IRENA

International Renewable Energy Agency

OCEAN THERMAL ENERGY CONVERSION

TECHNOLOGY BRIEF

IRENA Ocean Energy Technology Brief 1

June 2014

www.irena.org

ABOUT IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

ACKNOWLEDGEMENTS

The brief has benefited from the participants of two review meetings on 21 January 2014 in Abu Dhabi, and 11 April 2014 in Brussels. Furthermore, very valuable feedback and comments have been received from Diego Acevado (BlueRise), Robert Cohen, France Energies Marine, Wilfried van Sark (Utrecht University), Paul Straatman (Utrecht University), Charlie Upshaw (University of Texas), and Jose Luis Villate (Technalia).

Authors: Ruud Kempener (IRENA), Frank Neumann (IMIEU)

For further information or to provide feedback, please contact: Ruud Kempener, IRENA Innovation and Technology Centre.

E-mail: *RKempener@irena.org* or *secretariat@irena.org.*

Disclaimer

Highlights

- **Process and Technology Status –** Ocean Thermal Energy Conversion (OTEC) technologies use the temperature difference between warm seawater at the surface of the ocean, and cold seawater at between 800–1 000 metres (m) depth to produce electricity. The warm seawater is used to produce a vapour that acts as a working fluid to drive turbines. The cold water is used to condense the vapour and ensure the vapour pressure difference drives the turbine. OTEC technologies are differentiated by the working fluids that can be used. Open Cycle OTEC uses seawater as the working fluid, Closed Cycle OTEC uses mostly ammonia. A variation of a Closed Cycle OTEC, called the Kalina Cycle, uses a mixture of water and ammonia. The use of ammonia as a working fluid reduces the size of the turbines and heat exchangers required.

  Other components of the OTEC plant consists of the platform (which can be land-based, moored to the sea floor, or floating), the electricity cables to transfer electricity back to shore, and the water ducting systems. There is considerable experience with all these system components in the offshore industry. The technical challenge is the size of the water ducting systems that need to be deployed in large scale OTEC plants. In particular, a 100 megawatt (MW) OTEC plant requires cold water pipes of 10 m diameter or more and a length of 1 000 m, which need to be securely connected to the platforms.

  So far, only OTEC plants up to 1 MW have been built. Although it is technically feasible to build 10 MW plants using current design, manufacturing, deployment techniques and materials, the actual operating experience is still lacking. It is therefore important to learn and share the experience from the 10 MW plants under construction to ensure continuous and accelerated deployment.

- **Performance and Costs –** OTEC provides electricity on a continuous (non-intermittent) basis and has a high capacity factor (around 90%). Although, small-scale applications have been tested and demonstrated since the late 1970s, most components have already been tested and are commercially available in the offshore industry.

  There are considerable economies of scale. Small scale OTEC plants (<10 MW) have high overheads, and installation costs lie between USD_{2010} 16 400 and USD_{2010} 35 400 per kilowatt (/kW). These small-scale OTEC plants can be made to accommodate the electricity production of small communities (5 000-50 000 residents), but would require the production of valuable by-products – like fresh water or cooling – to be economically viable. For island states with electricity prices of USD 0.30 per kilowatt-hour (/kWh), OTEC can be an economically attractive option if the high up-front costs can be secured through loans with low interest rates.

The estimated costs – based on feasibility studies – for larger scale installed OTEC plants range between USD_{2010} 5 000-15 000/kW, and the costs for large scale floating OTEC plants could be as low as USD_{2010} 2 500/kW that results in a levelised cost of electricity of around USD 0.07-0.19/kWh. These cost estimates are highly dependent on the financing options. Furthermore, these cost projections require large-scale deployment and a steep learning curve for OTEC deployment costs.

» **Potential and Barriers –** OTEC has the highest potential when comparing all ocean energy technologies, and as many as 98 nations and territories have been identified that have viable OTEC resources in their exclusive economic zones. Recent studies suggest that total worldwide power generation capacity could be supplied by OTEC, and that this would have no impact on the ocean's temperature profiles. Furthermore, a large number of island states in the Caribbean and Pacific Ocean have OTEC resources within 10 kilometres (km) of their shores. OTEC seems especially suitable and economically viable for remote islands in tropical seas where generation can be combined with other functions *e.g.*, air-conditioning and fresh water production.

The existing barriers are high up-front capital costs, and the lack of experience building OTEC plants at scale. Most funding still comes from governments and technology developers, but for large scale deployment, suitable finance options need to be developed to cover the upfront costs. From an environmental perspective, OTEC plants at scale will require large pipes to transport the volumes of water required to produce electricity, which might have an impact on marine life, as well as the infrastructures to transfer the water (for land-based systems) or electricity (for off-shore systems) to and from the coast line. Also because it is not a tried and tested technology at large scale, there are unknown risks to marine life at depth and on the seabed where there is large scale upward transfer of cold water with high nutrient content. From a technical perspective, the large-scale pipes, bio-fouling of the pipes and the heat exchangers, the corrosive environment, and discharge of seawater are still being researched.

I. Process and Technology Status

Ocean Thermal Energy Conversion (OTEC) projects have been around since the 1970s (Cohen, *et al.*, 1986). Since the beginning of the millennium, a number of OTEC projects are being actively pursued. These projects are particularly focused on the multi-use possibility of power generation and cooling on islands in tropical regions.

OTEC power generation makes use of temperature differences between upper surface layer and deeper layers (800–1 000 m) of the sea, generally operating with temperature differences of around 20 degrees centigrade (°C) or more. Considering that temperature levels at one kilometre depth are relative constant at about 4°C, this means that OTEC is particularly suitable for mean surface temperatures around 25°C (Commonwealth Scientific and Industrial Research Organisation (CSIRO), 2012).

This small temperature difference is converted into usable electrical power through heat exchangers and turbines. First, through a heat exchanger or a flash evaporator (in the case of an open cycle turbine) warm seawater is used to create vapour pressure as a working fluid. The vapour subsequently drives a turbine-generator producing electricity. At the outlet of the turbine, the working fluid vapour is cooled and condensed back into liquid by colder ocean water brought up from depth or the sea bed. A heat exchanger is also used for this process. The temperature difference, before and after the turbine, is needed to create a difference in vapour pressure in the turbine. The cold seawater used for condensation cooling is pumped up from below and can also be used for air-conditioning purposes or to produce fresh drinking water (through condensation). The auxiliary power required for the pumps is provided by the gross power output of the OTEC power generating system.

The advantages of OTEC include being able to provide electricity on a continuous (non-intermittent) basis, while also providing cooling without electricity consumption. The capacity factor of OTEC plants is around 90%-95%, one of the highest for all power generation technologies. Although the efficiency of the Carnot cycle is very low (maximum 7%), this does not impact on the feasibility of OTEC as the fuel is 'free'. The energy losses due to pumping are around 20%-30%.

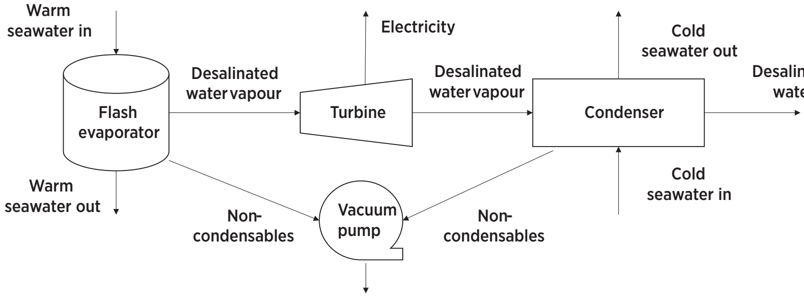
The technological challenge is that the small temperature difference requires very large volumes of water at minimum pressure losses (Cooper, Meyer and

Varley, 2009). This requires large seawater pumps, large piping systems, and large cold water pipes operating almost continuously in a hostile and corrosive environment. For example, 100 MW OTEC plants would have several seawater pumps, each the same size as a locomotive engine. These pumps would guide 750 tonnes per second of seawater through the OTEC system (US. Department of Energy (DOE), 2012).

There are four main types of OTEC. These are as follows:

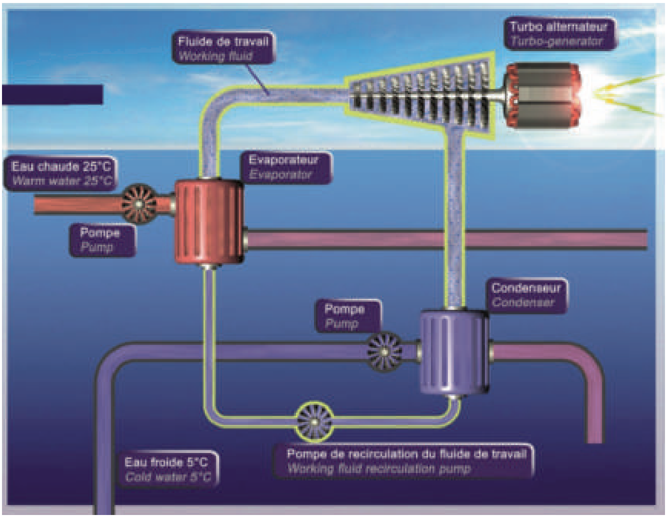
- **Open cycle OTEC –** Warmer surface water is introduced through a valve in a low pressure compartment and flash evaporated. The vapour drives a generator and is condensed by the cold seawater pumped up from below. The condensed water can be collected and because it is fresh water, used for various purposes (figure 1). Additionally, the cold seawater pumped up from below, after being used to facilitate condensation, can be introduced in an air-conditioning system. As such, systems can produce power, fresh water and air-conditioning. Furthermore, the cold water can potentially be used for aquaculture purposes, as the seawater from the deeper regions close to the seabed contains various nutrients, like nitrogen and phosphates.

Figure 1 – Open cycle OTEC



- **Closed cycle OTEC –** Surface water, with higher temperatures, is used to provide heat to a working fluid with a low boiling temperature, hence providing higher vapour pressure (figure 2). Most commonly ammonia is used as a working fluid, although propylene and refrigerants have also been studied (Bharathan, 2011). The vapour drives a generator that produces electricity; the working fluid vapour is then condensed by the cold water from the deep ocean and pumped back in a closed system. The major difference between open and closed cycle systems is the much smaller duct size and smaller turbines diameters for closed cycle, as well as the surface area required by heat exchangers for effective heat transfer. Closed conversion cycles offer a more efficient use of the thermal resource (Lewis, *et al.*, 2011).

Figure 2 – Closed cycle OTEC



Source: DCNS

» **Kalina cycle OTEC –** The Kalina cycle is a variation of a closed cycle OTEC, whereby instead of pure ammonia, a mixture of water and ammonia is used as the working fluid. Such a mixture lacks a boiling point, but instead has a boiling point trajectory. More of the provided heat is taken into the working fluid during evaporation and therefore, more heat can be converted and efficiencies are enhanced.

» **Hybrid system –** Hybrid systems combine both the open and closed cycles where the steam generated by flash evaporation is then used as heat to drive a closed cycle (Charlier and Justus, 1993; Vega, 2012). First, electricity is generated in a closed cycle system as described above. Subsequently, the warm seawater discharges from the closed-cycled OTEC is flash evaporated similar to an open-cycle OTEC system, and cooled with the cold water discharge. This produces fresh water.

All four types of OTEC can be *land-based, sea-based,* or based on *floating platforms*. The former has greater installation costs for both piping and land-use. The floating platform installation has comparatively lower land use and impact (figure 3), but requires grid cables to be installed to land and has higher construction and maintenance costs. Finally, hybrid constructions (figure 3) combine OTEC plants with an additional construction that increases the temperature of the warm ocean water (*e.g.*, solar ponds, solar collectors, and waste water treatment plants). They are mostly fixed on the shallow seabed not far from the coast.

Figure 3 – Onshore hybrid OTEC plant (left) and floating OTEC plant (right)

Source: DCNS.

» **Multifunctionality of OTEC –** Besides electricity production, OTEC plants (figure 4) can be used to support air-conditioning, seawater district cooling (SDC), or aquaculture purposes. OTEC plants can also produce fresh water.[1] In Open-Cycle OTEC plants, fresh water can be obtained from the evaporated warm seawater after it has passed through the turbine, and in Hybrid-Cycle OTEC plants it can be obtained from the discharged seawater used to condense the vapour fluid.

Another option is to combine power generation with the production of desalinated water. In this case, OTEC power production may be used to provide electricity for a reverse osmosis desalination plant. According to a study by Magesh, nearly 2.28 million litres of desalinated water can be obtained every day for every megawatt of power generated by a hybrid OTEC system (Magesh, 2010).

The production of fresh water alongside electricity production is particularly relevant for countries with water scarcity and where water is produced by the desalination process. For island nations with a tourism

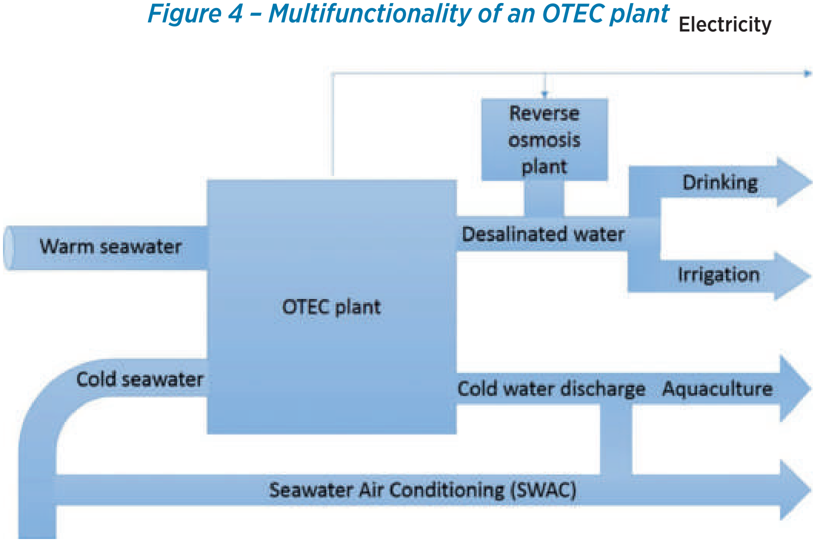
1 Alternative technologies that can make use of the deep seawater to produce freshwater include dehumidification or Low Temperature Thermal Desalination (LTTD) technologies.

industry, fresh water is also important to support water consumption in the hotels. Based on a case study in the Bahamas, Muralidharan (2012) calculated that an OTEC plant could produce freshwater at a costs of around USD 0.89/kgallon. In comparison, the costs for large-scale seawater desalination technologies range from USD 2.6/kgallon to 4.0/kgallon.

Given that deep seawater is typically free of pathogens and contaminants, whilst being rich in nutrients (nitrogen, phosphates, etc.), land-based systems could further benefit from the possibility of using the deep seawater for parallel applications, such as cooling for buildings and infrastructure, chilled soil, or seawater cooled greenhouses for agriculture, and enhanced aquaculture among other synergetic uses.

Using deep seawater to cool buildings in district cooling configurations can provide a large and efficient possibility for overall electricity reduction in coastal areas, helping to balance the peak demands in electricity as well as the overall energy demand.

Figure 4 – Multifunctionality of an OTEC plant



» **Innovation challenges –** Most technology components for OTEC plants up to 10 MW are well-understood and demonstrated, but several issues remain to be resolved in scaling up plants to 100 MW and beyond. Existing platforms, platform mooring, pumps, turbines and heat exchanger technologies are modular, and can be scaled up easily. However, marine power cables, cold water pipes and the platform/pipe interface still present deployment changes for larger scale facilities (Coastal Response Research Center (CRRC), 2010; Muralidharan, 2012). For example, based on experience from the offshore oil industry, cold water pipes for 10 MW facilities (4 m up to 7 m in diameter) can be constructed, but they have not been successfully demonstrated yet. Cold water pipes for 100 MW plants (10 m diameter) have yet to be constructed. Other scaling issues that still need to be addressed are biofouling of heat exchangers, corrosion, frequency instabilities in generator and violent outgassing of cold seawater in condensers (Commonwealth Scientific and Industrial Research Organisation (CSIRO), 2012; Lewis, *et al*., 2011).

On the positive side, new advances from the offshore industry can be used to support and de-risk the development of larger scale OTEC projects. Furthermore, there are a number of projects that are looking at potential by-products from OTEC, including hydrogen, lithium, and other rare elements, which could improve the economic viability of OTEC (Lewis, *et al*., 2011).

Finally, there are also developments in OTEC utilisation expected by raising the temperature difference between the cold sea water and the surface water. For example, the surface water temperature could be increased in combination with offshore solar ponds or solar thermal heating, although the flow of water required for a 10 MW plant (100 000 m^3/hour) is too large for any common heating device or method.

» **Overview of plants and projects –** Currently, the largest OTEC project built is still the 1 MW plant located in Hawaii, which ran from 1993 to 1998. There are a number of 10 MW plants that are in various stages of development, and planned for operation by 2015. A number of smaller projects, to provide cooling in particular, are set up or are in the process of being set up; *e.g.*, at Curacao Airport and as part of the resort industry on Bora Bora,

Besides these projects, ideas and prototypes are also being explored for plants elsewhere, *e.g.*, in China, Curacao, France (La Réunion), Malaysia, Oman, Philippines, South Korea, the USA (Hawaii, Guam, Puerto Rico), and Zanzibar. Also, sites are being explored on some parts of the African coast for later initiatives (University of Boras, 2013). OTEC companies include, amongst others, Bell Pirie Power Corp., Bluerise Delft, DCNS France, Energy Island Ltd., Lockheed Martin, Offshore Infrastructure Associates, Inc., Ocean Thermal Energy Cooperation, OTEC International, SBM Offshore, and Xenesys.

Table 1 – Currently known projects and ongoing updates

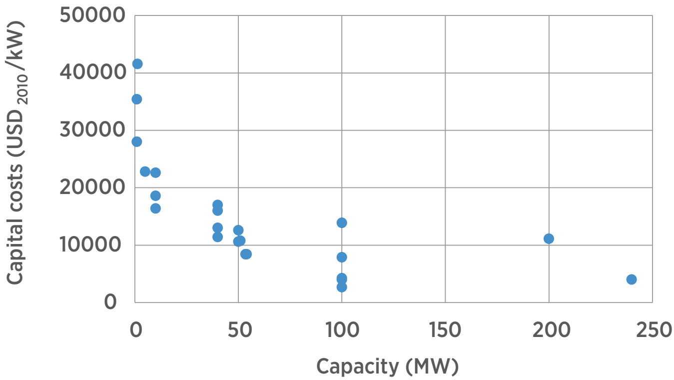
Location	Power output planned	Specifics available	Developer
Hawaii	103 kW	Closed cycle, One of the oldest installations installed in 1979	NELHA Natural Energy Laboratory
Hawaii	1 MW	Open cycle, operated between 1993 and 1998. Power generation, also focused on use of water for aquaculture; a land-based plant.	OTEC International LLC and NELHA Natural Energy Laboratory Hawaii
Hawaii	10 MW	Closed cycle, near shore platform, planned to be in function in 2013, but shelved. Funded with a grant of USD 4.4 million of the Naval Facility Engineering Command, meant to also serve as a pilot for further development in isolated areas/islands- military basis/ remote settlements. Prior to 2009, Lockheed Martin was also awarded USD 12.2 million for preparatory OTEC design and exploration.	Lockheed Martin Naval Facility Engineering Command
Japan/ Nauru	120 kW	Closed cycle, operated in 1982 and 1983 for scientific research; around 90% goes to pumping and energy used to operate the plant.	Japan Institute for Ocean Energy Research
Japan, Imari	30 kW	Demonstration plant; several others have been built in earlier stages by Saga University. The multi-purpose 30 kW is from 2003.	Saga University; other partners
Japan/ Okinawa	50 kW	Completed on 16 June 2013 – a research, development and demonstration plant near Kumejima Island- land-based plant used for electricity generation and research on other OTEC applications, aquaculture, agriculture, cooling; later possible scaling up to 125 MW could take place as estimated by Xenesys.	Xenesys Incorporated, IHI, and Yokogawa

Location	Power output planned	Specifics available	Developer
India-Tuticorin South India	1 MW	Ammonia-based closed cycle, started in 2000, but not completed due to problems with the pipes for pumping the seawater; floating plant.	Indian Government/ Indian Institute of Technology
Southern China	10 MW	On 13 April 2013, agreement signed for development of a 10 MW land-based OTEC installation on the Southern Coast of China, between Beijing Based Reignwood Group and Lockheed Martin.	Lockheed Martin, Reignwood Group (Lockheed Martin, 2013)
Martinique/ Bellefontaine	10 MW	Floating platform of DCNS Consortium – planning in more progressed state as of 2014, focusing on 2016 for operation. Also other sites are being thought of, *e.g.*, Reunion. A second plant is also considered.	DCNS France
South Korea	20 kW	Installed in 2013.	KISOT
Bahamas/ Baha Mar	NA	USD 104 million project providing cooling for Baha Mar Resort; permit issues/infrastructural and ecological issues - conflicts with navigation issues and cabling, coast protection issues, seemed to have stalled the project -at least temporarily.	Ocean Thermal Energy Conversion Corporation
Bora Bora	NA	Land-based, used for air conditioning only, no power generation.	Intercontinental Hotel Bora Bora
Tetiaroa	NA	Land-based, used for air conditioning only, no power generation.	The Brando Hotel, Tetiaroa

II. Costs and performance

There is limited actual project cost data available for OTEC. Instead, most cost references are based on feasibility studies from a limited number of sources (mainly Lockheed Martin and L.A. Vega). Figure 5 provides an overview of the latest cost projections for a range of OTEC plants.

Figure 5 – Capital cost estimates for OTEC plants



Based on data from Muralidharan, 2012

The capital costs projections are a function of four parameters. First, the scale of the project has an important impact on the cost projections. Due to the large overhead costs, small scale OTEC plants in the range of 1-10 MW have relatively high installation costs of around USD 16 400–35 400/kW. However, combined with the production of fresh water they become economically viable for small island states or isolated communities (up to 100 000 residents), especially if OTEC resources are within 10 km of the shore (Muralidharan, 2012). OTEC plants in the 10-100 MW range are estimated to cost between USD 15 000/kW and USD 5 000/kW when installed (Muralidharan, 2012; Vega, 2012). Larger OTEC plants built on moored ships could have costs as low as USD 2 650/kW.

The other parameter is the choice between open and closed cycle designs. Closed cycle designs are estimated to be slightly cheaper than open cycle designs. For example, a comparable feasibility study of a 50 MW OTEC plant design, estimates installation costs of USD 8 430/kW for the closed cycle, and USD 10 751/kW for the open cycle design. However, the open cycle design could produce 120 000 m^3 of water per day, which is equivalent to 240 litres per capita for a population of 500 000 residents (Vega, 2010).

A third parameter is the production of by-products. Water can be produced as a by-product, which increases the initial installation costs, but improves the overall economics for regions where fresh drinking water is valued. Also, large-scale OTEC plants can be combined with the production of energy-intensive products or energy carriers, like hydrogen, ammonia or methanol. Interestingly, technologies to increase the temperature difference may reduce overall investment costs by reducing the size of the evaporators, condenser units, and heat exchangers (Straatman and Sark, 2008; Lewis, *et al.*, 2011).

A fourth parameter is the environmental conditions at the location where the cold water is extracted. On the one hand, the surface temperature gradient may be more beneficial off the coast, but would require either longer pipes (for an onshore plant) or longer subsea cables (for an offshore plant). According to estimates by Magesh (2010), a 100 MW OTEC plant located 10 km offshore would have capital costs of USD 4 000/kW. Increasing the offshore distance to 100 km or 400 km would increase the capital costs to USD 6 000/kW and USD 12 300/kW, respectively. On the other hand, extracting cold water closer to the coast could lead to disturbances in the environment for other ocean activities, like tourism and fishing. Other factors to consider are the nature of the seabed, which has an impact on anchor and mooring costs, and the weather conditions that impact the designs of the platform.

The capital costs of an OTEC plant can be broken down into six categories: 1) the platforms, 2) the power generation system, 3) the heat exchangers, 4) the electricity cables, 5) the water ducting systems (including the cold water pipes), and 6) the deployment and installation processes (Muralidharan, 2012).

Relative platform costs could be as low as 10% for land-based systems, or as high as 35% for medium-scale (50 MW) moored plants. The water ducting systems could be as high as 50% of the total costs for small-scale (1-5 MW) land-based plants, but their cost significance decreases with increasing scale. For large scale plants (>100 MW), water ducting systems cost is reduced to around 10%. In contrast, the costs for heat exchangers can increase to around 50% of the total installed costs for large scale OTEC plants (Muralidharan, 2012). The energy transfer systems (evaporators and condensers) represent 20% to 40% of the total plant cost, and can be reduced by improving heat exchanger performance (Lewis, *et al.*, 2011). Operating and maintenance costs are in the order of 1.4%-2.7% of total investment costs.

The capital costs of the individual components themselves are relatively predictable as most components are commercially available for other offshore applications. For OTEC plant components these would include vertical pipes (~ USD 500/m), pumps (USD 700-2 000/kW), heat exchangers (USD 200-800/m^2) and components for thermodynamic cycles, such as the Rankine cycle (USD 1 000/kW) among others.

Based on the same studies, recent estimates suggest the following levelised costs of electricity production (LCOE):

Table 2 – Cost estimates for OTEC and hybrid OTEC

	Source of LCOE (USD/kWh)[2]				
Size (MW)	**Vega (2007; 2012)[3]**	**Energy and Environ-ment Council (2011)**	**Straatman & van Stark (2008)**	**Upshaw (2012)**	**Muralidharan (2012)**
1-1.35	0.60-0.94	0.51-0.77			
5[4]	0.35-0.65				
10	0.25-0.45	0.19-0.33			
28				0.13-0.65	
50	0.08-0.20	0.10-0.16	0.11-0.32		
50 (combined with offshore solar pond)	0.03-0.05		0.04-0.06		
100	0.07-0.18				0.19
200					0.16
400					0.12

a All costs are converted into USD using currency rates at the date of publication.

b An 8% interest rate for 15 year loan, annual inflation of 3%, and US labour costs.

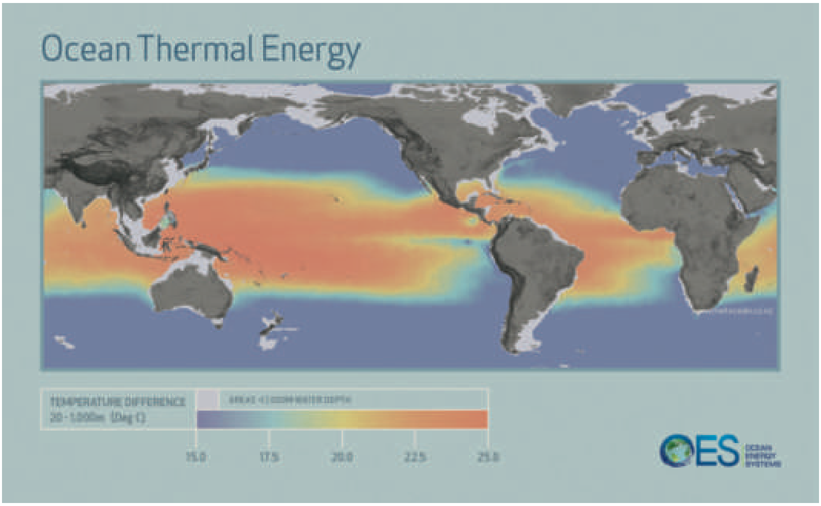
c Plants smaller than 5 MW of are scheduled to be used in combination with seawater air-conditioning systems, which share in the cost of the infrastructure and provide a significantly lower LCOE from the plant, thus it may not be relevant to show a specific price for this range.

Due to the capital intensity of OTEC, interest and discount rates have a high impact on cost estimates. According to Vega (2012), government bonds (4.2% over 20 years) instead of commercial loans (8% over 15 years) could reduce the LCOE of OTEC power generation to around USD 0.10 for a 5-10 MW plant, and around USD 0.03 for a 100 MW plant (Vega, 2012).

III. Potential

With an estimated 300 exajoules (EJ) per year or 90% of the global ocean energy potential, OTEC has the largest potential of the different ocean energy technologies (Lewis, *et al.*, 2011). Extracting this energy would have no impact on the ocean's thermal structure. The total estimated available resource for OTEC could be up to 30 terawatt (TW) and deployments up to 7 TW would have little effect on the oceanic temperature fields (Rajagopalan and Nihous, 2013).

Figure 6 – Thermal resource regions for OTEC (areas in the yellow-red range)



Source: International Energy Agency – Ocean Energy Systems (IEA-OES) 2014

OTEC resources are widespread. At least 98 nations and territories have been identified with access to OTEC thermal resources within their 200 nautical mile exclusive economic zone (figure 6). The African and Indian coast, the tropical west and south-eastern coasts of the Americas, and many Caribbean and Pacific islands have sea surface temperature of 25°C to 30°C (Vega 2012). More specifically, most Caribbean and Pacific countries have the required temperature degrees between 1-10 km of their coast-line. Similarly, many African countries have viable OTEC resources within less than 25 km of their coast-line (NREL 2004) and a recent potential study identified high potential for OTEC at specific locations in Mozambique, Comoros, Réunion, and Mauritius (Hammer, *et al.* 2012).

The economic potential for OTEC is not only determined by the quality of the OTEC resources, but also depends on the needs of the different countries. Many island states are dependent on diesel imports for electricity generation, which has an important impact on their economies and results in electricity generation prices of more than USD 0.30/kWh. For these countries, OTEC makes for an attractive alternative especially if it can be combined with fresh-water production. At the same time, many island states are isolated and have limited logistical access to the rest of the world. Shipping of components and construction personnel might increase costs and result in construction delays.

For industrialised countries and for countries with rapidly increasing electricity demand, the scaling of OTEC plants become an important parameter. Feasibility studies suggest that there are considerable economies of scale, however building OTEC plants beyond 10 MW has yet to be tried.

IV. Challenges and Drivers

OTEC seems most suitable, and economically viable for island countries and remote island states in tropical seas where generation can be combined with other functions, as *e.g.*, air-conditioning and fresh water production. Several countries are actively pursuing large-scale deployment of OTEC. For example, companies and governments in France, Japan, the Philippines and South Korea have developed roadmaps for OTEC development (Brochard, 2013; Marasigan, 2013; Kim and Yeo, 2013; Okamura, 2013). Furthermore, Indonesia is mapping its OTEC potential (Suprijo, 2012), Malaysia is proposing a new law on ocean thermal energy development (Bakar Jaafar, 2013), and the Philippines has been considering feed-in tariffs for OTEC (NREB, 2012).

Moreover, the technical concept for a 10 MW plant has been proven and the economics for scale-up of plants are promising. The key requirement for further deployment is to have the first mega-watt scale plants built and successfully operated. The advantage over other type of renewables, such as solar and wind, is that OTEC is continuous and can also produce without direct availability of sun or wind. However, there are some challenges that still need to be overcome. For current plants, there are some issues with construction in fragile marine environments, sealing of the different parts of the installation against sea water, maintenance of material in the sea environment, and bio-fouling of the pipes and other parts of the installation. For larger installations, *e.g.*, 10 MW or even 100 MW, the pipes are of considerable width – from 4 m to 20 m, which may impact the coastal structure, and more importantly, the transfer of the cold water up and the discharge in the warmer water could affect the marine life in the vicinity of the plant (*e.g.*,exhaust water at 3 degrees below surface water temperature could cause algae bloom). Thus, water effluent needs to be discharged at a certain depth, as the discharged cold water at the surface could influence the temperature of the surface water required for power production. This impact could be compared with the temperature issues of, for example, a gas-fired power plant.

A second area that still presents some challenges is the environmental impact. The siting of OTEC projects combined with protection of marine bio-diversity and recreational activities and tourism can create problems. Furthermore, there is unknown risk for marine life at the seabed due to the large scale up-ward transfer of cold water with high nutrients content. The same applies for marine life at higher surface waters.

Another environmental aspect to be considered is fish entrapment although, this could be resolved by fencing (Myers, *et al.,* 1986). Some of the problems can be solved by locating the larger installations farther off the coast. The US Department of Energy (DOE) has recently brought out a more detailed study regarding the ecological aspects of OTEC (DOE, 2012). This study, which is based on computational models, suggests that OTEC plants with discharge at 70 m of depth or more have no effect on the upper 40 m of the ocean's surface, and that the effect on picoplankton in the 70-110 m depth layer is well within naturally occurring variability.

The third challenge is from a financial/planning perspective. Large scale OTEC plants require high up-front capital costs, and the current prices per kWh are not competitive with other mainland energy generation technologies. However, the planning process for large scale OTEC can already start now by identifying those countries and islands that are using more than 100 MW of oil-derived electricity and by helping them study and monitor potential sites. A new development is that some companies are now offering bankable turnkey projects (Brochard, 2013; Johnson, 2013). Land planning issues may also create a problem. On the positive side, however, OTEC could be used as flexible base-load in a system with a large amount of variable renewables. A combination of different renewables in hybrid technologies can have positive impacts on the investment prospects.

References

Bakar Jaafar, A. (2013), "Framework on OTEC development in Malaysia", The International OTEC Symposium, Honolulu Convention Center, Oahu 9-10 September, *http://hinmrec.hnei.hawaii.edu/wp-content/uploads/2013/09/1.5-A-BakarJaafar_Framework-4-OTEC-Development-Malaysia.pdf.*

Bharathan, D. (2011), "Staging Rankine Cycles Using Ammonia for OTEC Power Production", Technical Report, National Renewable Energy Laboratory, NREL/TP-5500-49121, March 2011, *www.nrel.gov/docs/fy11osti/49121.pdf*.

Brochard, E. (2013), "DCNS Roadmap on OTEC", The International OTEC Symposium, Honolulu Convention Center, Oahu 9-10 September, *http://hinmrec.hnei.hawaii.edu/wp-content/uploads/2013/09/1.4-Brochard-E_DCNS-OTEC-Roadmap-for-France.pdf*.

Cassedy, E.S. (2000), *Prospects for Sustainable Energy: A Critical Assessment,* Cambridge University Press, New York.

Charlier, R.H. and J.R. Justus (1993), *Ocean energies: Environmental, economic, and technological aspects of alternative power sources*, Elsevier Science Publishers B.V., Amsterdam.

Cohen, R., et al. (1982), "Energy from the Ocean" Philosophical Transactions of the Royal Society A, v. 307, p. 405-437, http://www.offinf.com/CohenEnergyFromOcean.pdf

Cooper, D.J., L.E. Meyer and R.J. Varley (2009), "OTEC Commercialisation Challenge", Offshore Technology Conference, 20170, Houston, Texas, USA, 4-7 May 2009, *http://e-book.lib.sjtu.edu.cn/otc-2009/pdfs/otc20170.pdf*.

CSIRO (Commonwealth Scientific and Industrial Research Organisation) (2012), "Ocean Renewable Energy: 2015-2050, An analysis of ocean energy in Australia, *www.csiro.au/Organisation-Structure/Flagships/Energy-Flagship/Ocean-renewable-energy.aspx*.

CRRC (Coastal Response Research Center) (2010), "Technical Readiness of Ocean Thermal Energy Conversion (OTEC)", CRRC, University of New Hampshire, Durham, pp. 27, *http://coastalmanagement.noaa.gov/otec/docs/otectech1109.pdf".*

DOE (US. Department of Energy) (2012), "Modelling the Physical and Biochemical Influence of Ocean Thermal Energy Conversion Plant Discharges into their Adjacent Waters", Makai Ocean Engineering Ltd., 29 September, *www.osti.gov/scitech/biblio/1055480.*

Energy and Environment Council, (2011), *Cost Estimation and Review Committee Report*, December, National Policy Unit, Japan.

IEA-OES (International Energy Agency – Ocean Energy Systems) (2014), "Worldwide database for ocean energy", IEA-OES, March 2014, *www.ocean-energy-systems.org/news/worldwide_database_for_ocean_energy/*.

Hammar, L., *et al*. (2012), "Renewable ocean energy in the Western Indian Ocean", *Renewable and Sustainable Energy Reviews*, Vol. 16, No. 7, pp. 4938-4950.

Johnson, T. (2013), "Commercialising/Financing OTEC", The International OTEC Symposium, Honolulu Convention Center, Oahu 9-10 September, *http://hinmrec.hnei.hawaii.edu/wp-content/uploads/2013/09/2.4-Johnston-T.-_-Ocean-Thermal-CorporationOTEC-_-Approved-for-Release.pdf.*

Kim. H.J., and K.D. Yeo (2013), "The Korean Roadmap to OTEC Industrialization", The International OTEC Symposium, Honolulu Convention Center, Oahu 9-10 September, *http://hinmrec.hnei.hawaii.edu/wp-content/uploads/2013/09/1.1-HJ-Kim_-Korea-OTEC-Roadmap.pdf*.

Lewis, A., *et al*. (2011), "Ocean Energy", In O. Edenhofer *et al*. (Eds.) *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, Cambridge University Press, Cambridge, and New York, http://srren.ipcc-wg3.de/report/IPCC_SRREN_Ch06.pdf.

Lockeed Martin (2013), Covenant Lockeed Martin, Reignwood Group, signed on 13 April 2013, *www.lockheedmartin.co.uk/us/news/press-releases/2013/october/131030-mst-otec-lockheed-martin-and-reignwood-group-sign-contract-to-develop-ocean-thermal-energy-conversion-power-plant.html.*

Magesh R. (2010) "OTEC Technology — A World of Clean Energy and Water". Proceedings of the World Congress on Engineering 2010, World of Clean Energy and Water, London, *www.iaeng.org/publication/WCE2010/WCE2010_pp1618-1623.pdf*.

Marasigan, M.C. (2013), "Philippine Government Policies for OTEC Development", The International OTEC Symposium, Honolulu Convention Center, Oahu 9-10 September, *http://hinmrec.hnei.hawaii.edu/wp-content/uploads/2013/09/1.6-M.-Marasigan_-Philipines-OTEC-Roadmap.pdf*.

Muralidharan, S. (2012), "Assessment of Ocean Thermal Energy Conversion", MSc thesis System Design and Management Program, Massachusetts Institute of Technology, February, *http://dspace.mit.edu/handle/1721.1/76927*.

Myers, E.P., *et al.* (1986), "The Potential Impact of Ocean Thermal Energy Conversion on Fisheries", National Oceanic and Atmospheric Administration (NOAA) Technical Report NMFS 40, June 1986, *http://spo.nwr.noaa.gov/tr40opt.pdf.*

NREB (National Renewable Energy Board) (2012), "Petition to initiate rule-making for the adoption of feed-in tariff", NREB, *www.climateinvestmentfunds.org/cif/sites/climateinvestmentfunds.org/files/NREB(Petition-FIT).pdf.*

Okamura, S. (2013), "Xenesys' Development on OTEC", The International OTEC Symposium, Honolulu Convention Center, Oahu 9-10 September, *http://hinmrec.hnei.hawaii.edu/wp-content/uploads/2013/09/2.7-S.-Okamura_-Xenesys_-OTEC-Roadmap.pdf.*

Rajagopalan, K., and G.C. Nihous (2013), "Estimates of global Ocean Thermal Energy Conversion (OTEC) resources using an ocean general circulation model", pp. 532-

540, *http://hinmrec.hnei.hawaii.edu/wp-content/uploads/2010/01/Global-OTEC-Resources_2013.pdf*.

Straatman, P.J.T., and W.G.J.H.M. van Stark (2008), "A new hybrid ocean thermal energy conversion – Offshore solar pond (OTEC-OSP) design: A cost Optimisation Approach", *Solar Energy*, Vol. 82, pp. 520-527.

Suprijo, T., *et al*. (2012), "Feasibility Study of Ocean Thermal Energy in Indonesian Waters", Institute Technology of Bandung, *www.lppm.itb.ac.id/research/?p=537*.

Upshaw, C.R. (2012) "Thermodynamic and Economic Feasibility Analysis of a 20 MW Ocean Thermal Energy Conversion (OTEC) Power Plant", MSc Thesis, University of Texas, May 2012, *http://repositories.lib.utexas.edu/handle/2152/ETD-UT-2012-05-5637*.

University of Boras (2013), "OTEC Africa conference", Boras, *www.otecafrica.org*.

Vega, L.A., (2007), *OTEC Economics*, Offshore Infrastructure Associations, 22 August 2007.

Vega, L.A., (2010), "Economics of Ocean Thermal Energy Conversion (OTEC): An Update", Offshore Technology Conference 2010, OTC 21016, Houston, Texas, 3-6 May, *http://hinmrec.hnei.hawaii.edu/wp-content/uploads/2010/01/OTEC-Economics-2010.pdf*.

Vega, L.A., (2012), "Ocean Thermal Energy Conversion", Encyclopedia of Sustainability Science and Technology, Springer, pp. 7296-7328, *http://hinmrec.hnei.hawaii.edu/wp-content/uploads/2010/01/OTEC-Summary-Aug-2012.pdf*.

IRENA
International Renewable Energy Agency

P.O. Box 236
Abu Dhabi
United Arab Emirates

IRENA Innovation and
Technology Centre
Robert-Schuman-Platz 3
53175 Bonn
Germany

www.irena.org

IRENA
International Renewable Energy Agency

www.irena.org

FSC
www.fsc.org
RECYCLED
Paper made from recycled material
FSC® C103749