Viability of renewable technologies from marine derived energy as global sources of electricity

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Abstract
Due to dwindling natural resources and continually increasing energy demands, renewable energy may be the solution to the world's future energy needs. The oceans represent a large reservoir of energy and marine derived renewable energy may in turn represent a significant source of global electricity. In particular, the marine renewables reviewed in this study are ocean thermal energy conversion and wave energy. Unlike more mainstream renewables, little research has been undertaken to determine the capabilities of these technologies. However, the authors believe that these technologies have the potential to contribute significantly to the global energy market. Global potential maps for each technology were constructed using analysis of data sets provided by the International Research Institute for Climate and Society (Columbia University) and a Geographic Information System. These show the best viability of OTEC to be concentrated around the Equator, where the vertical ocean temperature gradients are at least 20oC/km, and that the most suitable areas for wave power are concentrated between the latitudes of roughly 40 to 60o N and S, where surface wind speeds average at least 8 m/s. Given these areas, gross potential outputs were calculated to be 605 TW for OTEC and 3368 TW for wave power, 1% of which is still greater than the global electricity demand (13.2 PWh, or 1.51 TW of power, in 2000 (EIA, 2007)). These results are promising, but they do not reflect technological, sociological and economical limitations. The environmental impacts of these technologies may range from local effects on ecosystems and biodiversity to long-term global climate and oceanic implications. Compared to modern non-renewable energy sources, these technologies have no significant greenhouse gas emissions. Given the globally significant potential outputs and limited environmental impacts of OTEC and wave energy, it is clear that marine renewable energy technologies are viable as future sources of electricity.

Keywords
Renewable energy sources, ocean thermal energy conversion (OTEC), wave power, ocean thermal gradient, global electricity demand.

Introduction

As oil prices soar and we are confronted with climate change and declining natural resources, renewable energy sources are being turned to as a potential means of meeting the world's ever-increasing energy demand. Currently, the global electricity market is largely dominated by fossil fuels (EIA, 2007). In the USA, fossil fuels produce 74.4% of the total electricity, whereas renewable resources other than hydroelectric power account for only 2.1% (Figure 1). A previously overlooked reservoir, the ocean, is however emerging for harvesting vast quantities of renewable energy. Roughly 50% of the world's population lives 200 km from a coast (Table 1) (EIA, 2007) and consumes more than 50% of the world's energy and electricity. Marine derived technologies, if viable as energy sources, are ideally situated to provide for the regions that are in the greatest need.

This study focuses on two particular up-and-coming marine derived renewable energies: ocean thermal energy conversion (OTEC) and wave power. Marine-generated energy cannot directly provide for fuel or transportation. Thus, for the purposes of this study, these technologies will be considered to provide electricity rather than energy. Unlike well-studied renewable resources such as solar and wind power, relatively little is understood about marine derived renewable energy, and most of the technologies in existence are only in the prototype or experimental stage. There exist very few operational power plants globally. Due to the small scale of the prototypes and short timescales of their experimental phases, the long-term practicality and environmental impacts of these power plants are hypothetical at best.

The purpose of this study is to ascertain whether or not marine derived renewable energy could contribute significantly to the global electricity demand, thereby providing insight into the ultimate worth of investing in the development of this energy for large-scale operation.

Techniques and Technology

Two end-member types of OTEC devices exist: an open system and a closed system (Pelc and Fujita, 2002; Heydt, 1993). The closed system involves heating of a fluid with a low boiling point, usually ammonia (Pelc and Fujita, 2002) or propane (Heydt, 1993), with relatively warm water from the surface. The production of vapour at this stage turns a turbine, generating energy. Cold sea water pumped from depths is then used to cool and recondense the vapour, creating a convection cell in the working fluid container. The fluid is then reheated and passed through the turbine in a continuous cycle.

The open system OTEC device does not contain a working fluid. Instead, it pumps the warm surface water into a vacuum chamber, flash evaporating the water and propelling it through a turbine. Cold water is then used to cool and recondense the water vapour. Fresh water is released from the system as a by-product.

Many different techniques have been developed to harness energy from waves (Baddour, 2004). Among the most promising is Ocean Power Delivery LMD's Pelamis Sea Snake design (OPD, 2007). The Pelamis Sea Snake measures about 150m in length and is composed of four articulated sections. The device is oriented with its length parallel to the incoming direction of the waves. Hydraulic rams are positioned in each of the joints which resist the motion induced by the waves. The rams pump high pressure oil through hydraulic pumps, which in turn generate power. Each of the joints has a capacity of about 250 kW, adding up to a total capacity of 750 kW per Sea Snake. In order for the Pelamis to produce significant energy, the device must be used in concert with several others, forming a "wave farm" (OPD, 2007; Thorburn and Leijon, 2006). A typical wave farm for the Pelamis includes about 40 devices set in a honeycomb type of layout occupying about 1 square kilometer and has a potential of about 30 MW[1] (OPD, 2007).

Methodology

Global maps of suitable locations for wave and OTEC power stations were created using the International Research Institute for Climate and Society's IRI/LDEO database (IRI, 2007). Data analyses was carried out using this database, imported into a Geographic Information System (GIS) program, and subsequently coupled with GPW global population data (GPW, 2007) and per capita energy/electricity consumption data from the year 2000 (EIA, 2007). Whereas electricity could presumably be transported to areas further than 200 km inland, this study only evaluates coastal regions as these would be regions most

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immediately affected by marine energy.
Mean annual ocean temperatures were obtained from the LEVITUS World Ocean Atlas 1994 (IRI, 2007). Ocean areas ideally suited for the utilization of OTEC technology were determined on the basis of an ideal thermal gradient of 20oC over ocean depths of 1000m (Tanner, 1995; Pelc and Fujita, 2002; Heydt, 1993; Nihous, 2005; Lennard, 1995). Wind speed at the air-sea interface was used as a proxy for wave height and period. Surface waves are created as a result of the friction between wind and the ocean surface, and Clément et al. (2002) claim that waves with periods of 7-10 s and amplitudes of ~2 m are at the threshold of producing a significant energy flux. According to Baddour (2004), these can be obtained in areas where wind speeds reach an average of 15-20 knots (7.5-10 m/s); thus, 8 m/s was chosen as a suitable minimum average for areas where wave energy could be harnessed. Wind speed data were taken from the DASILVA Atlas of Surface Marine Data 1994 (IRI, 2007). Data were provided as monthly meridional and zonal[2] wind speed means; using IRI, monthly mean scalar wind speed values were calculated and averaged to yield an annual mean.

	Within 200km from coast	Globally
Population	2.94 billion	5.96 billion
Energy Consumption	64.7 PWh (7.29 TW)	116 PWh (13.3 TW)
Electricity Usage	7,500 TWh (0.856 TW)	13.2 PWh (1.51 TW)

Table 1: Population (GPW, 2007), energy and electricity (EIA, 2007) usage from the year 2000.

Global populations within coastal regions directly adjacent to OTEC- and wave-power-suitable waters were calculated, as well as along coasts within a 500km radius from these regions. Energy and electricity consumption within these regions was also calculated on a per country, per coastal city and per capita basis. Direct comparison of these values was used to calculate the potential yield of marine-derived energy technologies, placing the viability of these technologies into context and giving an indication of how they fit into the global energy market.

The arbitrary simplification was made in which only one OTEC platform could operate for a square kilometer of ocean, and Lennard (1995) estimates that the low-end potential electricity output for an OTEC installation is 5 MW. A Pelamis Sea Snake wave farm approximately one square kilometer in size is anticipated to have a 30 MW capacity (OPD, 2007).

The ocean areas suitable for marine derived energy technologies were evaluated in 5 discrete areas up to 1000 km offshore, as well as within the entire area that could be potentially harnessed for these energies. The entire potential area is the most extreme end member case for coverage. The scale of the different increments was chosen considering the resolution of the datasets that were used to construct the maps, as well as the feasibility of transport of electricity over long distances.

In order to calculate the global potential power generation of OTEC and wave technologies, per-kilometer power capacities were multiplied by the areas viable for utilization of each respective energy technology. In addition, the areas required to meet the electricity demands of various coastal populations (i.e., within 200km of a coast, within selected coastal cities, etc) were calculated and compared to the areas actually viable for each energy technology. In the context of the global population and electricity demand from the year 2000, a number of coastal cities of high and low electricity demand (EIA, 2007) are presented later in the study.

Results

Suitable ocean areas for OTEC (where the thermal gradient over 1000m depth is at least 20oC) straddle the Equator in tropical regions up to ~20oN and ~30oS (Figure 2). This ideal gradient is limited to ocean waters beyond continental shelves and platforms, and does not include coral reefs or areas where there is significant upwelling of water from depth.

The most advantageous waters for installation of wave power plants (where surface winds average 8 m/s) are in mid-range latitudes, from roughly 30o-60o N and 40o-60o S (Figure 2). Anomalously windy regions extend north above Scandinavia towards Svalbard along the northern North Atlantic storm track, south along some coasts of Antarctica, and in more tropical areas such as northern South America, southern Madagascar, the Horn of Africa and the east coast of China. It is important to note that these potential areas can be reduced by negative local atmospheric and surface oceanographic parameters, such as storm frequency and seasonal ice cover. Suitable ocean areas for installation of OTEC and wave power plants are presented in Table 2, as well as the potential electrical outputs for each technology within various distance increments from shore. Table 3 shows that it would be possible to provide a significant amount of electricity from the ocean for several coastal cities with the highest and lowest electricity demands globally.

Environmental Consequences

There has been no published research focusing on the large-scale ecological consequences of offshore renewable energy development (Gill, 2005) as these technologies exist only in prototype phases. Studies of impacts from fishing, marine dredging and other activities were used to evaluate the possible environmental impacts of OTEC and wave power (Gill, 2005). However, these proposed impacts have not been demonstrated on real electrical plants and their long-term consequences remain uncertain.

OTEC plants incur minor environmental impacts compared to traditional power plants (Pelc & Fujita, 2002). The only significant CO2 emission would occur during construction (Matsuno, 1998) and operation phase. Approximately four years are required to offset the CO2 emissions associated with their construction compared to non-renewable plants (Vega, 2003). The CO2 released during operation, related to the outgassing of sequestered carbon into the atmosphere (Pelc & Fujita, 2002), represents less than one percent of the amount released by a fuel oil plant (700 grams/kWh, from Vega, 2003).

Distance from shore (km)	Ocean area suitable for OTEC (km^2)	Potential power assuming maximum coverage by OTEC (TW)	Ocean area suitable for wave energy (km^2)	Potential power assuming maximum coverage by Wave Power (TW)
Total area	121.1	605	112.3	3368
0-100	15.2	76	5.2	156
0-200	32.4	162	10.9	327
0-500	71.6	358	30.4	912
0-1000	103.6	518	63.1	1892

Table 2: Maximum potential electricity production by OTEC and Wave Power installations. Suitable OTEC areas are located where there exists a 20oC thermal gradient over 1000m depth; suitable wave areas located where average surface wind speeds reach 8 m/s. OTEC installations assumed to produce 5 MW/km2 of electricity; wave installations assumed to produce 30 MW/km2.

Other impacts from an OTEC station may include a change in the thermal structure of the ocean, the release of toxic chemicals and the entrainment of small organisms by intake pipes (Pelc & Fujita, 2002). With time, the continual mix of cold and warm water could lead to a change in the overall temperature gradient (Avery, 1994) resulting in mortality in coral and fish communities and damaging the local ecology (DiChristina, 1995). Furthermore, the addition of deep nutrient rich water could impact the shallow low-nutrient ecosystems typical in tropical regions. The release of toxic working fluids (such as ammonia and propane) would occur only in the case of mechanical problems, breakdowns, and storms, and would damage local marine ecosystems. Entrainment of marine species is proportional to the amount of water pumped into the system and would be less significant for smaller installations. OTEC devices can provide cold water for mariculture and air-conditioning as well as desalinated fresh water, reducing energy demand for air-conditioning and minimizing emissions due to the transportation of fresh water to islands.

Wave power technologies interact with both near-shore

1 Values for potential capacity are given in power, thus TW and not TWh
2 Meridional refers to a vector parallel to latitude; zonal refers to a vector parallel to longitude

Cities of highest electricity usage	Total electricity consumed by city (TWh)	OTEC			WAVE			OTEC and WAVE	
		Area suitable for OTEC within 0-100 km from coast (km^2)	Area suitable for OTEC within 0-200 km from coast (km^2)	Area required to provide total electricity (km^2)	Area suitable for WAVE within 0-100 km from coast (km^2)	Area suitable for WAVE within 0-200 km from coast (km^2)	Area required to provide total electricity (km^2)	Percentage of city's electricity demand provided by OTEC and Wave within 0-100km from coast (TWh)	Percentage of city's electricity demand provided by OTEC and Wave within 0-200km from coast (TWh)
Tokyo	184				5000	43900	698	**1300**	**11600**
Paris	69.5					580	264		**150**
London	65.4					5200	248		**1400**
Taipei	48.9	1300	20200	1110	17200	89100	186	**4600**	**24400**
Nagoya	37.4				1800	23700	142	**480**	**6200**
Sydney	32.6					10300	124		**2700**
Hong Kong	31.8				6400	25900	121	**1700**	**6800**
Yokohama	23.3				7200	46500	88.4	**1900**	**12300**
Rio de Janeiro	19.9		2600	452					**110**
Manchester	16.3				57	6400	62.0	15	**1700**
Lome	0.0592	6500	41400	1.35				**290**	**1800**
Monrovia	0.0461	5100	39100	1.05				**220**	**1700**
Ambon	0.0421	13700	71300	0.959				**600**	**3100**
Port-au-Prince	0.0324	7200	52700	0.737		4400	0.123	**320**	**3500**
Freetown	0.0261		18200	0.595					**800**
Belmopan	0.00306		16500	0.0697					**730**
Malabo	0.00143	7900	35800	0.0327				**350**	**1600**

Table 2: Maximum potential electricity production by OTEC and Wave Power installations. Suitable OTEC areas are located where there exists a 20oC thermal gradient over 1000m depth; suitable wave areas located where average surface wind speeds reach 8 m/s. OTEC installations assumed to produce 5 MW/km2 of electricity; wave installations assumed to produce 30 MW/km2.

activities and marine species. By extracting energy from waves, they weaken the force of waves, which while helpful in reducing erosion of a sensitive coast, could alternatively reduce food supply for benthic populations and harm species that rely on suspension to carry their larvae (Pelc & Fujita, 2002).

Large wave farms near the shore could negatively interact with local fisheries and recreational areas. Underwater noise would increase and affect marine mammal and fish species which communicate or navigate sonically. Grease or fluids in contact with sea water could pollute the surrounding marine ecosystem.

In order to minimize the environmental impacts of OTEC and wave power plants, several measures can be taken such as avoiding important fishing, recreational and sensitive areas, using biodegradable and non-toxic hydraulic fluids where possible, minimizing installation size, locating wave farms at least 2 km offshore, spacing their individual generators 150m apart and avoiding high discharges of cold water in shallow warm water.

Discussion

The calculated potential capacities yield a maximum end member (every square kilometer suitable for the techniques) of 3368 TW for wave power and 605 TW for OTEC. The low end member scenario, building installations solely within 100 km of the shore, yields outputs (156 TW for wave; 76 TW for OTEC) several orders of magnitude larger than the global electricity demand (1.51 TW in 2000) (EIA, 2007). Even a small fraction of the potential of these techniques could still amount to a very significant source of power; for example, 1% of the low end member marine potential, 2.32 TW, is still greater than the global electricity demand.

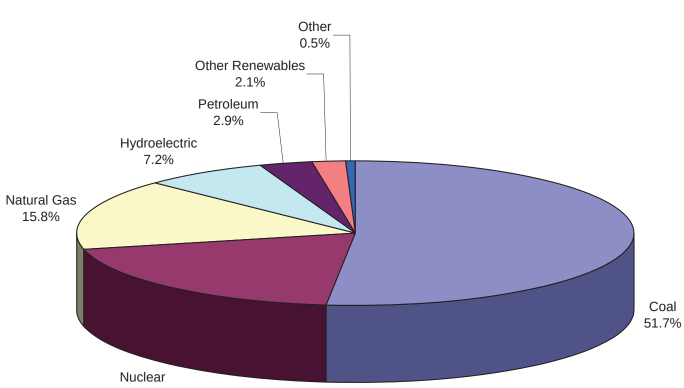

Figure 1: USA Electricity Generation in 2000 (EIA, 2007)

Table 3 shows that the electricity needs of many coastal cities could be met by installations placed within 100 km of the shore, and a larger number could be provided for by plants installed within 200 km. Meeting the energy needs for smaller cities is completely feasible within a few km2, but an unrealistically large area of the ocean would be necessary to provide for the larger cities. It is encouraging, however, that even a fraction of the area covered by these stations may still contribute significantly to these electricity needs.

With insignificant direct environmental impacts and positive by-products such as fresh water, food through mariculture and air conditioning, OTEC power is a promising energy alternative. However, it is important to keep in mind that this technology has the potential to modify the ocean thermal structure with time and could release toxic fluids into the ocean. It is difficult to model the effect of a large scale OTEC emplacement on the marine thermal gradient. Nonetheless, any variations in the gradient would affect not only water temperatures, but also other factors such as marine currents, nutrient distribution, and the interactions between the ocean and the atmosphere, resulting in changes in global climate and ecosystems both in the ocean and on land. The negative impacts of wave power appear to be inconsequential.

Compared to emissions from transportation and conventional fossil fuel energy, are the environmental impacts of marine renewables less harmful? Would these impacts with time bring similar problems to those incurred from new technologies such as wind farms affecting birds and local climate? Indirect ecological effects are especially important because they are the ones usually forgotten. Placement of a marine renewable energy plant could have an effect on biodiversity, food availability, and species competition, predation and reproduction. These could have wider effects than expected on the marine fauna and change the present ecology of the ocean. There are no certainties about the long term impacts of these technologies on the environment.

All the possible sources of error need to be considered before the potential energy outputs can be fully taken into account. The initial estimates for the energy output by each station may be incorrect, thus changing their overall capacities. The original data used to construct the maps in this report may also provide error and change the map results. While accurate to a certain extent, using wind as a proxy for wave power is imprecise. Another source of imprecision is the data collected from INGRID, which is provided at a coarser resolution than the maps constructed on GIS. These and other variables can affect the calculated potentials of these technologies and thus the values obtained in this paper could be either over- or underestimated. Nevertheless, the exact quantities stated in this paper

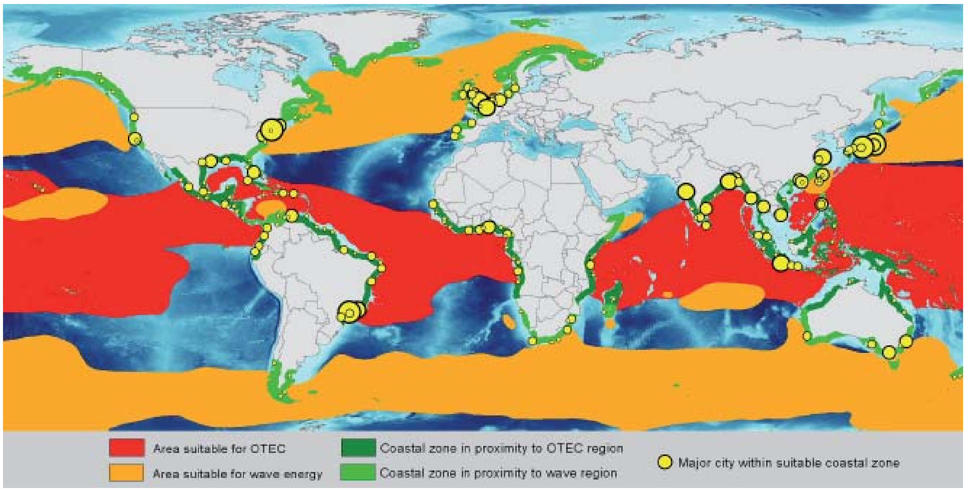

Figure 2: Areas suitable for OTEC (where marine thermal gradients are 20oC/km and greater) and wave-derived energy (where average wind speeds reach a minimum of 8 m/s), and major cities within coastal regions situated in proximity to the areas suitable for these technologies. Sizes of yellow circles are proportional to city populations.

are of less importance than the demonstration that these technologies have the potential to produce a significant amount of electricity.

Conclusion

The calculated values indicate that marine energy sources have the potential to become a significant source of power (2.32 TW at 1% exploitation of lowest end member) for the future global market. Furthermore, the techniques would be highly advantageous for certain isolated areas, such as island nations, and could be used to power less accessible regions that do not have sufficient natural resources to cover their own energy needs. However, the potentials of each technique differ to an extent. Both OTEC and wave power are feasible as global sources of energy, but OTEC may have limited effectiveness due to its potential effects on the thermal gradient of the oceans. Hence, it may be most useful only in areas near the Equator where its by-products can be fully exploited without affecting a large amount of water.

Wave power is thus the technique with the most global potential discussed in this paper. Its environmental impacts are, as far as it can be determined, insignificant. It is relatively simple to design and can be installed anywhere with the required wave heights and periods. Through a combination of both OTEC and wave power, marine derived energy could potentially provide most of the electricity needs of the world. Thus, even if these technologies are not implemented to work at their full capacities, they could still provide a significant amount of renewable electricity for most of the globe.

Marine energies could have the effect of reducing the utilization of fossil fuel and non-renewable energy as well as reducing greenhouse emissions. Future investment in marine renewable technology must be undertaken in order to answer several questions that cannot be addressed without actual full-sized installations, such as confirmed outputs of these plants and their long term impacts on their environments and ecosystems. By establishing that marine derived renewable energy technologies have the potential to produce measures of electricity comparable to the current electricity demand, this study validates such future investment and provides an optimistic perspective on the future global energy market.

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