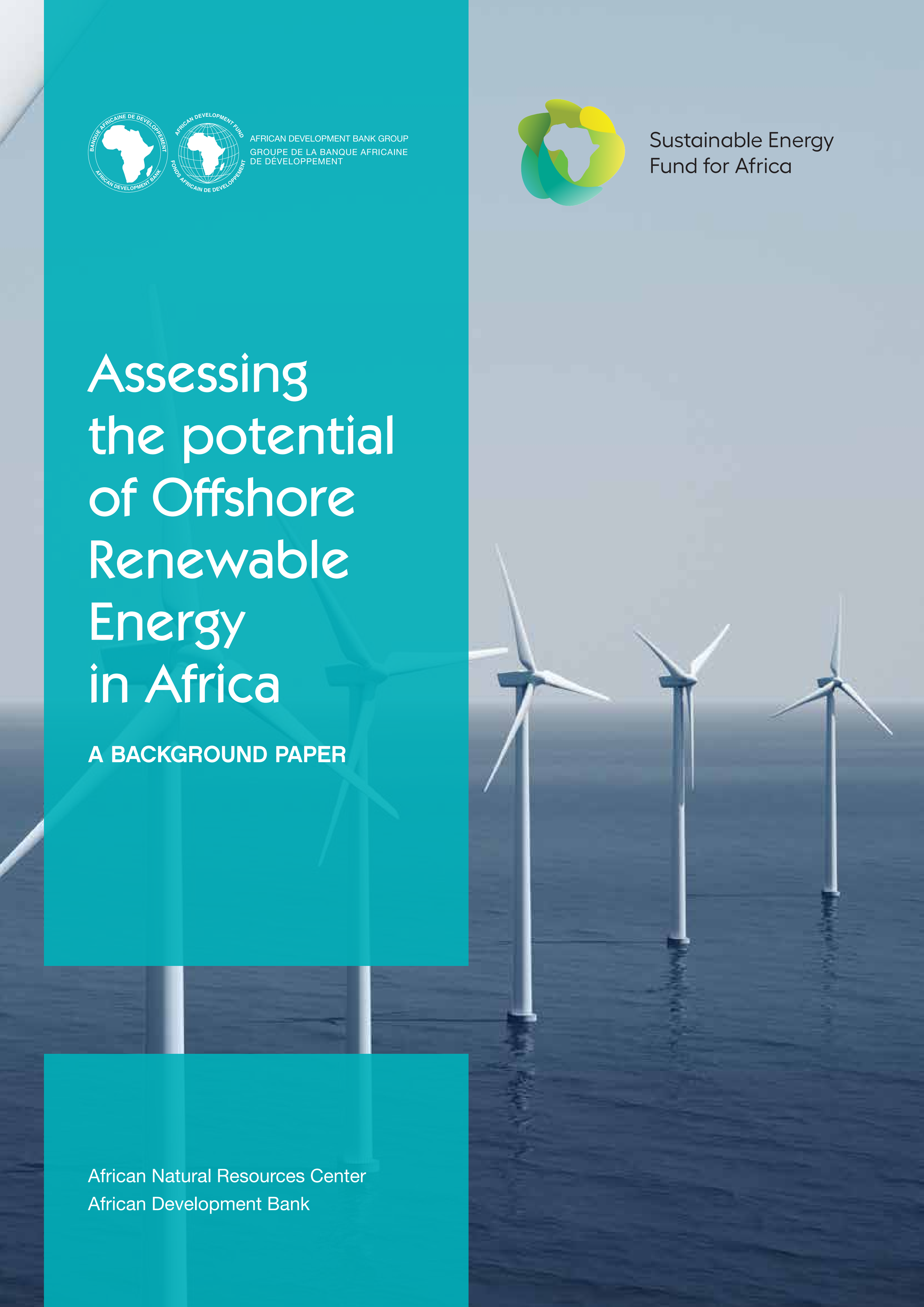

AFRICAN DEVELOPMENT BANK GROUP
GROUPE DE LA BANQUE AFRICAINE
DE DÉVELOPPEMENT

Sustainable Energy
Fund for Africa

Assessing the potential of Offshore Renewable Energy in Africa

A BACKGROUND PAPER

African Natural Resources Center
African Development Bank

acknowledgments

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TABLE OF ACRONYMS

CAPP	Central African Power Pool
COMELEC	Comité Maghrébin de l’Electricité
EAPP	Eastern Africa Power Pool
ENSO	El Niño Southern Oscillation
FPV	Floating photovoltaics
GHG	Greenhouse Gasses
IEC	International Electrotechnical Commission
IPCC	Intergovernmental Panel on Climate Change
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
ITCZ	Inter-Tropical Convergence Zone
LCOE	Levelized Cost Of Electricity
MSP	Marine Spatial Planning
NDC	Nationally Determined Contributions
OTEC	Ocean Thermal Energy Conversion
PV	Photovoltaic panels
SAPP	Southern Africa Power Pool
SDG	Sustainable Development Goals
SST	Sea surface temperature
WAPP	West Africa Power Pool
WEC	Wave energy converter

SUMMARY

How can the ocean contribute renewable energy to the African 'Blue Economy', bringing opportunities to millions of Africans and reducing or replacing carbon emissions, and which strategic actions can help it reach this potential?

This background paper is an overview of offshore renewable energy sources across coastal Africa, including a review of six technology types: wave power, tidal stream power, ocean current power, ocean thermal energy conversion (OTEC), offshore wind power, and marine floating solar power (FPV). Analyses are based on a synthesis of available data and literature, including a review of their physical, technical, and socio-economic features.

The power quality of offshore renewables is relatively high, being more predictable and less variable than many other renewables. The results indicate that coastal Africa, according to available data, has high technical potential for all offshore renewables, apart from tidal stream power.

In the **near future**, the outlook for utilizing offshore renewables is most promising for African **small island states**, where land is scarce and imported fuels are expensive. Here, fossil fuel power generation may be partly substituted by offshore renewables. Offshore wind power, OTEC, marine FPV, and wave power offer opportunities at different islands across Africa. At this moment, only offshore wind power is technically mature. Among small island states, Cabo Verde has the best wind resources. Marine FPV is currently being deployed in the Seychelles. The OTEC technology is not yet commercially viable but may eventually prove feasible due to its high capacity and the fact it produces freshwater as a highly attractive byproduct. On the basis of site screenings and an in-depth feasibility study on Mauritius, several African small island states have potential.

Continental Africa has plenty of offshore renewable energy sources but also an abundance of land-based renewable energy, which is more feasible to extract today. Nevertheless, countries with existing offshore industry such as oil and gas drilling may possess, or can develop, a strong offshore capacity that will enable them to use offshore renewables at scale – starting with offshore wind power.

In the **longer term**, several offshore renewables may become important contributors to the overall energy mix of African power pools, as well as producers for small grids at remote locations.

Eastern Africa has high and diverse potential for offshore renewables, including offshore wind power, wave power, OTEC, marine FPV, and ocean current power. The Indian Ocean island states have excellent conditions for

renewable offshore technologies and the long coast of Somalia also holds great energy opportunities for the future.

Southern Africa is surrounded by energetic seas with high potential for offshore wind and wave power, and possibly even ocean current power. Mozambique seems to have conditions for all studied energy kinds, with certain potential for OTEC and wave power. Namibia and Angola have good opportunities too.

Countries of **Central Africa** have more limited potential for offshore renewables but some of the studied technologies can be used successfully for harvesting freshwater energy resources on rivers and lakes which could be an interesting opportunity to investigate.

Western Africa has good conditions for both offshore wind and wave power. Far offshore, at the continental shelf, conditions are prime for floating OTEC, although this potential may be more relevant for future production of energy carriers than for grid connection because of the distances to shore.

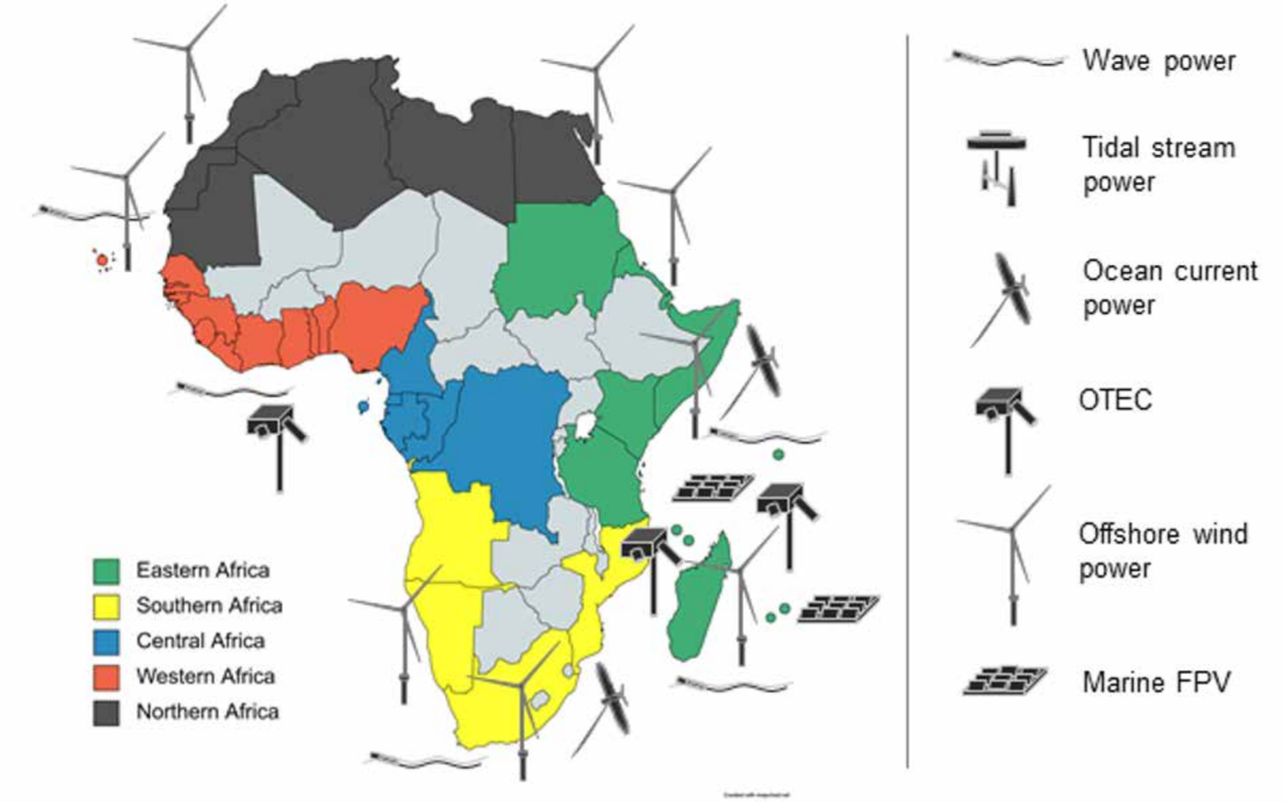
Surrounded by the enclosed Mediterranean and Red Sea, Northern Africa has limited potential for wave and tidal power. Strong winds however create potential for offshore wind power both along the Atlantic, Mediterranean, and Red Sea coasts.

The development of offshore capacity holds the key to offshore renewables. The sea is a challenging environment for any moored equipment and most of the technologies analyzed are still at pre-commercial stage. But the resources are there, ready to become part of a prospering ‘Blue Economy’ when circumstances are right. Since the African continent is blessed with renewable energy of many sorts, the suitability of offshore technologies will always be a compromise determined by the local availability of land-based, less challenging, alternatives.

Figure 1 provides an illustration of the offshore renewable energy hotspots across the African continent. Policy recommendations are listed in chapter 7.

FIGURE 01

Approximate hotspots for the six different offshore renewables assessed in this background paper. OTEC indicates potential for ocean thermal energy conversion and FPV denotes possible sites for floating solar power (photovoltaics). Further details are provided in the main text.



Assessing the potential of Offshore Renewable Energy in Africa

1. CONTEXT AND FOCUS

The African Development Bank's Ten Year Strategy, reflecting the aspirations of the entire African continent, has the twin objectives of supporting African countries to achieving inclusive growth and transition into green growth [1]. The New Deal on Energy for Africa 2016-2025 [2] emphasizes the critical role of access to energy for productivity, employment, and social and economic progress. It observes that "energy is the lifeblood of the economy", suggesting that other development strategies are dependent on the power sector and the provision of modern energy to industry, business, and households. Through the New Deal on Energy, the African Development Bank aspires to achieve universal access to energy across the African continent by 2025. Increased generation and distribution of electric power to support these development goals is imperative.

The African Union Agenda 2063, with its aspiration to support a prospering Africa based on inclusive growth and sustainable development, recognizes the 'Blue Economy' where the marine environment is sustainably used to drive growth, as a priority [3]. This recognition of the opportunity led to the development of the Africa Blue Economy Strategy [4], where the potential harnessing of marine energy resources constitutes one of its cornerstones.

The strategic rationale behind harnessing offshore renewable energy[A] from African waters is dual: expanding reliable energy access for people and industry across the continent and at the same time transforming Africa's energy reliance away from a dependence on fossil fuels to using renewable energy. This approach will help the African continent to move closer to achieving Sustainable Development Goal (SDG) 7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all by 2030, as well as making progress on SDG 13 by taking urgent action to combat climate change. The SDG High Level Panel for a Sustainable Ocean Economy also noted that the ocean offers significant potential for supporting a rapid decarbonization of the global energy system [5].

The African continent has low per capita energy consumption, with many sub-Saharan countries suffering exceptionally low electricity access in rural areas. Energy sector insufficiencies and inequalities, particularly in distribution, are inhibiting economic development and often severely impacting human health. Population growth and increasing energy demand from businesses seeking to industrialize and communities seeking modern standards of living challenge the energy sector to find solutions rapidly [4]. For energy access to improve, significant investments are needed within power generation (on-grid and off-grid), power transmission and distribution. There is also an important need to replace highly unsustainable and damaging energy sources such as traditional cooking fuel [2] and inefficient and polluting generators.

[A] In this paper offshore renewable energy, or offshore renewables, refers to ocean energy, offshore wind power and floating solar power. Among ocean energy technologies, wave power, tidal power, marine current power, and OTEC are covered. Osmotic power (salinity gradient energy) and algae biofuel are not included and do not necessarily require ocean space.

Africa has enormous potential for renewable energy (>10 TW) with a variety of resources available across the continent [6]. Numerous national and international interventions aiming to improve energy access are in place, or being implemented, in the form of renewable energy resources such as hydro power, solar power, geothermal, and wind power.

In theory, the sea could also contribute vast amounts of renewable energy [4]. Wave power, tidal power, ocean current power, and ocean thermal energy conversion (OTEC) are emerging technologies collectively known as ocean energy. Offshore wind power is already a cornerstone of the 'Blue Economy' in some parts of the world but not yet in Africa. Floating solar power (FPV) is new to the marine context but is based on extending proven technology from inland waters for marine application. The Africa Blue Economy Strategy emphasizes the need to seriously assess the potential of these energy sources.

For offshore renewables to contribute to the future African energy mix they need to complement, or provide some advantage over other renewable energy alternatives. These advantages could include resource availability, reliability, investment and maintenance costs, or social and environmental externalities. The marine environment is generally harsh to technical equipment; it is comparatively inaccessible and exposed to tough environmental conditions such as storms or cyclones. Most energy harvesting principles are new in this environment. The real physical challenges of offshore conditions will reduce the viability of many projects as they progress between the cutting-edge theoretical stage and reaping the actual socio-economic potential benefits anywhere, not least in Africa.

Nonetheless, harnessing offshore renewable energy has already knocked on the door of some African countries and communities [4] as the natural resources are plentiful. Questions of providing the right support and investment strategies are now tangible and this paper explores some of them.

Developing offshore renewable energy requires marine space at the most favorable sites, but also the creation of an environment to enable its success. This includes the development of government policy, the provision of local infrastructure as well as technical skills in offshore marine engineering. Early European experiences with offshore wind power development have shown that slow progress and delays are common. This will be true also for offshore renewables in Africa. Early awareness, preparedness and planning will all be necessary to enable this segment of the 'Blue Economy' to develop successfully in Africa.

The aim of this background paper is to assess the potential of offshore renewables and identify geographical areas where their advantages may compare favorably with land-based alternatives and eventually become valuable components of future energy systems.

Importantly, out of all technology types addressed, only offshore wind power is fully commercially viable today. The business case economics such as levelized cost of electricity (LCOE) are in some cases based on prototypes and in other cases based on modelled projections or theoretical claims and are therefore not reliable for direct comparison. Brief notes on LCOE provided for some technology types and level of technological readiness is presented in Table 1. In order to avoid misleading judgements at this early stage of development, this background paper does not attempt any structured cost estimate comparisons.

Readers' guide

The assessment framework applied is presented in chapter 2, followed by a description of each technology type in chapter 3. The energy resources are mapped in chapter 4, including an assessment of the technical potential per country (see tables) and a crisp summary for each technology type. Chapter 5 addresses geography, climate, and energy sector characteristics. Brief qualitative suitability assessments are provided in chapter 6, reviewing the opportunities for offshore renewables in each African region. A summary and recommendations are presented in chapter 7. Country profiles with background indicators are available as supplement (Table S1 - Annex 01).

2. FROM RESOURCE TO POWER

The basic starting point for harvesting offshore renewable energy is the physical energy resource itself, such as waves, tides, currents, heat gradient, wind, or insolation (solar energy). The amount of energy present forms its theoretical potential.

More interesting is the technical potential, which is the amount of energy that could possibly be harvested and converted by technology [7]. Data limitations and the early stage of technological development or readiness, of most offshore renewable subsectors makes it difficult to make accurate assessments of technical potential. But hints are given by understanding spatial information about the resource density together with technical requirements provided by research and developers.

The technical potential is never a feasible target. Economic, social, and environmental factors limit the amount of energy that can realistically be extracted. The characteristics of the existing energy sector and the potential of other energy sources will also determine the interest in offshore technology. All these aspects form the socio-economic potential. In this background paper we address the socio-economic aspects only briefly, as we review the suitability of each technology type.

For offshore renewables to be attractive options, their advantages in terms of power quality and relative cost must align with the current (or future) energy system. Complementing energy sources, grid connectivity, and demography may serve as indicators.

Advanced offshore technology requires offshore capacity, preferably in the form of a pre-existing industry complex [8]. At least part of production and maintenance needs to be locally-based or the investment is unlikely to be successful in the long run [9], [10]. The existence of this capacity was therefore considered among the preconditions and it suggests one aspect which can change over time, altering the attractiveness of the business case.

The environment limits the socio-economic potential and suitability in different ways. First, technology must withstand local climatic conditions including rare events such as extreme weather. For many technologies it will be difficult to obtain the certification to deploy in areas with tropical cyclones and other severe phenomena. Secondly, the environment may restrain the use of certain technologies due to their possible impact on local ecosystems. Such assessments generally require site and technology specific studies. This important aspect of preparedness is not covered in this paper, but assessments of generic ecological risks from offshore renewables are available elsewhere [11]–[14].

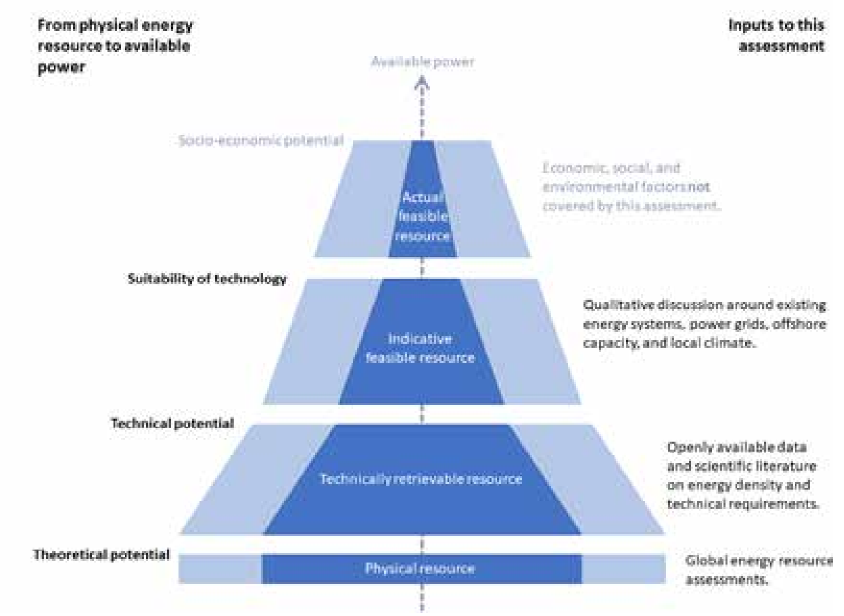
2.1 ASSESSMENT FRAMEWORK AND METHOD

The pathway from resource to power forms the assessment framework of this paper, depicted in Figure 2. The assessment is based on literature and openly available data. Literature includes technical reports, policy papers, and an exhaustive structured search in the scientific database Web of Science (09-09-2020) using search terms including each different technology in combination with coastal African countries (141 papers retrieved). All data and literature are referenced and retrievable.

The reader should be aware of the risk that all relevant information might be not have been identified and that applied assumptions might be brief and generic.

FIGURE 02

The assessment framework applied in this paper, which focuses on both the technical potential and the suitability of different offshore renewables. Color shades serve to demonstrate uncertainties. This conceptual model is not drawn to scale.



3. UTILIZING OFFSHORE RENEWABLE ENERGY

Two thirds of the planet is covered by an ocean that receives and stores energy from insolation, wind, celestial gravitation, and planetary rotational forces. This energy can be extracted and converted to electric power and is continually renewable. Seawater could also have energy-related uses, such as for cooling, but its potential was not covered here. In general, offshore renewable energy is abundant, predictable, and complementary to other energy sources [15].

Although use of offshore renewable energy has been researched for decades, only offshore wind power is commercially mature[B]. Nevertheless, dedicated research and development has led to hundreds of advanced prototypes, numerous pilot plants, and a few commercial deployments of other offshore renewables. It appears likely that several offshore renewable projects will be fully commercialized and readily available within the foreseeable future.

In this paper offshore renewable energy[C] refers to wave power, tidal stream power, ocean current power, ocean thermal energy conversion (OTEC), offshore wind power and floating solar power (FPV). These technology types, or subsectors, may become valuable components of the global Blue Economy in places where their advantages match or suit local conditions.

[B] Tidal barrage technology can also be considered mature, but this technology is not further explored in this paper because of the limited tidal range on the continent.

[C] Note that the labelling and categorization of ocean energy resources and technologies may differ among studies and contexts.

It is therefore essential to understand under which conditions each type of technology would work. First, what level of resource density must be available for the technologies to operate efficiently? To assess the technical potential or even economic viability, is particularly difficult at an early stage of technological readiness. Technical development will influence the resource requirements over time and new potentials will rise as more efficient technology becomes available. It is also important to consider the inherently intermittent nature of offshore renewables. Variability and predictability over time will strongly influence the quality of power and thus the potential value for connecting generators to a specific grid. This assessment is also shifting, as energy storage technology is rapidly developing and it is likely that some of the renewable energy intermittency issues may be mitigated through grid connected batteries and green hydrogen. This chapter presents the basic principles behind the five offshore renewables. See Table 1 for a summary of important parameters, including technological readiness, and Figure 3-6 for schematic illustrations. The geographical distribution and technical potential across the African continent will be explored in chapter 4.

TABLE 01

Characteristics of offshore renewable energy technologies

TECHNOLOGY	RESOURCE DENSITY REQUIREMENTS FOR TECHNICAL POTENTIAL [#1]	INTERMITTENCY (VARIABILITY AND PREDICTABILITY)	TECH
WAVE POWER	**WAVE POWER** High: >15 kW m-^{1} Good: ≥8 kW m-^{1}	Seasonal and inter-annual variability **Moderate predictability**	**Pre-c** Many or de
TIDAL STREAM POWER	**Tidal spring speed (m/s)** Moderate: ≥2 m s-^{1} Restricted: ≥1.5 m s-^{1}	Diurnal and monthly variability **Extremely high predictability**	**Pre-c** Many demo
OCEAN CURRENT POWER	**Current speed (m/s)** High: ≥1.5 m s-^{1} Moderate: ≥1 m s-^{1}	Seasonal variability **High predictability**	**Dem** Some
OCEAN THERMAL ENERGY CONVERSION (OTEC)	**TEMPERATURE GRADIENT Δ AND DISTANCE TO SHORE** High: Δ ≥22 °C AND ≤5 km to shore Moderate: Δ ≥20 °C AND ≤5 km to shore	Seasonal variability **High predictability**	**Pre-c**
OFFSHORE WIND POWER	**WIND SPEED AT 100 M** High: ≥10 m s-^{1} Moderate: ≥8 m s-^{1}	Diurnal, seasonal & inter-annual variability **Low to moderate predictability**	Com Pre-c
MARINE FLOATING SOLAR POWER (FPV)	Irradiance and site-specific conditions related to sheltered near-shore waters and depth	Diurnal and seasonal variability **High predictability**	**Pre-c** Fresh

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[#1] See main text and subsequent tables for more precise assumptions.

3.1 WAVE POWER

The resource

Surface waves are generated as wind blows over the ocean. As waves rise and fall and slowly move across the ocean, they contain both kinetic and gravitational potential energy. The wave resource is often measured in kilowatts per meter (kW/m), referring to the energy density per wave crest at a given stretch of the ocean or coastline.

The wave power resource varies both seasonally and diurnally. It takes some time for wind to build up waves, and waves may also last long after wind has ceased. Waves can carry energy a long distance from their windy origin and therefore wave power is considered less variable and more predictable than wind power.

Global wind patterns make wave energy most abundant at high latitudes and on the western-facing shores of the continents (typically 50-100 kW/m). Wave power is much lower in the tropics (up to 10-20 kW/m). Yet tropical ocean swell, the gentle remnant from far away winds and storms, is a predictable and

INOLOGICAL READINESS	DEVELOPMENT CONFORMITY	INTENDED TYPE AND SCALE OF DEPLOYMENT	DEPLOYMENTS IN AFRICA
commercial devices are also at prototype monstration level	Diverse with multiple devices with different working principles	Arrays of 10 - 1000 devices	Planned *Previously deployed in Ghana*
commercial devices are also at prototype or nstration level	Few different working principles	Arrays of 10 – 1000 devices	Anecdotal reports from Mozambique (micro-scale turbines)
onstration devices are at prototype level	Few different working principles	Arrays of 10 - 100 devices	No
commercial	Few different working principles	Single units	Planned
nercial (bottom fixed) ommercial (floating)	Established working principles	Arrays of 10 - 100 devices	Planned
commercial (marine) water FPV is commercial	Established working principles	Arrays	Planned

convenient form of extractable wave energy. In contrast, enclosed seas such as the Mediterranean and the Red Sea have low wave power density because of their limited ‘fetch’, the horizontal distance over which the wind blows to generate waves.

Operating principles and development

Extracting wave energy has been researched for about 50 years and hundreds of wave power prototypes have been developed and tested at pilot scale. Several full-scale devices are currently deployed at test sites around the world [16] which are being closely studied. In contrast to other ocean energy technologies, wave power engineering has not converged very much and a plethora of different promising working approaches remain. Based on prototypes and pre-commercial devices, the capacity factors for a preferable African development would be 30 – 70%. See Khan et al. [17] and Rusu & Onea [18] for more details on wave power and Figure 3 for schematic illustrations.

To date, only a few megawatts of wave power have been deployed worldwide [19], [20] and the technological readiness of wave power can be considered pre-commercial [21]. The levelized cost of electricity (LCOE) for commercial devices is difficult to project but currently most devices have LCOE well above $0.3 per kWh.

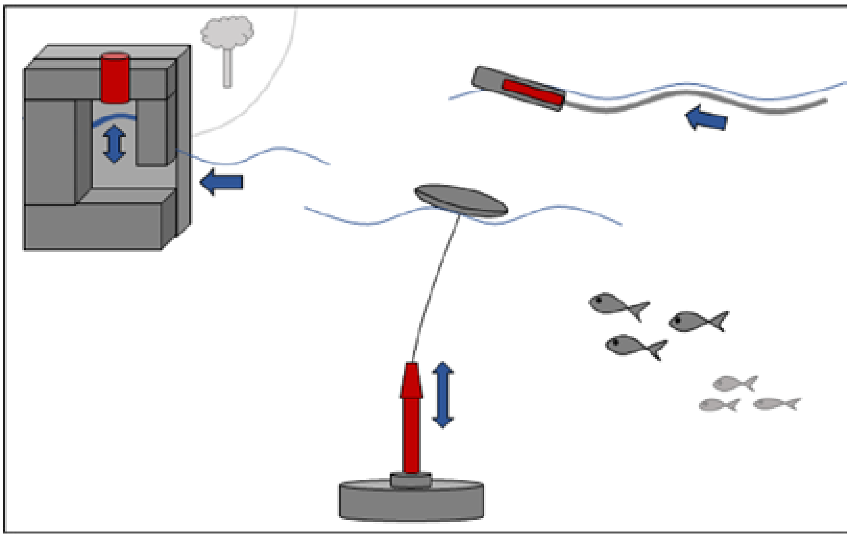
Some wave power devices are shore-based while others are aimed specifically for near-shore or fully offshore deployment. The capacity of each unit is in the range of a few kilowatts up to megawatts. This means that wave power installations typically require deployment of arrays with multiple units.

Assessment criteria

Devices require different levels of wave energy density. A resource density above 20 kW/m may indicate high resource potential [22], [23] but some wave power technologies are preferable for locations with under 15 kW/m [24]. Such conditions can often be favorable since calmer water means better working environments, less wear on the technical system, and sometimes higher resource continuity. A recent study of global wave energy potential concludes that modest energy density, low-variability, swell dominated wave energy might in fact represent the most promising and low-risk conditions for wave power [25]. If the utility factor is high, wave power may even become viable at locations with low resource density [26]. In some cases, such as desalination, wave power may even be useful in conditions below 8 kW/m, as some developers have argued. For these reasons, we consider above 15 kW/m to represent a high potential while 8-15 kW/m indicates a good technical potential and a number of factors need to be taken into account beyond purely the energy density.

FIGURE 03

Wave power, showing three selected working principles: oscillating water column device, bulge wave device, point absorber device. The schematic illustrations visualize the workings and are not to scale. Power generating components are marked red. Blue arrows indicate main water movements.



International

Most wave power engineering has taken place in Europe and North America although testing and deployments are global. In Africa, wave power is at an advanced stage of consideration in several countries, including Mauritius, Cabo Verde, and South Africa. In Ghana, six units were deployed in 2015 but were later decommissioned due to unsuitable positioning [20].

3.2 TIDAL STREAM POWER

The resource

TTides are the result of the complex interaction between Earth and numeral celestial bodies, most obviously the moon. This resulting force is a gravitational pull that raises and lowers the water level with a rhythm that follows the monthly lunar cycle (a period of 14.5 days). This rise and fall constitutes the tidal range which indicates the amount of potential gravitational energy. In Africa, tides are semi-diurnal, which means that the water rises and falls two times per day[D]. Tides are always stronger during full and new moons (spring tide) but weaker during half-moons (neap tide).

The tidal range also depends on the coastal morphology. Bays with gentle slopes exaggerate the tidal wave and increase the tidal range. In Africa, the bay of Beira in Mozambique has a spring tidal range of 7m which is higher than elsewhere on the continent but not exceptional in global terms.

[D] Horn of Africa and East coast of Madagascar have mixed semidiurnal tides, with two unequal peaks each day.

Strong currents are produced when the tidal wave passes through narrow straits, particularly where such straits coincide with significant tidal range. The tidal currents represent kinetic tidal energy that can be harvested by other principles than the tidal range. Water is heavy and the energy content of tidal currents has a cubic relationship to its speed. Like tidal range, tidal currents undergo temporal variations within and between days.

Given the celestial origin of tides, and the long historic records of tidal dynamics, this energy source is highly predictable.

Operating principles and development

Energy from tides can be utilized either by harvesting the tidal range or tidal currents. Tidal range has been harvested in some form for centuries. The concept behind tidal range energy conversion is to temporarily trap water in a barrage or artificial lagoon, letting the water in and out though conventional hydropower low head turbines, out of phase with the natural rhythm. Large scale tidal barrages exist at a few locations worldwide. However, the suitability for tidal barrages in East Africa, where the best resources are located, has previously been evaluated and rejected [23] and as a result tidal barrage technology is not covered in this paper.

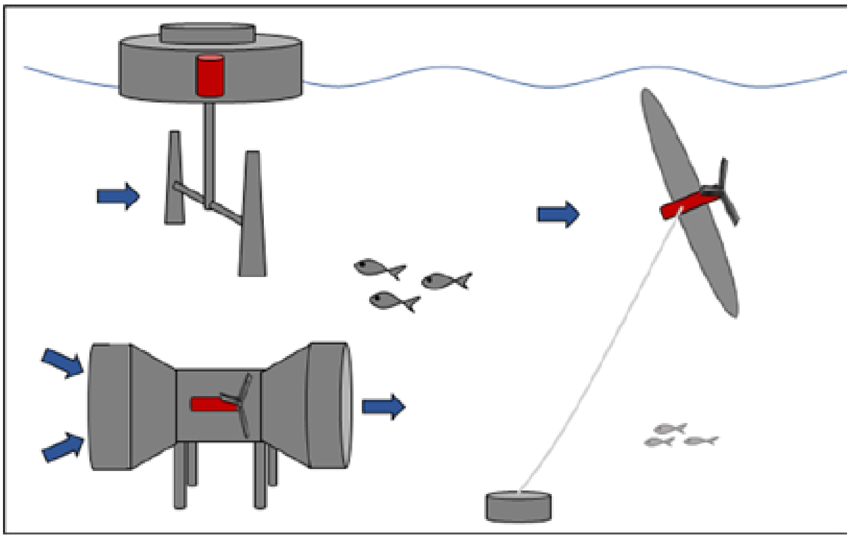
The idea behind harvesting tidal currents relies on open turbines or hydrofoils that extract the kinetic energy during ebb and flow. This technology, tidal stream power, has seen many different prototypes in recent years. Many have been evaluated in the field and it is generally believed that tidal stream technology has a higher degree of technological convergence and is also slightly more mature than wave power [21], [27]. The dominant method of conversion from tidal power to electricity depends on horizontal axis turbines, as modern wind power also does. Since water is denser than air, rotors need not be very wide to capture energy. All tidal stream devices are rather small (measured in kilowatts to a few megawatts) and will be deployed in banks or arrays. The capacity factor is low, about 20 – 35% for African sites, providing for the temporal dynamics of tides. The World Energy Council [27] offers a useful overview of the technical principles and Figure 4 provides schematic illustrations.

Many full-scale tidal stream devices have been deployed around the world, with a total installed capacity of approximately 10 MW [19], [21]. Overall, its technological readiness may still be considered pre-commercial. As for wave power, LCOE for a commercial tidal stream power is difficult to project at this stage. But current devices typically suggest a LCOE above $0.3 per kWh.

Small and flexible designs exist and some of them may become appropriate for micro-scale tidal power at remote locations with low power demand [28].

FIGURE 04

Tidal stream power (left) and ocean current power (right), showing selected working principles: floating vertical axis tidal stream device, stationary horizontal axis tidal stream device, and the powerkite ocean current power device (can also be used in tidal streams. The schematic illustrations serve to give a brief overview and are not to scale. Power generating components are marked red. Blue arrows indicate principal water flows.



Assessment criteria

The cubic relationship between water speed and energy content means that tidal stream power will only be efficient in extraordinary tidal currents. At least 2 m/s (maximum spring tide speed) is needed for a moderate resource availability, or technical potential. Under certain conditions even 1.5 m/s might be interesting to consider [23]. At some sites it is possible to constrain the natural flow to achieve higher water speeds.

International

Until now tidal stream developments have taken place in Europe, North America, and East Asia [20]. No developments are reported from Africa, other than anecdotal information on small (pico-scale) tidal stream power used by fishermen in central Mozambique for refrigeration and phone charging [29].

In this paper we consider tidal streams associated with oceanic tides. The tidal stream technology can also be used in rivers, thereby harvesting kinetic energy from Africa’s many rivers without needing the construction of dams.

3.3 OCEAN CURRENT POWER

The resource

Oceanic currents carry immense water volumes and contain correspondingly high amounts of kinetic energy. The force is largely created by Earth's rotation which results in the strongest currents appearing along the western rims of the world's oceans. Despite their rich energy content these ocean currents run slowly and have relatively low energy density, with higher speeds developing where flow is compressed by landmass. The current intensity varies over seasons and fluctuations are generally predictable [30].

The Somali-Agulhas current system along eastern Africa is exceptionally strong with frequent speeds above 1.5 m/s. Another strong current is the Guinea current in West Africa (strongest during the northern hemisphere summer months) although speeds are significantly lower than in eastern Africa.

It should be noted that according to recent findings, the magnitude and speed of ocean currents increases with global warming. A significant 5% increase over the past 30 years has been observed [31].

Operating principles and development

The energy of ocean currents may be harvested under the same principles as tidal stream power with the significant difference that ocean currents are located further offshore and are hence less accessible. The global potential of ocean current power has been recognized for decades and several concepts exploring how to harness the energy have been developed [30], although there have been few or no pilot projects actually realized. In general, developments in ocean current power seem to be pending, awaiting a breakthrough in tidal stream technology with technological readiness stuck at a demonstration level. In comparison to tidal stream technology, ocean current power will be likely to have higher capacity factor and lower variability, because of the nature of ocean currents.

A pioneering example of a converter applicable for ocean current power is an underwater kite that runs in the transverse direction of flow, thus magnifying the actual speed of water across kite-mounted turbines [32]. This powerkite technology, which is under evaluation at full scale, has the advantage of accessing energy from even moderate flows. While this highly efficient design relies on multiple small units (up to one megawatt), other prototypes for ocean current power may be much larger in size and have higher capacity per unit [33]. See **Figure 4** for a schematic illustration.

Assessment criteria

The water speed and power density of ocean currents are lower than those of tidal currents. But strong ocean currents are unidirectional and more consistent as they fluctuate over seasons, rather than hours and days as tides do. Therefore, lower speeds are required for ocean current power compared to tidal power. A consistent flow of 1.5 m/s can be considered a high technical potential and even 1 m/s may be extractable under certain conditions [23].

3.4 OCEAN THERMAL ENERGY CONVERSION (OTEC)

The resource

Oceanic deep water is always cold because saltwater has its highest density around 4°C. In the tropics, where surface water temperatures are high, a significant heat gradient builds up. This heat gradient can be utilized for power generation through technology referred to as ocean thermal energy conversion (OTEC). The larger difference in heat gradient, the higher the energy potential and a difference of more than 20°C is necessary for the heat gradient to be exploitable. For land-based OTEC, the distance between suitable location and water depth of about 1000 m, where water is cold enough, must be short [34]. Ocean heating and circulation are stable processes implying that variations are small, and the heat gradient resource is highly predictable [35].

Operating principles and development

OTEC principles have been understood for a century and a number of test plants have been deployed over the years. OTEC works by pumping cold water from the depths and warm water from the surface, using large diameter pipes, into a floating or land-based facility where electricity is generated using heat engine principles [12], [17], [36]. The heat exchange can take place through open cycle, closed cycle, or hybrid designs. In the open cycle design, warm water is vaporized in low-pressure chambers that lead through steam turbines before the vapor is condensed again by the cold water. Because this design vaporizes seawater it also generates freshwater (and saline concentrate) as by-products. Freshwater can be just as important a by-product as the power generated.

In the closed cycle, the warm and cold water flows are used to vaporize a recycled working fluid which drives the turbine. The hybrid design means that warm water is vaporized just like the open cycle, but in turned used to heat the working fluid like in the closed cycle. In all cases massive amounts of water are needed and intake pipes need to be large diameter and driven by high-capacity pumps. In addition, exhaust water must be discharged at a depth and location where it does not interfere with intake water temperatures and where it does least the environmental harm by changing natural water properties. See Figure 5 for a schematic illustration.

Since the exploited heat gradients are small and intake pumps require a lot of energy, it takes both significant engineering capability and scale to reach an efficiency that is economically viable. The efficiency is low (~5 %) but the capacity factor can be remarkably high (~90 %), and variability is also generally low. Compared to wave and tidal power which are designed to be deployed in arrays, commercial OTEC plants will be much larger, in the order of 10-100 MW per unit. The OTEC technology is yet to be fully refined and the technological readiness can be considered pre-commercial [15][21]. Projected LCOE estimates are around $0.2 per kWh [37]. A recent study shows $0.16 per kWh for Indonesian conditions [38], although this report is theoretical.

The preconditions required differ significantly between land based and floating OTEC designs. Land based designs have direct access to the power grid and infrastructure for distributing desalinated potable water. To build the OTEC facility onshore also makes it much less vulnerable to challenging ocean conditions. But land based OTEC requires long cold-water intake and discharge pipes to reach sufficient depths (about 1000 m in depth). Laying such pipes is expensive and pumping requires energy therefore sites suitable for land based OTEC are therefore restricted to a few places where the continental slope is steep and very close to land.

In contrast, floating OTEC designs avoid this cost by their direct access to cold deep water. In addition, the energy potential is never exhausted, because floating OTEC may be mobile and shift location during their operation to find more advantageous positions. However, floating OTEC is challenged by weather and then by transporting the converted energy, and potable fresh water, to shore. Energy carriers such as liquid hydrogen may be a future solution for floating OTEC.

Assessment criteria

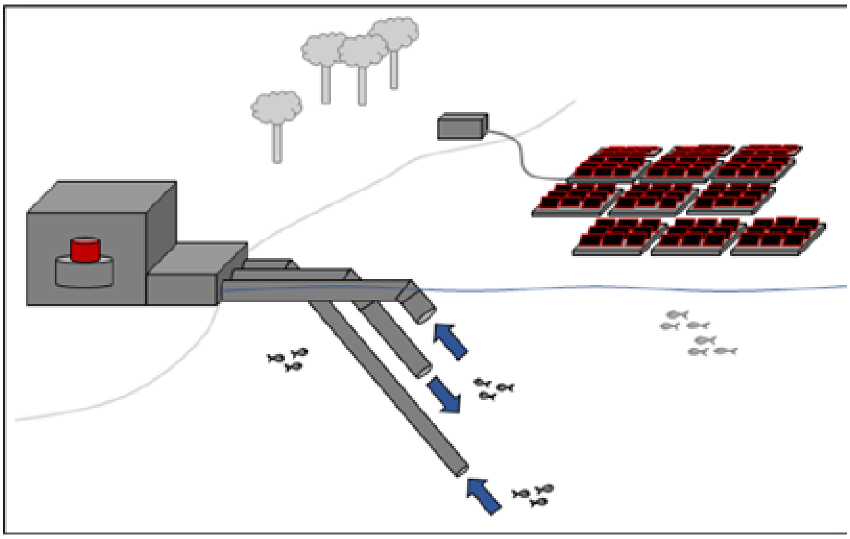
A temperature difference of at least 22 °C and close distance (under 5km) to shore may be required for a high OTEC potential. Locations with lower heat gradient or further distance to shore may have more moderate potentials [23].

International

A few smaller OTEC plants are currently operational (in Japan and South Korea) and several projects are underway (in the Philippines, Malaysia, Curacao, Martinique and Kiribati) [20], [39]. OTEC research has also taken place in Hawaii for many years and an onshore test facility has been operating at La Réunion in the Indian Ocean. The apparent benefits of OTEC, including reliable power generation, high capacity per installation, and freshwater by-products are so transformational in relation to African challenges, that they have even incited a Sweden-based NGO to have the specific ambition of promoting of OTEC in Africa [40].

FIGURE 05

Land-based OTEC (left) and marine FPV array (right), showing selected designs. The schematic illustrations serve to give a brief overview and are not to scale. Power generating components are marked red. Blue arrows indicate principal water flows (surface water intake, mid-water discharge, deep water intake at 1000 m depth).



3.5 OFFSHORE WIND POWER

The resource

Wind energy occurs from pressure differences caused by the uneven solar heating and cooling of the atmosphere. Winds dissipate with friction which means that they are typically stronger at high altitude and where Earth surface is flat, such as over water. The resource is usually measured as Watts per cross section area (W/m2). Average wind speed (m/s) at different altitudes provides a good estimate.

The International Electrotechnical Commission (IEC) categorizes wind conditions into four classes, where class 1 denotes the strongest wind climates with an annual average wind speed exceeding 10 m/s and where wind turbines would need to be capable of withstanding wind gusts of 70 m/s.

Winds may vary quickly on an hourly and daily basis, but wind patterns are much more predictable on a seasonal basis. Earth's rotation gives rise to more predictable trade winds, the westerlies and easterlies between the equator and Polar Regions. This results in dominating easterly winds in the subtropics and westerly winds in temperate regions. In the Indian Ocean, the pattern give rise to annual westbound cyclones.

Operating principles and development

Wind power is a well proven technology using wide horizontal axis rotors mounted on tall steel towers. Offshore applications typically rely on larger and taller turbines, targeting winds at about 100 m altitude [41]. The systems are moored to the seabed either by gravity foundations or piled steel foundations with a depth limit of around 50 meters, which limits the number and size of potential suitable offshore locations [41]. Floating offshore wind power is under continuous development and will eventually unleash new territory, farther offshore, for wind development. See Figure 6 for a schematic illustration.

Wind power turbines come in different sizes and are deployed in arrays, or wind farms, of many turbines connected to one or several transformers. Modern offshore wind power turbines are large, and the development trend points at 5-20 MW per unit.

For several reasons offshore wind power is more technically challenging and expensive compared to land based developments. Cabling, foundations, and complicated maintenance are much more expensive at sea. The main driver[E] for choosing offshore wind power is that winds are often stronger and more predictable at sea, the capacity factor is higher[F], and variability is lower. It has been argued that recent technological advancements and experience are now closing the gap between onshore and offshore wind economics, making offshore wind power an increasingly attractive alternative for developing countries [41], [42]. The global average LCOE for offshore wind power was $0.13 per kWh in 2018 (Statista).

The transport of electricity to shore constitutes a profound barrier to distant installations because sub-sea high voltage cables are expensive. However the underdeveloped grid in many African countries which necessitates relatively nearby power generation, may potentially make cost analyses play out differently on the continent compared to other parts of the world. It may favor offshore, and even floating wind power.

Assessment criteria

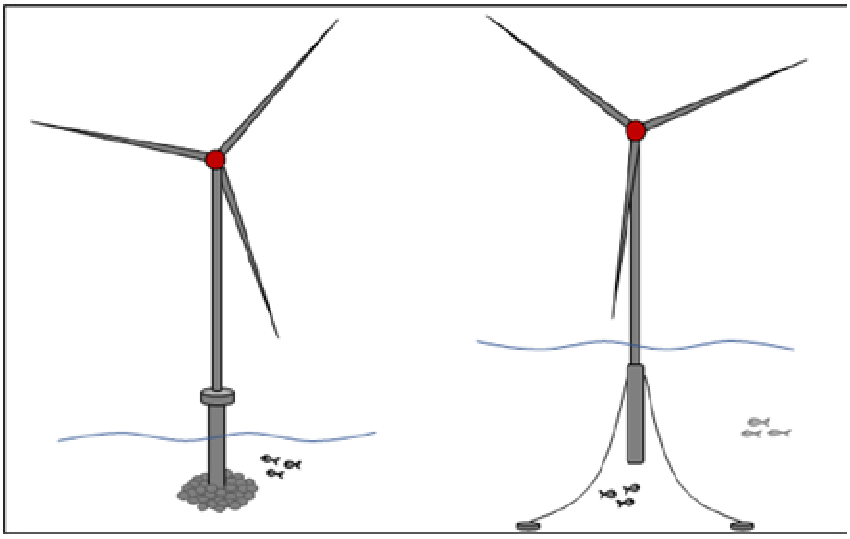
The economic assessment of wind power involves many factors but wind speeds of 8-10 m/s are generally required for offshore applications. In the subsequent analysis of their technical potential, average annual wind speeds above 10 m/s indicate high potential (classified as IEC wind class 1: High Wind) while 8-10 m/s (classified as IEC wind class 2-3: Medium-Low Wind) denotes moderate potential. Obviously, offshore wind power may only be relevant where it has economic advantages over a land-based alternative.

[E] Crowded land use and visual interference with neighboring settlements are equally important drivers in parts of the world, but expectedly not in Africa.

[F] Offshore wind capacity factor typically exceeds 40% and can be much higher under optimal conditions.

FIGURE 06

Offshore wind power, showing selected mooring principles: fixed to sea bottom (left), floating (right). The schematic illustrations serve to give a brief overview and are not to scale. Power generating components are marked red.



International

As of 2019, 650 GW of total wind power has been installed globally of which 29 GW was constituted by offshore wind power. The bulk of installed capacity is in Asia and Europe, with Europe leading offshore developments. About 1% of the global wind power capacity is installed on the African continent, and only on land thus far [41], [43]. Nonetheless, wind power is growing steadily on the African continent [41] and offshore developments have been proposed [44].

3.6 FLOATING SOLAR POWER (FPV)

The resource

Solar energy is by far the most readily available energy source on Earth [7]. More than two thirds of the planet is covered with water, which means that most solar energy is offshore. Floating photovoltaic systems, or FPV, are an extension of ordinary photovoltaic technology, targeting the virtually infinite energy source of the sun.

The FPV resource is measured by the same units as ordinary PV, such as irradiation (kWh/m2/day), and all of Africa has enough insolation for PV technology to work well. However, due to regular cloud cover, tropical West Africa, Central Africa, as well as eastern coasts, have much lower irradiance than more arid parts of the continent. Like any solar power, the FPV resource is highly predictable and varies diurnally and seasonally. During the night, of course, productivity is zero.

Operating principles and development

Floating solar power is based on similar principles to ordinary solar PV systems, but the solar panels are mounted on floating rafts. The main drivers for FPV are often the scarcity of available land or to efficiently utilize the surface of man-made water bodies such as hydropower dams. An advantage is the assisted cooling from the water body beneath, which may increase power generation by a few percentage points [45].

FPV systems consist of floating structures, PV generation equipment, inverters, mooring systems, submerged cables, and a transformer station on shore. Since water movements abrade the solar cells, special materials or solutions are needed to promote their longevity [45]. Typical FPV plants have capacities in the order of 100 MW but consist of thousands of smaller modules. As an example, a 70 MW FPV system in China consists of multiple rafts with a total of 195 000 panels, covering 63 ha of freshwater, and produces sufficient energy to power about 20,000 homes [46].

Commercial FPV was developed for calm freshwater conditions, such as hydropower dams, reservoirs, and abandoned mines but given the tremendous solar resource at sea, the FPV technology is currently moving offshore [45], [47]. Industry is developing marine FPV systems for near-shore and oceanic environments and trying to overcome the challenges of saltwater corrosion and the harsh weather conditions at sea [48]. Current technology can withstand significant wave heights of up to 4 meters, but even higher tolerance will be needed for the technologies to be widely used at sea. As a result, the technological readiness level of marine FPV can be considered pre-commercial. See Figure 5 for a schematic illustration.

Without accounting for synergies from any hydropower output, freshwater-based FPV is typically slightly more expensive than land based PV. FPV systems currently have LCOE from $0.06 - $0.11 per kWh and are reducing [45], [48]. At optimal conditions, FPV may be fully competitive to land based PV but deployment at sea means more advanced technology and higher costs. However, a planned 5 MW marine FPV in the Seychelles is rated at a competitive $0.10 per kWh.

The African continent has high insolation and plenty of opportunities to combine FPV with hydropower. In a recent study, Gonzalez Sanchez et al. [49] estimates that the pan-African hydropower output could be increased by >50% just by covering 1% of the dams with FPV. The potential for ordinary land-based PV is enormous in most countries. Therefore, marine FPV may only become a rational choice under very specific conditions, even once the marine FPV technology is mature. Such conditions may be likely to occur at heavily populated islands with sheltered nearshore waters [48].

Assessment criteria

The entire African continent has sufficient irradiation for PV systems. But like any floating structure, FPV shadows the ocean bottom. At sea, large-scale FPV will cover several hectares and hinder photosynthesis for marine life below, which in shallow waters will have a detrimental effect on algae, corals, and seagrass meadows. Such impacts on coastal ecosystems would have socio-economic consequences for nearby communities and are unlikely to comply with environmental standards. Therefore, marine applications of FPV may only be relevant at deep water where direct photosynthesis plays a reduced role for biodiversity and ecosystem services. For these reasons, a minimum depth of 40-50 meters has been used as a criterion in this paper when addressing FPV site availability as a basis for the technical potential. Without this premise, the potential for marine FPV would be much higher than reported here, but often at the expense of local environment. Exceptions exist, such as the opportunities of exploiting already deprived shallows around industrial harbors, but this very specific condition has not been included in the analyses.

International

The technology has been successfully used for several years, most strikingly in China and Japan but also in other parts of Asia, Europe, Oceania, and Latin America [46], [50]. African countries are considered to have great potential for hydropower-FPV hybrids [48], [51], [52]. The continent has, to the knowledge of the authors, so far only seen a small FPV system on a vineyard in South Africa [53].

Globally, marine FPV is not nearly as common as freshwater FPV given the technical challenges. A 96 kW FPV was deployed in 2016 at a remote island in the Maldives and larger systems are underway[G]. The Seychelles is currently launching a 5 MW marine FPV in the le Rocher lagoon, producing 5.8 GWh annually, corresponding to about 2% of expected national consumption[H]. The array will cover 40,000 m2 and use 13,500 solar panels. It is reported that large scale marine FPV is also planned elsewhere in eastern Africa [50].

[G] See web page https://swimsol.com/

[H] See web page https://www.pv-magazine.com/2020/04/02/seychelles-to-host-5-8-mw-of-floating-pv/

4. RESOURCE ABUNDANCE AND TECHNICAL POTENTIAL

This chapter addresses resource distribution and potential across Africa. Where available, assessments of the physical resource are provided to give an idea of the theoretical magnitude and spatial patterns. The technical potential, how much energy we could possibly harvest with the available technology, has been assessed using openly available data and scientific literature. Results are indicative because the uncertainties are large.

4.1 WAVE POWER POTENTIAL

Theoretical potential

The instantaneous wave power resource of African waters has previously been estimated to be 324 GW [54] or 422 GW [55]. Table 2 shows how this estimate is distributed across the continent.

TABLE 02

Accumulated theoretical wave power resource in African water, disregarding areas with energy densities below 5 kW/m. Adopted from Mørk et al. [55].

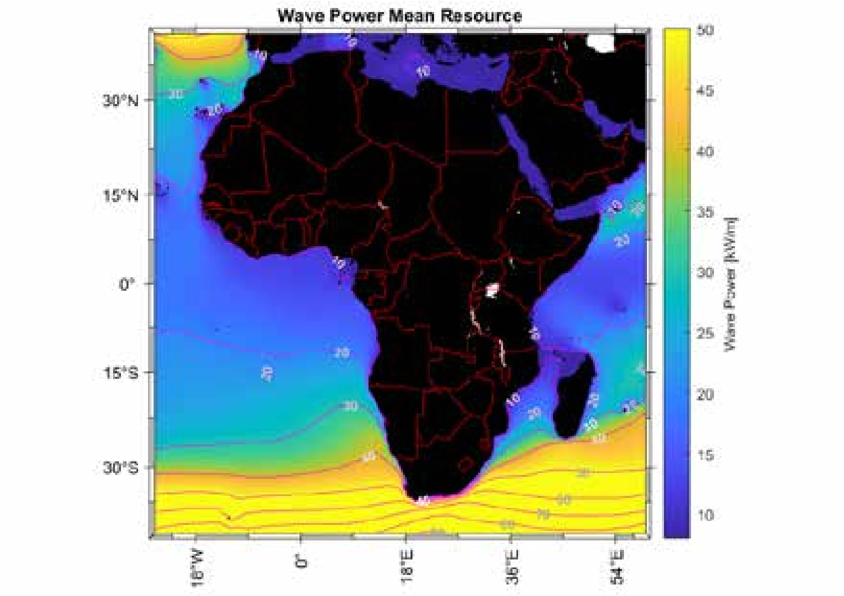
Region	Theoretical wave power resource
North Africa	40 GW
West and Central Africa	77 GW
Southern Africa	127 GW
East Africa	178 GW

The World Energy Council recently estimated Africa’s theoretical potential for wave energy to reach a total of 3500 TWh per year [27]. The highest resource density is found at subtropical latitudes in the south and north-west. Equatorial Africa and the sheltered Red Sea and Mediterranean have relatively low wave energy densities. See Figure 7.

Fairly et al. [25] recently classified wave power resources on a global scale, based on detailed wave and climate characteristics. South Africa was classified as having ‘high-energy coastlines influenced by long period swell and storm conditions’. Atlantic countries from Morocco to Liberia along with the Comoros, Madagascar and Southern parts of Mozambique were classified as having ‘moderate-energy coastlines primarily influenced by long distance swell.’ Equatorial West Africa and Central Africa were classified as having ‘moderate energy with influence of local storms’.

FIGURE 07

Overview of wave power resource density around the Arican continent



Technical potential

Moving from theoretical to technical potential for wave power is a fundamental step that ideally should also take specific site characteristics and technical performance into consideration. Such details have not been fully incorporated to this background paper. Gunn & Stock-Williams [54] estimated that around 4% of the African theoretical wave energy resource might be technically available. This calculation was based on the technical specifications of a specific wave energy converter (WEC) designed for high-energy environments and consequently disregarded the energy available in milder, yet extractable, wave climates in equatorial waters.

The coastal wave resource presented in Figure 7 and Table 2 provides an indication of the technical potential across Africa[i]. The most powerful wave climate is found in South Africa, Namibia, Mauritius, and Madagascar. Other locations with high potential for wave power (above 15 kW/m) are found in Cabo Verde, Morocco, Mozambique, Somalia, and Senegal. Many of the tropical countries have calmer but still good wave power conditions (≥8 kW/m). With the right type of WEC that targets a lower energy density, these milder wave climates might become of particular interest because of the lower stress on equipment [25], [26].

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[i] Since these data are derived from remote sensing and not based on local measurements the numbers may be considered high-end estimates

Despite the promising conditions across the continent, many locations will be inappropriate for developments due to bathymetry (ocean depth), coastal morphology, or inaccessibility. Detailed assessments of technical potential must be based on a good understanding of the local geography as well as local wave climate, variability, and seasonality. Since wave energy converters (WECs) have different working principles it is also necessary to carefully select the most appropriate technology to best address the power output in a given location as each WEC's efficiency is impacted by the conditions in which they operate.
The scientific literature on wave power potential in Africa waters shows that wave energy in many countries has been thoroughly investigated. These studies typically take into consideration technology performance, temporal variability, and sometimes site-specific measurements. Considerable technical potentials have been identified for locations in South Africa [56], Morocco [57], Cabo Verde [58], [59], and Mauritius [60]. In a recent study focusing on the intra- and inter-annual variations of wave energy in Indian Ocean, Kamranzad et al. [61] concludes that Somalia, Mauritius, La Réunion, southern Madagascar, and Mozambique all have suitable conditions.

The less powerful but reliable wave power resource of Benin has been noted [62] and it appears that, in general, moderate wave conditions around 8-15 kW/m may actually be more helpful for African wave power developers compared to high-energy locations where equipment suffers from aggressive wearing. Moreover, some studies have highlighted the technical potential for small-scale installations of WECs for the benefits of desalination in Africa, which would be feasible even at locations with relatively mild wave climate, for example Kenya and northern Madagascar [63], [64].

WAVE POWER

African coasts receive plenty of wave energy. The most powerful waves are in southern and eastern Africa, from Mozambique, southern Madagascar, and Mauritius to Namibia. South Africa has the most energetic waves. The long Somali coastline also has high potential, together with Senegal, Cabo Verde, and Morocco on the Atlantic coast. Other parts of western and northern Africa have good potential with lower but reliable wave power. São Tomé and Príncipe and the Congo Republic in Central Africa, along with tropical eastern Africa, also receive reliable swell. The moderate low-risk wave climate is likely to be preferable to many developers.

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https://www.ocean-energy-systems.org/ocean-energy/gis-map-tool/

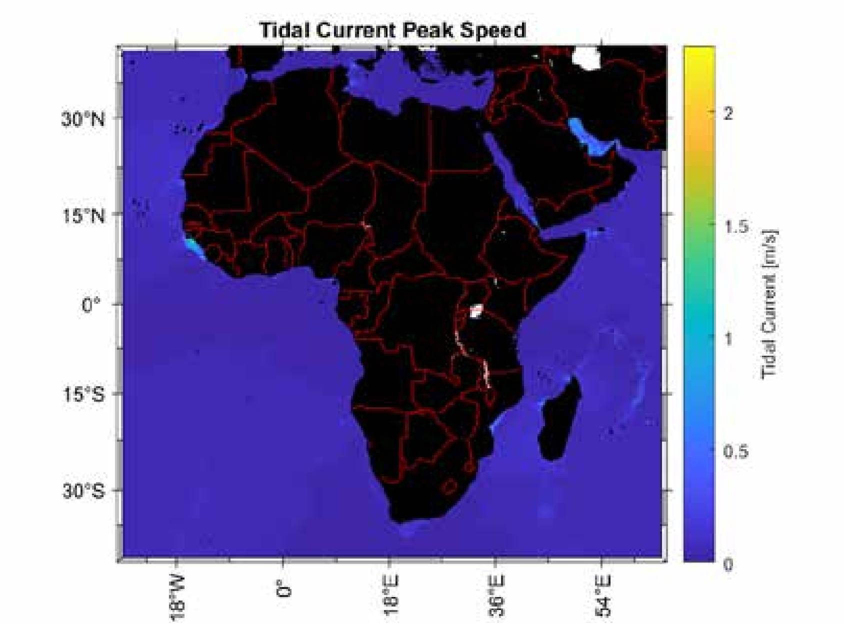
4.2 TIDAL POWER POTENTIAL

Theoretical potential

Because of the strong dependence on site conditions, there are no reliable estimates of global or African theoretical potential for tidal stream power. Given that Africa does not possess globally remarkable tides, the tidal power potential is likely to be insignificant at most locations[J]. Some scattered hotspots nevertheless exist in eastern and western Africa where the semidiurnal tidal amplitude is higher than elsewhere. Figure 8 illustrates tide-influenced current patterns across Africa.

FIGURE 08

Overview of tide-influenced currents around the African continent. Peak currents develop during ebb and flood at spring tide



Technical potential

Based on available data from multiple sources, Table 3 showcases modeled and occasionally measured tidal current speeds. These data can be used as a rough indication of technical potential. Water speeds corresponding to moderate technical potential are found at specific locations in Kenya, Tanzania, Mozambique, Guinea, Guinea-Bissau, and Morocco.

Even at sites with sufficient tidal streams the extractable resource may be limited by coastal morphology and bottom structure. Also, it is typically assumed that only 10% of the available energy can be extracted to minimize

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[J] As a point of reference, the tidal stream potential of Europe has been estimated to 48 TWh/yr distributed over 106 sites predominantly around the British islands (WEC 2016).

TABLE 03

Indicative technical potential for wave power across coastal Africa[#1]

Country / Territory	Technical potential * [#2]	Hotspots	Near-shore wave power (kW m-1)[#2]
EASTERN AFRICA			
Sudan	-	Suakin	2
Eritrea	-	Dahlak	2
Djibouti	-	Djibouti	1
Somalia	High	Ashira, Xaafuun, Bandarbeyla, Eyl	18, 18, 16, 14
Kenya	Good	Kilifi, Lamu	7, 8
Seychelles	Good	Outer islands	12
Tanzania	-	Mafia Island	5
Comoros	-	Grande Comore	4
Madagascar	High	Faux Cap, Ambalade, Toamasina	35, 15, 10
Mauritius	High	Troux-aux-Biches, Le Morne, Ilot Brocus	28, 33, 34
SOUTHERN AFRICA			
Mozambique	High	Ponta do Ouro, Inhaca Island, Chidenguele, Tofo-Zavora	18, 13, 12, 16
South Africa	High	Port Nolloth, Cape Town, Cape Agulhas, Jeffreys bay	27, 40, 40, 36
Namibia	High	Oranjemund, Luderitz, Walvis Bay	33, 30, 34
Angola	Good	Namibie, Tombua	11, 11
CENTRAL AFRICA			
DR Congo	-	Nsiamfumu	7
Congo Republic	Good	Baie de Banda	9
Gabon	-	Port Gentil	7
São Tomé and Príncipe	Good	São Tomé	12

Equatorial Guinea	-	Malabo, Cabo San Juan	7, 6
Cameroon	-	Kribi	6
WESTERN AFRICA			
Nigeria	Good	Lagos-Lekki	8
Benin	Good	Cotonou	8
Togo	Good	Lome	8
Ghana	Good	Adah Foah, Akwidaa	10, 10
Côte d'Ivoire	Good	San Pedro, Abidjan	10, 10
Liberia	Good	Monrovia	10
Sierra Leone	-	Freetown	7
Guinea	-	Guinea	4
Guinea-Bissau	-	Guinea Bissau	4
Senegal	High	Dakar	16
Gambia	-	West coast	6
Cabo Verde	High	Santo Antão, Ilha do Sal	20, 20
NORTHERN AFRICA			
Mauritania	Good	Nouadhibou	12
Morocco	High	Agadir, El Jadida, Safi, Guerguerat, Lagouira	23, 16, 16, 12, 12
Algeria	Good	Jiel-Collo, Cap de Fer	6, 8
Tunisia	-	Cape Serrat	6
Lybia	-	Al Bayda	4
Egypt	-	Baltim	2

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[*] Based on wave power at hotspots [#1] Information sources supporting this table: Institut français de recherche pour l'exploitation de la mer [65]; European Centre for Medium-Range Weather Forecasts [66]. [#2] Technical potential categorized by annual average wave power close to shore (<10 km) and at shallow depth (<50 m): High (>15 kW m-1), Good (8-15 kW m-1).

environmental impact. Furthermore, the technical conversion efficiency delimits the available resource since all kinetic energy cannot be converted to electricity. Cut-in speeds around 0.7 m/s and conversion efficiencies of 0.35-0.5 have been reported [23], [28].

Importantly, the current speed at any location varies between maximum speed and zero several times per day because of the semidiurnal tidal cycle. This means that tidal power output from a single location varies and is often zero, which has implications for tidal stream contributions to small grids or off-grid applications [28]. Still, some loads such as battery charging, and desalination can be suitable even where power output is variable.

There are few scientific studies on the potential for tidal stream power in Africa. Kharrich et al. [67] finds that most investigated locations in Morocco have currents which are much too weak for energy extraction. However, Nachtane et al. [68] highlights the strong currents of northern Morocco (near the Strait of Gibraltar) as having good potential for tidal stream power. For Mozambique, Hammar et al. [28] report that investigated sites have limited potential, but also argues that some locations could offer enough power for useful application in rural communities, if capital costs are low and maintenance carried out locally. Similar conclusions are drawn for eastern Africa based on a review of existing data [23]: sites with sufficient tidal streams exist but are rare. Amoo [69] evaluates the suitability for tidal stream power in Nigeria and reports several locations with sufficiently strong currents, however, the extraordinary data may need further validation.

In summary, the sparse available data from African tidal streams do not indicate great resources, but with more sampling interesting locations may still emerge. For instance, Guinea-Bissau may have hidden potentials, based on local tidal-range data and coastal morphology.

TIDAL STREAM POWER

The potential for tidal power in Africa seems low. It appears unlikely that the scattered resources will support larger tidal power developments. Sufficient current speeds have been reported from a few locations in Kenya, Tanzania, Mozambique, Guinea, Guinea-Bissau, and Morocco. Validations of these data would be needed. The strong site-dependence of tidal currents makes it difficult to obtain reliable data without numerous current speed measurements.

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https://www.ocean-energy-systems.org/ocean-energy/gis-map-tool/

TABLE 04

Indicative technical potential for tidal stream power across coastal Africa #1 *.

Country / Territory	Technical potential ** #2	Hotspots	Near-shore wave power (kW m-1)#2
EASTERN AFRICA			
Kenya	Moderate	Watamu, Mobass	2.5, 3.5
Tanzania	Moderate	Kunduchi, Dar es Salaam, Mbudya	3.5, 1.7, 1.5
SOUTHERN AFRICA			
Mozambique	Moderate	Montepuez Bay, Bazaruto Island, Inhaca Island	2.5, 1.5, 1.5
South Africa	Restricted	Cape Morgan, East London	1.5, 1.5
WESTERN AFRICA			
Nigeria	Restricted	Lagos	1.8
Benin	Restricted	Cotonou channel	1.8
Sierra Leone	Restricted	Turtle Islands	1.5
Guinea	Moderate	Boke, Conakry-Bintimodiya	2, 1.5
Guinea-Bissau	Moderate	Bissagos Islands, Tombali, Bissau	2, 2, 1.5
NORTHERN AFRICA			
Mauritania	Restricted	Nouamghar-Iwik	1.5
Morocco	Moderate	Tangier	2

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* Note that reported speeds may be partially influenced by rivers and oceanic currents, in addition to tides. ** Based on current maximum speeds hotspots #1 Information sources supporting this table: All – E.U. Copernicus Marine Service Information [70]; Mozambique, Kenya – Hammar et al. [23]; Kenya – Onundo & Mwema [71]; Tanzania – Ngusaro [72]; Nigeria – Amoo [69]; Morocco – Alaoui [73]. Note that the tidal component of flows may not always be entirely separated from river flow and oceanic currents. #2 Technical potential categorized by reported current speed maximum values: Moderate (≥2 m s-1), Restricted (≥1.5 m s-1).

4.3 OCEAN CURRENT POWER POTENTIAL

Theoretical potential

Secure estimates of the African potential for ocean current power is lacking but the Somali-Agulhas Current system, from Somalia to South Africa, doubtlessly provides potential (Figure 9). To lesser degree, the Guinea Current also offers seasonal current energy in western Africa.

Technical potential

As indicated in Table 4, the fastest and most consistent nearshore water speeds are found in Somalia, at southern (Kismayo to Mogadishu) and northern (Puntland) locations, and in south-eastern South Africa. These areas seem to have a high technical potential for ocean current power. The Somali-Agulhas system may also provide a moderate technical potential in Kenya, Tanzania, northern Madagascar, northern Mozambique. Elsewhere, sufficient conditions may also be found suitable in Guinea-Bissau, and possibly in Guinea, and in Morocco by the Strait of Gibraltar.

Despite the promising conditions in eastern and southern Africa, the technical constraints of ocean current power are still substantial. Technologies for harvesting this resource are still in an early development stage and it is difficult to assess their technical potentials even at large orders of magnitude. Most sites with strong currents are also in deep water. The powerkite device, which can harness relatively slow currents, is moored to the sea bottom and may not be deployed of the continental slope. The combination of strong flows and relatively shallow depth will define the potential for ocean current power. On the other hand, long stretches of strong currents in combination with a homogeneous bottom slope seem available in Somalia. Site-specific studies could reveal the opportunities more accurately.

The relatively continuous flow of the Somali current suggests a strong potential in this region. In contrast, the Guinea current in western Africa varies seasonally and much of the year the water flow is too slow to utilize, which obviously lowers its technical potential.

Few scientific studies address ocean current power development in Africa. Francisco et al. [63] propose that the currents off south western South Africa could be feasible for power desalination plants supporting local communities. A data overview by Hammar et al. [23] indicates further potential for ocean current power in Kenya, northern Mozambique, and Somalia.

OCEAN CURRENT POWER

Oceanic currents near land are available from the Somali-Agulhas Current system along the African coast of the Indian Ocean. Somalia and South Africa have the best conditions. Suitable current speeds may also exist in Kenya and at scattered locations in Tanzania, Madagascar, and Mozambique.

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https://earth.nullschool.net/

FIGURE 09

Overview of ocean currents. Annual mean speeds are shown, but seasonal differences can be substantial

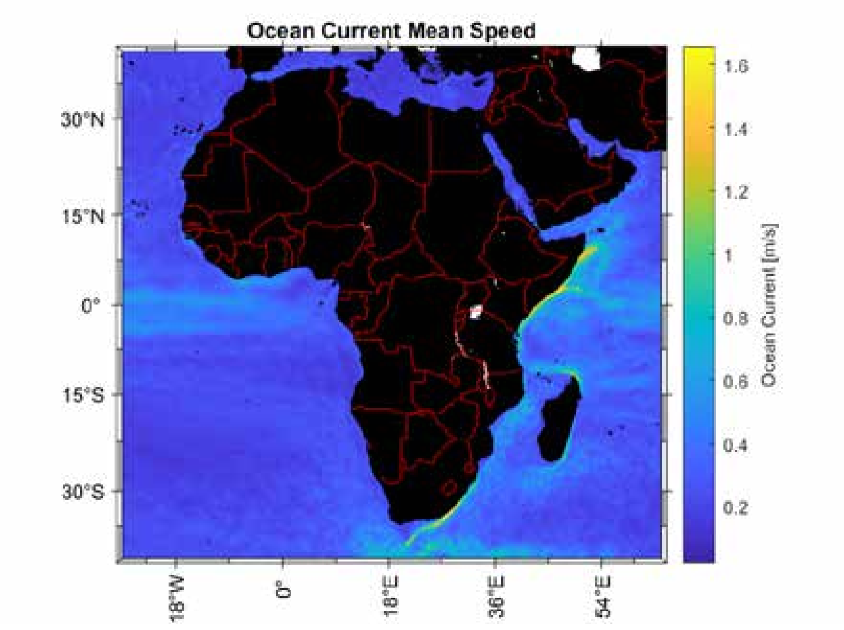

TABLE 05

Indicative technical potential for ocean current power across coastal Africa [#1].

Country / Territory	Technical potential * [#2]	Hotspots	Near-shore wave power (kW m-1)[#2]
EASTERN AFRICA			
Somalia	High	Mogadishu, Puntland	2, 1.8
Kenya	Moderate		1.9
Tanzania	Moderate	Pemba, Mafia	1.5, 1.3
Madagascar	Moderate	Antisiranana, Taolanaro	1.8, 1.4
SOUTHERN AFRICA			
Mozambique	Moderate	Cabo Delgado	1.4
South Africa	High	Durban-Coffee Bay	2
Western Africa			
Ghana	-	-	1
Côte d'Ivoire	-	-	0.8
Liberia	-	-	0.8
Guinea-Bissau	Moderate	Bissagos Islands	1
NORTHERN AFRICA			
Morocco	Moderate	Tangier	2

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* Based on current speed and abundance [#1] Information sources supporting this table: All – E.U. Copernicus Marine Service Information [70]; South Africa – Rouault et al. [74]; Kenya – Hammar et al. [23]; Kenya – Onundo & Mwema [71]; Tanzania – Semba et al. [75]; Morocco – Alaoui [73]. [#2] Technical potential categorized by annual average current speed: High (larger stretches with ≥1.5 m s-1), Moderate (limited areas with ≥1.5 m s-1 or larger areas with >1 m s-1).

4.4 OTEC POTENTIAL

Theoretical potential

Heat gradients exceeding 20°C are widespread across the tropics apart from upwelling zones, where deep cold water rises to the surface. In global comparison the highest temperature difference, and thus the greatest potential for OTEC, is found in the western Pacific (where the temperature difference is >24 °C). The global OTEC resource is around 120,000 TWh/yr [7] and it is believed around 25% could be extractable without altering oceanic temperature fields [76]. By a large margin, OTEC carries the highest resource potential among ocean energy sources [7]. There is no exhaustive assessment of OTEC resources for the African continent, but the potential is clearly significant [27], [77].

The Gulf of Guinea, with equatorial western and central Africa, offers good OTEC conditions even in global comparison, as the heat gradient annual average exceeds 22°C. In this area, however, the continental slope is rather far from shore, in the Exclusive Economic Zones. Corresponding gradients may also be found at some locations in African Indian Ocean.

Technical potential

Based on the heat gradient between the surface and deep water, the potential for floating OTEC is high along the African west coast from Guinea to Gabon. For instance, Adesanya et al. [36] recently performed an economic analysis of the OTEC potential in Nigeria, finding that conditions are suitable for viable development of floating 100 MW OTEC plant which would return investment costs within 15 years. However, in this part of Africa, only Equatorial Guinea, San Tomé and Principe have access to the heat gradient resource from land, enabling land based OTEC.

In eastern Africa, temperature gradients are not as large, but some nearshore locations have steady differences of at least 22° C, which suggests good OTEC potential. Therefore, Comoros, Seychelles, and Mozambique have indications of high technical potential for land based OTEC (Table 5, Figure 10). Several countries have more moderate potential, either because of lower heat gradient or based on the distance to land. The OTEC potential in this region has previously been reviewed by Hammar et al. [23].

While coarse data indicate that Mauritius has only a moderate heat gradient but a remarkable proximity to land, a specific study on OTEC in south-western Mauritius deems conditions to be very suitable. According to Singh Doorga [78], a land-based 95 MW OTEC would return investment costs by a factor of four at this location.

OTEC may be designed to produce fresh water as by-product, to be used for agriculture or human drinking water consumption. This is more feasible for land based solutions and may be an important component for the economic viability of OTEC in arid parts of Africa.

OTEC

The theoretical potential of OTEC is enormous, but much of the resource hides far offshore and it remains unclear whether the OTEC technology will become sufficiently economically competitive. Several locations in eastern Africa currently meet requirements for land based OTEC. The Seychelles and Comoros have the best conditions and probably the highest technical potential for OTEC in Africa. Good conditions are also found in northern Mozambique. Western Africa has high technical potential for floating OTEC, which implies finding ways to meet the challenges of transporting electricity and fresh water produced to users on land.

RECOMMENDED MAP SERVICE FOR OVERVIEW

https://www.ocean-energy-systems.org/ocean-energy/gis-map-tool/

FIGURE 10

Land-based Ocean Thermal Energy Conversion (OTEC) requires access to both warm surface water and cold deep water close to shore. A depth of 1000 m within a few kilometers offshore might be required. Such conditions are often found at remote tropical islands.

TABLE 06

Indicative technical potential for OTEC across coastal Africa [#1.]

Country / Territory	Tech. potential[*#2]	Hotspots	Heat gradient Δ (°C)	Dist. to shore (km)	Potential capacity (MW)[**]
EASTERN AFRICA					
Seychelles	High	Desroches Island, Poivre Island, Coetivy Island	22, 22, 23	3, 3, 3	101, 101, 105
Tanzania	Moderate	Kilwa, Lindi	22, 22	8, 9	98, 89
Comoros	High	Anjouan, Grande Comore, Moheli, Mayotte	22, 22, 22, 22	2, 2, 5, 6	106, 93, 84, 107
Madagascar	Moderate	Andranovondronima, Masondrono, Ampondrabe, Vohemar, St Augustin	22, 21, 22, 21, 20	6, 8, 9, 9, 8	92, 94, 109, 93, 84
Mauritius	Moderate[#3]	Mauritius	20	1	86
SOUTHERN AFRICA					
Mozambique	High	Nacala, Memba, Calajulo, Matibane, Pemba, Quisiva Island	22, 22, 21, 22, 22, 22	3, 4, 5, 6, 8, 8	101, 100, 89, 100, 99, 102
Angola	-	-	20	>10	-
CENTRAL AFRICA					
DR Congo	-	-	20	>10	-
Congo Republic	-	-	20	>10	-
Gabon	-	-	21	>10	-
São Tomé and Prince	Moderate	São Tomé Principe	21 22	3 6	99 109
Equatorial Guinea	Moderate	Malabo Annobón	22 20	7 5	105 76
WESTERN AFRICA					
Nigeria	-	Offshore	23	>10	***
Benin	-	Offshore	23	>10	***

Togo	-	Offshore	22	>10	***
Ghana	-	Offshore	23	>10	***
Côte d'Ivoire	-	Offshore	23	>10	***
Liberia	-	Offshore	23	>10	***
Sierra Leone	-	Offshore	23	>10	***
Guinea	-	-	21	>10	-
Guinea-Bissau	-	-	20	>10	-
Cabo Verde	Moderate	Ilha Brava Ilha do Fogo Ilha de Santiago	20 20 20	7 4 4	76 70 71

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[*] based on heat gradient and distance to shore ** for land-based OTEC *** High potential for floating OTEC [#1] Information sources supporting this table: MHK Atlas [79]; GEBCO [80]. [#2] Technical potential categorized by heat gradient and distance from shore: High (ΔT ≥22 °C AND ≤5 km), Moderate (ΔT ≥20 °C AND ≤5 km OR ΔT ≥22 °C AND >5 km). [#3] Conditions might be economically viable according to site-specific study [78].

4.5 OFFSHORE WIND POWER POTENTIAL

Theoretical potential

The gross offshore wind energy resource in African waters has been estimated to be 27 TW, based on installed capacity of 3 MW turbines per km2 [41]. In brief, sufficient wind speed conditions occur in north Africa, east Africa and southern Africa and near surface wind conditions across the coast of Africa have been scrutinized by Olaofe [81], who concludes that southern Africa has excellent conditions for offshore wind power which has been strengthened by recent global climatological changes, with local drifts and particular along Africa's south east coast.

Technical potential

According to a study by Elsner [41], based on satellite data[K], the technical offshore wind energy potential of the African continent is around 2,400 TWh/year for near-coast wind power (based on current technology, down to 50m depth) or 11,000 TWh/year based on future technology with floating wind power (800m depth). Results from Elsner's pan-African analysis, which are available for each country in that paper, point at significant near-coast offshore wind power potential for two thirds of all African coastal countries. The analysis reveals particularly good offshore wind power conditions in Mozambique, South Africa, Somalia, Madagascar, and Morocco.

[K] Wind data derived from satellite data (BSW Blended Sea Winds data set) tend to slightly overestimate the actual wind speed.

Country-specific reports of technical potential for offshore wind power are available for selected countries [44]. Their summary report states that sub-Saharan Africa has a strong potential for offshore wind (2.3 TW) while northern Africa has a moderate wind resource. In both cases however, most of the resource is in deep water that would require floating foundations. Country-specific numbers are provided in Table 6. Based on wind speed data from these reports and the Global Wind Atlas [82], the technical potential for offshore wind power is high (≥ 10 m/s wind speed average at 100 m altitude) in Madagascar, South Africa, Namibia, Eritrea, Somalia, Mauritania, Cabo Verde, Morocco, and Egypt. Moderate potential (based on wind speed averages from 8 m/s) is found in Mozambique, Djibouti, Sudan, Kenya, Mauritius, Angola, Senegal, Algeria, Tunisia, and Libya. The scientific literature contains few country-specific studies but the existing analyses point at suitable conditions for offshore wind power in Benin [83] and in Egypt [84], [85].

It is important to note that sources for offshore wind power potential provide different results for given countries because of different assumptions and data quality. Nevertheless, there is no doubt that coastal Africa holds strong potential for offshore wind power. In several regions the potential may play important roles for regional power pools, as will be discussed in chapter 6.

OFFSHORE WIND POWER

Coastal Africa has a mix of suitable wind conditions in all directions except in tropical latitudes. The strongest winds are in southern Africa, in the north-west and north-east. The technical potential exists for many countries but in most cases the onshore wind potential is high as well.

RECOMMENDED MAP SERVICE FOR OVERVIEW

https://globalwindatlas.info/

TABLE 07

Indicative technical potential for offshore wind power across coastal Africa [#1].

Country / Territory	Tech. potential[*#2]	Essential wind speed range[**]	Total potential capacity per foundation type[***]	Hotspots
EASTERN AFRICA				
Sudan	Moderate	6-9	-	Aqiq
Eritrea	High	4-10	Fixed 27 GW Floating 35 GW	Southern Red Sea
Djibouti	Moderate	5-9	Fixed 27 GW Floating 35 GW	Obock, Lake Ghoubet
Somalia	High	7-10	Fixed 63 GW Floating 268 GW	Puntland, Southern coast
Kenya	Moderate	6-8	Fixed 9 GW Floating 34 GW	Kiunga – Kilifi
Seychelles	-	5-6	-	-
Tanzania	-	5-6	-	-
Comoros	-	3-5	-	-
Madagascar	High	6-10	Fixed 45 GW Floating 109 GW	Antsiranana –Antalaha, Androka – Tôlanaro
Mauritius	Moderate	5-8	-	Savanne
SOUTHERN AFRICA				
Mozambique	Moderate	6-8	Fixed 11 GW Floating 75 GW	Maputo, Xai-Xai
South Africa	High	7-10	Fixed 57 GW Floating 589 GW	Kwazulu Natal, South coast – West coast
Namibia	High	4-10	Fixed 19 GW Floating 701 GW	Lüderitz, Oranjemund
Angola	Moderate	4-9	-	Namibe

CENTRAL AFRICA

DR Congo	-	3-4	-	-
Congo Republic	-	3-4	-	-
Gabon	-	3-4	-	-
São Tomé and Príncipe	-	2-3	-	-
Equatorial Guinea	-	3-5	-	-
Cameroon	-	4-5	-	-

WESTERN AFRICA

Nigeria	-	4-5	-	-
Benin	Moderate[#3]	5-6	-	-
Togo	-	5-6	-	-
Ghana	-	5-6	-	-
Côte d'Ivoire	-	4-5	-	-
Liberia	-	3-4	-	-
Sierra Leone	-	3-4	-	-
Guinea	-	3-4	-	-
Guinea-Bissau	-	5-6	-	-
Senegal	Moderate	7-8	Fixed 13 GW Floating 32 GW	Dakar, Saint-Louis

Gambia	-	6	-	-
Cabo Verde	High	7-10	-	Santo Antão, São Vicente, São Nicolau, Brava, Fogo
NORTHERN AFRICA				
Mauritania	High	7-10	Fixed 91 GW Floating 84 GW	Dakhlet Nouadhibou
Morocco	High	6-10	Fixed 22 GW Floating 178 GW	Agadir-Safi, Tangier-Nador, Tan Tan
		8-10	Fixed 104 GW Floating 235 GW	Dakhla, Southern coast
Tunisia	Moderate	7-8	Fixed 90 GW Floating 169 GW	Tunis
Lybia	Moderate	7-9	Fixed 52 GW Floating 287 GW	Gulf of Sidra, Darnah
Egypt	High	6-10	Fixed 28 GW Floating 208 GW	Gulf of Suez, Berenice

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[*] based on wind speed ** (m s-1) at 100 m *** based on country reports [#1] Information sources for this table: Offshore Wind Technical Potential Country Reports [44]; Global Wind Atlas [82]. [2] Technical potential categorized by annual average wind speed at 100 m altitude: High (≥10 m/s), Moderate (≥8 m/s). High corresponds to IEC wind turbine class 1 (High Wind). Moderate corresponds to IEC wind turbine classes 2-3 (Medium-Low Wind). [#3] Suitable conditions for offshore wind power in Benin has been declared based on case-study [83].

4.6 FLOATING SOLAR POWER (FPV)

Theoretical potential

The insolation on African coastal and offshore waters provides an enormous theoretical potential for floating solar power. In theory, the resource is sufficient to power all coastal states with FPV. To fully cover the sea with solar panels would however neither be possible, legal, or desirable.

Technical potential

From a strictly technological viewpoint the technical potential for marine[L] FPV can be considered high in any sheltered nearshore[M] water along the African coast. This includes many bays, inlets, island leesides, and manmade shelters such as piers and harbor structures. The true technical potential is therefore large, provided that the equipment can resist the tough marine conditions.

[L] Marine FPV refers to solar power floating at sea, as opposed to the conventional FPV deployed in freshwater systems such as reservoirs, dams, or lakes.

[M] Even in sheltered waters it is important to have close access to shore because subsea cables are very costly.

To make the assessment more nuanced, the analysis presented in Table 7 also accounts for (A) environmental concerns, avoiding shallow waters where sensitive seabed habitats would be shadowed, and (B) disregards areas in proximity to uninhabited and unvegetated space on land (because it will probably always be more cost-effective to install PV on available land rather than the sea).

Based on this further prioritization most of the FPV hotspots are located in the east African tropical islands and archipelagos. In addition, some locations in São Tomé and Príncipe seem plausible, although irradiation is lower here than in other parts of Africa. If the issue of land use is disregarded, then many more suitable locations emerge, for example in Mozambique, Madagascar and several countries along the Red Sea and the Mediterranean.

The technical potential for freshwater FPV in Africa is undoubtedly extremely high. See Gonzalez Sanchez et al. [49] for country specific estimates of FPV-hydropower synergies.

FLOATING SOLAR POWER

All coastal Africa has sufficient insolation for solar panels. Opportunities for land and freshwater based PV are enormous. But floating PV at sea may only be relevant where other options are absent. According to this analysis, which also accounts for environment and land use rationale, such marine FPV mostly have potential among remote islands of the Indian Ocean.

TABLE 08

Indicative technical potential for floating solar power (FPV) across coastal Africa [#1].

Country	Tech. potential[#2]	Hotspots[#3]	Indicative irradiation value[1]	Indicative irradiation value[2]
EASTERN AFRICA				
Seychelles[#4]	High	Agalega	5.8	4.6
		Providence, Farquhar	5.9	4.7
Tanzania	High	Pemba Zanzibar	5.5	4.3
		Mafia	5.8	4.6
		Mtwara	5.8	4.6
Comoros	High	Grande Comoro	5.3	4.2
		Anjouan	5.2	4.1
		Moheli	5.2	4.2
Madagascar	Moderate	Sainte-Marie	5.2	4.2
Mauritius	High	East coast	5.4	4.3
SOUTHERN AFRICA				
Mozambique	Moderate	Quirimbas	6.0	4.7
CENTRAL AFRICA				
São Tomé Príncipe	Moderate	Príncipe	4.7	3.7

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[1] GTIopta (kWh m-2 day^{-1}) [2] PVOUT^{GlobalSolarAtla}s (kWh/kWp day^{-1})

#1 Information sources supporting this table: Global Solar Atlas [86]; GEBCO [80]; Google Earth. [#2] All of Africa has enough insolation for FPV but technical potential is categorized based on locations fulfilling site-specific technical, socio-economic, and environmental conditions required for the technology to constitute a relevant alternative. Categories: High (many locations); Moderate (few locations). Note that the actual technical potential of FPV in Africa is much higher than shown here. [#3] Required hotspot conditions: Sheltered water (bay/fringe/lagoon) AND depth >50 m AND proximity to land (<5 km) AND scarcity of unbuilt and unvegetated land. [#4] Seychelles are currently planning a 5 MW FVP at a populated lagoon site at the main island Mahe.

4.7 SUMMARY OF TECHNICAL POTENTIAL

The indicative technical potential for different offshore renewables in African waters is summarized in Table 8. See also Figure 1 for an overview of hotspots.

TABLE 09

Summary of indicative technical potential for different offshore renewable energy sources per country, based on the assessments in chapter 4.

Country Territory	Wave power	Tidal power	Ocean current power	OTEC	Offshore wind power	Marine FPV
Tech. readiness	Pre-commercial	Pre-commercial	Demonstration	Pre-commercial	Commercial	Pre-commercial
EASTERN AFRICA						
Sudan	-	-	-	-	Moderate	-
Eritrea	-	-	-	-	High	-
Djibouti	-	-	-	-	Moderate	-
Somalia	High	-	High	-	High	-
Kenya	Good	Moderate	Moderate	-	Moderate	-
Seychelles	Good	-	-	High	-	High
Tanzania	-	Moderate	Moderate	Moderate	-	High
Comoros	-	-	-	High	-	High
Madagascar	High	-	Moderate	Moderate	High	Moderate
Mauritius	High	-	-	Mod. or High	Moderate	High
SOUTHERN AFRICA						
Mozambique	High	Moderate	Moderate	High	Moderate	Moderate
South Africa	High	Restricted	High	-	High	-
Namibia	High	-	-	-	High	-
Angola	Good	-	-	-	Moderate	-
CENTRAL AFRICA						
DR Congo	-	-	-	-	-	-
Congo Rep.	Good	-	-	-	-	-
Gabon	-	-	-	-	-	-
São Tomé P.	Good	-	-	Moderate	-	Moderate

E. Guinea	-	-	-	Moderate	-	-
Cameroon	-	-	-	-	-	-
WESTERN AFRICA						
Nigeria	Good	Restricted	-	-	-	-
Benin	Good	Restricted	-	-	Moderate	-
Togo	Good	-	-	-	-	-
Ghana	Good	-	-	-	-	-
Côte d'Ivoire	Good	-	-	-	-	-
Liberia	Good	-	-	-	-	-
Sierra Leone	-	Restricted	-	-	-	-
Guinea	-	Moderate	-	-	-	-
Guinea-Bissau	-	Moderate	Moderate	-	-	-
Senegal	High	-	-	-	Moderate	-
Gambia	-	-	-	-	-	-
Cabo Verde	High	-	-	Moderate	High	-
NORTHERN AFRICA						
Mauritania	Good	Restricted	-	-	High	-
Morocco	High	Moderate	Moderate	-	High	-
Algeria	Good	-	-	-	Moderate	-
Tunisia	-	-	-	-	Moderate	-
Libya	-	-	-	-	Moderate	-
Egypt	-	-	-	-	High	-

5. AFRICAN GEOGRAPHY AND POWER SECTOR CONTEXT

5.1 CLIMATE AND COASTAL CHARACTERISTICS

Africa covers about one-fifth of the total land surface of Earth. The continent is bounded on the west by the Atlantic, on the north by the Mediterranean Sea, on the east by the Red Sea and the Indian Ocean, and on the south by the blended waters of the Atlantic and Indian Ocean. Africa's coastline is approximately 30,500 km, shared by 38 coastal countries, some with islands. The climate and the ocean dynamics have always been major forces shaping the coast, leading to gradual shoreline shifts over large distances. Africa can be divided in five subregions: (i) Eastern Africa; (ii) Southern Africa; (iii) Central Africa; (iv) Western Africa; and (v) Northern Africa. Each region has distinctive ecosystems and natural assets, and each is vulnerable to a degree to extreme weather and climate change. Climate variability and extreme events are among the key drivers affecting sub-Saharan Africa [87]. The coastal and marine environments of the African region are uniquely situated to serve diverse human needs for food, transport, and recreation. In some respects, the marine resources of Africa are less degraded than those of other continents [88] and the true potential for the Blue Economy is believed to be large [89] and largely unmapped.

Eastern Africa

The eastern African climate is diverse but typically equatorial, with high temperatures year round and little seasonal variation [87]. Characteristics of the region include frequently occurring severe drought and floods [90]. Local populations are heavily dependent on the rainfall which is in short supply in most of the region but with wide regional diversity. Rainfall is higher in the mountains and low in the north. Northern Somalia is one of the driest regions, with an average annual rainfall of just 130 mm whereas the southern coasts typically receive more than 1200 mm a year. There are two short rainy seasons: April-May-June (AMJ), and October-November-December (OND). Rainfall is strongly influenced by the Inter-tropical Convergence Zone (ITCZ) that streams low pressure around the equator [87]. El Niño years cause more rainfall in eastern Africa especially during AMJ. In contrast, La Niña generates drier than normal periods in the south [87]. Eastern Africa lies on the fringe of the West African and Indian monsoons both of which influence its rainfall and wind.

Southern Africa

Southern Africa is characterized by a warm climate, mostly above 17°C annual average. Rainfall has a considerable variation across southern Africa due to the influence of the ocean currents and prevailing winds. The majority of southern Africa has two distinct rain seasons – a wet season from November to March, and a dry season from April to October. Tropical cyclones make landfall on the coastlines of Madagascar and surrounding islands, Mozambique and occasionally South Africa, bringing significant rainfall and associated flooding. The average climate is determined by four main factors: (i) The position of the subcontinent in relation to the major circulation patterns of the southern hemisphere (quasi-stationary high-pressure systems); (ii) the migration of the Inter-Tropical Convergence Zone (ITCZ); (iii) the complex regional topography; and (iv) the influence of the warm Indian Ocean on the east coast and the cold Atlantic Ocean on the west coast – which brings higher and lower rainfall, respectively.

Coastal southern Africa is vulnerable to flooding because of sea-level rise, changes in winds and local wave regimes, coastal erosion and under-scoring, as well as a combination of extreme events such as sea storms during high tides [91]. Shoreline stability and ongoing erosion is affected by many processes and activities, some of which are natural and some of which are caused by anthropogenic drivers, resulting from human activities such as pollution [92]. The coastal ocean acidification also impacts the region. The upwelling in Benguela Current system along the west coast has a naturally lower pH (7.60 and 8.25), depending on the season [93]. Studies indicate that the climate-driven acceleration of the South Atlantic subtropical gyre is likely to intensify upwelling system Benguela [94]. Upwelling and ocean acidification are less intense by the Agulhas Current system along the east coast.

Central Africa

Central Africa has been considered one of the most important climatic regions in the world and the Congo Basin forms the largest water catchment in Africa. It is ranked as one of three global centers of thunderstorm activity [95] and has very high rainfall, 2000 mm in the north. Being connected with one of the major global convective systems and part of the large-scale air circulation that transfers warm air from the tropics towards the poles, the region has a large influence on climate and weather across Africa and the globe. Three peak rainfall periods are typical for the region: MAM (March-April-May), JAS (July-August-September) and OND (October-November-December). During rainy seasons, the Congo is the wettest place on Earth, responsible for adding 3.5 mm to global sea level each year [96]. The Congo rainforest is also a vital carbon store for the planet and is ranked as the second most critical forest for offsetting climate change [95]. The regional ocean climate is influenced by the differences in surface air pressure between the Atlantic and Indian oceans which drive an air circulation cell, causing more variable rainfall over southern central Africa [95]. Other oceanic key factors include pressure and sea surface temperature variations in the South Atlantic High, Atlantic, and Indian oceans, and as far away as the North Atlantic [97].

Coastal central Africa remains one of the most vulnerable regions to climate and human induced risks. The coastline, coastal communities, and infrastructures are increasingly at risk, including a possible risk to the adjacent Exclusive Economic Zone [98]. In addition to ecosystems already degraded or lost, several marine ecosystems are under threat from sea level rise and anthropogenic activities. Together, these pressures exacerbate coastal erosion, flooding, salinity intrusion in freshwater systems as well as habitat and ecosystem loss, with a high potential of multiplied effects in sectors such as health, administration, peace and security.

Western Africa

The climate across western Africa varies from arid desert in the north to humid tropical monsoon conditions along the southern coast. The Sahel region is semi-arid, extending from northern Nigeria in the east to Senegal in the west. The primary factors affecting the climatic conditions of western Africa include altitude, the proximity of the tropical Atlantic Ocean, the migration of the ITCZ, and the location of dominant atmospheric high and low pressure systems. The West African monsoon affects much of the region; it is driven by the alternation of winds from dry northeasterly winds from the Sahara to southwesterly winds that bring moist air from the warm topical Atlantic Ocean [99]. Most of the region receives the majority of rainfall in a single rainy season during April to September, coinciding with the northerly migration of the ITCZ, and experiences drier conditions from October to March. However, the coastal regions of Ghana and Cote d'Ivoire experience a two-peaked rainy season. Temperatures across the region are relatively high throughout the year. Southern coastal regions have low temperature variability, typically from 21°C to 30°C.

Northern Africa

Northern Africa is characterized, in general, by a hot and dry to very dry climate. The northern coast has a Mediterranean climate, which is marked by mild, wet winters and warm, dry summers, with ample rainfall of 400 to 600 mm per year. Inland, the countries of North Africa have semi-arid and arid desert climates. Along the coast, the rainy season typically runs from October to March or April. Torrential downpours during the rainy season can cause devastating flooding, and droughts occur frequently in the dry inland regions, sometimes lasting for years at a time. An important distinctive climatic feature of northern Africa is the sirocco, a hot, dry, southerly wind that occurs year round, generally lasting 10 to 12 hours. The winds originate over the Sahara Desert and blow north across the coast, over the Mediterranean Sea, and into southern Europe. Because siroccos flow from the desert, they typically contain large amounts of sand and dust that limit visibility and can damage machinery. Siroccos are caused by the west to-east progression of extratropical cyclones (low pressure systems) across the Mediterranean [100].

5.2 CLIMATE CHANGE: OPPORTUNITIES AND RISKS FOR OFFSHORE RENEWABLES

According to the Intergovernmental Panel on Climate Change (IPCC), “Africa is one of the most vulnerable continents to climate change and climate variability, a situation aggravated by the interaction of multiple stresses, occurring at various levels, and low adaptive capacity” [101]. For example, the IPCC projected sea level rise will increase the number and severity of coastal flooding events causing further severe damage to the coastal and marine environments and the resources and services they provide, and ultimately endanger coastal populations and economies.

Coastal infrastructure is at risk in 30% of coastal Africa, threatened by partial or complete inundation due to accelerated sea-level rise. Unfortunately inundation has been experienced by coastal settlements in the Gulf of Guinea, Senegal, Gambia, Egypt, and along the east-southern African coast. Sea-level rise threatens many coastal and marine ecosystems such as the lagoons and mangrove forests in most sub-regions of Africa, and will inevitably impact urban centers and ports. According to UN-Habitat, the major African cities at risk due to sea-level rise include Casablanca, Algiers, Alexandria, Mombasa, Dar-es-Salaam, Maputo, Durban, Port Elisabeth, Cape Town, Luanda, Douala, Lagos, Accra, Cotonou, Lomé, Abidjan, Monrovia, Conakry, and Dakar. Both observational data and global climate models show that the Indian Ocean is warming up due to global warming, with an average rise of 1.0 °C (0.15 °C per decade) during 1951–2015, over which period the global average sea surface temperature (SST) warmed about 0.7 °C (0.11 °C/decade) with high confidence. The SST and ocean heat content (upper 700 m) trends are highly likely to continue in the future, under different emission scenarios. Climate models project a rise in tropical Indian Ocean SST by 1.2–1.6 °C and 1.6–2.7 °C in the near (2040–2069) and far (2070–2099) future across greenhouse gas (GHG) emissions scenarios RCP4.5 and RCP8.5, compared with 1976–2005. Warm sea surface temperatures (SSTs >28 °C), occur over a large part of the tropical Indian Ocean (TIO, 40°E - 115°E; 30°S - 30 °N). This favors deep atmospheric convection [102] and intensifies the global atmospheric circulation, particularly the Hadley circulation and the Walker circulation thereby modulating the major elements of global climate such as the Indian monsoon and the El Niño Southern Oscillation (ENSO) among other patterns. The rate of warming in the tropical Indian Ocean is the fastest among tropical oceans and accounts for about one quarter of the increase in global oceanic heat content over the last two decades [103]. The expansion of the Indian Ocean warm SST>28 is changing the weather variability at sub-seasonal scale. This has direct influence on rainfall, particularly on extreme rain over the Africa continent. In addition, heat waves, droughts, floods, tropical cyclones, and extreme sea-level changes are becoming more frequent and intense around the Indian Ocean as regional climate patterns respond to anthropogenic climate change [104].

Even if the sum of these changes means more energy in the oceanic system around Africa, thus higher theoretical potential, the increased variability and associated coastal risks makes planning for offshore renewables increasingly challenging.

Ocean commitments following the Paris Agreement

Prior to the Paris Agreement, countries were encouraged to submit their strategies for reducing or mitigating greenhouse gas emissions and invited to communicate their undertakings in climate adaptation planning (the adaptation component) in their 'intended nationally determined contributions'. Renamed as Nationally Determined Contributions (NDC) after ratification and entry into the force of the Paris Agreement, NDCs set out the actions planned by countries pursuing shared global objectives to respond to climate change, including mitigation, adaptation, and other measures. In essence, this means striving to limit the rise in average global temperatures to well below 2°C above pre-industrial levels and ideally to 1.5°C during the present century [105]. Basically, most developing countries' NDCs comprise of conditional contributions, contingent upon international support, and unconditional contributions that the country intends to carry out regardless [106].

Offshore renewable energy can considerably support the expansion of renewable energy capacity, for coastal and island countries [107]. This can be applied just as much to the coastal and island countries of Africa, where offshore renewable energy represents opportunity to significantly expand renewable energy capacity. In fact, using such ocean based renewable energy carries the mitigation potential of a considerable amount of carbon dioxide, which could potentially meet African NDC commitments. NDCs can play a critical role in supporting the acceleration of offshore renewable development by sending clear, consistent signals to the industry, including signals to shape and stimulate further investment. This is particularly important for small island developing states attempting to lower the energy costs associated with importing liquid fuel [107].

Options for including ocean-based renewable energy in new or updated NDCs may include greenhouse gas (GHG) targets related to offshore renewable energy (capacity goals or contribution goals); development of area-based tools for synergies between offshore renewables and marine conservation; and the decarbonization of marine transport, freshwater production, and aquaculture through offshore renewables.

Climate associated risk

Climate induced extreme weather events and weather variations will inevitably affect both energy demand and the resilience of energy supply systems around the world [108]. Tropical cyclones are a dramatic component of global equatorial weather systems. On landfall, they frequently cause severe damage in adjacent countries. In Africa they pose major hazards along the central and northern coasts of Mozambique and Madagascar, along with Comoros and Mauritius, between November and April. Landfalls with storm winds, torrential rains, and coastal and inland floods take place on an almost annual basis, causing loss of life and property damage.

On average 12 cyclones affect the African mainland per year. They form in the southwest Indian Ocean (mainly between 10°-25°S) and represent approximately 15% of tropical cyclones globally. Some of these cyclones may be generated in the Mozambique Channel (15-20°S), or travel into the channel from the open waters east of Madagascar [109]–[111].

These tropical cyclones could damage or disturb offshore energy arrays or coastal infrastructure. Severe weather conditions accompanying cyclones are likely to interrupt operations as well as affecting power production. The specific potential impact of extreme events on energy systems has been difficult to quantify due to the unpredictability of the intensity of future weather events and the increase in destructive power due to climate change [108]. Southern Africa, and to lesser degree also other parts of the continent, also endures ordinary storms which in severe cases will prohibit access to energy installations and sometimes cause damage or interruption.

Special attention must be paid to the design and deployment of any offshore energy systems, and particularly so in any cyclone-exposed region. Recommended standards must be followed to secure operation and safety. It is reasonable to assume that equipment deployed at the surface is significantly exposed to storm risk, while systems deployed well below the surface are less at risk.

Other risks to both offshore and shore-based investments include erosion from sea-level rise, inundation (where land is permanently submerged), flooding (where dry areas become wet temporarily), and dusty winds, as described above exposed.

5.3 AFRICAN POWER SECTORS

The potential of offshore renewable energy must be viewed in the context of pre-existing power systems and currently used energy sources. The power sector of a country includes the functions of power generation, transmission, and distribution. In most of sub-Saharan Africa, all three power sector functions are being expanded to meet the development goals of electrification and industrialization.

Power generation

Power quality is essential, meaning that enough power must be available at any time of day and year to the population that needs it. Sufficient power infrastructure is an important component, but every large power grid also needs both a stable, continuous supply and high dispatchability, meaning that output can be quickly adjusted to meet changes in power load. Fossil fuel, hydropower, geothermal, and biomass all have high dispatchability, which is also a necessary enabler for using intermittent renewables like solar power, wind power and most offshore renewables.

African power generation is dominated by fossil fuel and some hydropower (Figure 11 and Table 9). By regional comparison, fossil fuels dominate in northern Africa, which also has higher generation than other regions, while hydropower contributes particularly to central Africa. Renewable energy sources other than hydropower currently contribute little to African power sectors, even if solar power, wind power, and biomass combustion are widely used at small scale. Kenyan geothermal power proves an exception, contributing more than a third of national power generation. Another exception is the substantial use of biomass combustion in Mauritius. Driven by fuel costs, energy security, and climate change policy, future investment in power generation will likely involve a greater proportion of renewable sources. As shown in Table 9, many African countries have ambitious goals for renewable power within the next 30 years, and natural resources are widely available.

Transmission and power trade

Power transmission is necessary to transport electricity over large distances, and for trading electricity between countries. African power sectors are interconnected, forming five regional power pools: Eastern Africa Power Pool (EAPP), Southern Africa Power Pool (SAPP), Central African Power Pool (CAPP), West Africa Power Pool (WAPP), Comité Maghrébin de l'Electricité (COMELEC). These power pools form energy markets necessary for energy security, business investment, and the inclusion of more intermittent renewable sources. The power pools undergo continuous development and, according to UNEP [6], SAPP currently has the most rigid infrastructure for efficient power trade. Trade and balancing between sources and loads in the wider power system are an important component of the potential for utilizing offshore renewables.

Micro-grid systems

Transmission is unfortunately costly to build and maintain, and always suffers losses of voltage. Many African countries have exceptionally high transmission losses. Off-grid electrification is the alternative, or complement, to long distance grid extension. Off-grid – or microgrid – systems occur in many rural areas and have an important role in the modern electrification of Africa, as they provide a less capital-intensive way of reaching remote communities and using local energy sources. Such microgrids have low capacities and intermittent sources such as offshore renewables must be very harmonized and aligned to load patterns. However, it is possible to adapt electricity loads to available power instead of the opposite [112]. In load-based control systems, power can be used for activities like water pumping and desalination when power is available.

Distribution and use

Electrification levels are high in northern Africa and most African island states. However, sub-Saharan mainland Africa and Madagascar have low to moderate access. Rural areas have exceptionally low access, because low population density makes distribution costly and for many other reasons provision is challenging [113]. The benefits of electricity are persuasive and there is little doubt that access to affordable electricity is a fundamental component of social and economic development. Available power must align with expected loads. Power is needed not only for lighting schools, hospitals, and homes, but also for industrial processes, agriculture, small business, communal infrastructure, and home cooking. This means that the output from offshore renewables should match the combined supply with the load pattern, which is particularly important where they would make proportionally large contributions to the power system.

FIGURE 11

This figure illustrates the sources of today’s power generation in regions of Africa, based on Table 9. The total generation is higher in northern (366 TWh) and southern Africa (257 TWh), and lowest in central Africa (22 TWh). Island states are included in the regions but also represented as a separate group (6 TWh) including Seychelles, Comoros, Mauritius, Madagascar, São Tomé and Príncipe, and Cabo Verde.

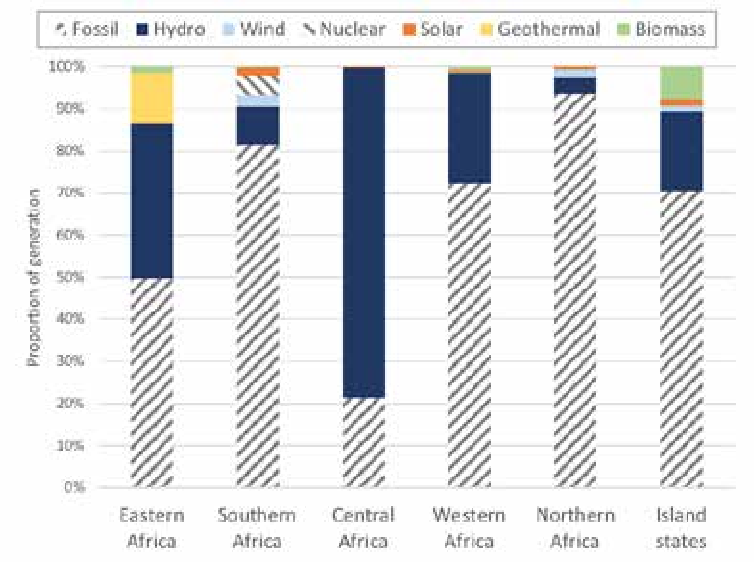

TABLE 10

AFRICAN POWER SECTOR CHARACTERISTICS [#1].

Country / Territory	Main sources of power (2018-2019)	Power access (2017)	Rural power access (2012)
	Source / capacity / generation		
EASTERN AFRICA			
SUDAN	Fossil 1745 MW 6301 GWh Hydro 1928 MW 9657 GWh Biomass 199 MW 118 GWh Solar 19 MW 20 GWh	56%	18%
ERITREA	Fossil 205 MW 419 GWh Solar 12 MW 19 GWh Wind 1 MW 2 GWh	48%	12%
DJIBOUTI	Fossil 123 MW 537 GWh Solar <1 MW 1 GWh	60%	13%
SOMALIA	Fossil 100 MW 350 GWh Solar 7 MW 11 GWh Wind 4 MW 6 GWh	33%	17%
KENYA	Hydro 837 MW 3355 GWh Fossil 750 MW 5205 GWh Geotherm 823 MW 5005 GWh Wind 336 MW 56 GWh	64%	<10
SEYCHELLES	Fossil 116 MW 417 GWh Wind 6 MW 7 GWh Solar 3 MW 5 GWh	100%	17%
TANZANIA	Fossil 1082 MW 5060 GWh Hydro 583 MW 1837 GWh Biomass 70 MW 143 GWh Solar 26 MW 46 GWh	33%	<10%
COMOROS	Fossil 22 MW 50 GWh Hydro 1 MW <1 GWh	80%	61%
MADAGASCAR	Fossil 622 MW 828 GWh Hydro 164 MW 998 GWh Solar 33 MW 23 GWh	24%	<10%
MAURITIUS	Fossil 610 MW 2483 GWh Biomass 91 MW 460 GWh Solar 83 MW 49 GWh Hydro 61 MW 125 GWh	98%	100%
SOUTHERN AFRICA			
MOZAMBIQUE	Hydro 2273 MW 13908 GWh Fossil 518 MW 351 GWh Solar 55 MW 2 GWh Biomass 14 MW 61 GWh	27%	<10%

Net power trade (2015)	Land-based potential	Renewable energy goals	Regional Power Pool
Balanced	Solar Wind	100% by 2050	EAPP
-	Solar Wind	70% by 2030	Potential EAPP
-	Solar Wind	-	Potential EAPP
-	Solar Wind	-	Potential EAPP
Import	Solar	100% by 2050	EAPP
Balanced	Solar	-	-
Import	Solar Biomass	100% by 2050	EAPP SAPP
Balanced	Solar Biomass	100% by 2050	-
Balanced	Solar Biomass	100% by 2050	-
Balanced	Solar Wind	-	-
Export	Solar Biomass	-	SAPP

SOUTH AFRICA	Fossil[#2] 49 GW 218 TWh Solar 3061 MW 4955 GWh Wind 2094 MW 6467 GWh Hydro 747 MW 889 GWh	84%	67%
NAMIBIA	Hydro 347 MW 1086 GWh Fossil 184 MW 133 GWh Solar 135 MW 180 GWh Wind 5 MW 18 GWh	53%	15%
ANGOLA	Hydro 2699 MW 7679 GWh Fossil 1781 MW 3086 GWh Biomass 51 MW 200 GWh Solar 13 MW 18 GWh	42%	<10%
CENTRAL AFRICA			
DR CONGO	Hydro 2772 MW 9936 GWh Fossil 135 MW 180 GWh Solar 19 MW 27 GWh Biomass 3 MW <1 GWh	19%	<10%
CONGO REPUBLIC	Hydro 214 MW 1242 GWh Fossil 170 MW 797 GWh Solar 1 MW 1 GWh	66%	12%
GABON	Hydro 330 MW 982 GWh Fossil 296 MW 840 GWh Solar 1 MW 2 GWh Biomass 1 MW 1 GWh	92%	45%
SÃO TOMÉ E PRÍNCIPE	Fossil 45 MW 96 GWh Hydro 2 MW 6 GWh Solar <1 MW <1 GWh	73%	47%
EQUATORIAL GUINEA	Fossil 274 MW 937 GWh Hydro 127 MW 127 GWh	67%	43%
CAMEROON	Hydro 732 MW 5109 GWh Fossil 705 MW 1884 GWh Solar 14 MW 20 GWh	61%	19%
WESTERN AFRICA			
NIGERIA	Fossil 10937 MW 22905 GWh Hydro 2111 MW 6823 GWh Solar 28 MW 28 GWh Biomass 10 MW 33 GWh	54%	34%
BENIN	Fossil 301 MW 325 GWh Solar 3 MW 5 GWh Hydro 1 MW <1 GWh	43%	15%
TOGO	Fossil 158 MW 692 GWh Hydro 67 MW 204 GWh Solar 3 MW 4 GWh	48%	9%
GHANA	Fossil 3161 MW 10195 GWh Hydro 1584 MW 6017 GWh Solar 63 MW 43 GWh Biomass 8 MW 358 GWh	79%	41%
CÔTE D'IVOIRE	Fossil 1298 MW 7042 GWh Hydro 879 MW 2962 GWh Solar 8 MW 7 GWh	66%	29%

Export	Solar Wind	8% by 2030	SAPP
Import	Solar	70% by 2030	SAPP
Balanced	Solar	Double by 2030	SAPP CAPP
Balanced	Solar Biomass	100% by 2050	EAPP SAPP CAPP
Import	Solar Biomass	85% by 2025	CAPP
Balanced	Solar	-	CAPP
Balanced	Solar Hydro	47% by 2030	-
Balanced	Solar	-	CAPP
Balanced	Solar Biomass	Double hydro by 2035	CAPP
Balanced	Solar	-	WAPP
Import	Hydro Solar	Hydro 110 MW by 2030	WAPP
Import	Hydro Solar	-	WAPP
Export	Solar	10% increase by 2030	WAPP
Export	Solar	-	WAPP

LIBERIA	Fossil 98 MW 98 GWh Hydro 92 MW 124 GWh Solar 3 MW 4 GWh	22%	<10%
SIERRA LEONE	Fossil 199 MW 80 GWh Hydro 61 MW 238 GWh Biomass 34 MW 4 GWh Solar 4 MW 6 GWh	23%	<10%
GUINEA	Hydro 368 MW 741 GWh Fossil 226 MW 1182 GWh Solar 13 MW 21 GWh	35%	<10%
GUINEA-BISSAU	Fossil 28 MW 38 GWh Solar 1 MW 2 GWh	26%	22%
SENEGAL	Fossil 866 MW 3714 GWh Solar 134 MW 233 GWh Wind 50 MW Biomass 25 MW 110 GWh	62%	27%
GAMBIA	Fossil 102 MW 392 GWh Solar 1 MW 3 GWh Wind 1 MW <1 GWh	56%	26%
CABO VERDE	Fossil 141 MW 340 GWh Wind 28 MW 80 GWh Solar 8 MW 9 GWh	-	47%
NORTHERN AFRICA			
MAURITANIA	Fossil 459 MW 875 GWh Solar 88 MW 144 GWh Wind 34 MW 104 GWh	43%	<10%
MOROCCO	Fossil 7723 MW 28035 GWh Hydro 1306 MW 1693 GWh Wind 1225 MW 3856 GWh Solar 734 MW 980 GWh	100%	100%
ALGERIA	Fossil 23508 MW 75880 GWh Solar 448 MW 507 GWh Hydro 228 MW 117 GWh Wind 10 MW 160 GWh	100%	100%
TUNISIA	Fossil 5782 MW 18774 GWh Wind 275 MW 453 GWh Hydro 66 MW 17 GWh Solar 62 MW 58 GWh	100%	100%
LYBIA	Fossil 10987 MW 37101 GWh Solar 5 MW 8 GWh	70%	100%
EGYPT	Fossil 58640 MW 181138 GWh Hydro 2851 MW 12726 GWh Solar 1668 MW 553 GWh Wind 1375 MW 2334 GWh	100%	100%

Balanced	Solar Biomass	-	WAPP
Balanced	Solar	-	WAPP
Balanced	Solar	30% by 2030	WAPP
Balanced	Solar	30% by 2030	WAPP
Import	Solar	-	WAPP
Balanced	Solar	100% by 2050	WAPP
Balanced	Solar	60 MW hydro by 2030	-

Balanced	Solar Wind	-	COMELEC
Import	Solar Wind	-	COMELEC
Export	Solar Wind	27% by 2030	COMELEC
Export	Solar Wind	100% by 2050	COMELEC
Import	Solar Wind	-	COMELEC EAPP
Export	Solar Wind	-	-

[#1] Information sources supporting this table: Statistical Profiles by the International Renewable Energy Agency [114]; UNEP Atlas of Africa Energy Resources [6]. [#2] Fossil energy figures for South Africa also include 5-10% nuclear power (not fossil).

5.4 OFFSHORE RENEWABLES FOR DESALINATION

Demand for fresh water for industrial, agricultural (irrigation), power generation and domestic uses is increasing [115]. As freshwater reservoirs continue to come under stress, and as scarcity of potable water may increase drastically due to climate change, seawater desalination is becoming the primary source of potable water for several countries, [114] despite its expense. However, desalination has another major disadvantage: it is an energy-intensive process, accounting for significant greenhouse gas emissions. As of 2015, desalination was responsible for an estimated 76 million tons of annual CO2 emissions [116]. The need to decarbonize is reinforced by the fact that global desalination capacity grew 54% while the energy use for this purpose grew 70% over the period 2010 - 2016 [117] .

The way forward is the right combination of renewable energy and desalination technologies which will allow the production of fresh water in an effective, economic, and environmental manner. Future desalination, which seems inevitable, must be driven by renewable energy sources. Solar energy works well and has great potential to reduce desalination carbon emissions [114]. It is also clear that some offshore renewables have the potential to power the production of potable water as a valuable by-product. Desalination is possible directly as by-product from OTEC or as contributing to the general energy mix in larger grids, or as small-scale units of wave power developed particularly for desalination purpose [63], [64]. Such approaches offer much greater efficiency compared to small scale-solar power.

5.5 OFFSHORE CAPACITY

The challenge for offshore renewables is that they are not only advanced, but also continuously subjected to the harsh and unforgiving nature of the marine environment. Saltwater speeds up corrosion, water movements erode moving or sensitive components, storms can break moorings and cables, access for technicians may require skills like diving and underwater maintenance, and the expensive use of helicopters, and advanced safety equipment. The deployment, maintenance, and decommissioning of offshore renewables will almost always require maritime or offshore engineering competence and a higher investment. This aspect of renewable energy should not be underestimated and countries with an existing domestic offshore industry and maritime infrastructure have a distinct advantage. The development of offshore renewable energy industries will benefit from co-development with other offshore industries such as shipping, aquaculture and offshore drilling and mining where skills and infrastructure may be quite similar. Several countries in central, western and northern Africa, along with Kenya, South Africa, and Angola may already possess good qualifications and many other African coastal states are currently developing their maritime and offshore sectors. All countries that consistently and strategically targets Blue Economy development may also build the necessary capacity over time.

6. SUITABILITY FOR OFFSHORE RENEWABLES IN AFRICA

The suitability assessment presented here should be regarded as an inexhaustive discussion based on technical potentials, their alignment with existing power sectors, technological readiness, offshore capacity, and climate conditions. Potential environmental impacts are not considered[N].

6.1 EASTERN AFRICA

Sudan, Eritrea, and Djibouti have clear technical potential for offshore wind power. But they are also countries where coastal wind resources and uninhabited land are readily available, and therefore offshore renewables are unlikely to be the most suitable options when cheaper and less complex alternatives exist.

The remainder of eastern Africa has a diverse flora of offshore energy. With high dispatchability from hydropower and geothermal power in the regional Power Pool (EAPP), mainland eastern Africa has an energy mix that matches intermittent offshore renewables. Port infrastructure already exists and offshore competence is growing in Kenya and Tanzania. The climate is both benevolent and predictable but sea-level rise and erosion pose will new challenges to nearshore installations.

Somalia's long coastline offers excellent conditions with technical potential for offshore wind power, wave power, and ocean current power. These resources may all become of interest in a future where political stability permits long-term infrastructure planning.

Kenya and Tanzania have decidedly more moderate conditions for offshore renewables and these technologies may therefore not be of most immediate interest. Development of the different technology types continues however, and viable opportunities may yet arise, so these countries might consider reevaluating in future.

Madagascar shows high technical potential for both wave power and offshore wind power. Utilizing these intermittent sources would need matching with land-based sources with high dispatchability and the high cyclone risk and limited offshore capacity are substantial barriers.

The highest suitability for offshore renewables rests in the small islands states of the region: the Seychelles, Comoros, and Mauritius. All these countries have high potential for marine FPV and this technology may be suitable at isolated grids of small islands where land space is very scarce. The current use of expensive fossil fuel provides opportunity for all renewables, but when fossils are phased out any intermittent source, such as marine FPV or wave power, must be combined with generators of high dispatchability. Biomass is particularly important here and Mauritius has high potential for biomass production. Another option may be OTEC, with resources seemingly available in the Seychelles, Comoros, and Mauritius. Once the OTEC technology is mature,

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[N] Exception: the assessment of technical potential for FPV includes some environmental consideration related to avoiding impact on shallow water ecosystems. Other technologies may also have substantial impact when located at the wrong site. For instance, OTEC must avoid emitting discharge water to sensitive ecosystems and some tidal turbines may harm wildlife. Environmental impacts are essential but require detailed site-specific feasibility studies not included here.

site-specific studies may reveal great opportunities for power generation with high dispatchability and potable water as useful byproduct. Land based OTEC is likely to withstand possible cyclones better than other offshore renewables.

6.2 SOUTHERN AFRICA

Southern Africa has particularly good conditions for wave power and offshore wind power, but also for ocean current power and OTEC at specific locations. The regional Power Pool (SAPP) is large and well connected. It contains sources with high dispatchability which can help to balance any additional intermittent renewables. This is a great advantage for utilizing the potential of large-scale offshore wind power.

Mozambique is the only country with technical potential for all types of offshore renewables discussed in this paper. Wave power and OTEC seem the strongest options. Mozambique's power sector is supplied with hydroelectricity from its vast interior. Its expanding power grid suffers losses in remote parts of the country and the need for additional high-capacity power supply in coastal provinces may become a driver for both offshore and land based renewables. The capacity and stable power characteristics of OTEC, and its ability to produce potable water as a by-product may eventually become more compelling in the northern provinces of Cabo Delgado and Nampula. This area is also expected to see a boom in offshore capacity driven by the pending natural gas extraction. Currently, political instability in this region inhibits such long-term investment and challenges the growth potential of the offshore sector. It is also possible that wave power may contribute to the power quality in the southern outposts of the Mozambican grid. Increasing floods, erosion, and inundation must be seriously considered and mitigated where possible, especially in the southern half of the country where the seabed is sandy.

South Africa has particularly advantageous prerequisites with high technical potential for three different offshore renewables and a well-developed power sector with wind power experience. Advanced port infrastructure and offshore capacity also exist. Although it has good potential for land based renewable energy, several types of offshore renewables are available too. Offshore wind is sufficiently mature technology and its suitability for South Africa is high. Large offshore wind farms may become significant complements to the existing grid infrastructure. In the future, wave power and ocean current power may play a wider role, offering predictability and more continuous generation.

Namibia also has high technical potential for offshore wind and wave power. Low population density and vast potentials for land based renewables may however be more practical alternatives and inhibit the suitability for offshore energy solutions in general.

In Angola, the technical potentials for wave power and wind power are good and moderate, respectively. Angola's experience from offshore drilling operations, with its associated industrial complex, may facilitate developments as power sector expands. Hydropower and biomass are both available for balancing intermittent power.

6.3 CENTRAL AFRICA

Central Africa does not have a great abundance of offshore renewable energy. The Congo Republic and São Tomé and Príncipe have moderate potential for wave power, but they both apparently have more competitive energy resources available on land.

Because of coastal upwelling, central Africa generally lacks the preconditions for OTEC. However, the technical potential is rated moderate in Equatorial Guinea and in São Tomé and Príncipe. This may motivate further investigations once the OTEC technology is mature. A single 100 MW OTEC plant would provide São Tomé and Príncipe with more power than its current capacity.

Although not part of this assessment, the abundance of freshwater bodies and powerful rivers in central Africa offers high potential for FPV to be used in dams and reservoirs [49] and for tidal stream turbines to be used for small-scale production in rivers without requiring dams. These could be fruitful options to consider further.

6.4 WESTERN AFRICA

Western Africa has an abundance of low intensity wave energy. The mild and predictable wave climate may constitute an advantage for the wave power industry since many developers have struggled to overcome the challenges of durable equipment in high-energy wave climates. Based on low-rated converters, wave power may become a suitable energy alternative throughout the region. National power sectors and the regional power pool (WEPP) contain enough hydropower, and high dispatchability, to balance variations in grid connected wave power and as a result, conditions for wave power seem suitable in the region.

Senegal and Cabo Verde have more winds and powerful waves compared to other parts of the region. The technical potential for wave power is rated high in both countries, and offshore wind power has particularly high potential in Cabo Verde. Both sources may become suitable components of the future Cabo Verde energy mix, counterbalancing the intermittency of other renewables in this island archipelago.

Because of the wide continental shelf, which separates land from cold deep-sea water, western Africa has low potential for land-based OTEC despite a sufficient heat gradient. Once the technology is more mature, it may provide vast resources for West African countries with advanced offshore capacity, for instance utilizing their experiences from oil and gas drilling. The climate is more benevolent for high seas deployments in western Africa compared to eastern and, particularly, southern Africa. The relevance and suitability of floating OTEC may grow over time. Today the challenges remain of transporting to land both desalinated water, as the byproduct, and the harvested energy products for use or for export (e.g., in liquid hydrogen).

6.5 NORTHERN AFRICA

North African power sectors and the regional power pool (COMELEC) are comparatively big and rely heavily on fossil fuels. To meet emission reduction targets and improve energy security, the power sectors of at least some northern Africa countries will need to diversify and include more renewable energy. The promising conditions for offshore wind power may fit well with the grid infrastructure. The frequent desert dust of the sirocco and coastal winds imply a technical challenge to be solved. While the offshore wind potential is high, northern Africa is also characterized by arid uninhabited land, which has excellent potential for solar and wind power development. In most areas these sources will be more accessible than their offshore equivalents. The suitability of wave power (and in Morocco tidal/current power) may for the same reason of competing land-based sources be limited.

7. POLICY RELEVANCE AND RECOMMENDATIONS

This paper demonstrates that African waters have abundant renewable energy. A good fraction of this energy can be harnessed through future investments in offshore renewable energy technology, contributing to the growth and diversification of African power sectors and meanwhile replacing or preventing carbon emissions.

7.1 PROSPECTS FOR OFFSHORE RENEWABLE ENERGY IN AFRICA

Most of southern Africa has excellent conditions for offshore wind and wave power. Eastern Africa has a more diverse palette of offshore energy resources, with high technical potential for offshore wind power, floating solar power (FPV), ocean thermal energy conversion (OTEC), wave power, and ocean current power. West Africa has evident potential for wave energy. Here, the wave resource is strongest in Cabo Verde and Senegal but a number of other countries in the region have a milder wave climate that, according to some views, might be even more appropriate for lower risk harnessing of energy. Western Africa also has an immense potential for OTEC, but these resources are far out at sea and would require long-distance transport of energy to shore which is expensive and riskier. Offshore renewables may not be as relevant for countries in central and northern Africa. The north has high technical potential for offshore wind power, but equally strong potential for land-based alternatives which will probably continue to be more attractive.

Near-future potential

Africa's Blue Economy Strategy sets a near-term future horizon of 2030. The most obvious potential for African offshore renewables in this time perspective is the option for small island states to generate power from their own nearby waters. On islands, land based alternatives are few, land is scarce, and imported fuels keep electricity prices high. The Seychelles, Comoros, and Mauritius have good opportunities for exploring both FPV and OTEC. FPV is fully modular and may, initially, serve smaller grids at remote locations. OTEC power plants are large by necessity and can provide a base supply that would be sufficient to cover the electricity demand for a larger island. Moreover, the possibility of having potable water as by-product of OTEC is tantalizing in the island context. On the Atlantic side, Cabo Verde may have good reasons to explore the prospects of wave power and offshore wind power which both could serve well as complements to other renewables in the archipelago.

In the near-future perspective, African developments in these sub-sectors may be driven by a few countries or partnering states. In addition to the island states, South Africa, with its promising resources and existing offshore capacity may become one of the pioneers for African offshore renewables.

Longer-term perspective

Year 2063 is the longer-term horizon set by the Africa Blue Economy Strategy. Given the promising and diverse resource availability, it is very possible that offshore renewables will become part of the energy mix in several African countries by this date. Their use will not be restricted to islands but found on the mainland as well and they could become valuable contributors to the regional power pools. The good power quality of some offshore renewables and the different variation patterns compared to land based renewables provide real advantages. Further technical development of the alternative technologies will influence which of the potential options assessed by this paper may develop into a significant industry on the continent: offshore wind power, OTEC, and wave power may all become substantial parts of the African Blue Economy.

The long-term perspective opens up the possible use of OTEC in western Africa. This may be realized only when floating OTEC is technologically mature and energy demand is sufficiently high for transport of power across sub-sea transmission cables or as liquid fuels (for example liquid hydrogen) to become viable.

In the longer term, opportunities may also be realized for countries currently not stable or affluent enough for offshore industries to boom. Somalia, for instance, has strong physical pre-conditions for offshore renewables. Likewise Mozambique would also be in a good position and is a country which also has taken a proactive approach to the Blue Economy. In all cases, countries with a strong Blue Economy agenda are more likely to create the necessary enabling environment for offshore business, which is also an essential prerequisite for sustainable profits from offshore renewables.

Uncertainties

This report assesses the potential for nascent or not-yet commercially available technologies across a vast, continental, geographical scale, with a focus on the largely uncharted oceanic environment. The multiple levels and types of uncertainties implied must be acknowledged. In addition, policy recommendations for future developments are inheritably inflicted by uncertainty since world development, climate change imperatives as well as unexpected technological breakthroughs, may alter the foundations of recommendations.

7.2 OCEAN POLICY AND PLANNING

Pressures from growing populations in coastal zones of Africa, expanding coastal tourism, intensified local fisheries and demanding international fisheries pose increasing threats which jeopardize the quality of coastal and marine environments, and affect the life of coastal inhabitants and future economic development. Climate change and the increasing incidence of extreme events already affects the coasts and marine ecosystems. The development of new industries that target marine resources will add to the cumulative pressure [11]. Offshore renewable energy must therefore be integrated with ocean policy and the strategic work towards a sustainable Blue Economy must be considered from an ecosystem-based perspective.

The Africa Blue Economy Strategy points out the need for regulatory frameworks to secure investments in sea exploration as well as sound policy for innovation and technology transfer. These recommendations are fully endorsed also by the findings of this background paper.

Marine Spatial Planning (MSP) is a valuable instrument to achieve the long term growth of Blue Economy sectors while integrating environmental and social premises [118], [119]. Recent global advances in MSP implementation were spurred by the need to support and guide the growth of offshore wind power. The rationale behind MSP is to achieve societal and maritime goals through increased predictability and synergies. Multiple offshore energy types may be encouraged to co-develop in the same area, creating offshore industry synergies.

Today, many African states are developing MSP [4]. For example, a regional MSP strategy is being developed by the Nairobi Convention and several of its member states have adopted MSP for their Blue Economy aspirations. Other Regional Seas Conventions may take corresponding roles. Offshore renewables are and must remain part of the MSP processes.

7.3 ENERGY POLICY RECOMMENDATIONS

For offshore renewables to be of strategic value they must be competitive and complementary to land based renewables. Energy extraction from the sea will usually be more expensive, complicated, and risky compared to any comparable land based alternative. For instance, if winds are equally strong over land it will be more viable to build onshore wind farms instead of going offshore. Yet, energy abundance and power quality may lead offshore renewables to become viable and even advantageous in some parts of the continent. According to findings from this background paper the natural resources are in place for several types of offshore renewables. The development of offshore capacity might be the key to eventually utilizing their potential in the coming years.

Strategic preparedness may include:

1. Build domestic and regional offshore capacity – not limited to offshore renewables – and invest in enabling environments for Blue Economy business and industry. This approach would enhance African competence and readiness to “leap-frog” more fossil-fuel dependent nations and build a new momentum of inclusive economic growth based on harnessing ocean resources.
2. Address offshore renewables not in isolation but in relation to complementary energy alternatives and relevant energy mixtures: from local off-grid systems to regional power pools.
3. Development at scale is necessary for a viable industry. Strategic support for offshore renewables should target comprehensive investment programs at scale rather than single ventures. Such a focus must however not hamper parallel bottom-up driven initiatives. Following the Africa ‘Blue Economy’ Strategy, create a conductive regulatory environment to support offshore renewable industries in a sustainable way, and consider the development of integrated master plans.
4. Strategic support to offshore renewables should be linked to the wider offshore industry complex. This may go hand in hand with the Africa Blue Economy Strategy objective of modernizing ports and maritime infrastructure. It must also be recognized that African countries have many academics with practical expertise in the various research fields of offshore renewables.
5. It might be valuable to narrow the scope of offshore renewable energy in the African Blue Economy Agenda. Technologies suitable for the African geography and socio-economic context should be in focus. This background paper may serve as a step towards identifying initial target areas.
6. Strategic environmental assessments including socio-economic feasibility studies must be launched at an early stage of planning and investment. Some technologies may have detrimental impact on coastal ecosystem services at specific locations which should be carefully considered and avoided or mitigated. The Africa Blue Economy Strategy calls for the development of environmental impact assessment guidelines.

7. Support to offshore renewables should set conditions for African ownership and deep-rooted involvement of domestic industry and local workforce, thereby assuring project longevity, capacity building, local added value and the nurturing of domestic intellectual property.
8. Strategic planning of offshore renewables should be incorporated with Marine Spatial Planning (MSP), to utilize synergies and avoid future conflicts with competing interests and environment.

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Annex 01

TABLE S1

Background indicators of African coastal countries.

Country / Territory	Average annual rainfall (mm)	Average annual temp (°C)	Land surface area (km²)	Coastal haz
EASTERN AFRICA				
Sudan	700	Su:[32] / Wi:[26]	2500.000	Floods, droughts, wildfires
Eritrea	[300 700]	Su:[31] / Wi:[16]	124 300	Floods, droughts, wildfires
Djibouti	[50 215]	Su:[30 40] / Wi: [22 30]	23 000	Floods, droughts, volcanos, wil
Somalia	280	27	632 540	Floods, landslides wildfires
Kenya	[250 2000]	24.29	582 646	Floods, landslides wildfires
Seychelles	1647.70	27.05	455	Floods, cycl
Tanzania	[550 3690]	22.18	945.1	Floods, volcanos
Comoros	[1000 5000]	[19 30]	1 861	Floods, cycl
Madagascar	[400 3700]	[23 27]	857 041	Floods, landslides wildfires
Mauritius	[900 1500]	Su: 24.7 / Wi: 20.4	2 011	Landslides, cy
SOUTHERN AFRICA				
Mozambique	No:800-1500/ Ce:600-1500/ So:<800	23.76	799 380	Floods, droughts, wildfires
South Africa	464	Su: [15 36] / Wi: [-2 26]	1 219. 602	Droughts, floodin extreme storm
Namibia	[25 600]	20.20	825 418	Floods, droughts
Angola	IN:>1200 / SAZ:< 300	Si: [22 23] / Wi: [18 20]	1 246 700	Floods, drou

ards	Coastline (km)	Population stats (million)	Primary energy supply (%)[1]	Economy/GDP per capita (USD)
volcanos, s	853	41.8	Oil (54%)	441.5
landslides, s	1 900	3.5	Renewables (77%)	642.5
landslides, dfires	372	1.0	Oil (54%)	3,408.8
, droughts, s	3 025	10.0	Renewables (94%)	126.9
, volcanos, s	400	51.4	Renewables (79%)	1,816.5
ones	491	0.1	Oil (99%)	17,401.7
, wildfires	1 424	56.3	Renewables (83%)	1,122.1
ones	340	0.8	Oil (54%)	1,393.5
, cyclones, s	6 603	26.3	Renewables (85%)	522.2
clones	177	1.3	Gas (57%)	11,203.5
,cyclones, s	2 515	29.5	Renewables (76%)	491.8
g, waves, s, fires	3 000	59.6	Coal (69%)	6,001.40
s, wildfire	1 500	2.4	Oil (65%)	4,957.5
ghts	1 650	30.8	Oil (48%)	2,973.6

CENTRAL AFRICA				
DR of the Congo	[800 1800]	[16 28]	2 345 000	Floods, wild
Congo Republic	1612	[23 26]	342 000	Floods, wild
Gabon	[1500 3500]	[21 28]	267 667	Floods, wild
São Tomé and Príncipe	[1000 5000]	[22 26]	1 001	Floods, drou
Equatorial Guinea	[341 1961]	[22.7 25.4]	28 051	Floods, landslides
Cameroon	[550 7500]	[20 28]	475 000	Floods, droughts, volcanos, wil
WESTERN AFRICA				
Nigeria	[450 3500]	[21 27]	923 768	Floods, droughts
Benin	No:700 / So-E:1500	Su: [31] / Wi: [26]	2 381 741	Floods, droughts
Togo	[850 1400]	[24 28]	56 600	Floods, droughts
Ghana	[750 2000]	[24 30]	238 535	Floods, droughts
Côte d'Ivoire	[1100 2000]	[20 30]	342 000	Floods, droughts
Liberia	Co: >3000 / In: <2000	[28 32]	111 370	Floods, landslides
Sierra Leone	[2000 5000]	26	71 325	Floods, landslides wildfires
Guinea	[1100 5000]	[23 27]	245 857	Floods, landslides wildfires
Guinea-Bissau	[1300 3000]	[24 30]	36 125	Floods, droughts
Senegal	[300 1200]	28.08	196 722	Floods, droughts
Gambia	860	Su: [23 33] / Wi: [18 30]	11 300	Floods, droughts
Cabo Verde	<250	Co: [25] / Al: [19]	4 033	Floods, lands

lfires	40	84.1	Renewables (98%)	545.2
lfires	170	5.2	Renewables (59%)	2,011.1
lfires	885	2.1	Renewables (54%)	7,667.4
ughts	209	0.2	Oil (63%)	1,994.9
s, volcanos	644	1.3	Gas (75%)	8,131.9
landslides, dfires	400	25.2	Renewables (75%)	1,497.9
, wildfires	853	195.9	Renewables (75%)	2,229.9
, wildfires	1 280	11.5	Oil (42%)	1,219.4
, wildfires	56	7.9	Renewables (78%)	675.5
, wildfires	539	29.8	Oil (45%)	2,202.1
, wildfires	170	5.2	Renewables (59%)	2,286.2
s, wildfires	563	4.8	Renewables (83%)	621.9
, droughts, s	506	7.7	Renewables (80%)	504.5
, droughts, s	320	12.7	Renewables (73%)	962.8
, wildfires	350	1.9	Renewables (84%)	697.8
, wildfires	700	15.9	Oil (50%)	1,446.8
, wildfires	80	2.3	Oil (51%)	751.3
slides	965	0.5	Oil (82%)	3,603.8

NORTHERN AFRICA

Mauritania	100-600 / Sahara [30 100]	27.75	1 030 700	Floods, droughts
Morocco	318.81	17.49	710 850	Floods, droughts, wildfire
Algeria	No:>1000/ Sa: <100	Su: [21 24] / Wi: [10 12]	112 622	Floods, droughts, wildfire
Tunisia	50-400	[16 20]	164 600	Floods

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[1] [%] of total primary energy supply

Su: Summer; Wi: winter; No: North; Ce: Central; So: South; IN: inland north; SAZ: semi-arid zone; Co: coast; In: Interior; Co: Coastal; Al: Altitude; No: North; Sa: Sahara

, wildfires	800	4.4	Oil (71%)	1,677.9
landslides, s	1 835	36.0	Oil (60%)	3,204.1
landslides, s	124	42.2	Gas (66%)	3,948.3
	1 300	11.6	Gas (48%)	3,317.5

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