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Perspective

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Sustainable pathways towards universal renewable electricity access in Africa

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Abstract

Half of the African population currently lacks the minimum levels of electricity access defined by the International Energy Agency. However, given the limited fossil fuel dependency and need for energy infrastructure expansion, there are expectations that at least some African countries could avoid fossil fuel dependency altogether and move directly to renewable energy (RE)-based electricity systems. In this Perspective, we present trends in Africa's RE development and access on a national level and discuss the respective country-specific capacities to lead the transition to sustainable RE for all. If all existing wind, solar and hydropower plants operate on full capacity and all proposed plants are implemented, 76% (1,225 TWh) of electricity needs projected for 2040 (a total of 1,614 TWh) could be met by RE (82% hydropower, 11% solar power and 7% wind power). Hydropower has been the main RE resource to date, but declining costs for solar photovoltaics (90% decline since 2009) and wind turbines (55–60% decline since 2010) mean solar and wind have potential to lead sustainable RE pathways going forward, while also protecting freshwater ecosystems. Efficiently combining the advantages of hydropower with wind and solar will be a more sustainable alternative to hydropower alone. As resource potential differs among countries, transnational electricity sharing is recommended to distribute resources and share nationally produced peak capacity. Comprehensive investigations should further assess and monitor socioeconomic, political and ecological impacts of RE development.

Sections

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Introduction

About 626 million Africans lack access to electricity (46% of total population; census: 2020)[1,2], with the population expected to nearly double by 2050 (2.5 billion people)[3]. In addition, financial difficulties of power providers cause blackouts, electricity rationing and financing backlogs for an urgently needed renewable capacity expansion[3]. The International Renewable Energy Agency (IRENA) states that 23.1% of the total electricity capacity installed in 2021 in Africa came from renewables, which is 15.2% less than the worldwide renewable electricity capacity[4]. To "ensure access to affordable, reliable, sustainable and modern energy for all" by 2030 (Sustainable Development Goal, SDG, 7)[5], the capacity for electricity production from renewable resources needs to increase so that countries can meet their nationally determined contributions, that is, the national climate pledges that each country committed to in order to reach the United Nation's Agenda 2030 goals.

There is an existing narrative that, in contrast to other continents, Africa can avoid a phase of fossil fuel dependency[6–8]. Providing electricity systems based on 100% renewable energy (RE) is technically and economically feasible[2,6,9,10], offers economic growth[11] and job creation potential[9,12,13], improves climate change resilience[10] and minimizes negative impacts of emissions on the environment and human health[14]. However, there is no single solution towards 100% RE that fits all the specific conditions for each African country or region[15]. Regional electricity access rates can vary substantially; for example, nearly 100% of people living in Morocco, Algeria, Tunisia and Egypt have at least four hours of access per day, whereas less than 20% in Burkina Faso, Niger, Chad, the Central African Republic, the Democratic Republic of Congo, Malawi and South Sudan have such access[16]. Countries with low electricity generation and/or few fossil fuel shares have the higher tendency to avoid a phase of high fossil fuel dependence and directly transit to clean renewable electricity systems. Countries with present-day high fossil fuel-based electricity production will have to gradually reduce their dependence, and they have the low tendency to fulfil SDG 7 by 2030. As a result, there is an urgent need for context-specific evidence that guides national pathways towards 100% renewable electricity systems considering current electricity access rates, fossil fuel and renewable shares in electricity systems, and population growth rates for each country or region[17].

In order to drive the transition to 100% renewable electricity systems that provide access for all, it is indispensable that different scientific disciplines and engineers cooperate, support local research and guide decision support and investments via scientific scenario analysis[18,19]. Sustainable renewable power plant and electricity system planning must build on good national practice and avoid previous management and planning mistakes[20,21]. It is further crucial to learn from the examples of environmental impacts of RE on other continents and avoid impairing infrastructure. As an example, Europe is spending millions to remove former hydroelectric and other dams to restore free-flowing rivers[22]. In African countries located within the Congo Basin, where (very) long free-flowing, biodiverse rivers associated with rich cultural traditions still remain[23], the costs of fragmenting infrastructure must be fully considered when planning renewable electricity sources. Increasing Africa's RE capacity sustainably includes manifold, site-specific solutions. Minimization of chronic plant failure[24,25], avoidance of harmful infrastructure[26], combinations of renewables via hybrid systems[27–29] and electricity sharing across boarders[30–32] are possibilities to ensure efficient and diversified RE systems to sustainably combat climate change and protect highly valuable ecosystems.

In this Perspective, we summarize past, current and future trends in the fast-growing RE development sector in Africa. We discuss trends and drivers that shape the debate on different renewable resource types, their impacts and electricity access strategies for all countries on the entire continent. We analyse national data on electricity access, population growth, and fossil fuel and renewable electricity shares to determine national starting points and future challenges related to a continental transition towards 100% renewable electricity systems. We further use georeferenced data on existing and proposed renewable power plants as an indicator to estimate the renewable capacity and electricity generation of each country or region. Using these site-specific data, we elaborate on potential alterations that might occur as renewable infrastructure tends to alter the system it derives electricity from. We discuss insights on the starting points and near-future prospects of a transition towards 100% renewable electricity for all Africa and what is needed to realize the Agenda 2063 vision to build "environmentally sustainable and climate resilient economies and communities"[33].

Past developments

Past development of electricity access and renewable power plant implementation determine the initial conditions from which African countries and jurisdictions start to align development and climate goals. These developments are often overlooked in global debates on the potential of Africa to directly transition to RE while bypassing fossil fuels, but such developments are crucial to provide context-relevant evidence for a clean energy future[17].

Development of electricity access in Africa

The status quo of energy systems and electricity per capita rates highly differs between countries, and in 2021, more than half of the population without electricity access lived in countries where an enabling policy environment is still at an early or middle stage[34,35]. Only three out of 54 countries have a higher electrification rate than the world average (Seychelles, Libya, South Africa; Supplementary Fig. 1). Concurrently, the three countries worldwide with the largest population lacking access are located in Africa: in 2020 Nigeria counted 66 million, the Democratic Republic of Congo 82 million and Ethiopia 59 million unserved people, which represents 35% of the worldwide population without access (584 million people without electricity access in 2020)[1,16] (Supplementary Fig. 2). Elsewhere, several countries including Ivory Coast, Ghana, Kenya, Rwanda and Senegal were able to reduce or stabilize the number of people without access between 2020 and 2021 despite the delays in making new connections owing to the COVID-19 pandemic[3]. Major disparities in access exist between urban and rural areas. Although the share of people with access is still higher in urban areas (83% versus 36% in rural areas), rural access rates improved faster than that in urban settings mainly owing to the development of mini-grid and off-grid systems[3,36,37].

Development of renewable energy in Africa

A total of 841 terawatt hours (TWh) of electricity is generated in Africa annually (census 2020), mainly by natural gas (41%), coal (29%) and hydropower (18%)[1]. Gas and oil (6% of total in Africa) dominate in north African countries, whereas coal is mainly exploited in South Africa. Nuclear (2% of total in Africa) and geothermal power (1% of total in Africa) have a minor role in the continental electricity generation mix.

To date, hydropower provides the greatest share of renewable electricity in African countries (63.8%, 2021)[4]. In Africa, the construction

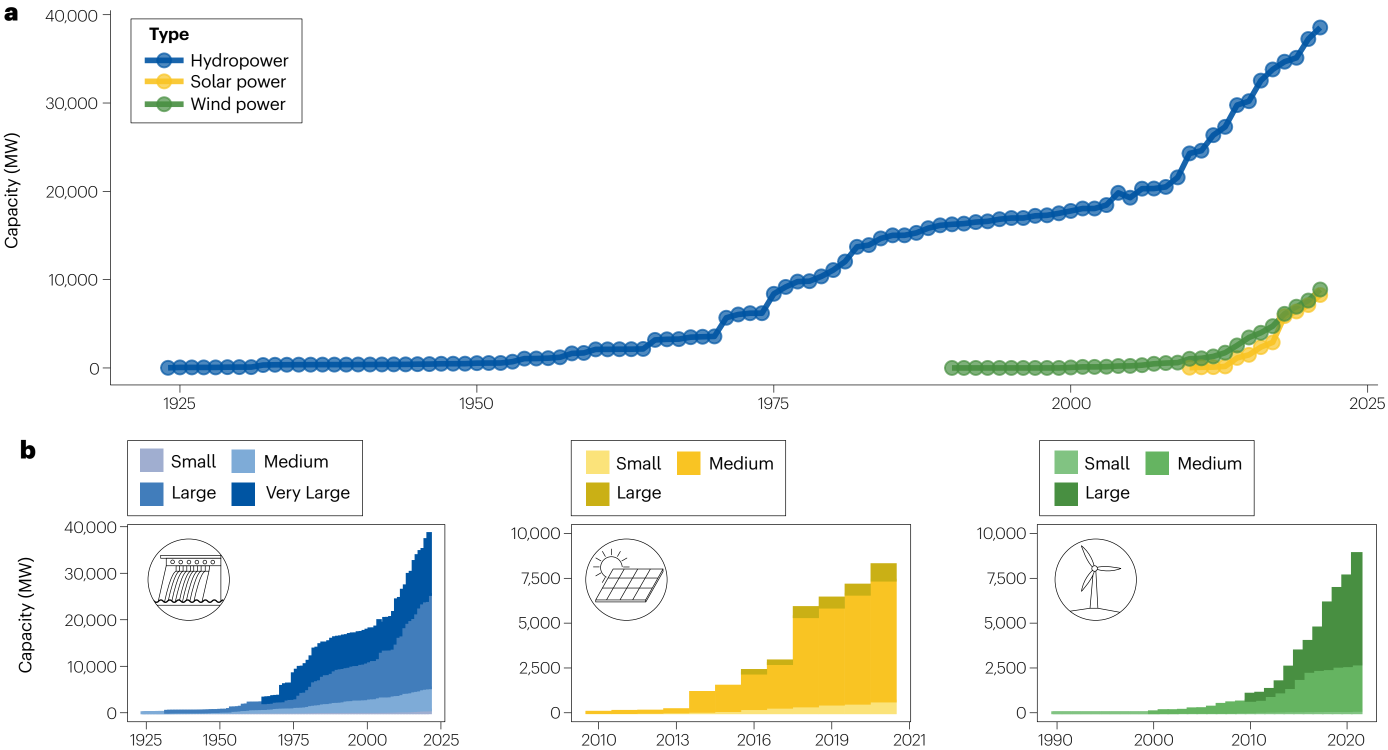


Fig. 1 | Development of renewable energy implementation in Africa. **a**, Annual cumulated installed capacity in megawatts (MW) for hydropower (blue), solar power (yellow) and wind power (green) plants from 1925 to present day. **b**, Composition of capacity for each renewable type (hydro, solar, wind) by plants of different size (small: 1 to 10 MW; medium: >10 to 100 MW; large: >100 to 1,000 MW; very large: >1,000 MW). Data source: Renewable Power Plant database for Africa (RePP Africa)[38]. Following the first hydropower boom in the 1970s, the global debate on the impacts of dams slowed its development in the 1980s, until the need for renewable electricity resources triggered a second hydropower boom in 2010 accompanied by increased implementation of wind and solar power plants.

of hydropower plants boomed until 1990, followed by consistent development until 2010 (ref. 38) (Fig. 1). Since the emergence of the first hydroelectric power plants, the construction of dams has been accompanied by a global debate on their negative impact on environment and society[39–41], which caused a stagnation of dam construction. However, the need for RE and the large hydropower potential fuelled a second boom from 2010 onwards[42] (Fig. 1). Hydropower has been the main RE of choice in Africa and worldwide because running costs are considered to be low and, for hydropower plants operating with reservoir storage, electricity production can be tailored on demand[43].

Since around 2010, falling prices and large technical resource potential have fuelled the emerging role of wind and solar power in the African renewable resource mix, with wind power (4% of total in Africa), solar photovoltaics (PV, 1% of total in Africa) and solar thermal power (<1% of total in Africa) experiencing ongoing increases in the continental electricity mix[44] (Fig. 1). However, the impact and potential also in combination with hydropower remain poorly quantified on a larger scale owing to a lack of openly accessible and spatially explicit plant data[29,44–46].

Despite falling prices for RE facilities, RE implementation is mainly hindered by high capital costs during the first project phase: once built, RE have low operational costs; but in contrast to fossil fuel plants, high political, legal and economic risks make RE plants particularly cost-intensive during the initial project phase[47]. In comparison to the global average, in which RE was mainly financed by the private sector (86%), most African countries are not able to attract private capital owing to these risks, and mainly public investments drive the RE development[48].

Between 2000 and 2019, the RE sector of Africa received 15% of the global public investment (US $64 billion), which is the lowest share in comparison to the RE sectors in other emerging economies, such as Latin America, the Caribbean and Asia. Large hydropower (>50 MW) received 78% of investment commitments in Africa, mainly from China (51%)[49,50]. Continental investments are distributed to the disadvantage of those who do not effectively attract private investors owing to fragile security conditions: whereas South Africa, Egypt, Nigeria, Morocco and Kenya receive more than half of the investment, the 33 least-developed countries in Africa with the globally greatest deficits in access to energy and electricity only received 37% of the globally committed investment for RE (2010–2019)[48]. Local investments become more important with African companies increasingly diversifying the economy and promoting a sustainable growth path[51].

The Continental Free Trade Area set out by the African Union aims to facilitate transnational investments by African companies. However, the Zimbabwean economist and general secretary of the Common Market for Eastern and Southern Africa Sindiso Ngweyna points out that the disparity between the treatment of foreign and national investors still inhibits local investment flows: investors carrying non-African passports can move easily and get better incentives than national or regional investors[51]. In order to attract and support local investment,

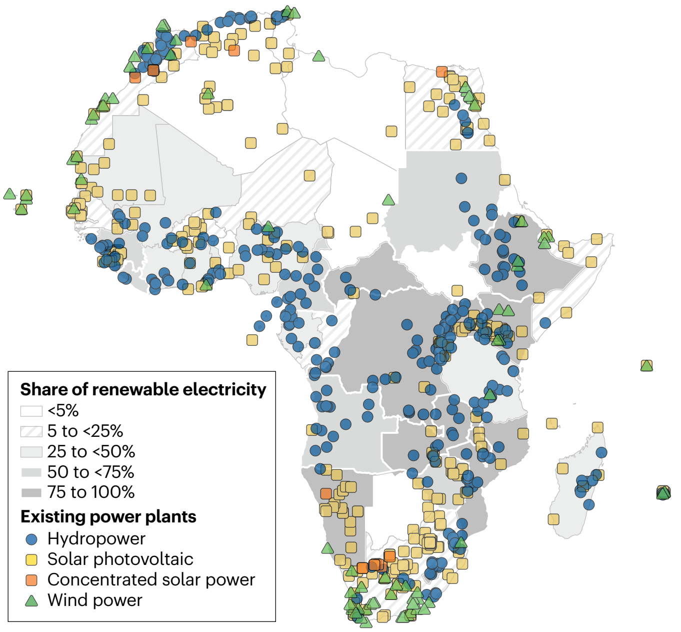


Fig. 2 | Existing renewable power plants and the share of renewable electricity generation. Polygons are coloured according to the share of renewable electricity for each country or region out of the total national or regional electricity generated in 2021. Symbols indicate existing power plants and power plants under construction, including hydropower (blue), solar photovoltaic power (yellow), concentrated solar power (orange) and wind power (green) plants. No plants are located on open water; all facilities not located on the mainland are located on islands. Data sources: Our World in Data[16] and RePP Africa[38]. The number of existing hydropower, solar power and wind power plants does not necessarily result in a high share of renewable electricity: regions in northern and southern Africa have a relatively large number of renewable power plants installed, but the high electricity demand and access rates result in an overall low share of renewable electricity.

national policies must continue to create an enabling environment that fosters intra-African investment.

Despite hydropower plants being still the most established RE technique in Africa and worldwide, a global debate on pros and cons of hydropower plants continues[39]. Particularly controversial are the negative impacts caused by hydropower plants operating with impoundment and dams because the created reservoir can result in short-term and long-term ecological, socioeconomic and political ramifications and irreversibly alter the natural flow, sediment and thermal regime of a river[26,39,40,52,53]. Less considered in this debate, but of equal importance, is that climate change[54–57], inadequate plant maintenance[25] and damage or (wanton) destruction of plants owing to wars (such as in Liberia during the civil war)[58] have in the past led to reduced plant output or failure of plants and lower hydropower electricity generation, a trend that also tends to affect future power plants and, thus, could reduce efficiency.

Current trends

Population size, population growth, access to electricity, share of renewables and current status of power plants and grid characterize the different starting conditions and future challenges each African country has to face on the path towards reliable and renewable electricity access for all. Conflicts of use and water–energy–food nexus problems emerge and need to be addressed and integrated in future pathways[59].

Access to electricity in Africa

Africa has more than sufficient energy resources to meet domestic electricity demands; however, almost half of its population does not have access to electricity[1,2]. To ensure the achievement of SDG 7, in Sub-Sahara alone, around 85 million people would need to be connected each year from 2020 to 2030 (ref. 42). Different countries face different challenges in order to achieve SDG 7. Among the most important factors determining the different starting points are current human population size, projected human population growth and current access to electricity (Supplementary Fig. 2).

The most populated countries – Nigeria, Democratic Republic of Congo and Ethiopia – still need to provide electricity access for 207 million people and these countries are predicted to (almost) double their population by 2050 (ref. 1). Central African Republic, South Sudan and Chad are the African countries with the highest proportional electricity access deficits; 95%, 93% and 94%, respectively, of the national population remains unserved in 2020. In other countries, major shares of the population have access, but owing to energy crises, electricity is rationed: in South Africa, 95% of the total population is connected, but parts of the national grid go offline for hours every day. An ageing fleet of coal plants that supplies 90% of the electricity of the country, too little short-term capacity in the pipeline, and cash scarcity of the power supplier Eskom led the country into a severe electricity crisis[60–62]. Zambia experienced enormous electricity failure and rationing because of a drop in hydropower generation brought on by drought[63]. These examples show that even countries with seemingly high access rates are affected by considerable electricity rationing. By contrast, most Global North countries with similarly high electricity access rates do not have to handle planned blackouts on an everyday basis.

Current energy systems in Africa

The current human population size, projected population growth and current access to electricity (Supplementary Fig. 2) determine the national starting points and future targets for the implementation of electricity access for all as envisioned by SDG 7. The current share of renewables, the current per capita electricity rate and the resource potential determine the national feasibility of a country to provide access to RE-based electricity systems (Fig. 2). In 2022, 401 hydropower, 411 solar power and 127 wind power plants are in existence or under construction with a combined installed capacity of 58.36 gigawatts (GW) hydropower, 10.56 GW solar power and 10.53 GW wind power (Fig. 2).

The total electricity generation from renewables in Africa in 2021 was 23% and differed significantly between countries (Fig. 2; mean: 40%, standard deviation: 35%)[16]. In 12 countries, the current renewable share in electricity is ≥75%; in most of these countries (such as Guinea, Central African Republic, the Democratic Republic of Congo, Zambia and Mozambique), electricity is mainly produced from hydropower. Eleven countries generate 5% or less of their electricity from renewable resources and are dependent on coal (for example, South Africa) or oil and gas (for example, Algeria, Libya and Egypt).

Although the nationally determined contributions outline that all African countries envision comprehensive clean and sustainable energy systems, research has since pointed out the high carbon lock-in risk for the continent, unless African countries and partners realize a large-scale cancellation of fossil fuel plants currently in the pipeline[64]. The overall demand for fossil fuels is also driven by exports: the invasion of Russia in Ukraine instigated an energy crisis in European countries and has increased the demand for African gas. However, following Agenda 2030 goals, development strategies that rely on natural gas production and exports are risky, as the world aims to transition to zero emissions and future gas demand is subject to large uncertainties. Jobs in the fossil fuel industry are not secure and employment is estimated to fall by around 75% by 2050 under a well below 2°C scenario[65].

At the same time, the continent holds the key ingredient to facilitate the global energy transition: 30% of all worldwide mineral reserves are located in Africa and include graphite, lithium, cobalt, copper, manganese and rare earth metals[66]; the production of these would need to increase by 500% if the worldwide investment in RE increases to levels required for a clean energy transition[67]. However, at the state level, national economies barely benefit from their mineral resources: value chains are generally outsourced and mineral ores are exported to foreign countries (such as China, North America and Europe) for further processing[68]. The international civil society must support the African civil society in its commitment to economic prospects and local value creation. A joint commitment can increase pressure on governments, international corporations and financial institutions to avoid exploitation and ensure fair benefit sharing. Host governments of foreign mining operations must create binding policy frameworks that attract investors but also maximize national benefits from foreign mining investment[69].

Some countries already have adopted policies that emphasize the need to attract investors to the mining sector, as, for example, in Rwanda[70,71]. Multidisciplinary approaches can provide the context-specific evidence that supports civil society and policymakers in their work. This context-specific evidence includes, for example, socioeconomic analyses on value chain dynamics in Africa[72] and research on the environmental impacts of mining as done for gold mines in Burkina Faso[73]. Bridging scientific disciplines and making research results openly available for policymakers is key to provide informed discussion support and shape a sustainable transition to 100% renewable electricity systems.

Although Africans still lack benefits from their mineral resources, several established sharing mechanisms increase continental co-benefits on renewable resource exploitation and electricity production. On a large regional scale, five established power pools enhance cross-border trade of electric power and create a cost-effective way of connecting excess capacity in one country or jurisdiction to demand in another (Box 1). On a smaller scale, multiple countries share transboundary renewable power plants. Whereas solar and wind power plants are normally not built at boarder locations, hydropower plants can sit in international rivers and operate with a transboundary dam, causing catchment-wide impacts. Transboundary tensions or conflicts can also arise if a hydropower plant located in one country causes flow regulation problems in a neighbouring downstream country or region[74]. In particular for hydropower plants, benefit-sharing arrangements are needed to positively impact an optimal outcome and diminish conflict between different riparian parties[31].

Future supply and demand

The potential for each African country or region to cover the future electricity demand of a growing population with renewables depends on the current reliance on fossil fuels and the number of renewable power plants in the pipeline. In particular, for low-income and middle-income countries, the need to provide electricity access to substantial portions of the population adds pressure on the renewable capacity expansion.

Shift from fossil fuels to RE

A transition to entirely RE systems requires not only the replacement of polluting fossil fuels for electricity generation but also a future in which the growing electricity demand is met with renewables[75]. A transition to hydropower, solar power and wind power systems would reduce global energy needs by 57%, energy costs by 61% and social (private, health, climate and environment) costs by 91% while avoiding blackouts, creating millions more jobs than lost and requiring little land[76]. However, for many countries that are highly dependent on fossil fuels, a RE transition implies that fossil fuels have to be eliminated on a large scale, including projects already at the planning stage[42]. Many countries are at risk of fossil fuel lock-in owing to the high number of fossil fuel power plants in pipeline and the investments announced worldwide to finance fossil fuel development[64,77].

Because many African economies rely on fossil fuel, a transition will create winners and losers. Justice consideration must be part of transition strategies incorporating the needs of affected communities[78]. For example, in Mpumalanga, a region in South Africa with an economy exclusively relying on coal, a just transition implies the empowerment of citizens and their communities to address risks and social disturbances created with a turn away from coal and to create enabling framework conditions for investments and economic diversification from which communities will benefit[79]. Pathways that can put fossil fuel-dependent countries on track for a RE transition should include long-term green-growth strategies and support schemes for business and workers in the fossil fuel industry[17].

The shift to RE-based systems is a particular multilevel challenge for upper-middle income countries that not only rely on fossil fuels but also have high electrification rates (highest sum of upper quartiles: Algeria, Botswana, Libya, Seychelles and South Africa). To overcome these challenges, countries outside Africa could consider phasing out of the import of fossil fuels from Africa while supporting the respective countries in finding feasible alternatives to earn revenue and simultaneously transit towards RE systems. The phase-out must include the cancellation of fossil fuel power plants proposed by foreign investors that are currently in the pipeline[64]. Open trade policies can further stimulate intracontinental and global investments in RE expansion[51,80].

By contrast, countries with low electricity generation (lowest quartile: Niger, Chad, Benin, Somalia, Burundi, Central African Republic, Guinea-Bissau, South Sudan, Djibouti, Togo, Rwanda, Burkina Faso and Madagascar) and/or few dependences on fossil fuels (lowest quartile: Lesotho, Central African Republic, Ethiopia, Democratic Republic of Congo, Namibia, Eswatini, Uganda, Kenya, Sierra Leone, Zambia, Malawi, Mozambique, Guinea and Burundi) could avoid a phase of fossil fuel dependency and aim for 100% renewable electricity systems by upscaling installed and implementing proposed renewable capacity. National policies must facilitate national and international investment in African RE development, whereas European and US Banks need to stop financing fossil fuel expansion. Twenty of the top 23 investors accounting for 50% of total investments in African fossil fuel extraction are headquartered in the USA and Europe, whereas only one is headquartered in the continent, in South Africa[77]. Expansion of RE systems can further provide decent work opportunities and career perspectives, in particular for young people: in Nigeria and Kenya, the expansion of decentralized RE systems increases the need for skilled local work staff and creates employment and capacity building in rural areas[81].

Finally, the global COVID-19 crisis and the invasion of Russia in Ukraine threaten to reverse the trend of cost decline since the 2010s for

Box 1

Renewable power plant operating types and energy distribution systems

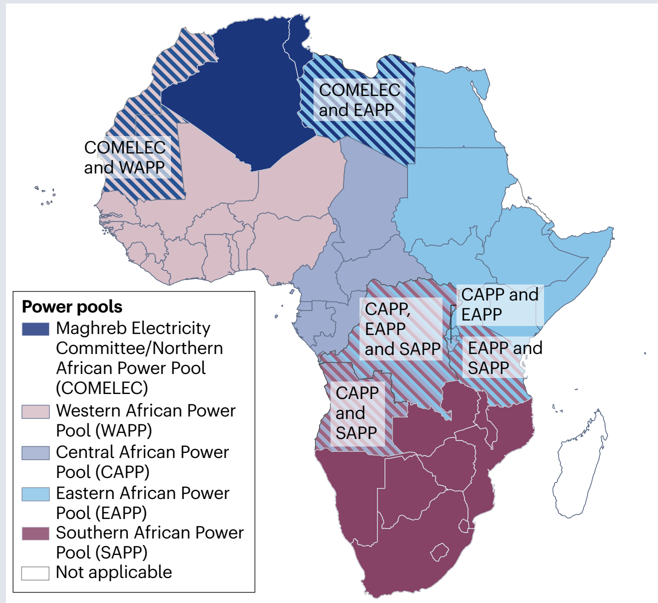
Hydropower, solar power and wind power plants are the main RE power plant types used for electricity production. Power from wind, the sun and water diversion is variable, especially in contrast to fossil fuel and controllable RE resources (such as impoundment hydroelectricity). Because these technologies are not dispatchable owing to their fluctuating nature, increasing the share of variable RE requires technological development and well-designed regulations for grid management and operation[175].

Hydropower. Three hydropower plant technology types can be distinguished: impoundment, diversion and pumped storage. Impoundment facilities are most common and use a dam to store river water in a reservoir. When water is released, it flows through a turbine and activates a generator to produce electricity. Impoundment facilities allow for flexible water release to meet changing electricity needs. Diversion or run-of-river facilities utilize the natural decline of the river bed elevation and channel a portion of a river through a canal and/or penstock; usually a small dam ensures that enough water enters the penstock pipes that lead to the turbines at a lower elevation. The water is then redirected to the main river flow. Reservoir storage is minimal. Pumped storage facilities operate with impoundment, but they use two reservoirs. In times of low electricity demand, water is pumped from a lower to an upper reservoir, and released back when electricity demand is high.

Solar power. PV and concentrating solar power (CSP) are the main solar power technology types. PV cells are utilized in solar panels and absorb the sunlight to transform it into electricity. CSP facilities use mirrors to concentrate sunlight into a central receiver. The concentrated sunlight heats a fluid, which transfers the thermal energy to a heat exchanger. The heat exchanger converts the thermal energy into steam, which can be used to drive a turbine and generate electricity. Concentrator photovoltaics (CPV) are a PV technology that uses curved mirrors to focus sunlight onto small multi-junction solar cells which reach far greater efficiencies than flat-plate PV cells.

Wind power. Wind farms harness kinetic energy from the wind using wind turbines. These turbines have rotor blades that spin when wind blows. The spinning blades are connected to a generator, which produces electricity. Onshore wind farms are located on land and feed on terrestrial air currents. Nearshore wind farms are sited on land less than 3 km from the coast. They harness both terrestrial and sea winds to produce energy. Offshore wind farms are built on open sea where the force of wind is greater at a lower altitude and more regular than on land.

Hybrid renewable power plants combine two or more technologies and can also include energy storage.



Regional power pools. Five collaborative initiatives have been established to manage and develop regional electricity networks, infrastructure and power generation resources across the African continent (see the figure). They are established to facilitate cross-border trade and create a cost-effective way of evacuating excess capacity between countries to offset peak demands: the Maghreb Electricity Committee or Northern African Power Pool (COMELEC), the Western African Power Pool (WAPP), the Central African Power Pool (CAPP), the Eastern African Power Pool (EAPP) and the Southern African Power Pool (SAPP).

minerals and metals that are essential for clean energy technologies[82]. In addition, new investments in fossil fuels are being made and new supply routes created for European countries to have alternative sources to Russian energy[83]. The UN COP 27 fell short on efforts to reduce emissions from fossil fuels, and African leaders argued that countries needed to exploit gas reservoirs to help generate universal electricity access, although African activists were claiming the opposite[84]. To facilitate a pan-African RE transition and reach climate goals, more finance needs to be unlocked and energy investments to be doubled to 2030 (ref. 3). To achieve universal electricity access in sub-Saharan Africa, US $30 billion is needed annually on top of the baseline investment (US $20 billion, +150%)[85]. Finance conditions for RE have strongly improved[86], but renewable technologies are still disadvantaged by the current financial practices in Africa[87]. For example, technological improvements alone will not suffice to make investment intensive CSP technology competitive. Policies for de-risking to risk levels set by the Organization for Economic Cooperation and Development are needed to assure that this RE technology is competitive throughout sub-Saharan Africa[88].

Proposed RE demand and supply

If all proposed plants were implemented, Africa would generate 1,225 TWh from renewable resources (hydropower, solar power and wind power)[38] (Fig. 3). The International Energy Agency projects for 2040 a continental electricity demand of 1,614 TWh (the Stated Policies Scenario) to 2,321 TWh (Africa case)[89]. The Stated Policies Scenario assesses the electricity demand by combining existing and announced policy frameworks with the ongoing evolution of known technologies. The African case scenario builds on Agenda 2063 and presents a pathway to attain inclusive and sustainable economic growth and development. Assuming that the existing plants operated at full capacity and all proposed plants were implemented, 76% (the Stated Policies Scenario) and 53% (Africa case) on average of the energy needs of Africa projected for 2040 would be met by RE. This gap outlines that the RE capacity currently in the pipeline is – even if it was fully implemented – far from being enough to achieve the goals of Agenda 2030 and 2063.

The two different scenarios of the International Energy Agency highlight that future electricity demand will be 44% higher if the RE transition "ensure[s] access to affordable, reliable, sustainable and modern energy for all" (SDG 7)[42] in order to build "environmentally sustainable and climate resilient economies and communities" (Agenda 2063)[33]. Nevertheless, there are national differences that need to be considered when addressing the narrative of a continent transitioning to 100% RE. Taking the number of existing and proposed RE power plants as an indicator of how African countries are concurrently positioned for a transition towards renewable electricity (Fig. 3), some countries have enough RE projects in the pipeline to perform a transition, whereas others are locked in fossil fuel dependency (Fig. 4).

Assuming the current national annual per capita electricity consumption[16] (kWh per capita and year), 29 African countries have already sufficient renewable capacity installed (2021) to meet the national electricity demand (±1,000 kWh), seven countries produce more than needed whereas 18 countries cannot meet the electricity demand with the national installed capacity from renewables (Fig. 4a, Supplementary Tables 1 and 2). Most of the latter are highly dependent on fossil fuels (Libya, Botswana, Algeria, South Africa, Egypt, Morocco, Senegal, Mauritius, Democratic Republic of Congo, Nigeria, Mauritania and Ghana; Fig. 2) and/or have high annual electricity consumption rates (above African average: Mozambique, Ghana, Democratic Republic of Congo, Botswana, Morocco, Tunisia, Algeria, Egypt, Mauritius, South Africa and Libya; Supplementary Fig. 1).

Of all countries which fell short in 2021, Nigeria, Zimbabwe and the Democratic Republic of Congo have enough RE capacity proposed to not only meet their own electricity demand by RE (considering the projected population number for 2050 (ref. 1)), but also produce a surplus (Fig. 4d, Supplementary Tables 1 and 2). Kenya can produce sufficient RE to meet domestic demand, whereas all other countries that are not capable to meet electricity demand with RE in 2021 will not have enough capacity proposed to change their status quo by 2050. Of the 29 countries that have enough RE capacity installed to theoretically meet their demand in 2021, only Burkina Faso and Mali fall short by 2050. Thirteen of these 29 countries can even produce a surplus if all proposed projects go online. All countries with surplus in 2021 have enough RE capacity proposed to also generate a surplus for their respective population projected for 2050.

The estimate of the potential of a country to supply its population with 100% electricity from renewable resources is sensitive to or contingent upon the actual implementation of proposed projects and, thus, not a proxy for the potential of countries for transitioning to 100% RE (Figs. 3 and 4). The underlying database provides the most consistent and curated dataset on the three renewable electricity sources in African countries so far[38]. Hence, the country-specific data (instead of continental estimates) allow for more realistic RE development scenarios based on actual projects. In addition, these calculations assume a constant electricity consumption in 2021 and 2050, which

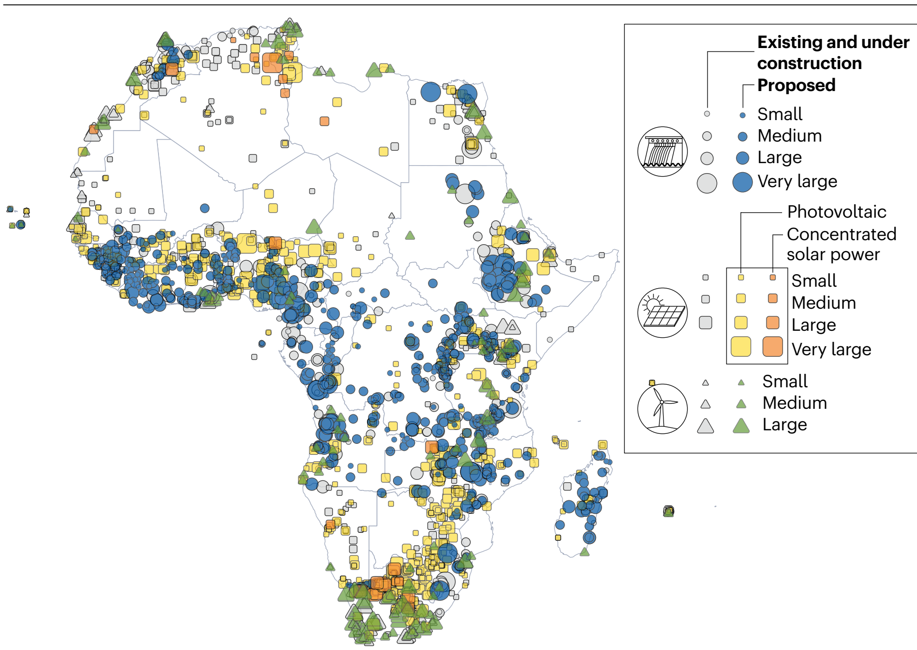


Fig. 3 | Existing and proposed renewable power plants by capacity size. Grey symbols indicate existing plants and those under construction. Proposed RE power plants are shown in coloured symbols, including hydropower (blue), solar photovoltaic power (yellow), concentrated solar power (orange) and wind power (green) plants from RePP Africa[38]. Symbol size increases with capacity (small: 1 to 10 megawatts (MW); medium: >10 to 100 MW; large: >100 to 1,000 MW; very large: >1,000 MW). The implementation of all the proposed renewable power plants would result in a 2.5-fold increase in the current installed capacity, with hydropower accounting for 68%, solar power for 23% and wind power for 10%. Figure adapted with permission from ref. 38 under a Creative Commons licence CC BY 4.0.

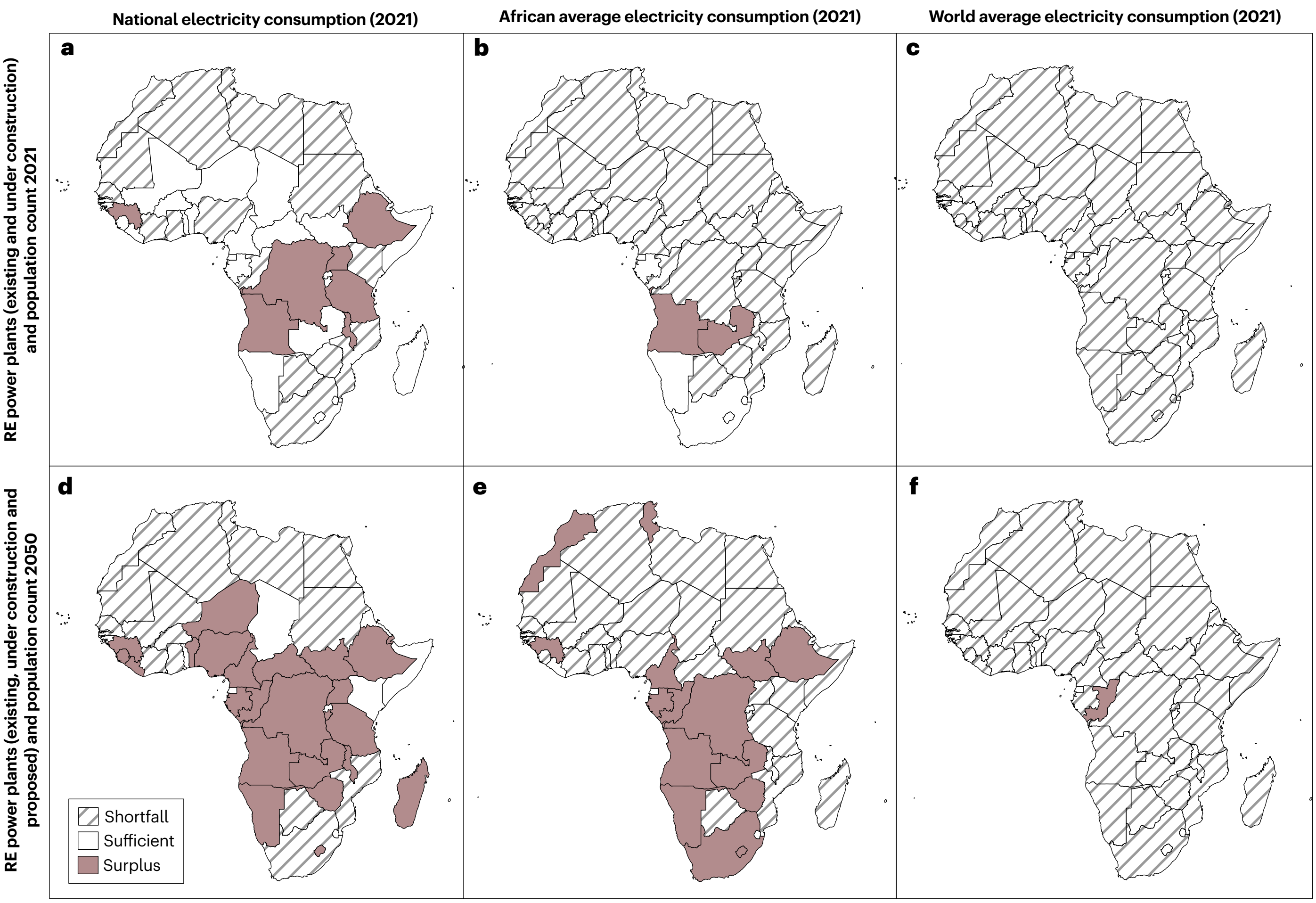


Fig. 4 | Coverage of current and projected electricity demand by renewable energy. a–c, The difference between national annual electricity demand and estimated electricity generation by existing and under-construction renewable power plants for 2021. **d–f**, Projected electricity demand based on the projected population by 2050 and electricity generation capacity estimated under the assumption that all existing, under-construction and proposed renewable power plants work at full capacity by 2050. Annual national electricity demand for 2021 (parts **a**–**c**) and for 2050 (parts **d**–**f**) was estimated considering national (parts **a**,**d**), African average (parts **b**,**e**) and world average annual per capita electricity consumption (parts **c**,**f**) and national population counts (2021, and projected for 2050). Electricity generation by hydropower, wind power and solar power plants was estimated based on available capacity data from RePP Africa for existing and under construction plants (scenarios 2021; parts **a**–**c**) and for existing, under-construction and proposed plants (scenarios 2050; parts **d**–**f**). For details on the calculations, please refer to Supplementary Note 1. The categories displayed with the shading are defined as follows: shortfall, >1,000 kWh (uncovered demand); sufficient, ±1,000 kWh; surplus, <−1,000 kWh. Sources of underlying data: UN[1], Our World in Data[16] and RePP Africa[38]. Population, electricity access and number of existing and proposed renewable power plants determine the potential of a country or jurisdiction to build electricity systems based entirely on renewables, whereas applying an African or world average access rate greatly diminishes the number of capable candidates for such a transition.

rather underestimates electricity consumption of most African countries, as they most probably experience substantial socioeconomic development.

If an African average annual per capita electricity consumption of 602 kWh (Figs. 4b,e, Supplementary Tables 1 and 2) or a world average of 3,513 kWh (Figs. 4c,f, Supplementary Tables 1 and 2) is assumed, the RE transformation potential reduces largely, manifesting the need for additional RE potential exploitation and innovation. Although the proposed renewable plants could still catch up with an African average per capita electricity consumption (Fig. 4d, Supplementary Tables 1 and 2), partly because of the large projected capacity to be installed (for example, the Democratic Republic of Congo has several very large hydropower plants announced, which would — if implemented and fully operational — exploit large amounts of the national hydropower potential of 3,942 MW (ref. 90)) and partly because of a national electricity consumption that is already above the African average, only few countries will be able to cope with a world average electricity demand by projected renewables. Fossil fuel-dependent countries in northern and southern Africa need to upscale their proposed RE capacity if they want to be capable to satisfy national electricity consumption with RE.

In any case, electricity consumption and demand determine the national transformation potential, for example, when aiming for renewable "energy for all" (SDG 7); it is essential to consider that more than half of all African countries have a domestic electricity consumption that is less than 10% of the global average (2021)[16]. Thus, the proposed RE capacity in Africa is huge, but at state level, not all countries are able to perform a transition to entirely RE-based electricity systems without innovation and further exploitation of available potential for solar and wind power and optimizing a RE mix (Figs. 3 and 4, Supplementary Tables 1 and 2).

A major challenge in the transition to exclusively RE supply systems originates in the main characteristic of hydropower, solar power and wind power: they rely on natural systems that undergo natural variations. These fluctuations mean that power generation is not as controllable as from fossil fuel power plants. Whereas hydropower plants operating with a reservoir have the capacity to cope with changing streamflow if adequately managed, solar and wind power plants completely rely on their variable resources driven by meteorological variations that cause sub-hourly to inter-annual changes[27,29].

Optimizing renewable energy systems

To assure a just RE transition with smart and sustainable power plant planning for the entire Africa, RE systems need to be optimized by minimizing RE plant failures and losses (from transmission), improving energy efficiency, minimizing negative ecological, socioeconomic and political impacts of RE facilities, and exploiting potential under consideration of climate change impacts.

Minimization of RE failures and losses

Failures and losses can negatively impact electricity generation from RE resources from a local individual power plant to an international power pool level. At the plant level, project delay, lack of maintenance and destruction caused by war, protests or other conflicts have reduced worldwide electricity generation in the past[25,91–93]. Sustainable renewable electricity relies on power plant operators that assure the availability of trained and qualified staff and guarantee financing materials and manpower for regular maintenance and technical upgrades. If renewable power plants are implemented and/or operated by foreign organizations, local and regional benefits and ownership should be the ultimate goal via strategies such as capacity building and local profit sharing[49,94].

Within power pools, electricity transmission losses are one of the major causes of the electricity access deficit; for example, 26% are lost on average from distribution companies within the West African Power Pool, which equals several tens of millions of dollars[95]. A major cause is fraud because centralized energy pools are more vulnerable to corruption than decentralized systems, which negatively impacts long-term power pool development[95]. Another reported reason for diminished electricity generation is the destruction of power plants by war. War has caused the destruction of transmission lines and substations in Libya[96] and the destruction of hydropower plants and other energy-related infrastructure in Liberia[97]. As an example, the Liberian Mount Coffee hydropower plant with 88 MW nominal capacity was destroyed during the first Liberian civil war in 1990 and was not recommissioned until 2016 (ref. 98). Further potential losses occur from a lack of or insufficient transboundary river basin management, as it implies a high risk of national and international conflicts[74] and violence[99], causing project delays[93] and missed opportunities[100].

If national politics, diplomacy and policy frameworks succeed to prevent conflicts by implementing peacebuilding and anti-corruption measures, and succeed to reduce the losses from these international African sharing systems, RE sharing has the potential to reduce national energy costs, shedding, infrastructure and need for land, and could create co-benefits for all participating countries[101]. Consequently, energy policy needs to acknowledge, analyse and learn from past failures in order to avoid multilevel generation losses and create an enabling environment[102,103].

Improving energy efficiency

As the African continent is facing an upsurge in energy consumption, improved energy efficiency is a key supplement to fuel a continental transition towards renewable electricity systems and keep modern energy affordable[76]. According to Gerrard, 'improved energy efficiency' means that less energy is consumed to produce the maximum economic output possible[104]. Whereas northern African countries have average efficiency levels of up to 94%, west African countries lag behind with average levels of only 49% or less[105]. Reliable electric grids have historically needed a minimum baseload, which is usually met by power plants that operate continuously to meet a minimum level of power demand[106]. Suitable resources are fossil fuels (coal and nuclear) or renewables (hydropower, geothermal heat, biomass and biogas)[107]. Solar and wind power are variable resources and can only store produced energy if storage capacity is provided, a challenge that needs to be addressed when aiming for a transition to exclusively renewable electricity systems.

Hybrid systems are economically feasible solutions[108–110] and will be entirely renewable if hydropower is used as a storage system[28,29,111]. As such, linking wind and solar power to the operation of the Grand Ethiopian Renaissance Dam (GERD) in eastern Africa could be an incentive to retain the seasonal flow regime of rivers and protect downstream riparian countries from GERD impacts, for example, on water supply for households and irrigation and on freshwater ecosystems, while maintaining grid stability[112]. One option to tackle the mismatch between varying renewable electricity supply and actual demand is hydropower plants that operate with pumped storage[113]. Further potential for improving RE plant efficiency is given by floating photovoltaics: even a low coverage of reservoirs by floating photovoltaics could generate all the solar energy needed to decarbonize the continent's electricity sector[114].

On a continental level, energy technology and material improvement will continue to reduce the continental electricity demand by 30% from the electricity demand today[3]. In addition, smart grid technologies will be able to match supply and demand in a more concerted and flexible way, making baseload power plants less relevant in the long term[115]. Transnational sharing and increased interconnection could further help mitigate negative climate impact on hydropower capacity production[116].

Minimizing negative impact of RE facilities

Power plant facilities can cause multiple ecological, social, economic and political ramifications. Integrated assessments are crucial to facilitate a sustainable long-term development of the renewable electricity sector[26,117,118]. Impacts of hydropower plants have been and are intensively studied, largely on a plant scale but also on a river catchment scale: dam construction and reservoir formation alter freshwater ecosystems and reduce water and sediment connectivity[119], truncate biogeochemical processes[120], and threaten biodiversity owing to habitat fragmentation, over-exploitation, pollution, species invasion and inhibited animal migration[121–123]. Dam-induced resettlement can cause conflicts with resettled people not sufficiently informed and compensated for the loss of their livelihoods[31,124–126]. Dam construction affects public health[127,128], and reservoir inundation can trigger earthquakes[129].

Wrong site selection and inadequate planning have repeatedly caused project cost overruns, which negatively impact national economy and political trust[93,130]. If hydropower is not part of an integrative planning that includes other land demands from the water–energy–food nexus, hydropower plant development can be inefficient and not sustainable[59,131]. Because approximately 60% of large rivers cross country or jurisdictional borders, geopolitical conflicts between countries or regions might emerge[32,74]; one prominent African example is the hydropolitical conflict surrounding GERD, which started with the upstream nation Ethiopia surprising the downstream countries Egypt and Sudan by publicly announcing the construction of GERD in 2011 without prior consultation[132].

International conflicts are easier to avoid for wind and solar power plants because of the resource characteristics of wind and sunlight: the area suitable for installing wind or solar power plant facilities is not restricted to rivers and in contrast to other electricity resources, simultaneous electricity generation and agricultural activities are possible, for example, farming or grazing animals under stand-alone solar systems or between wind turbines within one wind park[133–135]. Even though many hydropower plants have irrigation as a co-purpose and support agricultural activities in the surrounding landscape, the area inundated for reservoir creation remains lost for terrestrial ecosystems, human livelihoods and other purposes[136–138]. The latter is an important argument when promoting wind and solar power because even though the land use per unit of electricity source has decreased intensively for wind and solar since the early 2000s[139], it is still larger than that for hydropower, gas, and nuclear power (onshore wind: 99 m^2 (project) or 0.4 m^2 (turbine) per MWh; CSP: 22 m^2 per MWh; PV (on-ground, silicon): 19 m^2 per MWh; hydropower: 33 m^2 (small) to 14 m^2 per MWh (large); coal: 15 m^2 per MWh; gas: 1 m^2 per MWh; nuclear: 0.3 m^2 per MWh)[140].

Reported impacts of onshore wind power plants mainly include increased habitat loss and animal mortality in particular for bird and bat species[141–144], noise pollution[145] and perception of visual impact[146,147]. Impacts of solar power plants strongly depend on the operational type and vary with size between rooftop and stand-alone PV, CPV, CSP and floating PV[148]. It is reported that large solar facilities alter a landscape and impact visual perception, biodiversity and microclimate[142,149]. Impacts of floating PV on a reservoir increase with the area covered and can cause algal blooms and reduce oxygen production (through shading), but remain poorly studied[114]. Failure to adequately address the mentioned impacts can hinder the short-term and long-term sustainable development of RE projects: large solar power plants proposed on an arable land can cause conflicts owing to intensified competition for land[150]; in Lesotho, proposed wind farms threaten the declining populations of the regionally endangered bearded vulture and globally vulnerable cape vulture[151]; and a lack of transboundary cooperation between Egypt, Sudan and Ethiopia when managing new and existing hydropower plants risks water supply and energy generation for the riparian population[152]. By contrast, integrative planning can create water–energy–food nexus benefits. For example, over one-third of unmet crop water requirements in sub-Sahara Africa could be supplied with stand-alone solar PV irrigation systems[153].

Climate change impact on RE potential

Energy from renewable resources depends on natural systems, which are driven by climate. Freshwater, sunlight and wind availability vary on a daily to annual timescale. Plants producing power from these resources are affected by this variability. Whereas hydropower plants operating with impoundment are able to cope with changing freshwater availability, wind and solar power output is not perfectly controllable by a transmission system operator, making them variable energy resources (Box 1). As such, renewable power plants create complex interactions and dependencies between nature and anthropogenic infrastructure: plant facilities impact natural systems in their surroundings, but also climate change impacts plant performance[154,155]. Although there is scientific consent that climate change impacts long-term plant performance and electricity generation of renewable power plants, a regional high-resolution quantification of wind and solar power plant potential under climate change is still at an early stage[156–158].

Africa holds one of the largest remaining hydropower potentials globally[116,159], which will increase in central Africa under a climate change-induced increase in streamflow caused by enhanced precipitation[55]. However, countries outside of this region will suffer from diminished existing and potential hydropower capacity because these countries will be increasingly affected by drought[24,116,160]. Consequently, relying on developing hydropower greatly increases the risk of climate-related electricity disruptions for eastern and southern regions[161]. Potential for wind and solar power is large for much of the continent, with an estimated total deployment potential of 4.9 TW for solar PV (average capacity factor of 21.4%) and 3.4 TW for onshore wind (average capacity factor of 54.9%)[162–164], and will on average remain stable under climate change[157,165,166]. A technical potential of >99% for each wind and solar PV and 51% for hydropower will remain if all proposed plants and plants under construction are implemented[38,164,167] (Fig. 3). Thus, an increase of wind and solar in the renewable mix could compensate for hydropower capacity losses[116] and simultaneously pave the path towards 100% RE-based electricity systems and stabilize the sustainable exploitation of renewable resources in the long term.

Finally, a major challenge that African countries need to address when planning sustainable RE systems in times of climate change is that the climate change-induced demand for cooling will put increasing pressure on the overall energy demand[168]. The cooling demand is supposed to quadruple by the end of 2030, and energy efficiency will be key to tackle this challenge[3].

Summary and future perspectives

Achieving universal electricity access implies that RE is cost competitive and can be offered at affordable prices. Ongoing technological progress has led to continuous increase in plant efficiency and capacity factors, increasing cost competitiveness in particular for solar PV and wind onshore[169]. On a global scale, new solar and wind projects are continuously undercutting the cheapest and least sustainable existing coal-fired power plants, which makes new solar and wind projects more economically attractive for nations that already rely on coal and supports them in fulfilling their nationally determined contributions[169].

If all announced hydropower, solar power and wind power plants are implemented, fully operating and used for electricity, up to 76% of the electricity needs of Africa projected for 2040 could be met by RE alone[38,89] (Fig. 3). The total capacity of all currently projected projects adds up to only 45% of the 300 GW additional renewable capacity targeted by the African Renewable Energy Initiative Action Plan for 2020 to 2030 (ref. 170). Even if African countries implemented all of the currently announced renewable power plants, further renewable resource exploitation and technological innovation within the next decade would be necessary to reach the ambitious goals of creating "environmentally sustainable and climate resilient economies and communities" (Agenda 2063)[33] with "access to affordable, reliable, sustainable and modern energy for all" (SDG 7)[5] (Fig. 4).

Research can support the search for adequate pathways by modelling future scenarios. For example, a multi-scenario analysis of the African energy landscape, including the Shared Socioeconomic Pathways, the Representative Concentration Pathways, and median and very dry water availability scenarios, suggests that hardly any new hydropower will be economically feasible after 2030 owing to the projected increase in the frequency and extent of droughts and the economic competitiveness of wind and solar power[19]. To implement adequate scenario modelling, georeferenced and plant-specific data must be openly accessible, so that researchers are enabled to provide science-based

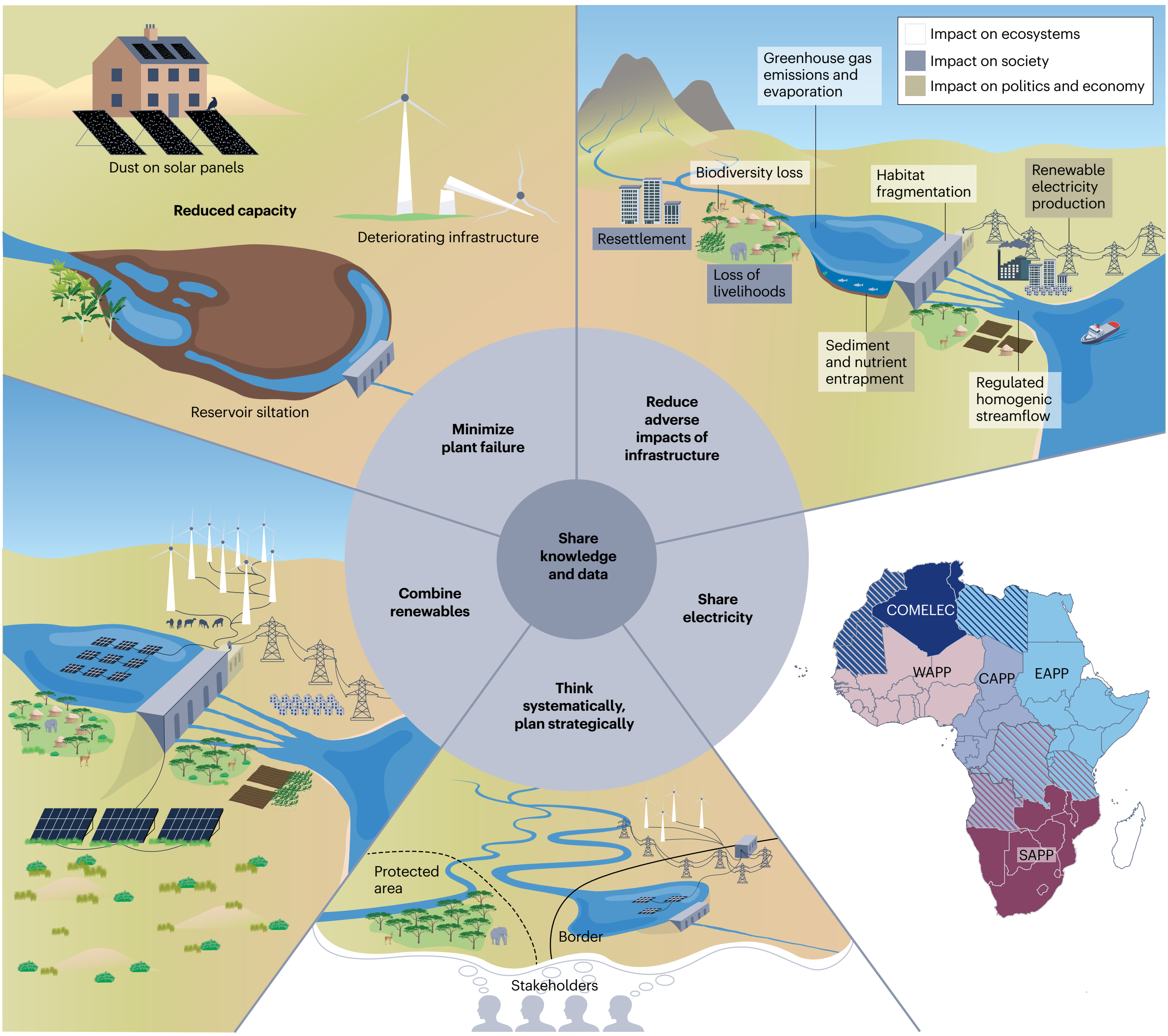


Fig. 5 | Optimization of renewable energy systems in long-term system-scale planning. Shared scientific knowledge and open data are key for strategic discussions that support the optimization and decision processes among stakeholders. Clear, context-shaped and sustainable future pathways need to integrate: (1) minimization of plant failure, for example, by improving maintenance of the existing infrastructure; (2) exploitation of the potential to combine different renewable technologies such as the operation of floating photovoltaics on a hydropower reservoir; (3) transparent and scientifically supported planning and discussion processes that bring all stakeholders together; (4) electricity and knowledge sharing across jurisdictional borders (such as within international power pools); and (5) the reduction of adverse impacts of renewable power plant infrastructure. Scientific knowledge and data are key to support evidence-based discussions on context-shaped pathways towards a sustainable renewable electricity access for all. CAPP, Central African Power Pool; COMELEC, Maghreb Electricity Committee or Northern African Power Pool; EAPP, Eastern African Power Pool; SAPP, Southern African Power Pool; WAPP, Western African Power Pool.

evidence for decision support. Building on up-to-date data, research must stop treating Africa as one entity and acknowledge different national starting points in terms of environmental, socioeconomic and political conditions[17,74]. National development status and electricity access, fossil fuel dependence, installed renewable capacity, potential for renewable capacity and the current political environment are further factors that determine the capacity of each country or region to implement a transition towards RE systems. Diverse and multidisciplinary research teams that integrate local knowledge and global learning will shape outputs that are needed to have broad impact and be locally accepted (Fig. 5).

To produce relevant and impactful research that can support the political discussion process, researchers have to integrate the following multilevel optimization processes to guide a science-based sustainable RE transition (Fig. 5): analysis on current power plant failure and transmission losses can help countries to identify where chronic plant failure currently reduces electricity output and how these losses can be eliminated; power plants need to operate efficiently, even under consideration of future climate developments; renewable hybrid options have the potential to support efficiency, but local and plant-specific data is lacking; research can support and realize integrated impact assessments for proposed power plants on larger scale to minimize negative ecological, socioeconomic and political impacts and include catchment-wide ramifications of hydropower plants. Wind and solar potential are far less exploited than hydropower.

Future research needs to further explore how a shift towards solar and wind power exploitation could reduce the dam-building pressure on African rivers (Fig. 5). To that point, models need to integrate local changes of climatic conditions as they impact renewable resource availability and power plant performance[155]. Also, a strategic planning of hydropower expansion can provide decision support when comparing the benefits of building dams against their socioenvironmental impacts[171]. Site-specific analyses of wind–solar complementarities in combination with existing hydropower as energy storage are crucial to reduce storage needs and land use. Hybrid plants and optimized resource exploitation will help to tackle the nexus problem of different parties claiming land for energy, water, agriculture or ecosystem protection (Fig. 5). Knowledge from existing research on how ecosystem integrity can be sustained while the potential for hydropower dams is increased could be applied to African rivers[172]. Investigations of diversified renewable energy systems and how a balanced renewable electricity mix can optimize performance started off in Ghana and points towards a path which future RE system research should explore in more detail[173].

To tackle the challenge of universal access, grid capacity and international connections need to be enhanced for urban areas whereas decentralized demand-driven off-grid and mini-grid solutions prove to be practical and cheaper for rural areas[94,174]. Centralized and decentralized energy system modelling for Africa has gained increasing attention but is always limited by the quality of available data, underlining the need for openly accessible datasets and critical model result interpretation. Openly accessible data must include existing and proposed renewable power plants that indicate the near-future implementation potential for each country or region, and data on renewable resource potential to determine the opportunities of each country for long-term renewable power plant planning. Furthermore, openly accessible and high-resolution data on electricity grids are crucial to compare centralized and decentralized connectivity options and forward the electricity access for all.

The transition to universal electricity access from sustainable RE resources promises potential gains in gross domestic product, employment, nationally determined contribution achievements, and human welfare[48]. Yet, to achieve SDG 7 (ref. 5), investments must more than double by the end of the century and multilateral development banks must make financial flows to Africa an absolute priority[3]. African countries have a lot of renewable power plants in the pipeline that form a solid foundation for a RE transition. Renewable power plant proposals open up opportunities for country-specific or region-specific research on optimal pathways to plan an efficient mix of renewable power plants. Local research will be key to inform and guide the implementation of enabling national and continental policy frameworks, which will then fuel investment and ensure national benefits. Integrating local research, policy frameworks and investment is crucial to guide a continental transition to efficient and equitable 100% RE-based electricity systems that consider future climate impacts and protect ecosystem functioning.

Data availability

Data on renewable power plants was used from the RePP Africa database, available at https://doi.org/10.6084/m9.figshare.c.6058565.v1.

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