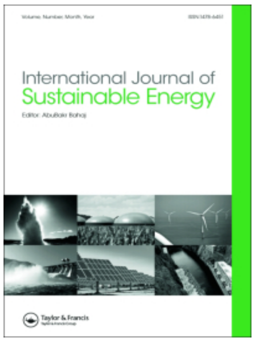

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The ocean as a source of renewable energy in sub-Saharan Africa: sources, potential, sustainability and challenges

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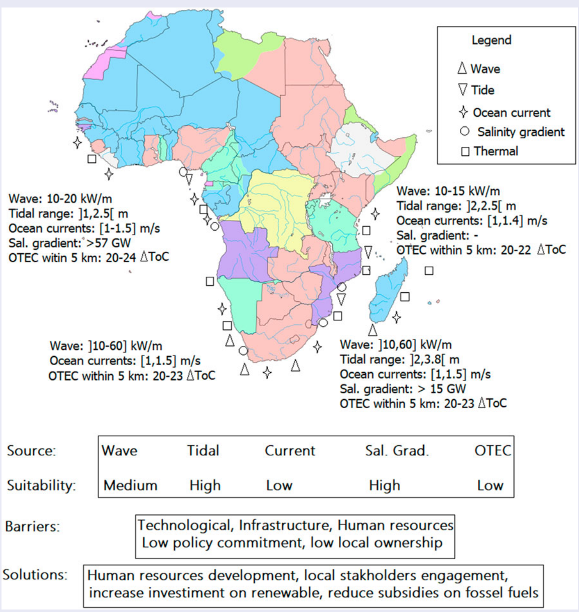
ABSTRACT

The present paper examines, based on literature review and data from Africa Energy Outlook 2019, the feasibility of adoption of renewable energy from the ocean for socioeconomic development in sub-Saharan Africa, given the enormous potential the region has for ocean-based sources of energy. The study concludes that mini tidal power plants and salt gradient power are the ocean energy sources most suitable for coastal development. It recommends a gradual reduction in subsidies of fossil fuel-based energy sources in favour of support to renewable energy, building human resources and technical capacity, the establishment of smart partnerships and mobilisation of resources for an effective promotion of ocean renewable energy. It recommends further, that community engagement is needed to assure ownership and acceptance.



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1. Introduction

Energy is vital for social and economic development. Many authors have argued that increased availability of energy services stimulates economic development (Carbonnier and Grinevald 2011; Toman and Jemelkova 2003; World Economic Forum 2012) and others have demonstrated that energy consumption is positively correlated to development (Eggoh, Bangake, and Rault 2011; Toman and Jemelkova 2003), even in the developed countries where energy efficiency initiatives tend to reduce energy consumption (Toman and Jemelkova 2003). Energy contributes to boosting socio-economic development in many ways, including powering industry, increasing production and productivity, creating jobs and improving education (Daka and Ballet 2011; Mushtaq et al. 2009). Electrification, for instance, makes increased hours of work and night classes possible and enables students to do homework at night, which is particularly beneficial to women (Dinkelman 2011). Although it is generally recognised that electricity access enhances economic growth, there is no robust scientific evidence available yet about such effects in sub-Saharan Africa. Most of the published studies were based on short-time data series.

A study by Gungor and Simon (2017) on financial development, energy consumption and economic development, using the Johanson co-integration test, in South Africa, for the period 1970–2015, showed that energy consumption was positively correlated with financial development as well as with urbanisation and industrialisation in the long run. Further, Dinkelman (2011) using empirical approaches to identify the impact of rural electrification in Kwazulo Natal, in South Africa, estimated the community-level employment growth rates due to rural electrification in the period 1996–2001; her results showed an increase in female employment of the order 9–9.5%, which represented an addition of 15,000 women participating in the labour force. Furthermore, her study revealed that rural electrification contributed to an increase in female labour of about 8.9 more hours per week, which represented a 3.5% increase in working hours.

Winklmaier, Santos, and Trenkle (2020) conducted a feasibility study of the decentralised energy grid on rural agriculture in Ghana and found that off-grid energy systems comprising only a diesel generator yield a negative profit whereas combined systems with diesel and solar photovoltaic and with biodiesel, yield profit of USD2,764 and US D14,052, respectively, producing 263 tons of maize. Studies in Nigeria, on the relationship between financial development, energy consumption and economic growth for the period 1971–2014, using a co-integration approach, showed that a 1% increase in financial development was associated with about 0.01% increase in energy consumption (Odusanya, Osisanwo, and Tijani 2016). A similar result was obtained by Salami, Odubunmi, and Atoyebi (2016) using the generalised method of a single equation model, also in Nigeria. Kirubi et al. (2009) estimated that the electrification of rural areas in Kenya has contributed to an improvement in productivity of the order of 100%–200%, per worker, which corresponded to an increase in income of the order of 20%–70%.

Eggoh, Bangake, and Rault (2011), analysing data in 21 African countries, during the period 1970–2006, found a co-integration relationship between real GDP and energy consumption. More recent studies by Nkalu et al. (2020) on the nexus between financial development and energy consumption/use in sub-Saharan Africa, using a panel vector error correction model, co-integration, and Granger causality tests over the period 1975–2017, found that a percentage increase in financial development and in Growth Domestic Product per Capita were attributed to about 23% and 3% increase in energy consumption, respectively.

In conclusion, most of the literature showed convincing evidence of a positive correlation between electricity use and access and economic growth in sub-Saharan Africa, implying that electricity expansion drives social and economic development as argued by many authors (Blimpo and Cosgrove-Davies 2019; Lee, Miguel, and Wolfram 2020; Nkalu et al. 2020), as it contributes to an increase in working hours, industrialisation, enhancement of the synergies between the agricultural and non-agricultural sector and to boosting production.

Table 1. GDP per capita and statistics of energy consumption and electricity network coverage in some Sub-Saharan African coastal countries, obtained from World Bank database (https://databank.worldbank.org/home.aspx).

Region	Country	Population (2021)	GDP per capita (US $) (2014)	Energy use (kg of oil equivalent per capita) (2014)	Electric power consumption (kWh per capita) (2014)	Access to electricity (% of population) (2019)	Access to electricity in rural areas(% of rural population) (2019)
West Africa	Angola	34,503,774	5,408.40	545	312	45.7	7.3
	Benin	12,996,895	1,291.40	417	100	40.3	17.4
	Cameron	27,198,628	1,542.60	335	275	63.5	24.0
	Congo, Republic	5,835,806	3,776.50	555	203	48.3	12.7
	Cote d'Ivoire	27,478,249	1,561.50	613	275	68.6	41.9
	Gabon	2,341,179	9,663.40	2,694	1,168	90.7	24.2
	Ghana	32,833,031	1,899.70	332	351	83.5	70.0
	Nigeria	213,401,323	3,099.00	764	145	55.4	25.2
	Senegal	16,876,720	1,396.70	279	229	70.4	47.8
Southern Africa	Madagascar	28,915,653	530.90	–	–	26.9	7.7
	Mauritius	1,266,060	10,153.90	1,111	2,183	100.0	100.0
	Mozambique	32,077,072	674.00	443	479	29.6	4.9
	Namibia	2,530,151	5,469.90	794	1,653	55.2	35.0
	South Africa	59,392,255	6,433.40	2,696	4,198	85.0	79.2
East Africa	Kenya	53,005,614	1,315.80	506	164	69.7	61.7
	Tanzania	63,588,334	1,030.10	497	104	37.7	19.0

Sources: https://data.worldbank.org/indicator/EG.USE.COMM.GD.PP.KD, https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC?locations=ZF, https://databank.worldbank.org/indicator/NY.GDP.PCAP.CD/1ff4a498/Popular-Indicators, https://data.worldbank.org/indicator/EG.ELC.RNWX.KH?locations=ZF, https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=ZF, https://data.worldbank.org/indicator/EG.ELC.ACCS.RU.ZS?locations=ZF, https://data.worldbank.org/indicator/SP.POP.TOTL?locations=ZG.

According to Avila et al. (2017), sub-Saharan Africa, where more than 950 million people live, is the region with the highest rates of electrical poverty in the world. Table 1 presents the GDP per capita and statistics of energy consumption and electricity network coverage in some sub-Saharan African coastal countries, obtained from World Bank database (The World Bank Group 2021). In 2014, the average energy uses in sub-Saharan African countries, excluding high-income countries, was 687 kg of oil equivalent per capita, whereas in the same year, the average global energy consumption was 1,922.13 kg of oil equivalent per capita. Ghana and Cameroon with energy consumption of 332 and 335 kg of oil equivalent per capita, respectively, ranked low in the energy use in sub-Saharan African coastal countries. Most of the sub-Saharan coastal countries presented in the table had energy consumption of less than 800 kg of oil equivalent per capita, with the exception of Mauritius which exceeded 1,000 kg of oil equivalent per capita, Gabon and South Africa exceed 2,000 kg of oil equivalent per capita. It should be mentioned, however, that most of the energy consumed in the majority of sub-Saharan African countries is from biomass, since the electricity consumption and electricity network coverage in these countries are low, as discussed below. The Electricity power consumption in sub-Saharan African countries, excluding high-income countries, in 2014, was 487 kWh per capita, compared with the world average electricity consumption of 3,131.68 kWh per capita observed in the same year. Low electricity consumption levels (<200 kWh per capita) were recorded in Benin, Nigeria, Kenya and Tanzania. High electricity consumption were observed in Gabon (1,1168 kWh per capita), Namibia (1653 kWh per capita), Mauritius (2188 kWh per capita) and South Africa (4198 kWh per capita).

Data for the year 2019 referring to access to electricity indicate that only 46.7% of the population in sub-Saharan African countries had access to electricity. Madagascar, Mozambique and Tanzania ranked low in electricity supply, with values ranging from 27% to 38% coverage. South Africa, Gabon and Mauritius, with more than 80% coverage, ranked high in electricity supply. Most of the sub-Saharan coastal countries listed had electricity supplied to 50–70% of the population. Regarding rural electrification, only 28.1% of the rural population had access to electricity in the whole of sub-Saharan Africa. Mozambique and Angola had the lowest rural electrification rates (<10% of the rural population). High rates of rural electrification were observed in Mauritius (100%), South Africa (79%), Ghana (70%) and Kenya (61.7%). Most of the sub-Saharan coastal countries had rural electrification rates in the range 20–45%.

Examining briefly the data in Table 1, it is possible to note that the energy consumption, electricity consumption and electricity access are all positively correlated with the population and GDP, supporting the argument that population is the main driver of electricity consumption and that energy availability drives broader economic productivity. However, some countries like Nigeria, have high GDP per capita (US$ 3,099.00), yet low electric power consumption (145 kWh per capita), a pattern that may be similar to few other developing countries; this may be due to other factors such as the inequalities in wealth distribution or application of the wealth in development initiatives for the wellbeing of people.

The International Energy Agency (IEA) estimated that demand for electricity in sub-Saharan Africa grew by 35% between 2000 and 2012, reaching 352 Tera-Watt-hours (TWh), and forecast that the total electricity demand in Africa will increase at an average rate of 4% per year until 2040. Until recent years, development relied mostly on fossil fuels in developed countries, whereas in the poor sub-Saharan countries, the main sources of energy are biomass, harvested from biological sources such as wood and dung, often processed as charcoal, sun used for drying and human and animal power (Carbonnier and Grinevald 2011; Toman and Jemelkova 2003). Several studies have indicated that wood and charcoal fuel consumption have a significant negative impact on economic growth, besides being unclean, and they recommend the employment of other renewable energy sources such as solar, wind and geothermal (Maji, Sulaiman, and Abdul-Rahim 2019; Sulaiman and Abdul-Rahim 2020).

The use of fossil fuels is driven by the fact that they are the cheapest source of energy available until now (Collier and Venables 2012; Schwerhoff and Sy 2017); oil and gas are easy to transport and store and can be stored in concentrated form (Carbonnier and Grinevald 2011). However, in view of the increased demand for energy and environmental concerns, efforts are being made to shift from traditional sources to renewable sources of energy, which are clean and reliable (Owusu and Asumadu-Sarkodie 2016). Deichmann et al. (2011) and Ouedraogo (2017) argued that sustaining increased development in sub-Saharan Africa would require increased energy and energy access, and further suggested that renewable energies, given the fact that they are diverse and widely distributed may play a major role in boosting socio-economic development. Indeed, in the past 2 decades (2000–2020), there have been noticeable efforts to promote renewable energy in Africa, because of the increased demand and reduction in investment costs (Hafner, Tagliapietra, and de Strasser 2018). Emphasis has been put on hydroelectric, geothermal, wind and solar power (African Development Bank 2017) and on bio energy from organic material or biomass. Biomass

Table 2. Energy production, supply and balance in kilotons of oil equivalent (ktoe), by source, in Africa: the status in 2018 and projection for 2040.

	Energy status in 2018				
Energy type	Production	Supply	Import	Export	Projected energy use for 2040
Crude oil	403,909		32,678	315,299	
Oil	–	189,512	118,170	37,520	362,000
Coal	157,479	113,511	12,336	55,922	100,000
Natural gas	207,147	133,336	10,581	84,393	290,000
Nuclear	3,017	3,017			19,000
Hydro	11,278	11,278			
Wind, solar, etc.	6,836	6,836			
Biofuel and waste	378,928	378,639	2	291	212,000
Sub-Total	**1,168,594**	**836,129**	**173,767**	**493,425**	**983,000**
Total renewable energy		18,000			223,000
Total					1,206.000

Source: https://www.iea.org/reports/africa-energy-outlook-2019.

includes surplus wood (International Renewable Energy Agency 2015), which is plentiful in Africa (Hafner, Tagliapietra, and de Strasser 2018). There has been little consideration of ocean renewable energy sources, for which sub-Saharan Africa has considerable potential, owing to the fact that it is surrounded by two Oceans, the Atlantic on the west coast and the Indian Ocean on the East coast. This paper reviews the opportunities associated with renewable energy sources from the ocean, their potential and sustainability and discusses the opportunities and challenges for harvesting these abundant and valuable renewable energy forms for economic development in sub-Saharan countries, as a means of diversification of energy sources for attaining sustainable development, in compliance with the stipulation in Sustainable Development Goal 7 (STD7), which urges all United Nations' Member States to 'Ensure access to affordable, reliable, sustainable and modern energy for all' by 2030 (United Nations 2021).

2. Energy production and supply in sub-Saharan Africa

Table 2 presents the energy production and supply for the year 2018 and energy supply projected for the year 2040, by source, for African countries, as obtained from the International Energy Agency (IEA) database (IEA 2019). Africa has abundant energy resources, including renewable and fossil sources. In 2018, the overall energy production in Africa was 1168 Mtoe (metric tonnes of oil equivalent) and the supply was 836 Mtoe. Oil provided 403.9 Mtoe and biomass 378.9 Mtoe, corresponding to 34% and 32% of the total production, respectively, followed by natural gas 207 Mtoe (17.7%) and coal 157 Mtoe (13.5%). Renewable and cleaner energy contributed less than 2%, and these included hydro 11 Mtoe (1%) and wind and solar 6.8 Mtoe (0.6%). *On international energy trade*, Africa is a net energy exporter. In 2018 the total energy exported was 493.4 Mtoe, which corresponded to about 42.2% of the energy production, against a total import of 173.8 Mtoe, which was about 14.9% of the total energy production. In all, the export surpassed the import by 319.7 Mtoe. The major sources of energy traded were oil, coal and gas.

The demand for energy in sub-Saharan Africa is driven by the need to meet the basic living requirements of the population and for economic development, mainly in terms of food production and processing, shelter, education and health care, industrial production, cooling and mobility (IEA 2019). Hence, the main drivers of energy demand may be laid out as follows: population, income, the degree of urbanisation and economic structure (IEA 2019; Kolawole, Adesola, and de Vita 2017). According to Kolawole, Adesola, and de Vita (2017) the population is the first main driver

Table 3. Energy supply in kilotons of oil equivalent (ktoe), by source, for 2018, in some Sub-Saharan African coastal countries, obtained from Africa Energy Outlook 2019 (https://www.iea.org/reports/africa-energy-outlook-2019).

Region	Country	Oil	Coal	Natural gas	Nuclear	Hydro	Wind, solar, plus	Biofuel & waste	Total
West Africa	Angola	7,559		702		751		6,369	15,381
	Benin	2,409		16				2,705	5,242
	Cameron	1,853		649		432	2	6,719	9,657
	Congo, R.	709		517		107		1,638	2,970
	Cote d'Ivoire	2,251		1,716		255		6,257	10,389
	Gabon	720		384		78		3,707	4,918
	Ghana	4,209		1,313		517	3	3,881	9,872
	Nigeria	23,490	29	15,822		555	2	119,983	159,882
	Senegal	2,449	430	11		31	7	3,707	4,566
Southern Africa	Madagascar								
	Mauritius	799	448			11	6	193	1,456
	Mozambique	1,572	33	719		1,197		6,955	10,429
	Namibia	1,327	7			98	6	327	2,053
	South Africa	20,129	98,284	3,985	3,017	95	1,228	7,907	134,242
East Africa	Kenya	4,998	262			343	4,491	17,581	27,677
	Tanzania	2,439	387	622		192	8	17,271	20,929

Source: IEA World Energy Balances.

of energy consumption in sub-Saharan Africa. Based on world data statistics, the total population in sub-Saharan Africa was estimated at 1,103.96 million inhabitants in 2019 (Statista 2020), increased to 1.181,162,740 in 2021, and is expected to grow at the rate of 0.81 up to 2040 (IEA 2019). Though currently most of the people are living in rural areas, the urban population is reported to be growing at high rates, from 22.1% in 1980 to 38% in 2015 (World Bank 2015). The observed increase in urban population would imply a substantial increase in energy demand. Accordingly, the International Energy Agency projected an increase in energy demand for Africa of about 17.6%, from 836 Mtoe in 2018 to 983 Mtoe in 2040. Notable foreseen changes in energy supply include 44% reduction in biomass, from 379 Mtoe in 2018 to 212 Mtoe in 2040 and a substantial increase, about twelve times, in renewable energy consumption, from 18 Mtoe in 2018 to 223 Mtoe in 2040. Furthermore, in 2040, the nuclear energy use is expected to increase by a factor of 5 with respect to consumption of 2018, and in the same period, the consumption of oil and gas is expected to increase moderately whereas the consumption of coal is expected to reduce slightly. The expected changes may result from the discoveries of oil and gas and the African energy policy aiming at reducing deforestation through the reduction of biomass and promotion of cleaner energy (IEA 2019).

Although the overall energy production and supply in Africa may suggest that there is sufficient energy to meet the demand, these resources are not distributed evenly across the countries in the continent, and within a country, there are huge asymmetries between urban and rural areas, which pose additional challenges for attaining equitable sustainable development (Tucho and Kumsa 2020). Table 3 presents the energy supply by source in some sub-Saharan African coastal countries, for 2018. Nigeria and South Africa, with 159.9 and 134.2 Mtoe, respectively were the leading energy consumers on the continent. Nigeria was the largest consumer of Biomass (~120 Mtoe), oil (23.5 Mtoe) and natural gas (15.8 Mtoe), whereas South Africa used a wide range of energy sources, including coal (98.3 Mtoe), oil (20.1 Mtoe), biomass (7.9 Mtoe) natural gas (~4 Mtoe) and nuclear (3 Mtoe). Mozambique led the hydro production (~1.2 Mtoe). Kenya and South Africa led the renewable energy production from wind and solar, with about 4.5 and 1.2 Mtoe, respectively.

With regard to electricity supply, sub-Saharan African has the lowest electricity generation capacity and the lowest rate of electricity access in the world, with two-thirds of the region's population lacking access. This is critical considering the fact that *electricity* offers *advantages* over other *energy* sources, enabling far more efficient technological deployment in industry, business and social development, such as education and health (Burke, Stern, and Bruns 2018). Table 4 provides figures for the electricity production by source for Africa, for 2018, as obtained from the International Energy Agency database. In all, the electricity production was about 72 Mtoe, with most of the electricity energy generated from natural gas (~28.8 Mtoe) and coal (~22.4 Mtoe), followed by hydro (11.7 Mtoe). The electricity generated from renewable energy sources (wind and solar) was only about 1.6 Mtoe.

Table 4. Electricity production in kilotons of oil equivalent (ktoe) by energy source in Africa, for 2018.

Source	Energy (ktoe)
Oil	5,737
Coal	22,373
Natural gas	28,759
Nuclear	996
Hydro	11,700
Wind	1,218
Solar PV	454
Biofuel & waste	178
Geothermal	446
Other sources	114
Total	**72,006**
Total from renewable (only wind and solar)	1,672

Source: https://www.iea.org/fuels-and-technologies/electricity.

Considering the fact that the main reasons for low electricity access in sub-Saharan Africa include the lack of generation capacity, poor electricity grid infrastructure and a widely spread rural population (International Renewable Energy Agency 2015), the obvious solution to address these challenges is twofold: first, the installed generation capacity should be expanded, and secondly, the electricity grid should be upgraded. Further, it should be taken into consideration that decentralised renewable off-grid and mini-grid systems are cost-effective, and so ideal solutions for the electrification of rural areas (Ugwoke et al. 2020). This may justify the massive investments in renewable energy, mainly wind and solar, in sub-Saharan Africa (Klagge and Nweke-Eze 2020). Subsequently, we are here arguing that renewable energy from the ocean, aside from providing a cleaner and sustainable energy source, can be a viable solution for energy supply in remote coastal areas of Africa, complementing the effort being made in harnessing wind and solar energy, and thus contributing significantly to increased energy security.

3. Renewable ocean energy sources and potential in sub-Saharan Africa

This section presents and discusses data and information on ocean energy sources and potential for sub-Saharan African coastal countries, extracted from published sources. Emphasis is placed on those energy sources that can be harnessed near the coast, in estuaries and in mangroves and tidal creeks, as these would, hypothetically, pose fewer challenges for deployment and maintenance of the respective ocean energy infrastructures compared to offshore infrastructures. Accordingly, relevant published data and information on waves, tides, which include tidal stream, marine currents and salinity gradients around the sub-Saharan coast were compiled and analysed, and the viability is discussed based on technical feasibility (Breeze 2014) and proximity to the coast. In the context of this paper, technical viability encompasses the amount of energy and availability, adequacy and suitability of the technology to sub-Saharan African countries.

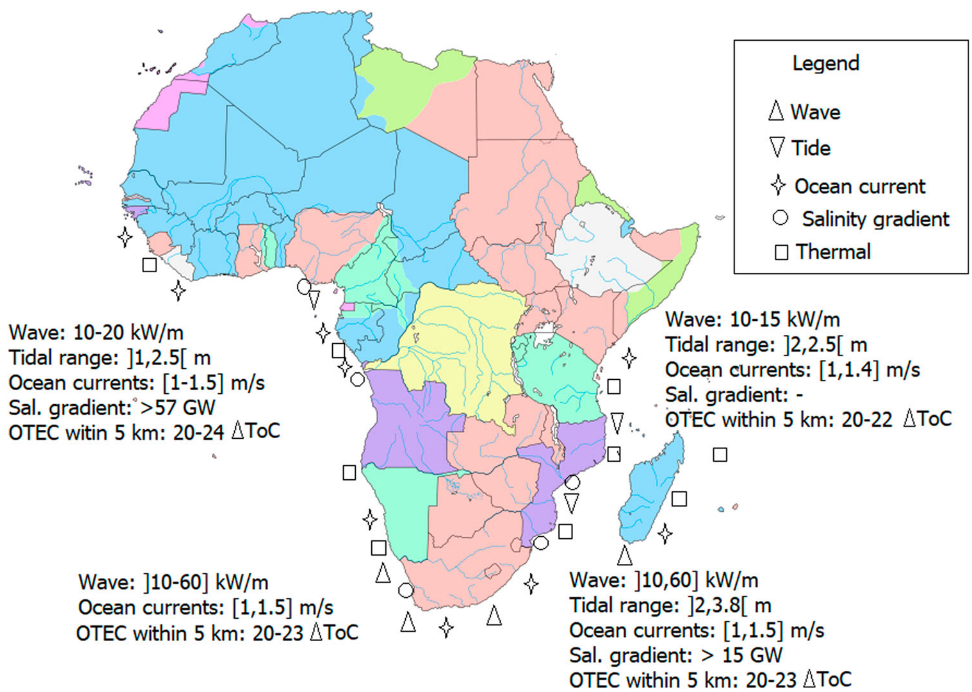

Figure 1. Potential and suitable locations for Ocean Renewable Energy in sub-Saharan Africa.

The main forms of ocean energy that can be harnessed in sub-Saharan Africa are waves, tides (including tidal streams), marine currents, and salinity gradient (Castellano et al. 2015; Hammar et al. 2012; Magagna and Uihlein 2015; UNEP 2017). The 2017 UNEP report on Africa Energy Resources stated that surface waves, tides and the power of ocean currents, if harnessed effectively, could generate enough power to cover all of African's electricity needs (ESI 2015; UNEP 2017). Figure 1 presents the potential and suitable locations for the deployment of Ocean Renewable Energy infrastructures in sub-Saharan Africa, extracted from many different published sources (Albergaria 2010; Canhanga and Dias 2005; Dei 2010; Diop 2010a, 2010b; Dubi 2006; Fourie and Johnson 2017; Magori 2008; Ojany 2010; Orme 2010; Searson 1994; Usoro 2010).

3.1. Wave energy

Surface waves are generated by winds, and so are highly dependent on ocean weather conditions (Fourie and Johnson 2017). Wave energy is extracted by devices that convert the potential energy of waves into kinetic energy which spins turbines or drags linear generators (Brekken, von Jouanne, and Han 2009), and it is often used to generate electricity. The systems are often installed offshore. Africa has a potential for generating 3,500 TWh annum of wave energy (Brekken, von Jouanne, and Han 2009; Qiao et al. 2020). Sub-Saharan Africa has an estimated potential of 5–10 kWh/m of wave energy, on average. The best prospects for wave power development are in southern Africa, around the coast of South Africa and from southern Mozambique up to Namibia, where the waves have 1.7–2.7 m average significant height and wave period in the range 5–11 s, with estimated potential to produce wave energy of about 15–45 kW/m (Banks and Schäffler 2005). In fact, South Africa has some of the biggest waves in the world for producing energy (Fourie and Johnson 2017). There were initiatives to deploy a 500 MW wave energy power plant in South Africa (ESI 2015). The other regions in sub-Saharan Africa with considerable energy power are East Africa, from the Somali coast down to Mozambique (Hammar et al. 2012) and West Africa, from Senegal down to Cameron, where the significant wave height is 0.53–1.52 m and periods of 3.06–9.23 s, with estimated wave energy potential of 5–20 kW/m (Sadio et al. 2017). The rest of sub-Saharan Africa has a potential of wave energy on average 5–10 kW/m (Fourie and Johnson 2017; Mørk et al. 2008). In Madagascar, in East Africa, the potential for wave power was found to be 12.86 kW/m (Contestabile and Vicinanza 2018). Assessment of the potential use of wave energy to produce freshwater from a reverse osmosis desalination system, in combination with the breakwater coastal defence was conducted in north-eastern Madagascar with encouraging results. The mean nearshore energy density was estimated at 3.3–9.95 kW/m, with low values in May and higher values in January (Contestabile and Vicinanza 2018). In West Africa, studies conducted in Ghana indicated that the use of ocean waves can be developed to meet the energy needs of Ghana, if harnessed using technology that is cost-effective and reliable (Aboagye et al. 2021), even though some studies have evaluated that the potential of wave energy in West Africa is low (<1 kW/m), slightly above the poorest wave energy record (UNEP 1983).

3.2. Tidal energy

Tidal energy is produced as a result of the gravitational fields of both the sun and the moon, which together with the earth's rotation around its axis lead to both high and low tides. Energy generated can be harnessed through two basic methods: (1) tidal barrages which make use of the tidal amplitude, where during flood tide the basin behind the barrage is filled and during the ebb tide the water is released through turbines that create electrical power though the use of generators, and (2) tidal stream generators which make direct use of the kinetic energy of moving water to power turbines, working in a similar way to wind turbines (Bryden 2004; Fourie and Johnson 2017). Tides present advantages in comparison to waves, wind and solar energy because they are predictable both in terms of time and magnitude, and hence are a very reliable source of energy (Neill and Hashemi

2018). Tidal energy is often harvested for electricity production (Chowdhury et al. 2021; Etemadi et al. 2011) and new applications include desalination. For desalination, the pressure increase due to waves, which are then channelled ashore to drive a reverse osmosis desalination system (Babu, KarthikBalaji, and Nishal 2017a; Babu, Selvamuthukumaran, and Arunkumar 2017b; Contestabile and Vicinanza 2018; Franzitta et al. 2016).

The tides vary quite significantly along the African coast. In East Africa, the tides are low, with a tidal range between 1.2 and 1.6, in most of the places along the coast (Aboagye et al. 2021; Guilcher 2010; UNEP 1983). However, in estuaries and tidal inlets, due to co-oscillation, the tidal range may attain high values. For instance, in the Geba estuary, on the northern coast of Guinea Bissau, the mean spring tide range is 5.1 m, increasing to 6.4 m at Port Gole, while the rest of the coast has a tidal range of 2.8 m (Diop 2010b). The coast of Nigeria exhibits moderate tides, with a tidal range of 2.6 and 3.0 m in estuaries and 1.9 m in surrounding areas (Usoro 2010). In East Africa, the tides vary from micro-tidal (0.3–1 m) observed in Mauritius and Reunion, mesotidal (1–2 m) observed mainly in the Seychelles, the eastern coast of Madagascar and Rodriguez to macrotidal (above 3 m) found mainly on the mainland coast, the Comoros and the western coast of Madagascar (Magori 2008). In Mozambique, in particular, the mean spring tide ranges are between 3.5 and 4.5 m, increasing to 5.6 m in central Mozambique (Albergaria 2010; Canhanga and Dias 2005; Orme 2010). In Kenya, the average spring tide range varies between 2.5 and 3.6 m, with a maximum of 4.0 m recorded at Kilindini (Ojany 2010). In South Africa, tides are typically in the range of 2–2.5 m (Searson 1994).

Theoretically, a tidal power station is considered economically viable in 20–40 m water depth with a tidal range not less than 5 m for a tidal barrage (Neill et al. 2018) and current velocities not less than 2 m/s, for a tidal stream turbine (Jackson and Persoons 2012; Roberts et al. 2016). However, there are tidal power plants in less than 5 m tidal range, e.g. South Korea (at 4.5–4.7 m) (Neill et al. 2018)and tidal stream turbines in less than 2 m/s, e.g. Morocco (at 0.9–1.8 m/s) (Alaoui 2019). These work because water has a high density, 1000 times higher than that of the air, which makes the tidal turbines generate electricity at speeds as low as 1 m/s (Jackson and Persoons 2012). Based on these thresholds, the sites with high potential for tidal power generation in sub-Saharan Africa are Kenya, Tanzania, Mozambique and Madagascar, in East Africa and Ghana and Guinea Bissau, in Western Africa (Kempener and Neumann 2014). Ghana was expected to commission its first undersea power generator by December 2016 at the Ada Estuary in the Greater Accra Region. A successful test generation of 14 MW was run in March 2015 (Gale-Zoyiku 2015). When fully operational, the plant will produce up to 1,000 MW (Contestabile and Vicinanza 2018; Ouedraogo 2017). For West Africa, Onundo and Mwema (2016) estimated tidal power in Kenya to be 1.9 GW (16.5 TW/h annum).

3.3. Marine currents

Marine currents can carry large amounts of water, driven by the tides, temperature and salinity spatial differences and wind, and modified by topography and the rotation of the earth (Quirapas and Taeihagh 2021). The strongest currents are associated with tides and waves, enhanced by topography narrowing, often found in straits between islands and the mainland or in shallow water around headlands, and in tidal channels (Bahaj 2013; Quirapas and Taeihagh 2021). Tides and wave-driven currents may reach velocities from 1.5 m/s to more than 3 m/s (Dodet et al. 2013; Gourlay 2011), which can provide an appreciable amount of energy considering that the threshold for an economically viable ocean current power station is set to 2 m/s. Further, like tides, currents are more predictable, and coupled with the higher density of water, it makes ocean current energy more reliable compared to wind energy (Jackson and Persoons 2012). The kinetic energy resulting from water movement is harvested and converted into electricity by water-current turbines, which operate in the same way that a wind turbine extracts energy from the wind, using either axial-flow horizontal-axis propellers or cross-flow Darrieus rotors, moored on a fixed structure from the sea bed or floating in the water column (Ponta and Jacovkis 2008). Sub-Saharan Africa has six main ocean boundary currents, namely, the Somali Current, East Africa Current, Mozambique current and Agulhas currents in the Western Indian Ocean and Benguela and Canary currents in West Africa, where the current speed at the core varies from 1 m/s to more than 2 m/s, and so the potential for ocean current energy is expected to be high (Fourie and Johnson 2017). Such currents, however, are found in the open sea, further away from the coast, which may pose additional challenges for their exploitation. In the Western Indian ocean region, the most notable places for ocean current power are along the coast of Kenya where the maximum current speeds recorded were 1.2–1.9 m/s (Hammar et al. 2012); Northern Mozambique, where a mean current speed of between 1 and 1.5 m/s and maximum speeds above 2 m/s have been reported (DiMarco et al. 2002; Ullgren et al. 2016); and the Tanzania–Zanzibar strait, where the observed current speeds were 0.7–1.5 m/s; along the Agulhas current, in Southern Mozambique and the East coast of South Africa where the current speeds attain 1.1–1.7 m/s (Lamont, van den Berg, and Barlow 2016). Further, sites with potential for ocean stream energy include those with high potential for tidal energy, discussed in the previous section. Dubi (2006) estimated tidal stream power of 133 kW/m for channels with velocity of 0.5–1.5 m/s, on the coast of Tanzania. In semi-enclosed bays, such as those established by alongshore reefs, waves may pile water into the bay during rising tides and set up a pressure gradient that may cause a fast and continuous current, regardless of the tides (Hoguane et al. 2019; Taskjelle et al. 2014).

3.4. Salinity gradient

Salinity gradient power is the energy created from the difference in salt concentration (Haddout et al. 2022; Helfer and Lemckert 2015; Schaetzle and Buisman 2015). It relies on osmotic pressure differences that occur in the interface between two water masses with different salinities (Schaetzle and Buisman 2015). The maximum potential of salinity gradient power is expected to occur in estuaries, where water from a river, with low salinity, meets the salt water of an ocean, with high salinity (Haddout et al. 2022; Jones and Finley 2003). Rough estimates indicate that in circumstances where water from the river has zero salinity and ocean water has salinity 35, energy equivalent to that of a 140−240 m high dam may be generated (Schaetzle and Buisman 2015). There are two main methods for harnessing salinity gradient energy. These are reverse electrodialysis (Govindarsu, Jai-Ganesh, and Kumaar 2020; Tristán et al. 2020; Tufa et al. 2020; Zoungrana and Çakmakci 2020) and pressure retarded osmosis (Altaee and Cipolina 2019; Chen et al. 2019; Ghaffour et al. 2019). Both processes rely on osmosis with membranes. The processes which generate electricity, however, yield brackish water as a by-product (Jalili et al. 2019; Zhu et al. 2017). The electricity produced can be used for many beneficial applications. Dubrawski et al. (2020) explored the use of the electricity generated to power a storm water disinfection plant.

There are few published studies regarding the potential of salinity gradient energy in sub-Saharan Africa. Estimates by IRENA (2014a) yielded 2690 TWh for theoretical potential and 503 TWh per year for technical potential of salinity gradient energy in Africa. Pawlowski, Crespo, and Velizarov (2016) indicated that Africa has 391 rivers with an estimated average discharge of 170,294 m^3/s, and an estimated theoretical and technical gross potential of salinity gradient energy of 311 and 190 GW, respectively. According to Kuleszo et al. (2010), Africa has three rivers, two in sub-Saharan Africa, ranked among the top 10 global rivers with high technical potential for salinity power, and these are the Zaire (57 GW), Nile (21 GW) and Zambezi (15 GW), and also several rivers with technical potential exceeding 1 GW.

3.5. Ocean thermal energy conversion (OTEC)

Ocean Thermal Energy Conversion (OTEC) is a process that can produce electricity by using the temperature difference between deep cold ocean water and warm tropical surface waters. OTEC plants pump large quantities of deep cold seawater and surface seawater and generate pressure differences that drive turbines coupled to generators and produce electricity (Etemadi et al. 2011; Vega 2012). OTEC plants can be closed-cycle or open-cycle. In a closed-cycle OTEC system, warm seawater vaporises a working fluid, such as ammonia, flowing through an evaporator (Hasan and Dincer 2020). The working fluid expands and turns a turbine. The vapour is then condensed by means of deep cold water and pumped back to evaporator, and the cycle is repeated. In an open-cycle OTEC system uses warm seawater as the working fluid. The pressure above the warm water is lowered sufficiently for the water to boil and vaporise at the ambient temperature of about 25°C, driving the turbine in the process. The vapour is then condensed and fresh water produced (Li et al. 2018). Hence, the open system produces freshwater as by-product (Liu 2018). Though the system is designed to produce electricity, recent studies have shown its potential to contribute to the development of large-scale open ocean mariculture, as it requires pumping deeper, cold and nutrient rich water to the photic zone, were it can trigger primary production (Liu 2018).

Locations with high potential for OTEC in the Western Indian Ocean are the Seychelles, Southern Mozambique with temperature differences $\Delta T > 22$°C, Northern Mozambique, Tanzania, Kenya, Comoros, Madagascar, Mauritius and Reunion with $\Delta T > 20$°C within 5 km of the coast (Hammar et al. 2012). Estimated potential of OTEC was 15–25 kW per metre of shoreline for Southern Mozambique and 25–50 kW/m for Southern Madagascar and South Africa (Hammar et al. 2012). In Eastern Africa, sites with potential for OTEC power are along the Equator. Benin and Ghana have $20^{o}\text{C} \leq \Delta T \geq 24$°C, Gabon and São Tome $20^{o}\text{C} \leq \Delta T \geq 22$°C (Breeze 2014). Initiatives for construction of OTEC power stations have been proposed for Côte d'Ivoire in 1939, St. Lucia in 1983, Mauritius in 2005 and La Réunion in 2009 (Fourie and Johnson 2017).

3.6. Suitable ocean renewable energy solutions for sub-Saharan Africa

As stated above, the suitability of the energy sources was determined based on technical feasibility and proximity to the coast. Subsequently, the following three indicators were used to gauge the suitability of the energy source: amount of energy that can be generated, availability and ease of deployment of the technology in sub-Saharan Africa and proximity to the coast of the location for deployment of the infrastructures for harvesting energy. Each indicator was scored, based on expert judgement, on scale of 1–3, where 1 = Low, 2 = Medium and 3 = High. The overall score of the suitability of each energy source was obtained by the sum of the score assigned to each indicator. The result is presented in Table 5. With respect to amount, waves score highest in southern Africa, on the cost of Namibia and South Africa, in southern Mozambique and Southern Madagascar (score = 3). Tides scored highest from Central Mozambique up to Southern Tanzania, where it was assigned a score of 3, and elsewhere the score attributed ranged between 1 and 2. Strong ocean currents are observed in the coastal upwelling zones, such as the Benguela current, Gulf of Guinea current and Somali current. Likewise, large ocean water temperature gradients are also found in the upwelling areas. The salinity gradient is expected to be strongest in all African estuaries, particularly the Zambezi, Congo and Niger estuaries, where it was attributed a score of 3. Concerning the availability and

Table 5. Suitability of ocean energy in sub-Saharan Africa.

		Technology adequacy				Suggested location
Energy source	Magnitude	Availability	Easiness of deployment	Proximity to the coast	Total	
Wave	3	2	1	2	8	Southern Africa
Tide	2	3	3	3	11	East & Western Africa
Ocean current	1	1	1	1	4	Somalia, West Africa
Salinity gradient	3	2	3	3	11	Nigeria, Congo, Mozambique
OTEC	1	1	1	1	4	Somalia, West Africa

adequacy of the technology, harvesting tidal potential and kinetic energy employs technology similar to that for river barrage and wind turbines, respectively. This technology is well-established and easy to deploy and service (Bryden 2004; Fourie and Johnson 2017). It was assigned a score of 3. Moreover, mini-tidal barrages can be established in tidal and mangrove creeks, using simple water blockage systems that fill tidal reservoirs during the high water of spring tides, and generate electricity during the falling tide (Neill et al. 2018). Likewise, harvesting salinity gradient energy for electricity generation employs simple and affordable technology. Conversely, OTEC systems are new and not well-developed and the technology for extracting wave energy is quite complex and demanding (Rusu and Onea 2018). They were assigned a score of 1 each on both the availability and ease of deployment indicators. With respect to the 'proximity to the coast' indicator, both the tidal and salinity gradient energy infrastructures have the advantage of being installed at the coast which also helps with maintenance. Hence, the 'proximity to the coast' indicator was assigned a score of 3. Conversely, the ocean currents, OTEC and wave energy conversion systems need to be installed offshore, therefore, they were attributed score 1, each, with respect to location. The result of the scoring (Table 5) suggests that mini tidal and salinity gradient power are the optimal technology options for ocean renewable energy exploitation in sub-Saharan Africa. Wave energy, already being exploited in South Africa, comes in third place. The others are still in the initial stage of development worldwide and it will take some time for them to be developed for commercial applications (Hasan and Dincer 2020; Li et al. 2018; Liu 2018).

4. Barriers and challenges in deployment of ocean renewable energy in sub-Saharan African countries

In the previous section, it was demonstrated, based in scoring data presented in Table 5, that sub-Saharan Africa has a large potential of ocean renewable energy and that mini tidal and salinity gradient power are the optimal technology options for wide application in the region, notwithstanding the wave energy that is currently being exploited by South Africa. Such renewable energy potential could contribute significantly to overcome the problem of the lack of access to electricity in rural areas, while fostering sustainable socioeconomic development.

Despite the recognition of the importance that renewable energy as a whole, and ocean renewable energy, in particular can play in rural development, there are still, however, barriers restraining their exploitation in sub-Saharan Africa. The present section analyses the main barriers to deploying ocean renewable energy in sub-Saharan Africa and proposes and discusses possible solutions to these challenges. There are many drawbacks to development of ocean renewable energy; however, there are seldom studies addressing these issues for sub-Saharan Africa. Nevertheless, it is expected that the barriers for the deployment of ocean renewable energy would be similar in nature to those pertaining to the deployment of other renewable energy, such as solar and wind, which have been better studied (Fischer, Lopez, and Suh 2011; Ganda and Ngwakwe 2014; Kuamoah 2020). Using current literature, this paper clustered the major problems into four main categories, as follows: Technological, Economical/financial, Policy and Socio-cultural.

4.1. Technological barriers

Technological barriers include limited availability of infrastructure and facilities (Belletti and McBride 2021; Fischer, Lopez, and Suh 2011), lack of human resources with appropriate skills for operating and servicing the systems (Belletti and McBride 2021), and technical complexities like energy generation capacity, intermittency and energy storage (Belletti and McBride 2021; Fischer, Lopez, and Suh 2011; Zhao, Chang, and Chen 2016). All of these are considered to have significant influence on the deployment of renewable energy as well as on economic barriers (Seetharaman et al. 2019).

The lack of adequate infrastructure, often due to the lack of funds, is thought to be the major obstacle for effective poverty alleviation and for full achievement of the economic growth potential in sub-Saharan Africa (Jerome 2012). Ocean renewable energy technology is relatively new and at different stages of development and deployment; some of the technologies are still in the research stage and not yet available for commercial use (Cho et al. 2013; Morrissey 2017; Situmbeko 2018). Further, the high cost for their acquisition and deployment (Belletti and McBride 2021; Dulal et al. 2013; Fischer, Lopez, and Suh 2011; Ganda and Ngwakwe 2014) makes them even more inaccessible for the poor Africa countries. Furthermore, due to the low level of education coupled with the newness of the ocean renewable technology, there is a lack of *appropriate* and skilled *human resources* for deployment and servicing ocean renewable infrastructures, to conduct assessment and feasibility studies and guide and advise on renewable energy initiatives (Kuamoah 2020; Seetharaman et al. 2019). Hence, there is an urgent need for investment in skills development in this area. In addition, renewable energy from the ocean is highly variable, excepting the tides whose variability is predictable. Tides provide most energy during the ebbing spring and least during the neap tides. The salt gradient exhibits seasonal variations and the others renewable sources of energy depend on the sea state. This results in intermittency and fluctuation in energy generation (Morrissey 2017), which would require additional effort to increase the storage capacity (Morrissey 2017; Situmbeko 2018). Integration of two or more renewable energy production sources and innovative approaches in managing the demand and supply dynamics could make the most use of the energy potential that can be generated (Morrissey 2017).

4.2. Economical/financial barriers

The major economic issues hindering the development of marine renewable energy development in sub-Saharan African are high investment cost, low profitability of renewable energy projects and continued employment of fossil fuel subsidy (Belletti and McBride 2021; Ganda and Ngwakwe 2014; Kuamoah 2020). The large capital cost is thought to be the major impeding factor in ocean renewable energy development in sub-Saharan Africa (Belletti and McBride 2021; Fischer, Lopez, and Suh 2011). Electricity generation, combining all sources of energy, is said to be already high in sub-Saharan Africa. Fischer, Lopez, and Suh (2011) provided an estimate of the electricity generation cost in sub-Saharan Africa in which the average cost of electricity production from all sources was estimated to be US$0.18 per kilowatt-hour with an average effective tariff of US$0.14 per kilowatt-hour, a value 2 and 3.5 higher than tariffs in East Asia and South Asia, respectively. The electricity generation cost from ocean renewable energy is expected to be even higher. According to the estimates of the IRENA technology, brief reports the cost of wave energy was on average EUR 330–630 per megawatt-hour (IRENA 2014b). The cost of the construction of a tidal barrage in Asia was estimated at USD 150/kW (IRENA 2014b), and the cost of tidal current devices were projected to be about EUR 0.17–0.23/kWh in 2020 (IRENA 2014c). The high cost of installation of these ocean renewable energy technologies was attributed to limited commercial experience (IRENA 2014b). The low profitability of renewable energy is said to be caused by the prevalence of low-income consumers and limited medium and large-scale industries fed by renewable energy, which in turn result in a lack of economy of scale (Fischer, Lopez, and Suh 2011). There is a need to develop and scale-up the energy market in order for renewable energy projects to be financially viable. Small systems such as mini-tidal power plants may be an ideal solution for electrification of small villages scattered along the coast, where energy could be used for lighting homes and businesses and support small-scale irrigation and aquaculture systems (Abdullah et al. 2021). The fossil fuel subsidy is implemented by the government with the aim of reducing the costs of energy generation. It is motivated by the need to secure energy access for poor people (Ganda and Ngwakwe 2014), the majority of the population in sub-Saharan Africa, and to stimulate industry and business. According to the IEA report, in 2009, the fossil fuel subsidy in 30 sub-Saharan African countries was estimated at US$26 billion (Whitley and van der Burg 2015). Although the fossil fuel subsidy is said to be beneficial to the economy, it has a negative effect on renewable energy development. Many studies suggest a shift towards an increased subsidy to a cleaner and renewable energy (Ganda and Ngwakwe 2014).

4.3. Policy barriers

Current laws and policies support the development of renewable energy in sub-Saharan Africa, but these are mostly concerned with solar and wind energy. Many sub-Saharan African countries have demonstrated a strong commitment to the adoption and expansion of renewable energy, mostly for electrification of rural areas. Some countries introduced fiscal incentives to attract public investments in renewable energy development, others have taken significant steps towards scaling up renewable energy technology in rural areas through off-grid and mini-grid systems (IRENA 2015). Ocean renewable energy, however, has not yet received tangible policy commitment from sub-Saharan African countries. Thus, despite the recent development of several renewable energy policies, *many studies agree that there* is still a great deal to be done to promote renewable energy in sub-Saharan Africa (Gordon 2018; Karekezi and Kithyoma 2003). High subsidies for fossil fuels, to the detriment of renewable energy (discussed above), are clear evidence of policy weakness in supporting renewable energy development (Gordon 2018; Karekezi and Kithyoma 2003). Other policy challenges for renewable energy development include inadequate planning policies, lack of co-ordination and linkage in the Renewable Energy Technology programme and weak dissemination strategies (Gordon 2018; Karekezi and Kithyoma 2003).

4.4. Socio-cultural barriers

The socio-cultural aspects of local communities need to be taken into consideration when introducing new technology, such as renewable energy, in order to assure effective acceptance, adoption and ownership (Antwi and Ley 2021; Bishoge, Kombe, and Mvile 2020; Colmenares-Quintero et al. 2020; Devine-Wright et al. 2017). Bishoge, Kombe, and Mvile (2020) pointed out that in many African countries, the acceptability of renewable energy is highly political. Several authors state that most of the projects that are state-led and finance-driven but with inadequate local-based involvement, participation and acceptance are not sustainable, and so are bound to fail after the project funds cease (Antwi and Ley 2021; Newell and Bulkeley 2017). Sovacool and Griffiths (2020) point out that cultural difference can cause the rejection of new technology. In order to reduce socio-cultural resistance and assure increased community acceptance and ownership of renewable energy, there is a need to involve the various stakeholders in all the stages of the project development, e.g. from the design up to the implementation, allowing for local leadership as much as possible, taking their interest and needs into account (Bishoge, Kombe, and Mvile 2020). This poses challenges, considering the fact that Africa has a diverse cultural and social setting in terms of ethnicity, religion, leadership hierarchy, economic classification, gender activity roles, and expectations (Wüstenhagen, Wolsink, and Bürer 2007). In addition, there is a high level of illiteracy, associated with the fact that renewable energy technology is relatively new in the African context. Together, this hampers understanding of how a technology works and its impacts and cost-benefits, which in turn constrains acceptance (Bishoge, Kombe, and Mvile 2020). Oluoch et al. (2020) observed that attitude towards acceptance of renewable energy in Kenya depended on awareness and education of the community. Hence, there is a need to raise awareness of the need and importance of renewable energy, through public education and decentralised training programmes for communities (Bishoge, Kombe, and Mvile 2020).

4.5. Solutions towards supporting renewable energy development

Based on the identified problems, the key solutions may be gathered in four main categories as follows: fostering the development of human capital, increasing funding and financial incentives to promote renewable energy development, promoting the scaling up of renewable energy technology and applications in rural development, and intensifying awareness and promotion campaigns on the importance of ocean renewable energy (Adams and Asante 2020).

Concerning human capital development, many sub-Saharan African countries have adopted an innovative systems approach as the means to sustain development, with science and technology (S&T) policy evolved to cover innovation policy and focusing more on capability building (Egbetokun et al. 2018). In the case of ocean renewable energy, sub-Saharan African countries are more users than developers of technology, and that is expected to continue for some time into the future. Hence, human capacity building should be directed towards guaranteeing domestic technical expertise capable of monitoring, assessing and forecasting technology trends, and guiding on technology acquisition, adoption and assimilation (Marton and Singh 1992; Siddharthan and Rajan 2003), through innovation (Morrissey 2017).

The development of ocean renewable energy in sub-Saharan countries would require substantial financial support and incentives from the public sector to develop infrastructure for renewable energy exploitation. African governments are already providing subsidies for fossil fuel-based energy. We are here arguing that the governments should phase-out of fossil fuel subsidies and take significant steps towards subsidising clean energy as suggested by many authors (Ayompe, Davis, and Egoh 2020; Monasterolo and Raberto 2019; Rentschler and Bazilian 2017; Whitley and van der Burg 2015). In addition, the government should attract private sector support by enabling an environment for investments in renewable energy, through tax incentives, protection of the investments and transparent governance (Hafner, Tagliapietra, and de Strasser 2018). There are two good examples, with different approaches, for funding renewable energy in sub-Saharan African countries which this paper wishes to highlight: the approach taken by Ethiopia, which is based on substantial public investment and the one taken by Kenya, which promotes private investment to run small, off-grid energy systems (Gordon 2018; Klagge and Nweke-Eze 2020).

Ocean renewable energy can be applied on small-, medium-, and large-scales (Mohamed 2021). However, for rural electrification using tides and salt gradient energy, small-scale projects are technologically and economically viable (Belletti and McBride 2021; Roberts et al. 2016; Segura, Morales, and Somolinos 2017). Such energy could be used to power pumps for irrigation of small-scale farms and filling in ponds in aquaculture units, powering refrigerators for storing fish from artisanal fisheries and for providing electricity to sustain small business and lighting homes in isolated small and off-grid systems. However, campaigns on the importance of renewable energy should be provided for stakeholders in order to assure their engagement and commitment and so the success of the projects (Kuamoah 2020).

5. Discussion and conclusion

This paper reiterates the importance of energy in social and economic development and stressed that sub-Saharan African countries have low energy production and consumption, despite high potential of energy, and hence high levels of poverty. The paper sustains that ocean renewable energy could complement the solar and wind energy, in providing electricity for isolated and scattered communities around sub-Saharan Africa. In so doing it could contribute significantly to overcoming the energy deficit, increasing the income of the people and boosting the economy in rural areas. In addition, it could help sub-Saharan Africa countries meet the energy Sustainable Development Goal. In all, the small-scale tidal and salt gradient energy are ranked as the most suitable forms of ocean renewable energy for development in sub-Saharan coastal areas, taking into consideration the adequacy of their technology and location on the coast for their installation. The major technological, economical/financial, policy and socio-cultural barriers to the deployment of ocean renewable energy in sub-Saharan Africa were identified and some possible solutions to overcoming these barriers were proposed. Bellow, an overall discussion on these issues is held and some conclusions are drawn.

5.1. Demand for energy and need for renewable energy

The demand for energy in sub-Saharan Africa is increasing and expected to increase at even higher rates in the future (Hafner, Tagliapietra, and de Strasser 2018; Sweerts, Longa, and van der Zwaan 2019; The World Bank 2017), due, mainly, to the population growth, which according to the UN estimate, will reach 4 billion by 2100 (Warner and Jones 2018). The projected increase in a population which already lacks reliable supplies of electricity and affordable modern cooking fuels (Hafner, Tagliapietra, and de Strasser 2018), coupled with the efforts for adoption of new technology to increase the production of goods and services and promote economic growth and improve the quality of life (The World Bank 2017), would imply an increase in per capita energy consumption. The overall increase in energy demand would exceed the energy available from fossil fuels, hence the reason for looking for alternative sources of energy, such as renewable energy and means for energy efficiency, such as improved stoves (Warner and Jones 2018).

The governments of sub-Saharan Africa have been making efforts towards increasing access to electricity, through increasing power generation capacity, and fostering initiatives aiming at the promotion of clean cooking fuels. Renewable energy is promoted as a means to meeting the Sustainable Development Goals and compliance with global climate change agreements and mitigation efforts (Warner and Jones 2018). Renewable energy is gaining further importance, as the decentralised energy systems are cost-effective and more appropriate to meet the challenges of rural electrification in (a situation of) scattered and remote villages where the majority of population live, a characteristic of most of the sub-Saharan Africa countries, as argued by many authors (ARE 2011; ARE 2012; Deichmann et al. 2011; Mahapatra and Dasappa 2012). Further, renewable energy has a potential to contribute to economic development of villages as reported by several authors (Chakrabarti and Chakrabarti 2002; Mahapatra and Dasappa 2012) and could contribute to better governance, reduction of inequalities between rural and urban centres and consolidation of democracy as argued by Philipp & Trotter (Philipp and Trotter 2016). Moreover, renewable energy devices have long life spans, low maintenance and operation costs and are flexible as they can be assembled in hybrid systems such as hydro, wind and solar (ARE 2011; ARE 2012).

The most promoted types of renewable energy in sub-Saharan Africa are the biomass, hydro, wind and solar (Bishoge, Kombe, and Mvile 2020; Hafner, Tagliapietra, and de Strasser 2018). There are many factors that may justify this trend, however, the key factors may be laid as follows: firstly, the region has considerable potential for these types of energy; secondly, the technology for capturing, transforming, conserving and applying these energy systems are well established, developed to commercial stage and affordable for low-income countries (de Jesus Acosta-Silva et al. 2019; Hatata, El-Saadawi, and Saad 2019; Kaunda, Kimambo, and Nielsen 2012; Madvar et al. 2019; Sinke 2019; Trappey et al. 2019); thirdly the access to these energy resources is eased by the fact that the power plant can be established on land, unlike ocean-based sources of energy (Kerr et al. 2018).

Sub-Saharan Africa has equally potential for fossil fuels and renewable energy (Avila et al. 2017; Pistelli 2020). Most of offshore oil and gas reservoirs have recently being discovered and are yet to be exploited (Mihalyi and Scurfield 2021). African countries are caught between keeping the current development which is dependent on fossil fuels given the recent discoveries of huge oil and gas resources and engaging in an energy transition from fossil fuels to renewable sources of energy (Graham and Ovadia 2019), which entail considerable socio-economic and technological changes (Pistelli 2020).

The transition to cleaner forms of energy is underway and irreversible (Bogdanov et al. 2019). For instance, the European Union, one of the leaders in technology development, is aiming to attain 100% net-zero greenhouse gas emissions by 2050, in compliance with the 2015 Paris Agreement (Turner, Katris, and Race 2020). Sub-Saharan Africa, being highly dependent on supplies and technology from developed countries, mainly from Europe, has to follow this trend. Hence, it is here argued that the sub-Saharan African countries can easily leap-frog to renewable energy, considering that the majority of the people, who happen to be rural, have no access to electricity, and so, the expansion of energy could be done though renewable energy as proposed by Pistelli (2020). This proposal is further supported by the argument that a decentralised grid is appropriate for rural electrification. However, for the effectiveness of the transition from fossil fuels to renewable energy, political commitment by sub-Saharan countries is essential and this should take into consideration the advantages of renewable energy for rural electrification (Deichmann et al. 2011; Mahapatra and Dasappa 2012).

5.2. Feasibility of adoption of ocean-based sources of energy in sub-Saharan Africa

On the effort towards adoption of cleaner energy, the ocean energy stands a good chance in sub-Saharan Africa and could play a significant role in socioeconomic development(Hafner, Tagliapietra, and de Strasser 2018; Owusu and Asumadu-Sarkodie 2016), judging from the enormous potential that exists in the region. This argument is further support by a successful trial of tide power in Ghana in 2015–2016 (Gale-Zoyiku 2015; UNEP 2017), initiatives to use wave energy to produce freshwater from reverse osmosis desalination system in Madagascar (Contestabile and Vicinanza 2018), initiatives for the development of 500 MW wave energy power plant in South Africa (ESI 2015), and initiatives for construction of OTEC power stations in Côte d'Ivoire, South Africa, Mauritius and La Réunion (Fourie and Johnson 2017).

Places in the region characterised by low energy production and consumption (Castellano et al. 2015) and struggling with electricity grid expansion for rural electrification (Ebhota and Inambao 2017; Philipp and Trotter 2016; Winklmaier and Bazan Santos 2018), are where, we argue that ocean renewable energy could play a significant role in rural electrification and in rural agriculture and aquaculture development for coastal communities. The main ocean renewable energy resource with potential for coastal development applications is micro tidal barrages, tidal currents and salt gradient power. Wave energy would take some time to be widely implemented in sub-Saharan Africa due to technical challenges, and Ocean Thermal Energy Conversion is unlikely to be applied in the near future in the region as it is harnessed further way from the coast, beside technical challenges.

Further, it is here argued that for renewable energy projects to succeed in sub-Saharan Africa they should be tied to social and economic development and should address, as much as possible, the market and business needs, not to neglect the community engagement to assure ownership and increased community acceptance. Accordingly, given the relatively low tidal range (<5 m) and tidal currents (<2 m/s), the micro-tidal current turbines as suggested by Hammar et al. (2012), of the order of 20–30 kWh as described in detail by ÁlvarezÁlvarez et al. (2014) may be ideal for generating electricity for coastal development in Sub-Saharan Africa. Such turbines would be deployed in tidal inlets and estuaries, and the electricity generated would be used for lighting homes and other buildings, powering refrigeration for artisanal fisheries, power pumps for irrigation of farms. Salt gradient power could be used for desalinisation of sea water as described by Jalili et al. (2019) and Zhu et al. (2017). The water produced could supply the coastal villages which are facing freshwater deficit, as the water from estuaries, wells and boreholes are saline due to salt intrusion.

Turning to the comparison between land-based sources of renewable energy, mainly wind and solar, whose technology is well developed and the proposed ocean-based sources of energy, whose technology is in development, the advantage of tidal and tidal stream power, is that they are predictable (Si et al. 2022) and many ocean current devices have higher technology readiness

(Curto, Franzitta, and Guercio 2021; Si et al. 2022). Solar and wind resources are highly dependent on weather conditions (Jackson and Persoons 2012; Neill and Hashemi 2018). A hybrid system, combining tidal power, solar and wind to assure more continuous power generation, is here proposed. This is in line with Kang and Jung (2020) who argued that hybrid systems are cost-effective and suitable for varying weather conditions.

The main challenges for ocean energy development in sub-Saharan Africa are training of human resources, building technical capacity, creating an enabling environment that includes good governance and incentives for renewable energy development, establishing mutually beneficiary partnerships, resources mobilisation and engagement of a community with diverse ethnic, cultural and religious backgrounds to assure ownership and acceptance of the new energy.

5.3. Concluding remarks and recommendations

The energy production and consumption in sub-Saharan Africa is actually low, however, the demand is high and is expected to increase in future, as the population and economy grow. Currently, the main energy sources are fossil fuels and biomass. The projected increase in energy demand is expected to exceed fossil fuel resources, despite the new discoveries of oil and gas in the region. Renewable energy is thought to be the viable way of meeting the increasing energy demand, particularly concerning rural electrification, and at the same time, addressing climate change mitigation. Ocean-based sources of energy, particularly tidal current and salt gradient power, could play a significant role in rural electrification and coastal zone development. Hybrid systems involving tidal currents, wind and solar power are recommended to combine land-based and ocean-based sources of energy and to assure continuous energy generation. From a policy perspective, governments of sub-Saharan Africa should undertake proactive measures to promote renewable energy from the ocean. Efforts should be addressed towards human resources capacity building, technology innovation, mutual beneficiary partnership development and attracting investment. Subsidies to fossil fuel-based energy should gradually be reduced in favour of support for renewable energy. Lastly, community engagement needs to be taken seriously at all stages of the renewable energy development programme to assure ownership and acceptance.

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