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A Grid for all Seasons: Enhancing the Integration of Variable Solar and Wind Power in Electricity Systems Across Africa

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Abstract

Purpose of review This review paper assesses recent scientific findings around the integration of variable renewable electricity (VRE) sources, mostly solar PV and wind power, on power grids across Africa, in the context of expanding electricity access while ensuring low costs and reducing fossil fuel emissions.

Recent findings In this context, significant research attention has been given to increased cross-border transmission infrastructure between African countries to harness the spatiotemporal complementarities between renewable electricity resources, as well as to storage options, such as battery storage and power-to-gas.

Summary Much of the recent, model-based literature suggests that a combination of increased interconnections in and between Africa's power pools, leveraging spatiotemporal complementarities between solar PV, wind and hydropower, as well as a large-scale deployment of storage options could help African countries meet their burgeoning power demand with largely decarbonized electricity supply.

Keywords Variable renewables · Solar power · Wind power · Hydropower · Grid flexibility · Storage

Introduction

Worldwide, an unprecedented expansion of electricity supply using modern renewable electricity (RE) sources is underway. Most of this expansion is driven by solar photovoltaic (PV) and wind power [1], underscored by these technologies' rapidly declining costs [2, 3••] and a desire to decarbonize power supply in the context of the Paris Agreement [4]. Solar PV and wind power are characterized as variable renewable electricity (VRE) sources: driven by meteorology (e.g. irradiation, temperature, wind speed), they vary on all timescales from sub-hourly to interannual [5]. As the share of grid-connected VRE grows, power systems will have to adapt to the new reality of short, medium- and long-term weather-driven variabilities to ensure reliable power supply without endangering grid stability [6].

This has vastly different implications across the world. For instance, Europe and North America have benefitted for decades from large-scale, interconnected, adequate grids. Here, the main challenge now lies in integrating VRE into existing grid infrastructure, which will require a certain level of technological adaptation to increase grid flexibility [7]. On the other hand, developing regions with low levels of electricity access and rapidly growing power demand, such as sub-Saharan Africa [8, 9, 10•], face a different challenge altogether: growing VRE *while growing the grid* [11•, 12, 13], simultaneously responding to the dual challenge of currently inadequate electricity access and the need to decarbonize electricity supply.

As such, many developing countries are "greenfields" for developing power systems with high VRE shares, and their power systems planning will need to focus on VRE integration from the outset—which could be an opportunity that Europe and North America never had. In this context,

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this review paper assesses recent findings on modelling the energy transition at various scales in Africa, with a focus on the specific recommendations for increasing flexibility and VRE shares in Africa's burgeoning power systems. The focus here lies on technical challenges and solutions available to African countries to successfully achieve high shares of VRE in the electricity mix. While there are undoubtedly a multitude of non-technical (e.g. political, financial) challenges to successful VRE deployment as well [14••], these fall outside the scope of this paper.

Getting VRE on the grid

The spatiotemporal variability of VRE sources will require increased grid flexibility to safeguard the supply–demand balance. It is generally helpful to break down the different flexibility measures into three categories: generation-driven, storage-driven and demand-driven [6, 15, 16], as indicated schematically in Fig. 1 where several prime examples of each category are provided. In the following, each of these categories and examples will be discussed in the context of VRE integration on the African continent. The focus will be on generation-driven flexibility, but attention will be given to storage-driven and demand-driven approaches as well.

Generation-driven flexibility

Flexibility to meet peak demands is currently mostly provided by natural gas and, where available, hydropower plants; in the future, concentrated solar power (CSP) with thermal storage, as well as biomass plants, could also play an important role. Logically, the flexibility of existing and planned gas, hydropower, CSP and biomass plants in Africa thus constitutes an obvious case to support VRE uptake.

Both natural gas reserves and hydropower potential in Africa are spatially very unevenly divided. While many countries make substantial use of domestic natural gas in their electricity mixes (e.g. Nigeria), other countries need to import natural gas from abroad (e.g. Benin) [18, 19]. As far as hydropower is concerned, some countries already today have large enough hydropower fleets to potentially support a massive uptake of VRE (e.g. Ghana, Ethiopia) [20, 21•], but others have either yet to substantially exploit their hydropower potential (e.g. Burundi, Central African Republic, South Sudan), or do not have potential to speak of [22].

For this reason, discussions on natural gas- and hydropower-driven flexibility for VRE uptake in Africa are often strongly linked to plans on cross-border transmission infrastructure and regional integration of power systems [11•, 18], especially for hydropower. For example, in the same way that Norway's hydropower provides much-needed flexibility to continental Europe's power system [23], there are several countries across Africa that could find themselves in comparable positions in a VRE-rich future, including Guinea in West Africa [11•, 18] and Ethiopia in East Africa [21•, 24, 25]. In this context, it is important to note that various older hydropower plants in Africa may need refurbishment to be able to provide better flexibility services to aid VRE integration in the future [26, 27].

Given that natural gas is an important emitter of carbon dioxide, it will eventually have to be phased out along with other fossil fuels to retain chances of meeting the long-term temperature goals of the Paris Agreement [4]. While natural

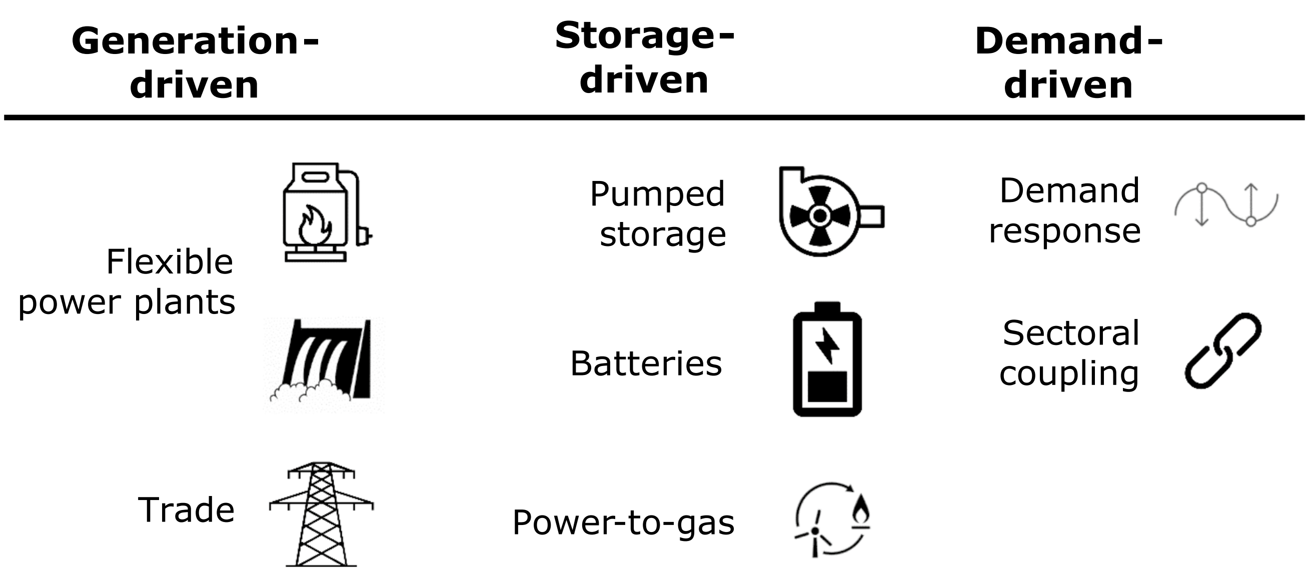

Fig. 1 Various categories of flexibility and prime examples of flexibility measures in each of these categories to enhance VRE penetration. Inspired by ref [17].

gas can therefore help in the near-term to support increased VRE penetration, especially for important natural gas producers like Nigeria (and its neighbours) [18], it cannot be considered a solution in the very long term, and significant expansion of natural gas to increase VRE penetration would be partially defeating the purpose of VRE. Therefore, in the context of generation-driven flexibility, it is desirable that where available, hydropower (provided that it meets environmental sustainability requirements) [28], CSP, and biomass, contribute strongly to generation-driven flexibility in the years to come.

The buildout of power pools across Africa would not only add value for hydro-rich countries seeking to export electricity to hydro-poor ones. In fact, significant spatial synergies exist in Africa between hydropower on the one hand and VRE on the other. Water-rich, rainy regions tend to have relatively low irradiation and wind speeds as compared to drier regions; the latter therefore have stronger (and thus cheaper) solar PV and wind power generation potential. Such spatial complementarities have been shown to exist between country pairs both across West Africa (e.g. Guinea and Senegal or Ghana and Burkina Faso) [11•, 18], East Africa (e.g. Ethiopia and Sudan) [21•, 24, 25, 29•] and Southern Africa (e.g. Zambia/Zimbabwe and South Africa) [30]. Reinforced grid interconnections may thus add value to VRE resources from hydro-poor countries by allowing them to complement hydropower from wetter regions [11•, 21•].

Some studies have even suggested that a smart deployment of VRE on interconnected regional grids may help reduce future investment needs for additional hydropower in water-rich countries, thus lowering sustainability concerns around environmental impacts of hydropower plants [11•, 31, 32•, 33, 34] as well as lessening competition for water resources amidst the water-energy nexus [35]. This is an important finding given the various barriers and controversies that surround the potential development of some of Africa's major unexploited hydropower resources, such as population displacement, disputed water rights, cost overruns and long lead times [34]. In the same vein, a diversification towards more VRE to reduce hydropower-dependency may reduce future power system shocks related to the impact of climate change on water resources [33, 36].

Next to hydropower's flexibility of dispatch to support VRE on (sub-)hourly timescales, hydropower and VRE exhibit pronounced seasonal synergies in many regions in Africa, with VRE tending to be highest during the dry season(s). For instance, such synergies have been documented for West Africa [11•, 37•], North-East Africa [21•] and South Africa [30]. In the context of regionally integrated power systems, this marks a strong case for seasonal patterns in imports and exports between countries to achieve more cost-favourable systems overall. These may even change prevailing patterns of trade between countries, with current importers of electricity potentially becoming strong exporters in the future [11•, 25, 37•, 38]. An example is Niger, which is currently importing most of its electricity from Nigeria, but could leverage its strong solar PV and wind resources to become a net exporter of electricity in the future [11•, 37•].

It has further been suggested that synergetic operation of hydropower with VRE may re-introduce natural seasonalities in the outflow of large, multi-year storage reservoirs, due to the increased need to dispatch hydropower during the low-VRE (i.e. rainy) seasons, which would have positive ramifications for river ecology [28]. A recent study suggested this concept as a potential way to mitigate an ongoing political conflict between Ethiopia, Sudan and Egypt on the Grand Ethiopian Renaissance Dam, while at the same time providing an opportunity to support enhanced VRE uptake across the region, including in other neighbouring countries such as Djibouti and South Sudan [21•].

In all the above contexts, much research attention has been given to five separate so-called "African Power Pools" (West, Eastern, Central, Southern and North) and their potential for achieving lower-cost electricity generation and lower emissions. Most covered in scientific and gray literature appear to be the West African Power Pool (WAPP) [10•, 11•, 18, 31, 37•, 38, 39] and the Eastern Africa Power Pool (EAPP) [21•, 25, 29•, 32•, 40], followed by the Southern Africa Power Pool (SAPP) [29•, 30, 41]. All of these cover a wide range of climate zones, ranging from wet and orographic highlands to dry, sunny and often windy flatlands, and could thus harness substantial hydro-solar-wind synergies leveraged by increased interconnections between countries dominated by different climates.

On the other hand, literature on the Central African Power Pool (CAPP) is relatively scarce. The available material mostly paints a picture of a region to remain dominated by hydropower in the foreseeable future [8, 42]. The latter is not unsurprising given that it is climatologically the most homogeneous of the African power pools, with most of its members being typical "hydrocountries", like DR Congo, Gabon, and Cameroon. However, it has also been suggested that the CAPP could become a substantial feeder to the SAPP whose electricity demand is much higher, mostly because of South Africa, currently Africa's second largest electricity consumer after Egypt [43].

Lastly, the North African Power Pool (NAPP) is an extreme at the other end: its hydropower potential is very low, and where it exists, it has largely already been exploited. Here, it is rather the potential for dispatchable Concentrated Solar Power (CSP) with thermal storage that is promising, thanks to extremely favourable direct normal irradiation (DNI) levels, with Morocco showcasing this in several large-scale projects. For this reason, CSP with thermal storage has been suggested as a strong candidate for investment to help support solar PV uptake in North Africa's future [44–46]. North Africa may also benefit from improved interconnections to the European mainland for electricity imports and exports [45, 47].

Such options related to electricity trade are not available for the various island states that are considered part of Africa. While a large island state like Madagascar could likely still make good use of spatiotemporal hydro-solar-wind complementarity by expanding power grids within its borders [48], small African island states (Comoros, Seychelles, Mauritius, São Tomé and Príncipe and Cabo Verde) will largely require other solutions to integrate VRE in their power mix [49, 50], such as storage technologies.

Notably, next to existing and future hydropower, planned biomass plants may also play important roles in flexibility provision in the future [37•]. Some countries with relatively high (unexploited) biomass potential, like Côte d'Ivoire, even foresee a more important role in the power mix for biomass (agricultural residues and wastes) than for solar PV by 2030, where it would be the third-largest contributor to the mix behind natural gas and hydropower according to current policy [51]—despite the much stronger expected cost reductions of solar PV [2]. Overall, however, the potential for biomass power generation in Africa is estimated to be substantially below that of hydro and VRE [52, 53], and it is thus likely to play more of a complementary role rather than a dominant one.

In the context of renewable resource complementarities in Africa, the somewhat less obvious ones should not be forgotten. For instance, despite their inherent lack of flexibility, solar PV and wind can mutually support each other thanks to temporal complementarities e.g. on diurnal scales [54]. Furthermore, next to its general flexibility of dispatch, biomass-based power may exhibit seasonal synergies with run-of-river hydropower in cases where the main cropping season falls outside the rainy season [24]. Geothermal power, on the other hand, for which the potential is mostly concentrated in African Rift countries (i.e. in the Eastern African Power Pool), may be more likely to be used for providing baseload power, contributing relatively little to flexibility [24].

Storage-driven flexibility

Generation-driven flexibility cannot support VRE indefinitely, primarily because natural gas plants are not compatible with the Paris Agreement, hydropower potential has clear upper limits, and biomass plants depend on agricultural output which is a seasonally limited resource. Thus, it will be of imperative importance that storage technologies are deployed at large scale across Africa to assist in VRE integration.

Worldwide, the most-used storage technology of the present-day is pumped-storage hydropower [55]. However, in Africa, only South Africa and Morocco have made use of this technology to date [56, 57] and current policy plans do not suggest that this is about to change, despite available potential [58]. In particular, pumped-storage hydropower may hold promise for small island states which cannot benefit from regional interconnections, such as Cabo Verde [59] and Mauritius [60], which both have pronounced orography (permitting high-head pumped-storage schemes) and high solar PV and wind power potential.

Thanks to the recent, unprecedented decreases in costs of battery storage [61], it appears more and more likely that a large-scale deployment of battery storage solutions to complement solar PV and, to a lesser extent, wind power generation, may play a substantial role in Africa's energy future. Recent studies on the West African [37•] and North African regions [62•] and on South Africa [63•], as well as on sub-Saharan Africa as a whole [3••], have suggested solar PV-plus-batteries as the most attractive future backbone of power systems on the basis of least-cost optimization—allowing to lower costs and CO_2 emissions while increasing employment opportunities (as compared to business-as-usual pathways without strong drives to increase VRE penetration).

Although the grid-scale battery storage sector is nascent on a worldwide scale and the above-cited studies remain projections for the time being, first steps are already being taken on the African continent. South Africa appears to be a frontrunner as of 2021, with its utility having issued a request for bids in 2020 for a large-scale storage facility to complement a local wind farm and provide ancillary services [64]. In coal-dependent and relatively hydro-poor South Africa, such projects are likely to be considerable assets for increasing VRE penetration while reducing the reliance on fossil fuels [63•].

Battery storage will, by nature, mostly be a lever to reduce intra-daily variability of electricity supply. For seasonal storage, it has been suggested that power-to-gas technologies could play important roles—not only for the power sector, but also to increase sectoral coupling and aid the decarbonization of e.g. industry [37•, 62•]. The relative importance of storage technologies will be strongly contingent upon the region [3••]. For instance, regions with substantial reservoir hydropower schemes (like West and East Africa) may leverage this to provide seasonal balancing and thus reduce the future need for power-to-gas technology [37•], which will not be the case for North Africa [62•].

Last, Concentrated Solar Power (CSP) with thermal (molten salt-based) storage has been successfully implemented in Morocco and South Africa. Further expansions of CSP capacity could further support VRE uptake in the years to come, potentially through explicit tendering of hybrid CSP/PV plants [46]. Such projects will be most attractive in the geographical regions benefitting from the highest DNI levels, e.g. North Africa and Southwest Africa [65].

Demand-driven flexibility

In addition to generation-driven and storage-driven flexibility measures, various levers for increasing VRE penetration while safeguarding a balanced power mix are to be found on the demand-side. Clearly, demand response measures within the power sector to shift loads to better match VRE infeed could be helpful; however, with electricity demands still strongly on the rise across Africa [8] and electricity access lagging behind [66], this is clearly not yet of prime concern and literature on the topic is scarce. What appears much more pressing at the moment in terms of demand is the need to reduce losses in transmission and distribution [67], such that unnecessary demand growth related to these losses can be tempered.

Looking at demand-side flexibility from a broader perspective, the topic of sectoral coupling could mark a strong case for supporting VRE penetration in the longer-term future. Various studies on cost-optimised power systems in Africa [37•, 62•, 63•, 68, 69] showed that sectoral coupling can lead to more cost-effective systems overall, across diverse regions of the continent with different resources and storage needs. For instance, power-to-gas technologies can contribute to sectoral coupling of electricity and non-electricity sectors across Africa if the produced gas is consumed in the industrial sector, instead of being used within the electricity sector as storage option [3••].

Conclusions and the way forward

The African continent has a unique opportunity to plan its future electricity (and energy) systems from the outset with a high VRE penetration as one of the targets. Many African countries are practically “greenfields” for VRE deployment, where even comparatively small capacity additions of VRE could have important ramifications for power system operation. It is therefore of high importance that all currently available technologies (notably flexible hydropower and gas plants, as well as interconnections and power pooling) are used to support an initial push for increased VRE penetration. At the same time, research and development efforts to further the prospects for near-term deployment of battery and other storage technologies, and those for longer-term demand response and sectoral coupling approaches, will be indispensable in going beyond what generation-driven flexibility can provide in terms of VRE support.

Various studies have shown that increasing VRE penetration across Africa could be cost-competitive as compared to continued fossil fuel- and hydro-dominance, and carry various climate and other environmental benefits, thus helping to achieve the goals of the Paris Agreement. Recently, however, the carbon lock-in risks for Africa have been estimated as high, with the share of non-hydro renewables projected to remain below 10% by 2030 unless a rapid shift to modern VRE and other renewable resources is undertaken [14••]. It is therefore urgent that all solutions mentioned above are leveraged to the extent possible to facilitate the transition to low-carbon electricity supply across Africa, while at the same time growing power grids and increasing electricity supply to larger shares of the population.

Next to the technological and economical aspects, governmental support for VRE will be imperative if such a transition is to succeed. This support can come in various forms; examples include explicit policy support for renewables [67], the creation of dedicated governmental agencies for renewables [70, 71], and training and capacity building of national stakeholders in all matters concerning long-term power systems planning with high VRE shares [16, 72].

In this context, the author of this review paper has recently been involved in the planning and organization of capacity building workshops on power system modelling with high VRE penetration with energy sector stakeholders in various African countries, including Côte d’Ivoire, Gabon, Niger, Mali and Cameroon. The objective of these workshops has been to support these countries’ revisions of their Nationally Determined Contributions (NDCs) in the run-up to the COP26 in Glasgow. In the author’s view, national VRE strategies and targets, as communicated e.g. in power sector masterplans and NDCs, can be prime opportunities for countries to showcase their desire to enhance VRE integration on a worldwide stage. Such visibility, in turn, may act as a catalyst for enhanced research efforts to chart pathways appropriate for each country’s specific circumstances to attain power sector decarbonization — something which today is still lacking, with many studies having an important region-wide focus but falling short of providing tailored advice for policymakers in individual countries.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflicts of interest.

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References

Papers of particular interest, published recently, have been highlighted as:
• Of importance
•• Of major importance

1. IRENA. Renewable Capacity Statistics 2020. 2020. https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Mar/IRENA_RE_Capacity_Statistics_2020.pdf. Accessed 26 Mar 2021.
2. IRENA. Renewable Power Generation Costs in 2019. 2020. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf. Accessed 26 Mar 2021.
3.•• Barasa M, Bogdanov D, Oyewo AS, Breyer C. A cost optimal resolution for Sub-Saharan Africa powered by 100% renewables in 2030. Renew Sustain Energy Rev. 2018;92:440–57. **Based on least-cost optimisation modelling, this study finds that massively expanded VRE, coupled with battery storage and power-to-gas, supplemented by flexible hydropower and biomass, could cover all of sub-Saharan Africa's electricity demand at low cost by 2030**.
4. Kuramochi T, Höhne N, Schaeffer M, et al. Ten key short-term sectoral benchmarks to limit warming to 1.5°C. Clim Policy. 2018;18:287–305.
5. Engeland K, Borga M, Creutin JD, François B, Ramos MH, Vidal JP. Space-time variability of climate variables and intermittent renewable electricity production — a review. Renew Sustain Energy Rev. 2017;79:600–17.
6. IRENA. Innovation landscape for a renewable-powered future: solutions to integrate variable renewables. 2019. https://www.irena.org/publications/2019/Feb/Innovation-landscape-for-a-renewable-powered-future. Accessed 26 Mar 2021.
7. Mathiesen BV, Lund H, Connolly D, et al. Smart energy systems for coherent 100% renewable energy and transport solutions. Appl Energy. 2015;145:139–54.
8. Ouedraogo NS. Modeling sustainable long-term electricity supply-demand in Africa. Appl Energy. 2017;190:1047–67.
9. Schwerhoff G, Sy M. Developing Africa's energy mix. Clim Policy. 2019;19:108–24.
10.• IRENA. Planning and prospects for renewable power: West Africa. 2018. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Nov/IRENA_Planning_West_Africa_2018.pdf. Accessed 26 Mar 2021. **This report shows scenarios for VRE expansion across all ECOWAS countries based on least-cost optimisation modelling, showcasing the high attractivity of increased solar PV deployment across all countries, supplemented by wind power and hydropower, and the leveraging power of improved interconnections to achieve lower emissions by 2030**.
11.• Sterl S, Vanderkelen I, Chawanda CJ, Russo D, Brecha RJ, van Griensven A, Van Lipzig NPM, Thiery W. Smart renewable electricity portfolios in West Africa. Nat Sustain. 2020;3:710–9. **Based on spatiotemporal modelling of solar PV, wind and hydropower across West Africa, this study finds that existing and planned hydropower could hold substantial potential to support VRE grid integration across the West African Power Pool, reducing countries' hydro-dependency and lowering the overall need for new hydropower plants**.
12. Lee JT, Callaway DS. The cost of reliability in decentralized solar power systems in sub-Saharan Africa. Nat Energy. 2018;3:960–8.
13. Russo D, Miketa A. Benefits, challenges, and analytical approaches to scaling up renewables through regional planning and coordination of power systems in Africa. Curr Sustain Energy Rep. 2019;6:5–12.
14.•• Alova G, Trotter PA, Money A. A machine-learning approach to predicting Africa's electricity mix based on planned power plants and their chances of success. Nat Energy. 2021;6:158–66. **This study finds that Africa's electricity mix is unlikely to be constituted of more than 10% VRE by 2030 under current policy, suggesting a high risk of carbon lock-in unless immediate action is undertaken to strengthen the position of renewables vis-à-vis fossil fuels and cancel fossil fuel plants in the pipeline**.
15. IRENA. Power system flexibility for the energy transition, part 1: Overview for policy makers. 2018. https://irena.org/publications/2018/Nov/Power-system-flexibility-for-the-energy-transition. Accessed 26 Mar 2021.
16. IRENA. Planning for the renewable future: long-term modelling and tools to expand variable renewable power in emerging economies. 2017. https://www.irena.org/publications/2017/Jan/Planning-for-the-renewable-future-Long-term-modelling-and-tools-to-expand-variable-renewable-power. Accessed 26 Mar 2021.
17. NREL. Sources of operational flexibility. 2015. https://www.nrel.gov/docs/fy15osti/63039.pdf. Accessed 26 Mar 2021.
18. Tractebel Engineering. Update of the ECOWAS revised master plan for the development of power generation and transmission of electrical energy. 2018. http://www.ecowapp.org/sites/default/files/volume_4.pdf. Accessed 26 Mar 2021.
19. IEA. Energy Statistics and Balances. 2020. https://www.iea.org/subscribe-to-data-services/world-energy-balances-and-statistics. Accessed 26 Mar 2021.
20 Danso DK, François B, Hingray B, Diedhiou A. Assessing hydropower flexibility for integrating solar and wind energy in West Africa using dynamic programming and sensitivity analysis. Illustration with the Akosombo reservoir Ghana. J Clean Prod. 2021;287:125559.
21.• Sterl S, Fadly D, Liersch S, Koch H, Thiery W. Linking solar and wind power in eastern Africa with operation of the Grand Ethiopian Renaissance Dam. Nat Energy. 2021;6:407–18. **This study finds that coupling the operation of Ethiopia's controversial Grand Renaissance Dam (GERD) to VRE in Ethiopia, Sudan and other Eastern African Power Pool countries could mitigate several of Sudan's and Egypt's concerns around GERD while reducing hydro-dependency, electricity generation costs, ecological concerns and fossil fuel use**.
22. Sterl S, Devillers A, Chawanda CJ, van Griensven A, Thiery W, Russo D. A spatiotemporal atlas of hydropower in Africa for energy modelling purposes [version 1; peer review: 1 approved]. Open Res Eur. 2021;1:29.
23. Farahmand H, Jaehnert S, Aigner T, Huertas-Hernando D. Nordic hydropower flexibility and transmission expansion to support

integration of North European wind power. Wind Energy. 2015;18:1075–103.
24. ENEL & RES4Africa. Integration of Variable Renewable Energy in the National Electric System of Ethiopia. 2019. https://www.res4africa.org/wp-content/uploads/2019/02/Abstract-Integration-Study-Ethiopia.pdf. Accessed 26 Mar 2021.
25. Remy T, Chattopadhyay D. Promoting better economics, renewables and CO2 reduction through trade: a case study for the Eastern Africa Power Pool. Energy Sustain Dev. 2020;57:81–97.
26. Killingtveit Å. Hydropower. In: Letcher T, editor. Managing Global Warming - An Interface of Technology and Human Issues. Cambridge: Academic Press; 2019. p. 265–315.
27. Muntean S, Susan-Resiga R, Göde E, Baya A, Terzi R, Tîrşi C. Scenarios for refurbishment of a hydropower plant equipped with Francis turbines. Renew Energy Environ Sustain. 2016;1:30.
28. Moran EF, Lopez MC, Moore N, Müller N, Hyndman DW. Sustainable hydropower in the 21st century. Proc Natl Acad Sci. 2018;115:11891–8.
29.• IRENA. Planning and Prospects for Renewable Power: Eastern and Southern Africa. 2021. https://www.irena.org/publications/2021/Apr/Planning-and-prospects-for-renewable-power-Eastern-and-Southern-Africa. Accessed 26 Mar 2021. **This report shows scenarios for VRE expansion across all Eastern and Southern African Power Pool countries based on least-cost optimisation modelling, showcasing the high attractivity of solar PV, wind, hydropower and improved interconnections to achieve markedly lower greenhouse gas emissions related to electricity generation by 2030**.
30. Gebretsadik Y, Fant C, Strzepek K, Arndt C. Optimized reservoir operation model of regional wind and hydro power integration case study: Zambezi basin and South Africa. Appl Energy. 2016;161:574–82.
31. Adeoye O, Spataru C. Sustainable development of the West African Power Pool: Increasing solar energy integration and regional electricity trade. Energy Sustain Dev. 2018;45:124–34.
32.• Wu GC, Deshmukh R, Ndhlukula K, Radojicic T, Reilly-Moman J, Phadke A, Kammen DM, Callaway DS. Strategic siting and regional grid interconnections key to low-carbon futures in African countries. Proc Natl Acad Sci. 2017;114:3004–12. **Based on an analysis of solar PV, CSP, and wind power potential across the Eastern and Southern African Power Pools, this study recommends that the most promising sites for solar/wind capacity expansion and siting strategies be centered around increasing international interconnections to achieve more cost-optimal electricity systems**.
33. Conway D, Dalin C, Landman WA, Osborn TJ. Hydropower plans in eastern and southern Africa increase risk of concurrent climate-related electricity supply disruption. Nat Energy. 2017;2:946–53.
34. Oyewo AS, Farfan J, Peltoniemi P, Breyer C. Repercussion of large scale hydro dam deployment: the case of Congo Grand Inga Hydro Project. Energies. 2018;11:4.
35. Liersch S, Fournet S, Koch H, et al. Water resources planning in the Upper Niger River basin: are there gaps between water demand and supply? J Hydrol Reg Stud. 2019;21:176–94.
36. Falchetta G, Gernaat DEHJ, Hunt J, Sterl S. Hydropower dependency and climate change in sub-Saharan Africa: a nexus framework and evidence-based review. J Clean Prod. 2019;231:1399–417.
37.• Oyewo AS, Aghahosseini A, Ram M, Breyer C. Transition towards decarbonised power systems and its socio-economic impacts in West Africa. Renew Energy. 2020. https://doi.org/10.1016/j.renene.2020.03.085. **This paper examines model results on cost-optimised power systems for West Africa, finding that by 2050 this would largely favour the deployment of solar PV plus storage across all ECOWAS countries, supported by wind, biomass and existing hydropower**.
38. Adeoye O, Spataru C. Quantifying the integration of renewable energy sources in West Africa's interconnected electricity network. Renew Sustain Energy Rev. 2020;120:109647.
39. Momodu AS, Addo A, Akinbami J-FK, Mulugetta Y. Low-carbon development strategy for the West African electricity system: preliminary assessment using system dynamics approach. Energy Sustain Soc. 2017;7:11.
40. Sridharan V, Broad O, Shivakumar A, et al. Resilience of the Eastern African electricity sector to climate driven changes in hydropower generation. Nat Commun. 2019;10:302.
41. Trotter PA, Maconachie R, McManus MC. The impact of political objectives on optimal electricity generation and transmission in the Southern African Power Pool. J Energy S Afr. 2017;28:27–42.
42. Pool Énergétique de l'Afrique Centrale. État d'Avancement des Projets au Portefeuille du PEAC 2019. 2019. http://www.peac-ac.org/pdfs/Portefeuille_de_projet_PEAC_2019.pdf. Accessed 26 Mar 2021.
43. Taliotis C, Shivakumar A, Ramos E, Howells M, Mentis D, Sridharan V, Broad O, Mofor L. An indicative analysis of investment opportunities in the African electricity supply sector — using TEMBA (The Electricity Model Base for Africa). Energy Sustain Dev. 2016;31:50–66.
44. Brand B, Boudghene Stambouli A, Zejli D. The value of dispatchability of CSP plants in the electricity systems of Morocco and Algeria. Energy Policy. 2012;47:321–31.
45. Brand B. Transmission topologies for the integration of renewable power into the electricity systems of North Africa. Energy Policy. 2013;60:155–66.
46. World Bank. Concentrating Solar Power: Clean Power on Demand 24/7. 2021. http://pubdocs.worldbank.org/en/849341611761898393/WorldBank-CSP-Report-Concentrating-Solar-Power-Clean-Power-on-Demand-24-7-FINAL.pdf. Accessed 26 Mar 2021.
47. Ouedraogo NS. Transition pathways for North Africa to meet its (intended) nationally determined contributions ((I)NDCs) under the Paris Agreement: a model-based assessment. Clim Policy. 2020;20:71–94.
48. Praene JP, Radanielina MH, Rakotoson VR, Andriamamonjy AL, Sinama F, Morau D, Rakotondramiarana HT. Electricity generation from renewables in Madagascar: opportunities and projections. Renew Sustain Energy Rev. 2017;76:1066–79.
49. Surroop D, Raghoo P. Renewable energy to improve energy situation in African island states. Renew Sustain Energy Rev. 2018;88:176–83.
50. Praene JP, Fakra DAH, Benard F, Ayagapin L, Rachadi MNM. Comoros's energy review for promoting renewable energy sources. Renew Energy. 2021;169:885–93.
51. JICA. Diagnostic du Secteur de l'Energie en Côte d'Ivoire - Rapport final de l'étude de collecte des données relatives au secteur de l'énergie électrique. 2019. https://openjicareport.jica.go.jp/pdf/12333894.pdf. Accessed 26 Mar 2021.
52. Dasappa S. Potential of biomass energy for electricity generation in sub-Saharan Africa. Energy Sustain Dev. 2011;15:203–13.
53. Hafner M, Tagliapietra S, de Strasser L. Prospects for Renewable Energy in Africa. In: Hafner M, Tagliapietra S, de Strasser L, editors. Energy in Africa. SpringerBriefs in Energy. Cham: Springer International Publishing; 2018. p. 47–75.
54. Sterl S, Liersch S, Koch H, van Lipzig NPM, Thiery W. A new approach for assessing synergies of solar and wind power: implications for West Africa. Environ Res Lett. 2018;13:094009.
55. Geth F, Brijs T, Kathan J, Driesen J, Belmans R. An overview of large-scale stationary electricity storage plants in Europe:

current status and new developments. Renew Sustain Energy Rev. 2015;52:1212–27.
56. Wright JG, Bischof-Niemz T, Calitz JR, Mushwana C, van Heerden R. Long-term electricity sector expansion planning: a unique opportunity for a least cost energy transition in South Africa. Renew Energy Focus. 2019;30:21–45.
57. Rehman S, Al-Hadhrami LM, Alam MM. Pumped hydro energy storage system: a technological review. Renew Sustain Energy Rev. 2015;44:586–98.
58. Hunt JD, Zakeri B, Lopes R, Barbosa PSF, Nascimento A, de Castro NJ, Brandão R, Schneider PS, Wada Y. Existing and new arrangements of pumped-hydro storage plants. Renew Sustain Energy Rev. 2020;129:109914.
59. Segurado R, Costa M, Duić N, Carvalho MG. Integrated analysis of energy and water supply in islands. Case study of S. Vicente, Cape Verde. Energy. 2015;92:639–48.
60. Timmons D, Dhunny AZ, Elahee K, et al. Cost minimization for fully renewable electricity systems: a Mauritius case study. Energy Policy. 2019;133:110895.
61. IRENA. Electricity Storage and Renewables: Costs and Markets to 2030. 2017. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017_Summary.pdf. Accessed 26 Mar 2021.
62.• Aghahosseini A, Bogdanov D, Breyer C. Towards sustainable development in the MENA region: analysing the feasibility of a 100% renewable electricity system in 2030. Energy Strateg Rev. 2020;28:100466. **This paper analyses options for the MENA (Middle East and North Africa) region to decarbonise their electricity systems by 2030, finding important roles for solar PV and wind power complemented by battery storage for all North African countries, with potentially important contributions from power-to-gas to serve industrial sectors**.
63.• Oyewo AS, Aghahosseini A, Ram M, Lohrmann A, Breyer C. Pathway towards achieving 100% renewable electricity by 2050 for South Africa. Sol Energy. 2019;191:549–65. **This paper examines pathways towards weaning South Africa's electricity generation off coal and decarbonise it fully by 2050, finding important roles for a mix of solar PV and wind power, batteries for diurnal storage and power-to-gas for seasonal storage**.
64. Burkhardt P. South Africa's Coal-Dependent Eskom Calls for Battery-Power Storage. 2020. https://www.bloomberg.com/news/articles/2020-08-03/south-africa-s-eskom-requests-bids-for-battery-power-storage. Accessed 11 Feb 2021
65. Wang Z. Chapter 2 - The Solar Resource and Meteorological Parameters. In: Design of Solar Thermal Power Plants. 2019. https://doi.org/10.1016/B978-0-12-815613-1.00002-X.
66. Falchetta G, Pachauri S, Byers E, Danylo O, Parkinson SC. Satellite observations reveal inequalities in the progress and effectiveness of recent electrification in sub-Saharan Africa. One Earth. 2020;2:364–79.
67. Ouedraogo NS. Africa energy future: alternative scenarios and their implications for sustainable development strategies. Energy Policy. 2017;106:457–71.
68. Bogdanov D, Farfan J, Sadovskaia K, Aghahosseini A, Child M, Gulagi A, Oyewo AS, de Souza Noel Simas Barbosa L, Breyer C. Radical transformation pathway towards sustainable electricity via evolutionary steps. Nat Commun. 2019;10:1077.
69. Jacobson MZ, Delucchi MA, Cameron MA, Mathiesen BV. Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes. Renew Energy. 2018;123:236–48.
70. Giner-Reichl I. Renewable energy in international and regional governance: Propelling development in Africa. Energy Res Soc Sci. 2015;5:116–9.
71. Hancock KJ. Energy regionalism and diffusion in Africa: how political actors created the ECOWAS center for renewable energy and energy efficiency. Energy Res Soc Sci. 2015;5:105–15.
72. Vogel C, Steynor A, Manyuchi A. Climate services in Africa: re-imagining an inclusive, robust and sustainable service. Clim Serv. 2019;15:100107.