An initial assessment of

Ocean Energy Resources in the Western Indian Ocean

LINUS HAMMAR AND JIMMY EHNBERG

Department of Energy and Environment
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

The demand for modern energy is accelerating in the Western Indian Ocean (coastal East Africa). A mixture of different energy sources will by necessity be the option for the long-term future and the most adequate solutions naturally vary between locations. The vast coastlines and many islands of the region make ocean energy (OE) a relevant field to explore. With an early understanding of the resources strategic planning towards sustainable development is facilitate. Moreover, early awareness facilitates a respectful integration of new technologies in the fragile and for local people invaluable ecosystems. This study provides a first assessment of the frontier OE technologies and corresponding resources in the region.

Five renewable Ocean Energy technologies have been reviewed and the physical resource abundance for respective energy source has been screened based on available literature and databases. The Western Indian Ocean is shared between nine African countries and two French departments. The studied countries are the Comoros, Kenya, Madagascar, Mauritius, Mayotte, Mozambique, the Seychelles, Tanzania, and Réunion. The energy situation is insufficient throughout the region, either as consequence of lacking domestic energy sources or rudimentary grid extension.

The results indicate that ocean energy resources are abundant in much of the region, but different sources have potential in different areas. Several countries have favourable physical conditions for extracting energy from waves and from the temperature gradient between the surface and deep water. Wave power is a young but currently available technology which can be utilized for both large- and small-scale applications. Ocean Thermal Energy Conversion is a technology under development that, once proven, may be applicable for large-scale power production.

The physical conditions for small-scale tidal barrage power, tidal stream power, and ocean current power are less pronounced but may be of interest at some locations. While tidal barrage power is a mature technology, tidal stream power is very recent, and ocean current power is still under early development.

The study has been limited to the physical resource availability and does not emphasize economical, environmental, or social factors.

1. INTRODUCTION

By the global ambitions of a reduced dependency on fossil energy sources ocean energy (OE) has gained renewed attention. The practice of extracting productive energy from the sea has a far-reaching history; from medieval tidal mills via electricity generating tidal barrages in the 20th century to the now flourishing diversity of upcoming OE technologies. Many of the modern OE systems were conceptually designed half a century ago but never reached commercial breakthrough in the competition with conventional, mainly fossil based, energy sources. Political drivers and extensive R&D have now put both new and old cards on the table.

Even though few OE systems have yet been put into operation there are great expectations on what the technologies will bring about for the forthcoming decades (EREC 2004, Callagan 2006, Ferro 2006, Englander and Bradford 2008). Its technical development has mostly taken place in industrial countries but pilot plants and implementations have as much been directed to developing countries. It has been suggested that the best opportunities for some OE technologies may lie in remote rural and island settings, where electricity costs are high and incentives for self-subsistence are strong (Bryden 2007, Wang et al. 2011). Such remote settings are not necessarily restricted to actual islands; the same conditions apply to many far-off coastal stretches with rudimentary infrastructure. There are consequently different areas of application for ocean energies; large-scale power plants for increasing supply in major grids, and micro-scale deployments for meeting the niche market of small decentralized grids.

In the Western Indian Ocean (WIO) region, the focus of this study, electricity consumption and electrification level are low. The 135 million inhabitants of the region consume only 22 TWh/yr and access to electricity applies to no more than 15 % of the population in most of the countries. But both population and wealth are growing; the extending grids suffer serious generation shortage and numerous areas comply with the above mentioned ‘remote island’ conditions. In very general terms, the national electric grids of the large countries are supplied with both hydropower and fossil fuel, while remote areas and the small island states are much dependent on fossil fuel import. Throughout the region are good quantities of unexploited renewable energy sources, such as hydropower, bioenergy, geothermal, solar power, and to some extent wind power (Brew-Hammond and Kemausuor 2009). But renewable energy is generally fluctuating and unpredictable and one source often needs to be complemented by another in order to secure a continuous and stable supply. The future energy mixture consequently has to involve a variety of sources and technologies, making newcomers like OE valuable.

1.1. The Western Indian Ocean

The ‘WIO region’ refers to the oceanic and coastal region of tropical and subtropical East Africa (Figure 1). Geographically, the region is defined by 12° N to 30° S and 30° to 80° E (Magori 2008). The countries included in this study are Kenya, Tanzania, Mozambique, Madagascar, the Comoros, the Seychelles, Mauritius and the two French departments of Mayotte and Réunion. South Africa and Somalia only partly belong to the WIO and are not in focus in this study.

The WIO region embodies a rich biodiversity, an extensive distribution of coral reefs, seagrass meadows and mangrove rich estuaries. The continental shelf is generally narrow and strong oceanic currents pass through the region. Smaller granitic and volcanic islands pierce the deep sea and the large island of Madagascar particularly affects climate and hydrology. The WIO is subject to monsoon climate with a North-East monsoon in December to March and a reverse South-West monsoon in June to September. The southern parts endure frequent cyclones within approximate latitudes of 10-25° S.

1.2 Livelihood and electricity supply in the Western Indian Ocean

With exception of South Africa and the wealthy French departments Réunion and Mayotte the WIO region is economically growing from a very low level; in many rural areas there is a scarcity of potable water and the access to modern energy is rudimentary. Sub-Saharan Africa is the least electrified part of the world (Brew-Hammond and Kemausuor 2009) and WIO is no exception. Nevertheless, the (small) populations at the Seychelles, Mauritius and the French departments have an almost complete access to electricity. Most of the larger countries in the region have vast hydropower resources in the highlands even though its exploitation is limited. Imported oil and diesel make up an expensive and often large proportion of the electricity supply; in most of the island states it is basically the sole source (Figure 1).

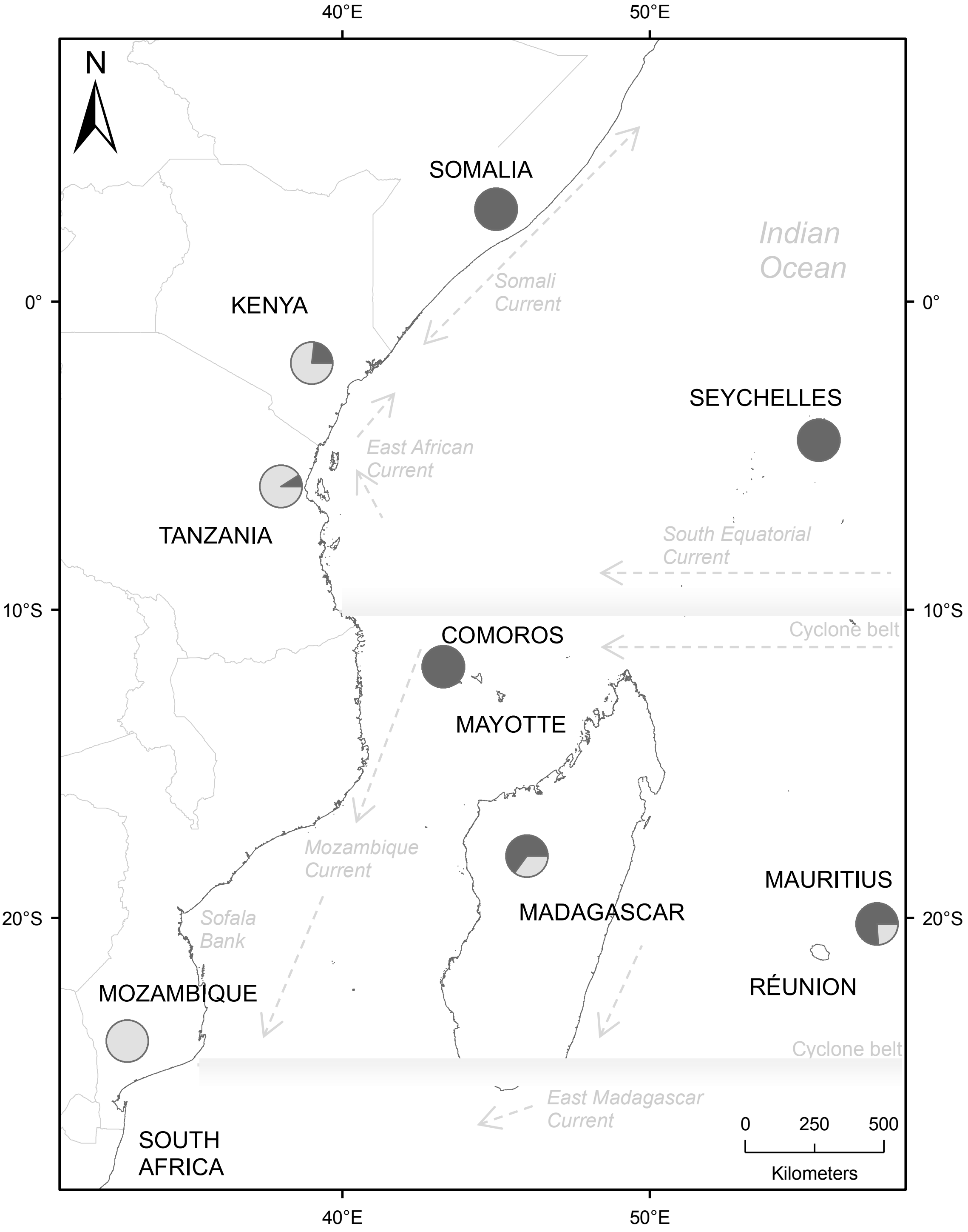

Figure 1. The Western Indian Ocean region with associated countries, main oceanographic features (dashed arrows indicate major surface currents and flow directions) and the approximate latitude frames of the cyclone belt. Diagrams indicate the proportions of fossil fuel (dark) and non-fossil fuel (light) sources in grid-connected electricity. Throughout the region small decentralized grids are supplied by diesel generators.

There is a major problem with distance and scattered populations. Many areas are too remote to be reached by grid extension even at a far time horizon and decentralized electricity grids becomes the only option (Holland et al. 2001); to the majority supplied by diesel generators.

The livelihood of coastal communities is to large extent sustained by indispensible coastal ecosystem services where small-scale agriculture is complemented by artisanal fishery and aquaculture. Concurrently the ocean is subject to industrial deep water fishery by foreign fleets (Shotton 2005) and other ocean resources may be soon added since several oil prospecting ventures are currently taking place.

1.3 Inventories of ocean energy resources for future energy supply

As defined by the International Energy Agency department of Ocean Energy Systems (IAE-OES) “ocean energy” refers to the extraction of energy from waves, ocean thermal energy gradients, tides (tidal range and tidal stream), ocean currents, or salinity gradients. As few OE technologies are yet proven and available resource inventories at this stage fill future oriented strategic purposes, in support of long-term planning. It must further be noted that resource availability is only one of many prerequisites for potential ocean energy extraction; the technologies must also be accepted and appropriate for the local setting, a broad issue which for this region has been discussed to some extent in Hammar et al. 2009.

Already in 1983 UNEP published a brief assessment of the OE potential in the West African region (UNEP 1983). Another OE resource inventory has recently been carried out for China (Wang et al. 2011). While the Chinese study concluded that China encompasses considerable reserves of virtually all different OE sources, the West African study found that the conditions are “very promising” for ocean thermal energy conversion (OTEC) and that oceanic bioconversion would be “ideal” regarding the physical conditions. A few sites in Nigeria, Angola and Namibia were found interesting for tidal barrage power. Salinity gradient energy was found to be of only far-fetched potential interest. Wave- and ocean current power were declared not to be applicable in the region.

However, hitherto has no corresponding inventory addressed the WIO region. In this study we investigate the resources and technology status for the above mentioned ocean energy sources with exception of salinity gradient energy, since the activities within this field are very limited. Another adjacent energy source is marine biofuel, or oceanic bioconversion. Despite the possible potential of these technologies, where marine algae is cultivated on land or in the sea to produce liquid fuel or electricity, it has not been included in this study.

2 OCEAN ENERGY RESOURCES IN THE WIO

This initial resource assessment is based on literature review and meta-analysis of existing data. Only the physical conditions are in focus, that is, environmental, economical and social prerequisites are not covered in this study.

2.1. Wave power

Oceanic surface waves are generated as the wind blows over the ocean. The wind energy caught in waves only dissipates very slowly and oceanic swell hence transports energy over large distances, far beyond the winds. To large extent, the global wave pattern still reflects the global wind pattern and most energy is allocated at latitudes dominated by the Westerlies (about 40°-60° N and S) and the easterly trade winds (about 3°-10° N and S) (Charlier and Justus 1993). With exceptions, the most energetic near-shore wave conditions are found at western facing coasts at high latitudes and eastern facing coasts at low latitudes. The time averaged energy flux P in surface waves can be calculated from the significant wave height H (m) and the wave period T (in seconds):

$$P = \frac{\rho g^2}{64\pi} H^2 T \qquad \text{(kW/m)} \qquad (1)$$

where ρ is the water density (kg/m^3) and g is the gravity acceleration (m/s^2). The unit kW/m represents power per meter of wave crest. In example, a coast facing a sea with a wave height of 2 m and a wave period of 8 seconds is exposed to about 15 kW per meter of the coastline. Notably, the expression is restricted to surface waves in water deeper than half the wavelength.

2.1.1. Wave power technology

There is a great variety among the technical devices developed for extracting wave energy. The rise and fall of water level, the rolling motion, or the build-up of pressure in an air chamber or liquid, may be used to rotate turbines or pull linear generators. Or, the in-rolling waves may be directed to fill up an elevated reservoir which is then emptied through a conventional low head turbine. Different wave power devices are designed for different depth conditions; some constitute floating arrays in deep water, others operate moored to the bottom in the shallows, and some are constructed as a wave breaker on the shore.

Devices also differ in terms of their sensitivity to wave direction. Point absorbers (devices which are symmetric about a vertical axis) are less sensitive while asymmetrical devices (which are elongated towards or along the wave front) can be very sensitive to the angle of the incoming wave. Further, the frequency spectrum of the wave power is of importance as devices may be tuned to certain wave frequencies. Only devices with a broad bandwidth of operation keep efficiency over a wide range of conditions (Thomas 2008).

To date only prototypes and a few full-scale devices are in operation but the expected development comprises large arrays with hundreds to thousands of units, each with a capacity in the order of tens of kilowatts to megawatts. Many devices consist of small modules and can be used both in arrays and in small-scale applications for supplying small facilities or communities. One example of a system specifically designed for remote areas is the Cape Verde converter (Euro Wave Energy) where two point absorbers are connected to a land-based generator by a cord. This design does not fully maximize efficiency but minimizes the requirements of maintenance. Each unit is rated to 30-50 kW where 10 kW are suggested for water desalination (30 000 l/day) and the remaining for electricity.

The wave power required for feasible power generation varies between different devices and project designs; several devices are optimized for 15-25 kW/m but projects are also being implemented in low-intensity areas with resource levels of 10 kW/m (e.g. Hemph and Rådahl 2008). Since wave power is indirectly driven by wind the resource becomes variable over time and subdue to seasonal changes. A measure of the seasonal variation can be calculated as the ratio of the minimum individual monthly wave power to the annual average (Barstow et al. 2008). The long-distance transportation of wave energy evens out some of the day-to-day variation and wave power is hence less variable than wind power (Charlier and Justus 1993).

Nevertheless, long periods of observation are required for accurate resource estimations and the inconsistency in generation has implications for the power grid and directing of loads, especially where wave power is used in small grids. Furthermore, offshore wave power requires long distance transmission to land; a costly set-back which is not experienced by shore-based devices.

There are no documented wave power projects in the WIO (Thorpe 2010), but several companies are known to have shown interest in the region. In southern South Africa, where the wave power potential is extraordinary, the technology has gained substantial attention. Since there are no available wave power assessments with focus on the WIO region we have assembled results from global level resource assessments and discuss the findings in relation to the specific region.

Wave power data sources and methods

The first methods used to screen global wave power resources much relied on visual observations from the maritime sector. Obviously, such methods are rather qualitative but have been defended by the assumption that visual observations generally tend to underestimate rather than overestimate the significant wave height. More recent methods are based on remote sensing observation data, with various ways of calculating the height and period of ocean waves. Some set-backs with remote sensing methods are inaccuracy in near-shore waters (Krogstad and F. Barstow 1999, Cornett 2008) and difficulties on fully accounting for energy in swell (Krogstad and F. Barstow 1999).

Three different global level wave power assessments have been considered in this study; Quayle and Changery (1981), Krogstad and Barstow (1999), and the WorldWaves project (in Barstow et al. 2008). The work by Quayle and Changery (1981) is based on visual observations which have been recalculated into wave power to generate a global resource assessment of coastal waters. In the latter two studies 2 and 10 years, respectively, of altimetry and measurement buoy data have been used to calculate the significant wave height and indirectly the wave period, which in turn has provided an estimate of the wave power resource at numerous globally distributed locations. The visual observation-based estimates by Quayle and Changery (1981) are slightly higher than those computed by Krogstad and Barstow 1999 and the WorldWaves project. Since the WorldWaves project (Barstow et al. 2008) is the most comprehensive in terms of observations, and generally more conservative than the visual observations, it was selected for illustrating the spatial distribution of wave power along the WIO coasts in this study. Annual and seasonal means were extracted and used for interpolations between the two most adjacent data points for each shoreline position. The distance between interpolated data points was approximately one degree (1°).

Table 1. Estimated wave power in coastal waters of the WIO region derived from three different sources. Estimates from Quayle and Changery (1981) are based on maritime sector observations whereas estimates from Barstow et al. (2008) and the WorldWaves project (Barstow et al. 2008) are based on satellite and measurement buoy data from 2 and 10 years respectively. All estimates are extracted from global level assessments.

Country	Location	Annual mean wave power (kW/m)		
		Visual observations	Satellite based	Satellite based
		Quayle and Changery (1981)	Barstow et al. (1998)	WorldWave Project
CO	Comoros	12	0-5	5-10
FR	Réunion	-	25-30	20-30
KE	Kiunga	16	10-15	10-15
MA	Andavadoaka	18	-	20-30
MA	Androka	38	25-30	30-40
MA	Cape East	-	15-20	15-20
MA	Fenoambany	-	25-30	20-30
MA	North-West	10	-	<5
MA	Tolagnaro	-	-	40-60
MO	Beira	27	5-10	10-15
MO	Inhambane	34	-	20-30
MO	Nacala	14	-	10-15
MO	Quelimane	19	-	10-15
MO	Quirimbas	12	5-10	<5
MS	Agalega	-	20-25	20-30
MS	Mauritius	-	30-40	30-40
SA	Durban	46	30-40	30-40
SA	St Lucia	46	30-40	20-30
SE	Seychelles	-	10-15	10-15
SO	Mugadishu	18	10-15	10-15
TA	Lindi	14	-	5-10
TA	Zanzibar	12	-	5-10

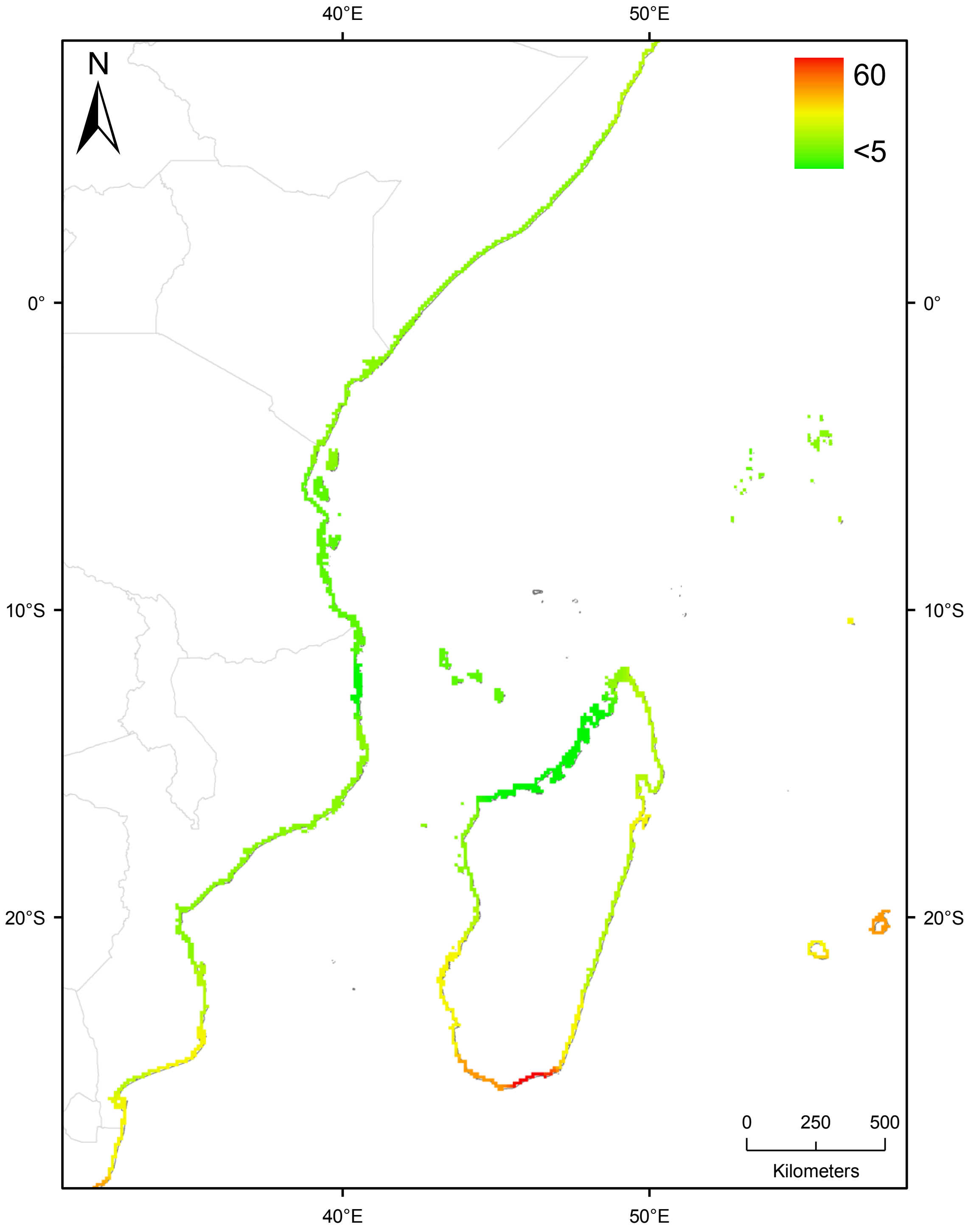

Figure 2. Annual means of coastal zone wave power (kW/m) in the WIO. Data was extracted and interpolated from Barstow et al. (2008).

2.1.2. Wave power resources in the WIO

The winds, and hence the wind driven waves, in the WIO are affected by the monsoon climate. During December to March the relatively weak North-East monsoon dominate the northern part of the region, giving raise to moderate easterly winds. In June to September the South-West monsoon develops with stronger winds throughout the region (Magori 2008) and the southern parts of the region are influenced by the powerful Westerlies (blowing from South-West).

The resulting wave climate, presented in Table 1 and Figure 2, shows particularly high power intensity (30-60 kW/m) in southern Madagascar, Mauritius, and South Africa. Also southern parts of Mozambique (the Inhambane region), south western Madagascar, and Réunion contain a significant wave power (20-30 kW/m). It should be noted, however, that these values are based on methods most appropriate for offshore conditions and the wave climate in shallow water is generally reduced. The reduction of wave power from 50 to 10 m depth would be in the order of 10 % (Folley et al. 2005). In-depth studies consequently require site specific data.

Table 2. Overview of seasonal differences in wave power at the most energy intense locations in the WIO. Data extracted from Barstow et al. (2008).

Country	Location	Wave power (kW/m)		
		Annual mean	January	July
FR	Reunion island	20-30	15-20	30-40
MA	Andavadoaka	20-30	10-15	30-40
MA	Androka	30-40	20-30	40-60
MA	Cape East	15-20	10-15	30-40
MA	Fenoambany	20-30	20-30	40-60
MA	Tolagnaro	40-60	30-40	40-60
MO	Inhambane	20-30	15-20	30-40
MS	Agalega	20-30	10-15	30-40
MS	Mauritius	30-40	20-30	40-60
SA	Durban	30-40	15-20	30-40
SA	St Lucia	20-30	20-30	30-40

At a global level comparison, the seasonal variation of wave power is typically lower in the southern than in the northern hemisphere (Barstow et al. 2008), which is reflected in a particularly low seasonality south of 15° S in the WIO region. The seasonal variations are shown in Table 2 for the most energy intense locations.

Another important factor is the frequency of destructive waves. This can be estimated as the ratio of the highest significant wave height over 100 years to the average wave height (here based on 10 years). This ratio is particularly low in the WIO, with the exception of northern Mozambique Channel (Barstow et al. 2008). This result indicates a relatively low probability of destructive waves for all of the high intensity areas of the region. Nevertheless the occurrence of cyclones in Madagascar, Mozambique, the Comoros, Réunion and Mauritius should be taken into account.

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2.1.3. Applicability of wave-power in the WIO

The results indicated good wave power availability in much of the southern parts of the WIO. Lower but still extractable resources (>10 kW/m) were indicated for most other parts of the region (except from the Comoros, northern Mozambique and southern Tanzania were the wave power is particularly low). However, most of the high-potential locations are found within the cyclone belt and may therefore not be suitable for wave power.

Large arrays of wave power, off-shore or land-based, may diversify and add capacity to main grids. The weather induced power fluctuations are somewhat predictable as a consequence of the monsoon climate.

Small-scale use of wave power may be widely applicable in the WIO outside the cyclone belt. In remote areas small wave power devices, with facilitated installation and maintenance, may be utilized to produce desalinated water and electricity to decentralized grids. Even at low-intensity conditions (10 kW/m) wave power converters can produce both electricity and thousands of litres of potable water. However, the power fluctuations require certain attention in small decentralized grids.

2.2. Ocean Thermal Energy Conversion (OTEC)

As the sun heats the surface of the sea and the global ocean circulation drive deep sea currents with cold dense water from the Polar Regions a substantial vertical temperature gradient is built up in low latitude oceans. While the surface water is heated to about 25-30° C in the tropics the deep water around 1000 m depth keeps a low temperature around 4-7° C (e.g. Hofmann and Maqueda 2006). By heat exchange technology this temperature difference (ΔT) can be utilized to drive electricity generating turbines; OTEC.

2.2.1. OTEC technology

Two fundamental OTEC principles have been in focus: open cycle systems and closed cycle systems. In addition there are hybrids of the two (Charlier and Justus 1993). Both principles imply that cold and warm water is taken from the depth and from the surface, respectively, via massive intake pipes. In the open cycle system the warm surface water is dispersed into low-pressure chambers where it is vaporized and run through large diameter turbines after which the vapour is condensed by the cold water. Dependent on system design the discharge products may be either water vapour and extra-saline deep sea water, or fresh water and saline condensate. In either case, an additional by-product is the change of temperature in the returned water. By the open cycle principle large quantities of potable fresh water can be obtained, adding value to the process.

In the closed cycle system the warm surface water is used to vaporize a secondary working fluid with low boiling point, such as ammonia or propane, which is then run through turbines and condensed again by the cold sea water. The working fluid is recycled and is never in direct contact with the water. By the closed cycle principle the only discharge is the cooling and heating of surface and deep sea water, respectively.

The original ideas of OTEC technology were launched more than a hundred years ago and during the 20th century substantial engineering was invested, not least by French, Japanese and American researchers. Numerous pilot plants were implemented and, after some years or months, taken down again. It has been difficult to cut down on costs, particularly regarding the heat exchangers, and no OTEC technology have yet reached close to competitiveness. In reviewing the OTEC technology Charlier and Justus (1993) states that there are no major technical breakthroughs required for OTEC. The main challenges for OTEC are the heat exchanger sub system, the prevention of biofouling (Charlier and Justus 1993), and the design and costs of the long cold water pipe (Anon. 2008). The recent advances in heat exchanger technology along with the experience from the offshore energy sector are regarded as highly beneficial factors for OTEC development. One frontier developer is Lockheed Martin who are currently about to construct a pilot plant where the cold water pipe is made from modern fibreglass and low-cost composite materials.

The required ΔT to run the OTEC process is about 20° C (Lennard 2007). The thermodynamic efficiency is low and much energy has to be spent internally for driving the pumps. However, advocates of the technology note that a low efficiency is of little matter as long as the fuel, warm surface water and cold deep sea water, is for free. The low efficiency of the OTEC technology implies that only large scale systems may become viable and that massive amounts of water will be in involved in any operating system.

Recent OTEC designs are much focusing on closed cycle offshore (floating or anchored) plants. But the multi-purpose of open cycle and hybrid plants, where electricity generation is complemented with fresh water production, are far from abandoned (Magesh 2010). There have also been suggestions of using the massive amounts of nutrient rich deep sea water to supply mariculture and the excess cold to provide air condition for surrounding facilities/towns. The prospects of such extensive alternation of environmental conditions may however be regarded as adventurous.

A recent suggestion of improving the efficiency of OTEC plants, called solar boosted OTEC, involves the application of solar thermal collectors or sun-heated basins to heat up the inflowing surface water before it reaches the heat exchanger. Straatman and van Sark (2008) estimated a four-fold increase in efficiency (from 3 to 12%) by the improved concept and Yamada et al. (2009) estimated an annual mean net thermal efficiency of 1.5 times an ordinary designed OTEC plant as the inflowing water was heated by 20° K during sun hours by use of simple solar collectors mounted on the OTEC facility.

A basic requirement for OTEC is that the ΔT is sufficient throughout the year. For land based systems the cold water source also has to be within accessible range from the shore. It is generally assumed that cold enough water can be found at 1000 m depth (in certain areas it may be found less deep) and that such depth must be reached within 25 km from land. In practice, the distance to the cold water source is an important economical factor and shorter distances are much preferable. Other physical factors to consider when selecting locations for OTEC are currents (the deep sea discharge must be removed while floating or moored structures must not be subject to violent forces) and bottom substrate and slope (the pipe must be safely moored).

The environmental impacts of OTEC strongly depend on plant design and location but may very well be high. Three main challenges are (1) the redistribution of oceanic properties (water body and temperature mixing), (2) chemical pollution (biocides, working fluid spills, corrosion), (3) structural damage (from Charlier and Justus 1993).

Based on the reviewed activities it seems a fair assumption that commercial OTEC technology will be implemented in tropical regions within the foreseeable future. Such modern OTEC plants are likely to be in the range of 10 to 100 MW. An OTEC plant generates a temporally steady electricity output with seasonal changes in efficiency; apart from solar-boosted OTEC, which implies different efficiency between night and daytime, there are no short-term variations (Yamada et al. 2009).

In the WIO Réunion and Mauritius have both shown interest in OTEC technology. While Mauritius has decided to wait until OTEC is proven by other countries the ambitions have been higher in Réunion. The island strives towards energy independence by 2025 and appropriate OTEC conditions have been identified. A first on-shore open cycle plant is now under preparation (Krock 2010). North of the WIO region India has constructed a 1 MW offshore OTEC pilot plant with the ambitions of adding several closed cycle commercial plants in the range of 10-50 MW capacity.

2.2.2. OTEC data sources and methods

There are several global level mappings of the physical key factors for OTEC (ΔT between surface and deep water and minimum distance to 1000 depth); e.g. Charlier and Justus (1993), Magesh (2010), Lennard (2007), and Nihous (2010). The studies apply different focuses and although valuable information can be extracted none of the available reports describe the conditions in the WIO at any detailed level.

For a screening of the OTEC conditions in the WIO region we have used bathymetry and temperature data acquired from the African Marine Atlas: shoreline (Wessel and Smith 1996) contour, 1000 m depth contour (BODC 2003), and ocean temperatures (Conkright et al. 2002)[1].

The distance from shore to 1000 m depth for each increment of the coast was calculated using ArcGIS software. The annual means of ΔT were extracted for all locations within 20 km distance from 1000 m depth. Global level maps of ΔT for February and August, produced by the Hawaii National Marine Renewable Energy Centre[2], were used for an overview of seasonal variations.

2.2.3. OTEC resources in the WIO

Global level assessments have notified a ΔT of 20-25° C for most countries within the WIO (e.g. Magesh 2010; Nihous 2010; Krock 2010). Where distance between land and 1000 m depth has been addressed it has been rated to 25 km or more for all WIO countries apart from the Comoros and the Seychelles (Charlier and Justus 1993, Krock 2010, Magesh 2010). However, by the spatial analysis presented in this study it is shown that for multiple locations in the WIO this distance is much less than previously accounted for.

Countries with locations showing both optimal accessibility (<5 km) and high average ΔT (22 °C) are Mozambique, the Comoros, and the Seychelles. The same ΔT but a somewhat lower accessibility (5-10 km) account for Mayotte, Tanzania, and Madagascar. In Mauritius and Réunion (France) the accessibility is optimal, less than 2 km, but the ΔT is reduced to 20-21° C. This result, presented in Figure 3 and Table 3, indicates good conditions for OTEC at numerous locations in the WIO.

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[1] http://iodeweb2.vliz.be/omap/OMAP/HYDROSPHERE/pages/physics.htm

[2] http://hinmrec.hnei.hawaii.edu/ongoing-projects/otec-thermal-resource/

Because of deep sea current properties the seasonal variations of ΔT is relatively high in the WIO (Nihous 2010). Even at the most suitable locations ΔT dips to 19-20 °C during winter (August). Additional analyses of seasonal variations would hence be advantageous for further evaluation of the OTEC potential.

Table 3. Minimum distance from shore to 1000 m depth and annual means of temperature difference between surface water and 1000 m depth. Data from GIS analysis and presented for locations in the WIO with distances below 20 km.

Country	Location	Distance (km)	Temp. diff. (°C)
CO	Anjouan	2.3	22
CO	Grande Comore	2.1	22
CO	Moheli	4.9	22
FR	Europa island	2.2	19.5
FR	Mayotte	5.7	22
FR	Reunion island	1.8	20.5
KE	Kiunga	17.5	21
MA	Ampondrabe	8.7	22
MA	Andavadoaka	12.8	21
MA	Andranovondronina	6.0	21
MA	Androka	13.5	19.5
MA	Besamata	10.7	20
MA	Fenoambany	17.3	20
MA	Itampolo	14.3	20
MA	Masondrono	8.2	21
MA	Nosy be	16.4	23
MA	St Augustin	8.4	20
MA	Vohemar	9.3	21
MO	Angoche	18.5	21
MO	Barroa	15.0	21
MO	Calajulo	5.0	21
MO	Ibo island	12.6	22
MO	Matibane	5.7	22
MO	Mecufi	11.4	22
MO	Memba	3.5	22
MO	Nacala	2.8	22
MO	Pemba Mozambique	7.6	22
MO	Quisiva island	8.0	22
MO	Vamizi	10.7	22
MS	Mauritius	1.3	20
SA	Mabibi	15.3	20
SA	St Lucia	19.7	18
SE	Coetivy island	3.0	22.5
SE	Desrouches	2.5	22
SE	Poivre islands	2.5	22
SO	Mareg	17.0	20
SO	Warshikh	15.0	20
TA	Kilwa	7.5	22
TA	Lindi	9.3	22
TA	Mtwara	13.0	22
TA	Pemba Tanzania	15.5	21.5

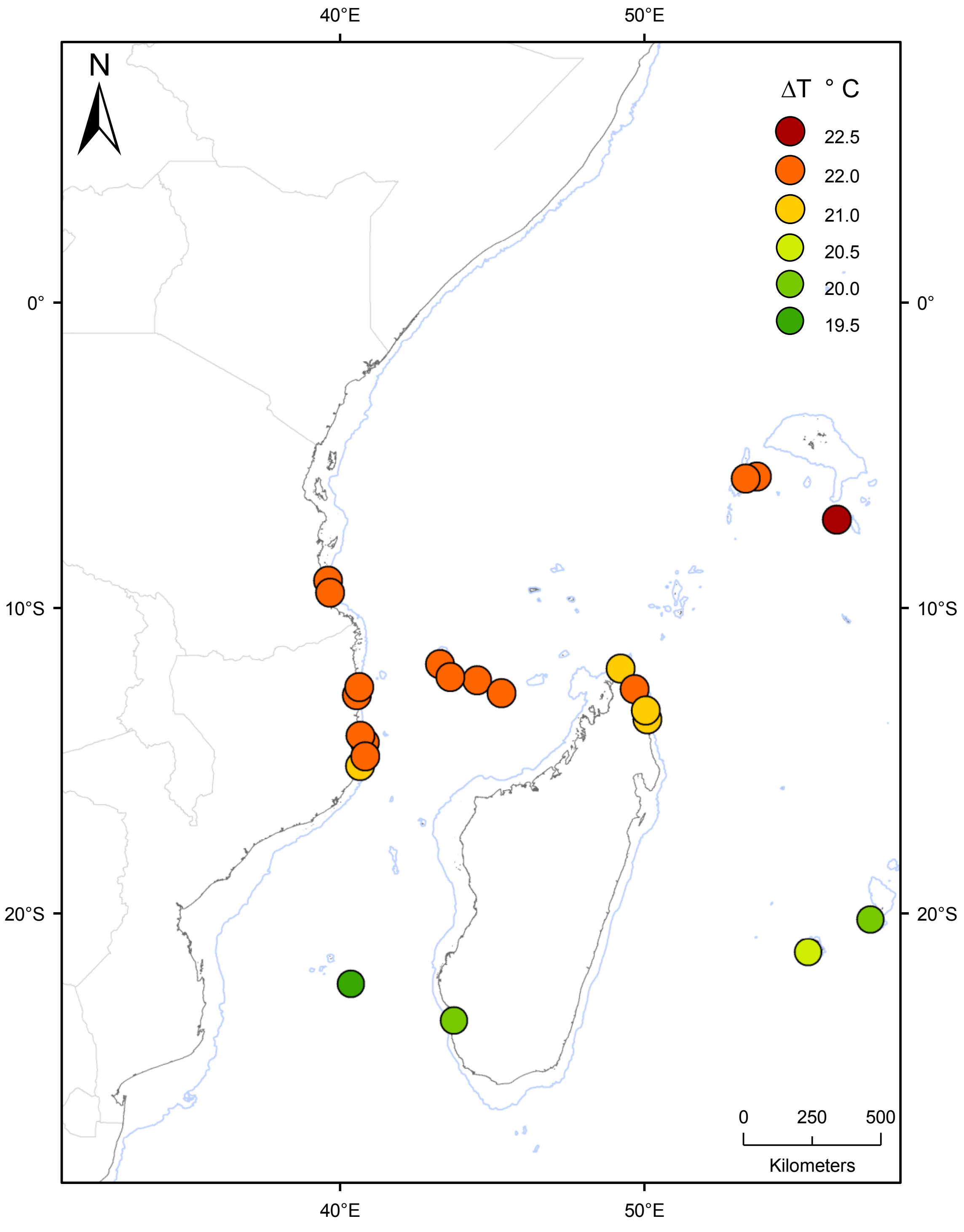

Figure 3. Geographical distribution of annual means of temperature difference (ΔT) in the WIO region at shore locations within 10 km distance from 1000 m depth. See Table 3 for exact distance. The 1000 m isocline is indicated.

2.2.4. Applicability of OTEC in the WIO

Based on the prevailing physical conditions the OTEC potential in the WIO is considerable; the distance to cold deep water is short at many locations, in favour of onshore systems which eases maintenance and energy transfer. The ΔT in the WIO is comparable to the conditions in Hawaii and India, locations where much of the modern OTEC research and pilot plant development takes place. With the development of solar-boosted OTEC's the efficiency and power potential will increase and it appears reasonable that the physical conditions at several locations in the WIO will make the technology appealing as a future energy source. Strong surface currents, cyclones and potential environmental effects are possible impeding factors.

Since OTEC is practical only at a large-scale basis the produced electricity, and freshwater in the case of open-cycle design, may be limited to national or provincial distribution and not small decentralized grids. The generation efficiency – dependent on ΔT – only fluctuates over seasons and the plant operation can be regulated by pumping of water, making OTEC a power source of low variability and favourable for any grid as it can be used for control purposes.

2.3. Tidal barrage power

Tides emerge from the gravitational forces between the Earth, the moon, the sun, and the centrifugal forces of the rotation of Earth around its own axis and along the solar orbit. More than a hundred factors affect the tides but the basic pattern can be described by the few major ones. The orbits of the three main bodies (Earth, moon, sun) result in a pattern where the tide rises and falls twice per day (semidiurnal tides) and where the force is amplified twice per month dividing the cycle into stronger spring tides and weaker neap tides. This basic variation of tides can be described as a twofold sinusoidal pattern with a daily (harmonic) period of 12 h 25 min and a monthly period of 15 days. While the tidal range in the open ocean is low its amplitude can be greatly exaggerated by ocean geometry such as the positioning of landmasses (e.g. Madagascar) and bathymetry. In addition, the tides are affected by weather, such as strong wind and air pressure, which is difficult to predict on long term basis.

2.3.1. Tidal barrage power technology

The potential (gravity based) energy endowed in the rising tides is immense and can be extracted by controlling the flows through a barrage where water is directed to pass through conventional hydropower turbines. For a tidal cycle the generated power, P_e, can be calculated by:

$$P_e = c_p \frac{\rho g \int Q(t)H(t)dt}{T} \qquad (2)$$

where c_p is the conversion efficiency, ρ is the density of sea water (kg/m^3), g is the gravitational force (m/s^2), Q is the flow through the turbines (m^3/s), H is the head (m) between the water inside and outside the basin, t is time and T is the period of the tidal cycle.

The principle of tidal barrage power is to trap a fraction of the high or low tide inside a barrage, hereby creating a head between the enclosed and the natural water levels, and to let the water levels even out while passing through low head turbines. Power can be generated during ebb only (one-way operation) or during both ebb and flood (two-way operation). In the case of one-way operation open gates allow water to fill up the basin during flood, after which gates are closed as the sea level recedes during ebb. When a sufficient head (H_{min}) is achieved between outside and inside the water is allowed to pass out through turbines until a new H_{min} has been reached, now at low water level. As the sea level raise again during flood the basin is refilled and a new water head can be extracted during the successive ebb. During two-way operation, which generally implies a higher efficiency and power availability to the cost of increased technical complexity, the water passes through reversed turbines during flood, instead of open gates.

Among the tidal barrages existing today, both principles have been used. Moreover, there are various ways of optimizing the extraction or control the temporal availability of power by dividing the impoundment into different basins and by allowing pumping between basins and sea. The barrage designs considered in this study are restricted to single basin one-way and two-way operation.

Since many decades the use of tidal barrage power has been applied in Canada, France, Russia, and China. The construction of dams is expensive and the pay-back time is long; planned projects in various countries have therefore been abandoned or postponed (Charlier 2003). In later years, however, tidal barrage technology has regained interest. A 90 MW project is being implemented in the Republic of Korea; tidal lagoons are being promoted in the UK (with the first plant soon to be constructed); and India are planning for a 3.75 MW demonstration plant (single basin one-way generation) and a 100 MW barrage (Bryden 2010). Tidal barrage power has also been discussed in northern Brazil, both regarding large- (Ferreira and Estefen 2009) and micro-scale (Anderson et al. 1993) installations.

Tidal barrage technology is applicable at a vast range of scale. A large impoundment area naturally means more potential power to tap and projected mega projects are in the range of thousands of km^2 (Gorlov 2001). This means high capital cost, high generation capacity, and potentially serious environmental concerns. However, economic attractiveness have also been found in small barrage designs (Charlier and Justus 1993) and construction work for small impoundments are of course much facilitated as well as the severity of natural tidal regime interference. Small tidal barrages have been employed by numbers in decentralized rural grids of China (Charlier 2001, Wang et al. 2011). At the end of the scale are the innovative micro-scale dams where removable plastic barriers are used to seal small tidal pools (Charlier and Justus 1993). With the developments in low-head technology, where turbines are now operational below 1.5 m head, the previous requirements on tidal ranges above 5 m have been altered, which imply a worldwide multiplication of potential sites (Charlier and Justus 1993).

Nevertheless coastal engineering is expensive and difficult, not less so in developing regions where infrastructure is limited. Regardless of size, construction costs have to be minimized if tidal barrages are to be an alternative. One given option is to take use of natural structures and hereby reduce the length of the barrier. Apart from a significant tidal range and a naturally occurring impoundment a feasible site also requires that bathymetry and sediment structure allow for the installation of barrage and turbines. Furthermore, the sedimentation rate inside the basin must be low for the volume not to rapidly decrease.

As the tides are predictable over years the power output from a barrage can be determined far ahead, only leaving small weather induced deviations. But a major set-back with tidal power is that the period of the tidal cycle does not equal the cycle of human activities (24 h). Electricity generation will consequently not match energy demand. To some extent the generation can be evened out by plant design and energy storage. As the diurnal tidal variation prevents a continuous power output a trade-off appear between power output and power availability over time. By modifying the H_{min} and the flow rate through the turbines a tidal barrage can be optimized with respect to either power output or power availability over time. To have power available over a larger part of the day may be of importance in small grids while the maximum power output may be the most relevant aspect in large grids.

In this study we have investigated the tidal range in the WIO region and calculated the potential power generation and its temporal availability for different tidal barrage designs.

2.3.2. Tidal barrage power data sources and methods

The tidal pattern in the WIO is well described in the oceanographic literature and there are some real-time data available from tidal gauges. For the calculations in this study we have used four months (March-June 2010) of tidal gauge data from ODINAFRICA[3] to calibrate a simple model of the monthly tidal cycle. Where no real-time data was available (Mozambique) official tidal predictions (INAHINA 2009) have been used. The tidal model is expressed as:

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[3] http://www.vliz.be/vmdcdata/iode/

$$Z = SR\cos\left(2\pi\frac{t}{T_1}\right).*\left[A - B\,cos\left(2\pi\frac{\left(t+\frac{T_2}{2}\right)}{2}\right)\right] \qquad (3)$$

$$A = 1 - \frac{(SR-NR)}{(2SR)}$$

$$B = \frac{(SR-NR)}{(2SR)}$$

where Z is the tidal level, SR is the spring range (average range during the two days of peak spring), NR is the neap range (average range during the two days of full neap), T_1 is the period of the daily tidal cycle and T_2 is the period of the monthly tidal cycle. The model does not account for the diurnal difference between the first and second (average is used) or the variations between months associated with the moon's distance to Earth. However, the period of data was selected not to include any extreme tides (lunar perigee or apogee). With the tidal cycle calibrated for each specific location the potential energy was calculated for tidal barrages using a) one-way operation mode, and b) two-way operation mode, by combining *Eq.2* and *Eq. 3* and optimizing the power output by altering H_{min} and the flow rate through turbines. To illustrate the possible trade-off between maximum power output and power availability different optimization strategies were run. All power calculations assume a constant basin area throughout depth (standardized to 1 km^2) and a conversion efficiency of 0.75.

All locations with available tidal data were investigated and the calculations were made for seven representative locations in the macrotidal part of the region; where spring tides exceed 3 m (Magori 2008). The tidal range is likely to be of comparable dimensions in coastal areas between each of the assessed locations but since the tidal amplitude is also strongly affected by coastal geometry and local bathymetry, which is little known, no interpolation has been done in this study. Unfortunately there is a lack of available data from the assumingly high tidal ranges in southern parts of the Sofala Bank (Mozambique).

Table 4. Tidal characteristics of the selected locations and calculated annual power for tidal barrages in one-way and two-way operation mode. Note that power output is given per km^2.

Country	Location	SR (m)	NR (m)	Power (MWh/yr per km2)	
				One-way operation	Two-way operation
KE	Mombasa	3.5	0.8	2,320	4,030
MO	Beira	5.5	1.7	6,340	11,080
MO	Mocimboa de Praia	3.6	1.3	2,890	5,080
MO	Pebane	3.6	1.1	2,720	4,730
MO	Quelimane	3.7	1.0	2,770	4,830
TA	Mtwara	3.4	1.2	2,670	4,480
TA	Zanzibar	3.7	1.3	3,020	5,290

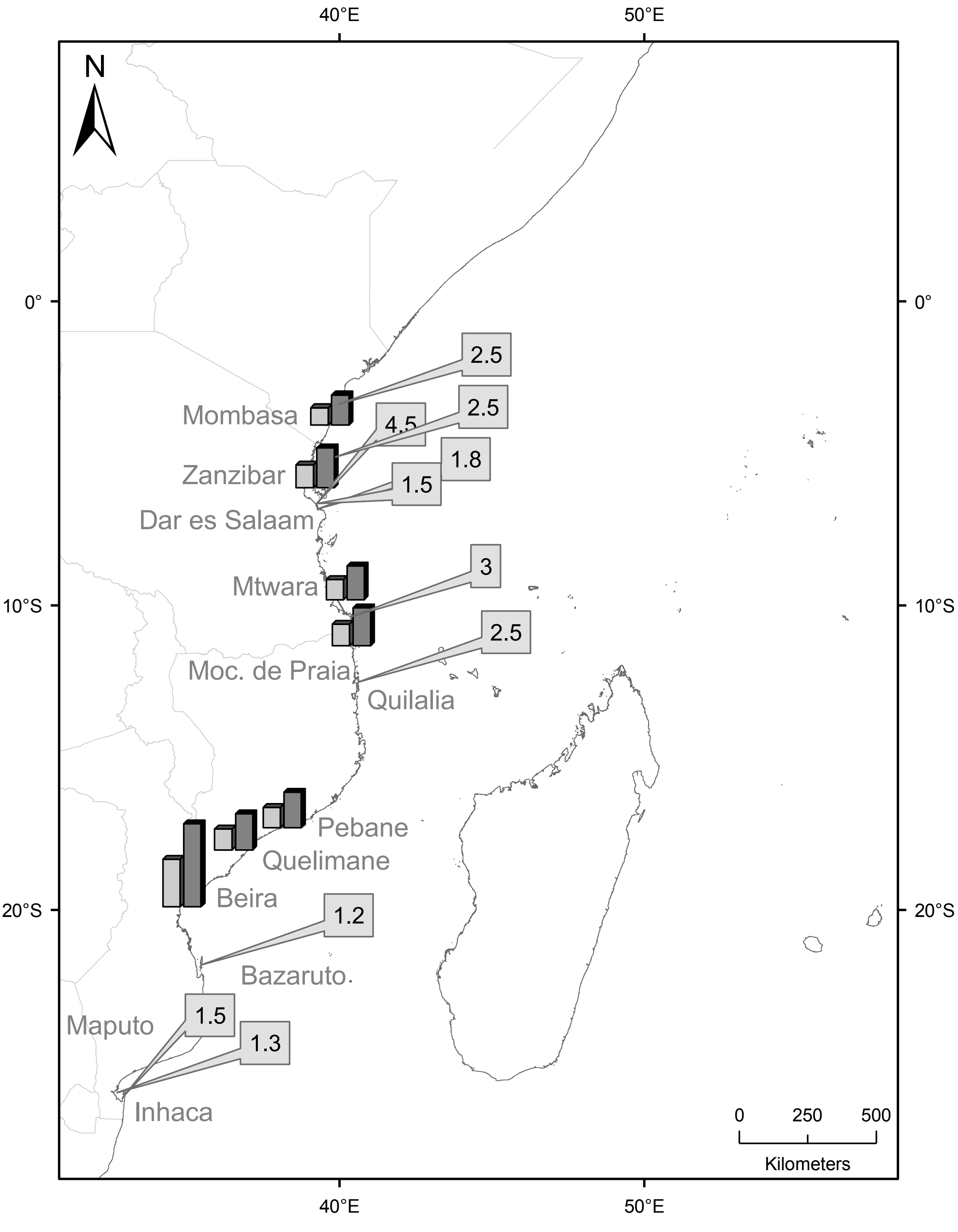

Figure 4. Distribution of locations with investigated tidal barrage potential and fast flowing tidal currents. Dark and grey bars give a relative measure on power output for one-way and two-way tidal barrages, respectively. Grey labels indicate the highest current speed (m/s) at identified sites.

2.3.3. Tidal barrage power resources in the WIO

The tidal pattern in WIO is much determined by the positioning of Madagascar which propagates the oceanic tidal wave over the East African coast, giving raise to macrotidal regimes in Kenya, Tanzania, Mozambique, western Madagascar and the Comoros (using the definition in Magori 2008). In contrast, the tides in Mauritius, Réunion, the Seychelles and eastern Madagascar are low. The highest tidal range in the WIO is found at the Sofala Bank in central Mozambique where the tidal wave is amplified by the gently raising slope of the basin. This particularly affects the Beira area, but also Quelimane and Pebane. Other areas with high tidal range occur where local coastal morphology such as peninsulas and bays propagates the tidal wave; e.g. Moçimboa de Praia in northern Mozambique. The tidal range and the calculated power output per km^2 for different technical designs at selected locations are presented in Table 4 and Figure 4. Since the number of locations has been limited by data availability it should only be regarded a rough indicator – the coastal stretches between locations are likely to have similar conditions.

The result shows that each km^2 of tidal barrage in the macro tidal part of the WIO have the potential to generate power in the order of 3 and 4.5 GWh/yr by one-way and two-way operation design, respectably. The inner part of the Sofala Bank (Beira) is an exception with a generation potential of 6.3 to 11.1 GWh/yr per km^2. By adjusting H_{min} either power availability (number of minutes with electricity production) or power output (total amount of Watt hours) can be maximized, this trade-off is illustrated for in Figure 5 which shows that one-way and two-way generation tidal barrages can be adjusted to produce electricity up to about 50 and 75 % of the time, respectively, while the power availability is only 30 and 40 % of the time at maximum power output.

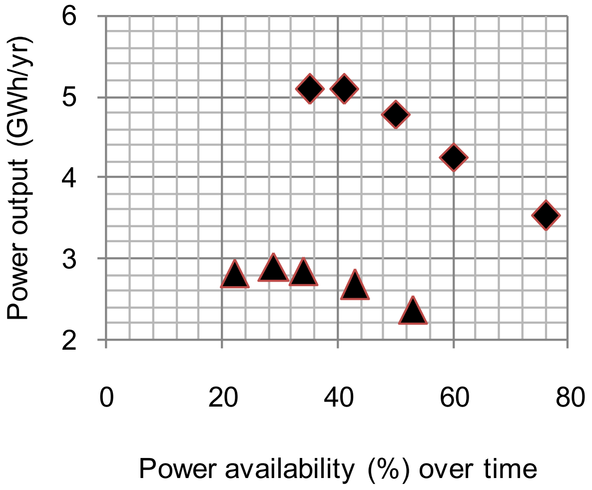

Figure 5. Trade-off between generated power and electricity availability for different values of minimum head (H_{min}), when flow is optimized for maximum power output. Triangles indicate one-way operation, diamonds indicate two-way generation. The example is based on the tidal characteristics of Moçimboa de Praia. Both H_{min} and flow rate are assumed to be constant throughout the tidal cycle.

Table 5. Examples of potential sites likely to meet the basic (non-economical) criteria for small-scale tidal barrages in Tanzania. Only areas close to the tidal gauges in Mtwara and Zanzibar in Tanzania were investigated and similar sites are likely to be found elsewhere. A S/B index (surface area divided by barrage length) was used for ranking purposes. Use Table 4 to estimate the annual power output at the locations.

S/B index	Barrage (km)	Area (km2)	Location		
				lon.	lat.
16	0.7	11	Mtwara city (Mtwara)	40.19	-10.26
8	0.6	5	Mikindani (Mtwara)	40.13	-10.30
2	2.3	4	Fumba (Zanzibar)	39.29	-6.28
1	0.6	1	Chuno (Mtwara)	40.15	-10.28

2.3.4. Applicability of tidal barrage power in the WIO

With exception of central Mozambique the tidal range throughout the WIO region is lower than what has traditionally been considered as economically feasible. The investment in large-scale tidal barrages is hence not likely to be attractive, certainly not when taking the environmental implications into account.

Small-scale applications may still be an option at sites where electricity is scarce and physical conditions are suitable. Small-scale tidal barrages, supplying communities or agriculture, operate under comparable tidal conditions in China (BaiSha Estuary, 640 kW) and Russia (Kislaya Guba, 400 kW) (Khan et al. 2009, Wang et al. 2011).

Some basic non-economical site criteria which have to be met are (1) a limited barrage length in relation to available power, (2) a solid bottom for construction, (3) a low interference with human activities and environment, (4) a low sedimentation rate, and (5) proximity to end-user. Table 5 shows some examples of sites expected to meet these criteria in Tanzania (Table 5). As a relative ranking between sites a S/B index was introduced; surface area (km^2) / barrage length (km). According to general coastal morphology similar sites are likely to occur throughout the macrotidal coast with exception of the mangrove fringed estuaries of central Mozambique.

Small- or micro tidal barrages are generally more easily maintained than other OE technologies since it is based on conventional low-head turbines, a technology proven from hydropower. The inherent fluctuations of tidal power may however be problematic in small grids as discussed above; energy has to be stored or load has to be tuned to the diurnal fluctuations. The simplicity of one-way operation has to be weighed against the extended power availability of two-way operation.

2.4. Tidal stream power

By the fluctuating tides water is continuously moved back and forth over the coast, movements which give raise to slow currents during flood and ebb. Where the water is forced to pass by narrow passages or peninsulas these currents can be strongly amplified. With the high density of water even relatively slow currents contain much energy and the energy invested in fast flowing currents is massive. The relation between flowing water and kinetic power, P, is given by:

$$P = 0.5\rho v^3 \tag{4}$$

where ρ is the density of sea water (kg/m^3) and v is the velocity of the current (m/s).

2.4.1. Tidal stream power technology

During the last decades there has been a fast development of turbines aiming to convert the kinetic energy in flowing water into electricity (Bryden et al. 2004, Hagerman et al. 2006, Block 2007, Grabbe et al. 2009, Rourke et al. 2010). Even though several full-scale devices have now been deployed the tidal stream power concept is young (Clarke et al. 2006, Block 2007, Bryden 2007, Rourke et al. 2010). The conversion principle varies between devices but in general a horizontal or vertical turbine is driven by rotor blades, much like wind power turbines. The device may be fixed to the bottom or anchored at the surface. The generated power P_e is basically determined by the water velocity, the area swept by the rotor, and the turbine efficiency:

$$P_e = 0.5C_p\rho A v^3 \tag{5}$$

where C_p is the conversion efficiency and A is the area swept by the rotor (m^2).

Tidal currents vary according to the twofold sinusoidal pattern of the tides, with a daily and monthly period of 12 h 25 min and 15 days respectively. Since the currents flow both during ebb and flood there are four peaks each day. As the power is cubed to water velocity most energy reside in the peak currents which in turn are highly variable in shallow areas as the dependence of local bathymetry is large. A good knowledge of the local tidal patterns becomes indispensable for accurate tidal current resource assessments.

Most tidal stream devices have a capacity between 10 kW and 5 MW. Most are aimed for use in large tidal farms of tens to hundreds of units in fast flowing currents (>2 m/s) and water depths above 20 m. At this level the requirements on structure and weight generates dimensions of up to hundreds of tons per device (Fröberg 2006). As a consequence of large dimensions and complicated installations many tidal stream developments focuses on large sites in proximity to infrastructure facilities.

Nevertheless there are several devices applicable for a small-scale employment with facilitated installation and maintenance (Bryden 2007). By applying a low cut-in speed and high generator efficiency at lower water velocity micro-scale devices can also operate in less harsh sites.

Although being highly predictable, the variation in power generation over the tidal cycle is an obvious drawback of tidal power. In similar to offshore wave power tidal stream power requires submerged transmission which can be expensive and complicated in violent waters. Most devices, and in particular the floating micro-scale devices, are likely to be inappropriate in water exposed to cyclones.

There has been one previous assessment of the potential for tidal stream power in the WIO (Dubi 2006). From the reading of tidal currents between small islands off Dar es Salaam (Tanzania) a maximum current velocity of 1.5 m/s was measured and a power potential of 132 kW/m was calculated. The results were interpreted as encouraging but no further investigations have been done in the region.

In this study we have gathered available observations on fast-flowing currents in the region and exemplified its potential for specific tidal current power devices.

2.4.2. Tidal stream power data sources and methods

Tidal currents are highly site-specific and to the knowledge of the authors there have been no extensive modelling of the tidal currents in the WIO region. However, some adequate information is available from oceanographic literature (Lwiza 1996, Kitheka 1998, Mavume 2000, Dubi 2006, Nhnyete and Mahongo 2007) and unpublished data (Mavume et al. 2005). In addition, qualitative information on fast-flowing tidal or coastal currents has been collected from consultancy reports and diver's observations. The compiled information was used to display the distribution of sites with current speed known to exceed 1 m/s. Strong currents at uninhabited islands, such as the Aldabra atoll, were not considered. The potential power output for different tidal stream devices was calculated by applying *Eq. 5* and a sinusoidal current speed model, *Eq. 6* (based on Fraenkel 2002):

$$v = \begin{cases} \left[MSS + MNS(\frac{2\pi t}{T_2}) \right] \cos\left(\frac{2\pi t}{T_1} \right) & nT_2 \le t \le \frac{(2n+1)T_2}{2} \\ -d_{fe}\left[\left[MSS + MNS(\frac{2\pi t}{T_2}) \right] \cos\left(\frac{2\pi t}{T_1} \right) \right] & \frac{(2n+1)T_2}{2} < t < (n+1)T_2 \end{cases} \qquad n = 1,2,3... \qquad (6)$$

where *MSS* is the maximum speed during peak spring and *MNS* is the maximum speed during peak neap as a proportion of *SS*, d_{fe} is the ratio between subsequent flood and ebb currents, *t* is time, T_1 is the period of the daily tidal cycle), and T_2 is the period of the monthly tidal cycle.

Based on the method used by Fröberg (2006), and later Grabbe et al. (2009), the acquired observations of maximum speed from the different locations were assumed to represent *MSS* while the MNS was set to 0.6. The flood/ebb ratio was set to 0.84 based on analysis of data in Mavume (2000).

For all power calculations a water-to-wire efficiency (C_p) of 0.40 were used (Hagerman et al. 2006). Where only surface speed was acquired from data the 7th power law (e.g. De Chant 2005) was used to adjust speed to mid-water depth. The power calculations were performed for three different tidal current power units:

- Large device; with technical assumptions based on the SeaGen tidal power device which is employed in the UK since 2008 (Khan et al. 2009). The rated power for the full scale unit was set to 1.2 MW in 2.4 m/s, with a cut-in speed of 0.7 m/s, and a swept area was 400 m^2 (corresponding to two rotors each with a diameter of 16 m). The device is piled to the bottom in high current waters at approximately 30 m depth.

- Small device; with technical assumptions based on the Verdant Free Flow Kinetic Hydropower System which is employed in the New York City´s East River since 2006 (Fröberg 2006, Khan et al. 2009). The rated power was set to 36 kW in 2.1 m/s, with a cut-in speed of 0.7 m/s, and a swept area of 20 m^2 (rotor diameter 5 m). The device is moored to the bottom at 6-20 m depth.
- Micro device; based on based on a hypothetical 5 m wide anchored raft employed with four single Gorlov Helical Turbines. The technical assumptions was a rated power of 20 kW at 2 m/s, a cut-in speed of 0.5 m/s, and a swept area of 10 m^2 (each helical rotor is 2.5 m deep and 1 m wide). The minimum depth for this device would be around 4 m.

2.4.3. Tidal stream power resources in the WIO

Based on the limited data tidal currents above 2 m/s were identified at five locations in Tanzania, Mozambique and Kenya, out of which two has been measured and three have only been reported as observations. Another five locations with lower current speed, between 1 and 2 m/s, was identified in Tanzania and Mozambique (Figure 4). The recording of 4.5 m/s in the Kunduchi Creek in Dar es Salaam is the highest, but this creek is very small and the speed should not be regarded as representative for any larger area. Since only the maximum speeds are considered it cannot be assured that the whole force stems from the tides, ocean currents or wave pattern may also be involved to some degree.

The geographical distribution of high speed locations is shown in Figure 6. There is no generic distribution pattern but all sites are found in areas influenced by islands, estuaries or peninsulas. Table 6 presents the potential power generation of the three discussed devices at each location and Figure 6 illustrate the temporal distribution of power over the monthly tidal cycle for the small device rated at 36 kW. It should be noted that power is calculated per unit (1 power device) while most sites allow for several units in arrays.

Table 6. Site description and calculated annual power output for the different tidal stream devices at known high-speed locations. Power output has only been calculated for devices which could be installed at each site, with respect to depth.

Country	Location	Speed (m/s)	Data quality	Depth at site	Power (MWh/yr)		
					Large device	Small device	Micro device
KE	Watamu National MP	2.5	Quant. data	6 m	-	148	79
MO	Bazaruto	1.2	Quant. data	15 m	-	19	11
MO	Inhaca	1.45	Quant. data	10 m	-	38	20
MO	Maputo Bay	1.3*	Unknown	6 m	-	15	10
MO	Quilalia island	2.5	Qual. obs.	50 m	3,727	-	-
TA	Dar es Salaam	1.8*	Unknown	Unknown	-	51	27
TA	Kunduchi	4.5	Quant. data	Shallow	-	-	129
TA	Mbudya Channel	1.5	Quant. data	15 m	-	43	23
TA	Mnazi Bay	3*	Qual. obs.	Unknown	5,075	160	86
TA	Pemba Zanzibar	2.5	Qual. obs.	Unknown	3,727	148	79

The power potential at fast flowing sites (Mozambique, Tanzania, Kenya) is considerable but the identified sites are few. However, since few measurements have been conducted in the region it is likely that unrevealed fast-flowing sites are to be added.

For most of the hitherto identified sites details are missing; e.g. it is well known that forceful currents occur in eastern Pemba (Tanzania) but it is not known whether the origin is solely tidal or to what extent offshore ocean currents are involved.

2.4.4. Applicability of tidal stream power in the WIO

Along the macro-tidal mainland coast high current speeds are identified at particular sites. From the available data it is not possible to quantify the abundance of such sites, but it is likely that several areas with currents around 1-2 m/s are still not detected. The physical conditions probably allow for both large and small devices at specific sites in the region.

Large-scale use of tidal stream power appears unlikely to be feasible as the known sites in the region are few and both installation and maintenance of such devices is technically demanding. Small-scale applications, based on small/micro units at specific sites with water flows from about 1.5 m/s may be a future option for remote area electrification and water desalination if easily installed and maintained devices become available. The variation in power generation would be a challenge but the peak power could be a valuable complement to low capacity sources; such as small scale solar PV. It has previously been suggested that remote area electrification may be the most adequate use of tidal stream power (Bryden 2007). Similarly to wave power, no small tidal stream devices are likely to be adequate within the cyclone belt.

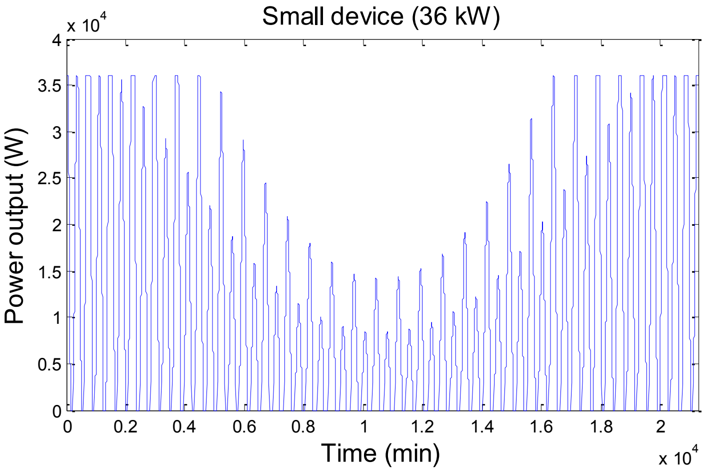

Figure 6. Power output over the monthly tidal cycle (14.5 days) based on the technical assumptions of a small (36 kW) tidal stream device at a site with a spring speed reaching 2 m/s.

2.5. Ocean current power

Oceanic currents primarily emerge from the Earth rotation, the Coriolis force, and are consequently strongest at the western rims of the great oceans. The mass transport in the oceanic currents is immense but the power density is still low because of the rather slow water velocities. However, where the currents are constrained by land or bathymetry the current velocities can be reinforced. One of the most powerful ocean current systems in the world is the Somali-Agulhas which prevails in the WIO (Charlier and Justus 1993).

The energy content in the ocean currents can be determined by the same principles as for tidal streams (*Eq. 5*) (Fraenkel 2002).

2.5.1. Ocean current power technology

Over the last fifty years there have been numerous inventions suggested for extraction of the large ocean currents (Charlier and Justus 1993). Since the ocean currents are slow and the inherent energy is cubed to the velocity much can be won by increasing the actual flow over the turbine during power extraction. This possibility has been approached by different designs, where the most common has been to construct a ducted shroud over the turbine. With a duct the water flow is dragged through the turbine by the experienced pressure gradient that develops from the shape of the duct and the increase in velocity becomes reflected in the conversion efficiency of the device.

The perhaps most daring system design, the Coriolis turbine, was suggested for extraction of Gulf Stream current off the coast of Florida. Each unit was initially designed to a capacity of 83 MW and the duct measured 171 m in diameter and set for anchoring in the deep sea (Charlier and Justus 1993). The unit size was later reduced but the device was never implemented. A recent and more small-scale approach to increase the experienced water speed over the rotors is to mount the turbines on an underwater kite which circulates driven by the current. This innovation, Deep Green developed by Minesto, is currently to be piloted in the Irish Sea. Each unit have a wing span of 12 m a rated power of 500 kW in 1.5 m/s and is mounted on the sea bed at depths of 50-120 m. The solution of sweeping the turbines through the water increases the experienced water speed over the turbine with a factor of 10, consequently improving efficiency radically and allowing extraction of relatively slow currents (1-2 m/s). By arrays of Deep Green devices approximately 8-12 MW would be installed per km^2. Apart from these specialized ocean current power devices some of the larger tidal stream power devices, such as the SeaGen turbine by Marine Current Turbines Ltd, have also been suggested for extracting ocean currents.

The relatively low power density, the rough deep sea conditions and expensive power transmission imply that ocean current power as future energy source will only be commissioned as large-scale projects. The temporal variations of power output will be seasonal rather than daily, as opposed to tidal power. To date there have been no realization of ocean current power anywhere. However, the South African energy company Eskom is currently investigating the resources in the Agulhas current off the Kwazulu-Natal coast.

2.5.2. Ocean current power data sources and methods

In this study we have examined the oceanic current patterns through WIO-related oceanographic literature. Seasonal observations of ocean current velocities have been obtained from the Global Drifter Program (Lumpkin and Garraffo 2005, Lumpkin and Pazos 2007) through the African Marine Atlas[4]. By this program a network of surface drifting buoys has been employed to collect hydrographical data including drift velocity. The obtained data show the monthly averages (with absence of April) but the geographical resolution is low and no interpolations have been done in this study.

2.5.3. Ocean current power resources in the WIO

The major ocean currents in the WIO are the Somali Current, the East African Coastal Current, the South Equatorial Counter Current, the South Equatorial Current, the East Madagascar Current, and the Mozambique Current (see Figure 1). The two latter currents ultimately join with the Agulhas Current which sweeps further along South Africa out of the WIO region.

The most fast-flowing currents in the region are the Somali Current, the Eastern African Current, and the Mozambique Current. The two former are strongest during the South West monsoon (June-September) and the latter is strongest during North East monsoon (December-March). Both the Eastern African Current and the Mozambique Current diverge from the South Equatorial Current at approximately 10° S (by the Comoros), northwards and southwards respectively. When the Somali Current is enforced by the Eastern African Current during South West monsoon the flow reach extreme velocities, reported up to 3.5 m/s (Magori 2008).

The data from the Global Drifter Program is illustrated in Figure 7. Off the northern tip of Madagascar the current velocity is 0.5 to 0.9 m/s throughout the year. Strong and consistent currents are hence likely to be found over the narrow continental shelf in this area. The buoy measurements from the western parts of the Mozambique Channel reach about 0.75 m/s during the North East monsoon and average 0.5 m/s during the South West monsoon. Unfortunately, no Global Drifter data is available from the north western section of the channel where particularly high velocities have been reported. However, the surface velocities of this western section of Mozambique Current (from 12° S down to 12° S) are from ship drift records known to be very high. DiMarco et al. (2002) refer to records indicating average surface currents of 1-1.5 m/s and occasional velocities beyond 2 m/s, southwards flowing. In parts of this area the continental shelf is very narrow (northern Mozambique and southern Tanzania) which is an additional prerequisite for expecting strong currents close to land and to facilitate mooring and energy transmission. There have been unverified reports of current velocities of 3 m/s from oil prospecting vessels off the coast of in northern Mozambique.

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[4] http://iodeweb2.vliz.be/omap/OMAP/HYDROSPHERE/pages/currents_gdp.htm

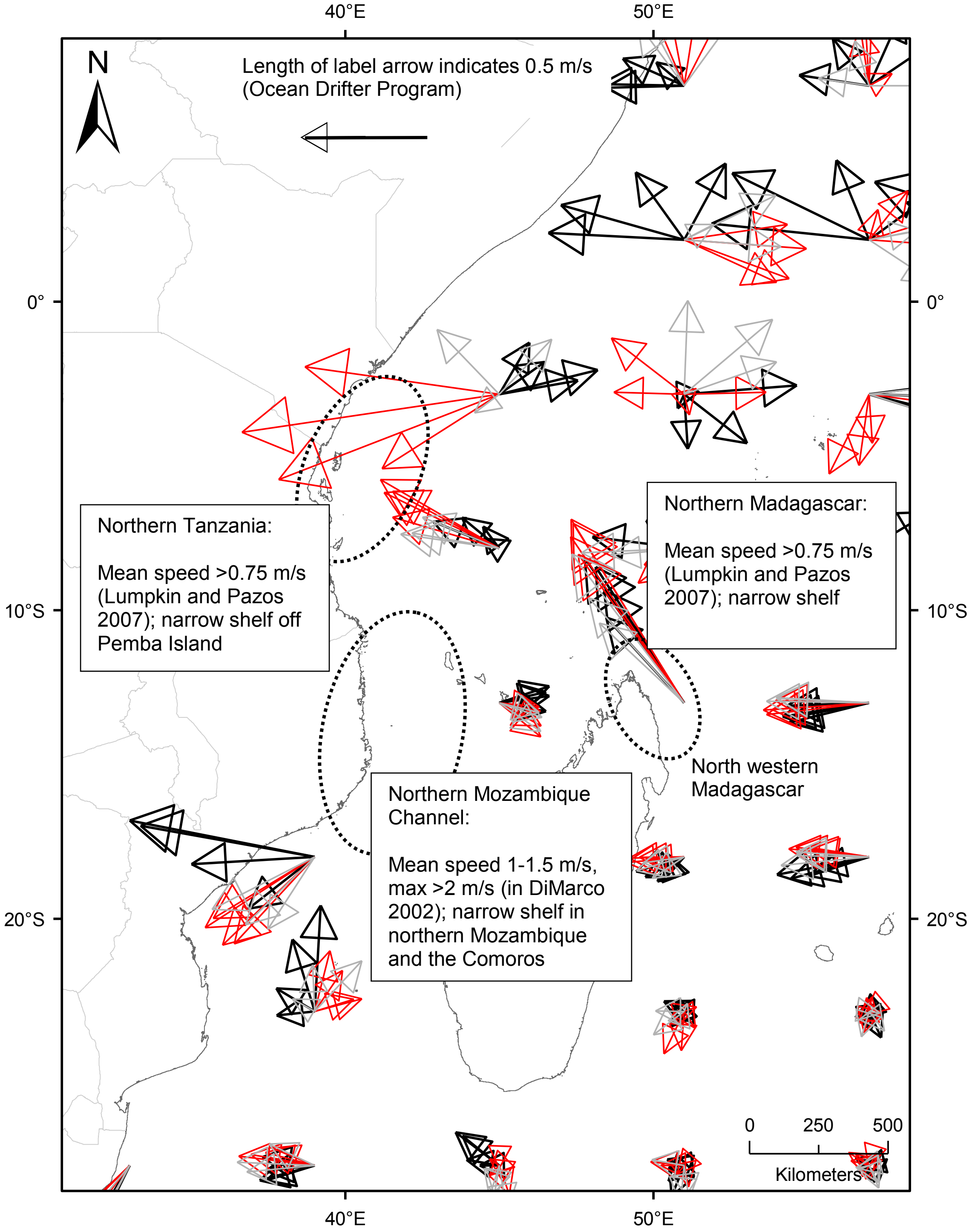

Figure 7. Overview of currents data in the WIO region from the Global Drifter Program (arrows). Current velocities are given as monthly averages (m/s) for the North-East monsoon (black arrows), South-West monsoon (red arrows), and other months (grey arrows). Areas of particular interest, based on the reviewed material, are indicated by dashed line and explained in labels. The strong currents in eastern South Africa (Agulhas Current) are not shown.

The examined data only provide samples of offshore current velocities and the coastal current patterns are not yet resolved. There is little doubt, however, that strong currents occur in the region and adequate velocities are likely to be found relatively close to shore at certain locations. For technologies that aim for harvesting currents of 1-2 m/s (such as the developing DeepGreen device) the areas of northern Mozambique, the Comoros, and perhaps north-eastern Madagascar may be of particular interest.

2.5.4. Applicability of ocean current power in the WIO

Despite great uncertainties adequate physical conditions for ocean current power is likely to be found at some locations in the WIO (Mozambique, Comoros, Madagascar, and perhaps Tanzania). The technology is still unproven and will require tough engineering challenges for mooring, maintenance, and transmission wherever to be installed. The units under development have a rated power from about 500 kW upwards and installations will be on array basis, consequently at large scale.

The speed and direction of ocean currents vary over seasons; power output will hence be predictable but variable over the year. The source is therefore most relevant as a contributor to large grids. Little is known about environmental impacts of this technology but there would obvious be concerns regarding migrating marine mammals.

3 OCEAN ENERGY RESOURCES AND ENERGY SITUATION IN THE WIO

The findings are summarized in Table 7 and the results have been categorized according to how the available resources meet the current requirements of each technology. This categorization is the authors' interpretation of technology requirements, with assumptions based on the reviewed literature. As technology develops such categorization will naturally be out of date and must be revised.

Based on the current knowledge the highest potential seems to rest in wave power and OTEC, but none of the investigated sources can be disregarded as insignificant for the future. Among the many criteria for an available energy sources to become of interest for a country, or a specific area, is its usefulness in relation to the prevailing, or future, demand; the amount and inherent variation of power output must fit loads and other energy sources utilized in the system.

Large- and small-scale utilization of the resources fills different purposes. Large installations of OE may be found appropriate to alleviate dependence on fossil fuels, diversify the supply, and/or stabilize grids where other generation is sparse. Small- or micro-scale installations may rather fill the purpose of remote area electrification; to provide basic energy services or to power rural micro industry such as agro-processing and fishery. The prime product from OE systems is electricity, but with the modern less expensive desalination systems parts of the power can be directly used to produce potable water.

In this last section the findings and potential applications are discussed with a focus on specific countries.

Table 7. Summary of results. The findings have been used to classify the OE resource availability in each country into the categories high, moderate, limited or highly uncertain, and insignificant (not shown). The criteria for each category are given. The parts of South Africa and Somalia where resources have been identified are indicated in brackets as these countries have not been in focus in this study.

	Wave power	**OTEC** (land based)	**Tidal barrage power**	**Tidal stream power**	**Ocean current power**
Technical development	Commercial devices available	In development, pilot plants	Proven technology	Commercial devices available	In development
Capacity per unit	10kW – 2MW	10 – 100 MW	150kW – 100MW	10kW – 2MW	>500kW
Inherent power fluctuations	Daily and seasonal Moderate predictability	Seasonal High predictability	Daily and monthly High predictability	Daily and monthly High predictability	Seasonal Moderate predictability
Level of certainty (data availability)	Adequate for screening	Adequate for screening	Adequate for screening	Low	Low
High resource availability	*30+ kW/m* Southern Madagascar Mauritius (South Africa)	*ΔT 22°C and distance <5 km* Northern Mozambique Comoros Seychelles (southern islands)	*>7 m tidal range*	*Current speed >2 m/s, high site availability*	*Current speed >1.5 m/s, high site abundance*
Moderate resource availability	*20-30 kW/m* Southern Mozambique Réunion	*ΔT 22°C and distance <10 km* Mayotte Southern Tanzania Northern Madagascar *ΔT 20°C and distance <5 km* Réunion Mauritius	*>5 m tidal range* Central Mozambique	*Current speed >1.5 m/s, high site availability*	*Current speed >1.5 m/s, narrow shelf* Northern Mozambique (South Africa)
Limited or particularly uncertain resource availability	*10-20 kW/m* Northern Madagascar Central Mozambique Seychelles (Northern Somalia)	*ΔT 20°C and distance <10 km* Southern Madagascar	*>3.5 m tidal range, available sites* Tanzania Northern Mozambique	*Current speed >1.5 m/s, low site availability* Tanzania Mozambique Kenya	*Indications of strong currents, narrow shelf* Northern Tanzania Northern Madagascar Comoros

3.1. Comoros and Mayotte

By the high surface water temperature and close proximity to cold deepwater the conditions for OTEC technology is good at the Comoros. Possibly, there may also be potential for ocean current power. About half the population in the Comoros have access to electricity, which is a high number for region. All electricity (about 21 GWh/yr) stem from imported oil and diesel, and much are lost due to dysfunctional diesel generators. The Comoros consumes and import 1 000 barrels of oil per day and the limited population of 800 000 endure a severe dependency on imported fossil fuel. The Comoro islands consequently have a high incentive to explore OTEC as alternative future energy source. The physical resource abundance is likely to be large enough to cover the whole or a large part of the national consumption. Environmental concerns may however be a limiting factor. While the OTEC technology is not yet mature the development of OTEC in nearby Réunion is a good reference for the proceedings of the technology. The possible availability of ocean current energy may become of interest at a point in time, but the cyclone frequency may become a difficult obstacle during installation and maintenance.

The electricity consumption in Mayotte was 139 GWh in 2005 and just like neighbouring Comoros there is a dependency on fossil fuels. The conditions for OTEC are reasonable, with a similar temperature difference as the Comoros but a somewhat longer distance to the cold water source.

3.2. Kenya

The Kenyan coast is exposed to a wave power of 10-15 kW/m. These conditions do not promise much for large-scale energy extraction but may be sufficient for small-scale applications and remote area electrification. The screening did not recognize any other OE resources in Kenya.

3.3. Madagascar

The wave climate in Southern Madagascar is very energy intense (20-60 kW/m) and favourable for wave power. In Northern Madagascar the conditions for OTEC were found to be reasonable and an unverified potential of ocean current power were indicated.

In Madagascar below 10% of the population have access to electricity. Hydropower accounts for 60 % of the electricity generation and the unexploited resource is reported to be massive. National reserves of oil and coal are recently discovered. With a large energy potential in both indigenous fossil fuel and conventional inexpensive hydropower there is little incentive for exploring large-scale unproven OE such as OTEC and ocean current power. Wave power, however, may be appropriate for remote area electrification in the southern provinces; the average electrification rate is currently below 5 % in rural areas. The seasonal variations in wave power are small and the resource intense coastline stretches over about 1 000 km. The occurrence of cyclones in the region would possible prevent use of floating devices.

3.4. Mauritius

Mauritius has good physical conditions for wave power year round (20-60 kW/m). Most of the 1.3 million inhabitants have access to electricity. The import of fossil fuel is extensive (23 000 barrels per day) and make up 76 % of electricity generation, but substantial contributions of renewable are also derived from the sugar cane industry. The government have launched serious plans of diversifying the energy sector and include alternative sources to reduce the dependency on imports. The combination of a strong political incentive and good natural resources makes large-scale wave power apparently suitable for the Mauritius energy sector. The inherent fluctuations of wave power can be outbalanced by the remaining controllable fuels. Extreme weather events, cyclones, may be impeding.

3.5. Mozambique

The ocean energy resources appear to be significant in Mozambique, with particularly good conditions for OTEC and possibly ocean current power in the north (province of Cabo Delgado), and adequate wave power density in the south (southwards from the province of Inhambane). The wave power in central parts of Mozambique is lower but not insignificant and the tidal range is adequate for barrages in the central parts of the country while limited but still not insignificant in the north.

The power generation in Mozambique is much dominated by the Cahora Bassa hydropower station, situated in the far west. There a few other energy supplies to the national grid but the potential of unexploited hydropower is assumed to be high. Despite the access to inexpensive electricity the rural electrification level is in the order of only 3 %, which much has to do with costly power transmission in a very large and dispersedly populated country. Most remote districts are hence poorly electrified by dysfunctional diesel generators.

Despite the situation of favourable hydropower resources in Mozambique OE could become of interest for some particular functions; large-scale applications of OTEC may be utilized to support (diversifying and stabilizing) the extensive and instable national grid in the north, and small-scale applications of wave power could be used for electricity and freshwater production in southern remote districts. While OTEC and ocean current power is yet not technically available and the environmental implications are little known the latter example, wave power, may be of more immediate interest. While the physical resources for tidal barrage power are adequate in central Mozambique this particular area is also exposed both to a massive sediment discharge from the many rivers and to frequent cyclones. Tidal power is consequently not likely to be a viable option in this region.

3.6. Seychelles

The Seychelles (Coetivy, Desrouches, and Poivre islands) offer the most favourable conditions for OTEC in the region. While the whole population have access to electricity the energy situation at the Seychelles is unfavourable in the aspect that all energy stems from imported fossil fuels (7 000 barrels per day). However, the population is small and dispersed on a multitude of small islands which make the large-scale approach of OTEC inappropriate.

3.7. Tanzania

The physical conditions for OTEC seem reasonable in southern Tanzania (Lindi) and the country has some potential for tidal power (both tidal barrage and tidal stream technology) and perhaps ocean current power. The electrification level in Tanzania is low but the energy demand is growing. The domestic generation, dominated by hydropower and supported by fossil fuel, is highly undersized and new power stations are required. There are considerable potential in hydropower but the seasonal shortages during drought is an incentive for diversification. There are additional potential in wind- and geothermal energy, but little has yet been exploited. Grid extension in the vast country is a huge undertaking and the rural electrification level is less than five percent.

OTEC may become interesting as a possible contributor to the future domestic energy supply in southern Tanzania. Small-scale tidal barrages, or even tidal stream units at specific sites, may be interesting for providing electricity and potable water in remote areas. At Pemba Island (Zanzibar) the currents are reported particularly forceful and the island also experiences some wave power. Tidal energy is predictable but not consistent which will have implications for the use of power. Wave power particularly varies over seasons at these latitudes and despite good availability during the South West monsoon the resource is barely sufficient during North East monsoon. Ocean current power may be a resource of future interest off the northern coast but the technology is yet far from available.

3.8. Réunion

Réunion Island has reasonable good conditions for wave power and OTEC. The island are currently importing fuel but has launched ambitions on energy independence in 2025. This is a good incentive to explore the OE sources which has also been commenced with the preparation of an OTEC plant in connection with a pre-existing power plant. Utilization of the wave power resource may be another step towards the goal.

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