local level. To this, we have provided an example analysis using the reported water-energy datasets, which allows large-scale as well as country-based analysis on the potential of renewable energies for the improvement of current irrigation areas. This example, in its simplicity, shows how the energy and water variables are inextricably linked and demonstrates that datasets and tools like those reviewed in this paper are essential to support future, macro-scale, planning initiatives.

6. Declaration of competing interest

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

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8. Data availability statement

The datasets used in this article are listed in the Appendix. Additional details for data in the presented maps are available upon request from the corresponding authors.

Appendix A: List of datasets

Table A1: List of datasets and tools for renewable energy potential assessment. The ticks indicate the availability of: Report (R), Publications (P), Statistics (S), GIS[2] data (G), Maps (M) and Tools (T) per each dataset.

Name	Description	Data					
		R	P	S	G	M	T
Eastern Africa Power Pool (EAPP) [191]	Institutional site, which is useful for obtaining information about energy development in the region, future investments, and energy data of member countries.	✓	✓	✓			
West Africa Power Pool (WAPP) [192]	Institutional site, which provides news on energy investments and a high voltage grid between states as well as a map that summarizes the actual, scheduled, and under-study projects.	✓		✓		✓	
Central Africa Power Pool (CAPP) [193]	Institutional site, which provides news and statistics regarding energy development in the region. We underline the interactive tool to visualize the statistics indicators and the map where are reported the energy infrastructure.	✓		✓	✓	✓	✓
Southern African Power Pool (SAPP) [194]	Institutional site, which provides information regarding the development of the energy sector in the region, with a map and statistics.	✓		✓		✓	
International Energy Agency (IEA) [195]	IEA statistics page. IEA is an intergovernmental organization that collects and publishes annual energy statistics and outlooks for 30 member countries and beyond.	✓	✓	✓			✓
IRENA Global Atlas [196]	IRENA (International Renewable Energy Agency), which is an online GIS-tool that collects over 1000 datasets produced by IRENA members with the aim of closing the gap between countries with access to datasets and evaluate their renewable potential [197].				✓		✓
IRENA dashboard [198]	IRENA (International Renewable Energy Agency) and REN21 (Renewable Energy Policy Network for the 21st Century) statistics and data, which collect many IRENA and/or REN21 studies and analyze the development of renewable energy around the word.				✓		✓
World Bank Open Data [2]	In this site are collected all the statistical indicators managed by the World Bank institution. They are easily accessible by a search bar and can be plotted and visualized on the map thanks to the integrated web-tools.				✓	✓	✓
ENERGYDATA .INFO [199]	It is a platform similar to a search engine, useful to find datasets and data analytics of energy sector from many sources, such as universities, governments, development organizations, etc. It has also a section where are listed a set of web-tools.				✓	✓	✓
SOLARGIS [95]	It is a GIS platform with weather data, online apps, and consultancy services. The platform aims to help reduce risks and optimize the performance of solar power plants. In the site is also possible to download free high-resolution GIS data for academic purposes.	✓			✓	✓	✓
Multi-criteria Analysis for Planning Renewable Energy (MapRE) [91]	Platform developed by the Berkeley university for the energy area SEAREZ[3] and IREZ[4]. It provides a spatial database and a useful GIS-tool that allow the combination of different data to identify the most suitable area for renewable energy development.				✓		✓
Open Energy Information [200]	A platform on which more than 1500 databases on renewable energy are compiled and organized by region, resource, data type, etc.	✓			✓	✓	✓
DLR Earth Observation Center (EOC) [201]	A portal that hosts *DLR Earth Observation Center (EOC)* satellite data on weather and environmental studies.				✓		✓

Table A1: List of datasets and tools for renewable energy potential assessments (continued).

Name	Description	Data					
		R	P	S	G	M	T
Knoema [202]	A platform that provides public data and statistics featuring approximately 2.5 billion time series for over 1000 topics. It is possible to directly plot and analyze data online and build personalized tools. Some functions are only available to "premium" users.			✓	✓	✓	✓
The Malaria Atlas Project (MAP) [203]	Platform, which allows researchers in different disciplines to collaborate in combating malaria and collects useful geospatial data, such as travel time to cities [204].	✓	✓		✓		✓
Google Earth Engine [205]	A project that facilitates geospatial analysis using Google's infrastructure. The main interface is the web-based IDE on which it is possible to write and run scripts and integrate external data. One example of its potential is demonstrated by the work of D.J. Weiss *et al.* [204] and described in the project blog.				✓		✓
Prediction Of Worldwide Energy Resource (POWER) [206]	A project supported by NASA in which climate changes are controlled to aid in renewable energy studies. It is possible to download solar and wind indicators with a resolution of 1° from 1981 on.				✓	✓	
Africa Information Highway [207]	The database portal of African Development Bank that collects socioeconomic indicators specific to African countries.	✓	✓	✓	✓		✓
Africa Power Plants map [208]	A map produced by the African Development Bank that records power plants in Africa by type.					✓	✓

Table A2: List of datasets and tools for renewable clean water analysis. Ticks indicate the availability of Reports (R), Publications (P), Statistics (S), GIS[2] data (G), Maps (M), and Tools (T).

Name	Description	Data					
		R	P	S	G	M	T
AQUASTAT [36]	A database developed by FAO that contains data on water resources and renewable water resources for all countries worldwide.			✓			
Aqueduct Global Maps 2.1 [209]	The World Research Institute (WRI) provides a global map and several indicators about water availability, quality, and ecosystem vulnerability with Aqueduct Global Maps 2.1 Data.			✓		✓	
Africa Water Vision 2025 [210]	A report by the Economic Commission for Africa, African Union, and Africa Development Bank that covers many aspects of the African water crisis and provides possible perspectives and features for the year 2025.	✓	✓				
Global Environment Monitoring System for Water (GEMS/Water) [211]	A UN program that aims to support scientific assessments and decision-making processes by providing global freshwater data.		✓	✓	✓		
Integrated Model to Assess the Global Environment (IMAGE) 3.0 [212]	A tool developed by the PBL Netherlands Environmental Assessment Agency that promotes the investigation of the human environmental footprint, land use, deforestation, pollution, etc.				✓	✓	✓
4TU.Centre datasets [213]	A long-term archive for storing scientific research data from hydrological studies of three Dutch technical universities (Delft, Eindhoven, Twente).		✓		✓		

Appendix B: Map of diffuse horizontal irradiation

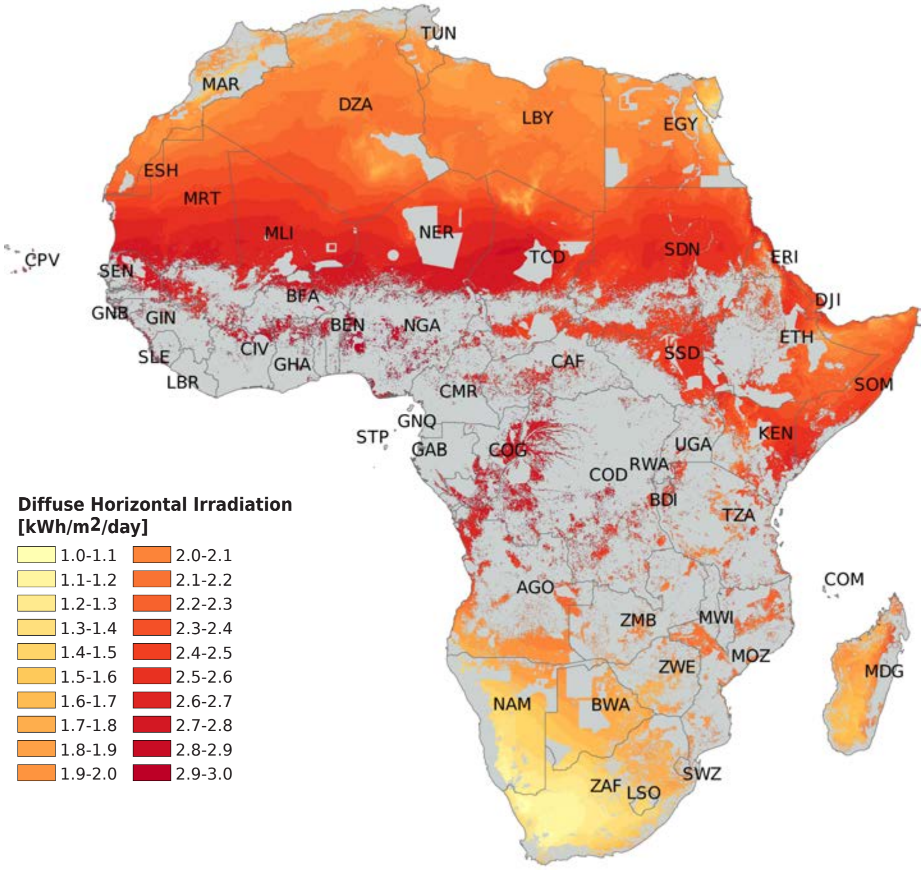

Figure B1: Overview of diffuse horizontal solar irradiation in Africa. Map computed with the method proposed in Ref. [89], using the data from Refs. [92–95].

Appendix C: Map of climate types

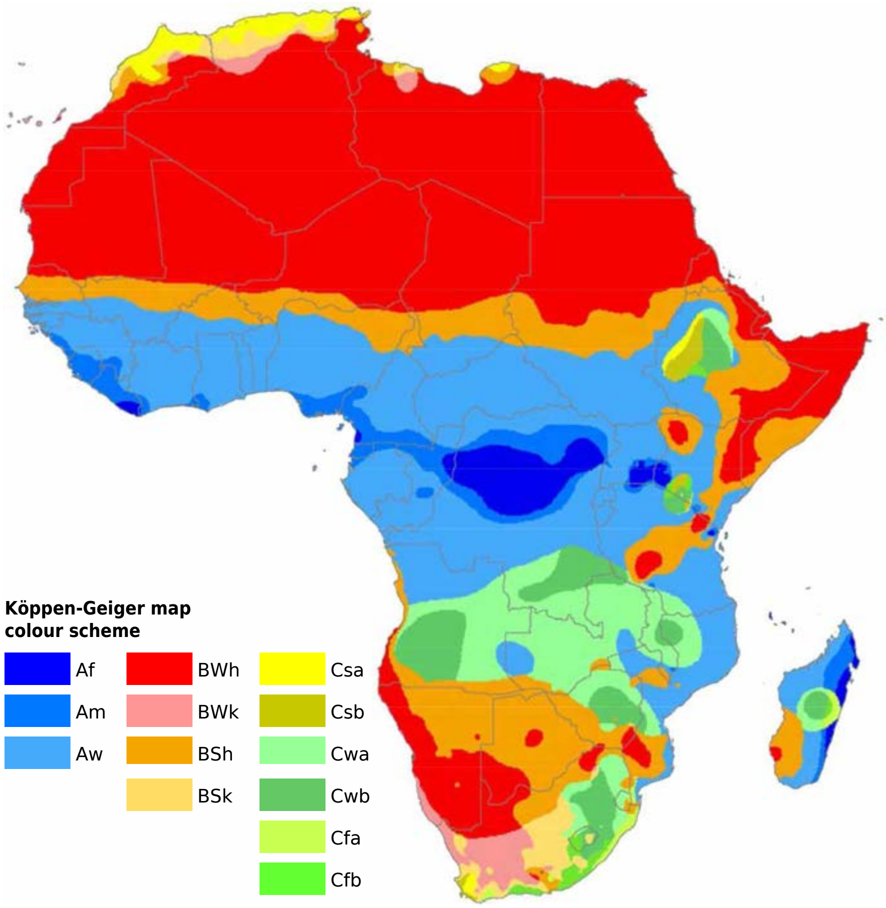

Figure B2: Africa Köppen-Geiger climate type study by M. C. Peel *et al.* (Source: M. C. Peel *et al.* [214, p.1638] available under CC BY-NC-SA 2.5): Tropical rainforest climate – *Af*; Tropical monsoon climate – *Am*; Tropical wet savanna climate – *Aw*; Hot desert climate – *BWh*; Cold desert climate – *BWk*; Hot semi-arid climate – *BSh*; Cold semi-arid climate – *BSk*; Hot-summer Mediterranean climate – *Csa*; Warm-summer Mediterranean climate – *Csb*; Monsoon-influenced humid subtropical climate – *Cwa*; Subtropical highland climate – *Cwb*; Temperate rainy climate – *Cfa*; Temperate oceanic climate – *Cfb*.

[2]Geographic Information System: indicate a type of dataset which store spatial data.
[3] Southern and East Africa (SAPP+EAPP)
[4] India Renewable Energy Zones

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