A Source (of Energy) for Garcia

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Abstract

The U.S. Navy maintains a remote installation on the island of Diego Garcia in the Chagos Archipelago, Indian Ocean. This facility uses more than 65 MWh of electricity and 350 M-gal of water annually. Reliability and costs of electricity supply and fresh water quality were concerns of the Navy in 1996. Prospective contractors were invited to submit proposals for provision of these services with some encouragement to use renewable energy resources.

As a capstone design project, three teams of 1st-class midshipmen (seniors majoring in ocean engineering at the U.S. Naval Academy) set about to identify and design an ocean energy system to compete, at least conceptually, with Navy contractors. These teams explored various renewable energy sources such as ocean thermal, wave, and offshore wind energy. In four-months time, each team researched the alternatives and developed a concept design for its selected energy source. Results were presented to a Review Panel consisting of Navy representatives and ocean engineering professionals. Brief details of this capstone experience and educational opportunities in renewable ocean energies at the U.S. Naval Academy are shared later in the paper.

Past developments and recent trends in renewable energy from ocean sources are this paper's principal focus. For example, France currently maintains the most significant ocean energy recovery plant - a 240-MW tidal power facility at La Rance. And, Denmark's "Energy 21" Plan calls for development of 4 GW of offshore wind power by the year 2030, sufficient to meet more than 25% of that nation's anticipated consumption of electricity.

Introduction

In this period of national tragedy yet increasing patriotism, there is an island that stands out on the horizon of my memories like that of Tortola featured in the movie "The Deep," and the site of my (and my spouse's) honeymoon. When in naval service (circa 1974), it was very necessary to install a marine fuel terminal for a critical naval facility. Newly established, Naval Support Facility (NSF) Diego Garcia was located somewhere on a coral atoll in the vast expanse of the Indian Ocean, just south of the equator. No commercial ship or plane could travel there. Yet, NSF Diego Garcia required two ½-mile submarine fuel lines and an offshore tanker mooring, and these facilities were needed expeditiously! What was the NSF to do?

The Navy sent Underwater Construction Team One, my unit, to install the three fuel facility components. How we toiled six days and rested on the seventh; dragged the fuel lines from shore to sea and set explosive embedment anchors for the mooring; and how, in three-months time, we completed the arduous tasks, even taking time to explore the pristine coral reefs within the lagoon and about the atoll's fringes, are experiences that I have no intent to tell here.

Rather, the point I wish to make is this. Throughout the globe, the U.S. Navy maintains numerous bases which depend on reliable sources of electricity and freshwater to support operations. Since most Navy bases are located on open coastlines, a viable potential exists to tap the renewable energy resources of the world's oceans. One base, in particular, was recently a candidate for ocean energy system implementation. That base was the Navy Support Facility on the Diego Garcia atoll.

The U.S. Navy has maintained a communication station on Diego Garcia, in the Indian Ocean, since 1972. By 1996, the existing utilities were nearing their service life, and reliability and costs of supplying electricity and fresh water were a concern. So, in 1998, the Navy solicited proposals from private industry to construct, operate and maintain power and water facilities that could satisfy station requirements. This Diego Garcia Repowering Project[1], as it was known, offered an excellent opportunity for a capstone design in ocean engineering. Three student design teams at the U.S. Naval Academy were challenged to develop the concept design of an ocean energy system that could compete favorably with a conventional power plant.

This paper summarizes this capstone experience and reflects on other opportunities at the U.S. Naval Academy to learn of renewable ocean energy technologies. But, first, a review of current capabilities and recent trends in offshore renewable energy recovery seems appropriate.

Renewable Offshore Energy Recovery Systems

Oceans cover nearly 70% of the earth's surface and represent a potentially large source of offshore renewable energy. Yet, the available power capacity from renewable offshore energy recovery systems is less than 400 MW. And, more than half of this is attributed to a single tidal power plant at La Rance, FR. Is it yet time to begin serious harvest of our ocean's renewable energy resources? Sentiments were expectedly positive at a recent European conference on renewable energy potential.[2] Reasons given were that existing energy reserves were insufficient for growing demand, renewals clearly have the necessary potential to overcome a mounting deficit, and use of renewables is apt to be environmentally benign compared to fossil fuels.

The European nations are clearly leading the harvest. Although renewables satisfy just 6% of Europe's current gross energy consumption, a recent European Directive requires that use of renewables be increased to 12% by 2010. Much of this will come from the offshore environment. Primary sources of offshore renewable energy include ocean currents, thermal gradients, tides, waves and offshore winds. Other potential sources include marine biomass, geothermal energy, and salinity gradients. What follows is a brief review of past and current developments and the near-term recovery potential for the most viable of these offshore renewables.

Tidal Energy. Tidal energy conversion provides the greatest proof of practicality in the recovery of offshore renewables. This is due in large measure to the very successful 240-MW plant built near the mouth of the La Rance River, c. 1966. Another 20-MW facility operates at Annapolis Royale, Nova Scotia, and China has eight smaller plants with a total capacity of (approximately) 6 MW. Table 1 lists the major tidal power plants that are currently operational worldwide.

Table 1. Major Tidal Power Installations Worldwide

Year	Name/Location	Country	MW
1966	La Rance River	France	240
1968	Kislogubsk (Murmansk)	Russia	0.4
1978	Baishakou	China	0.6
1980	Jiangxia Creek	China	3.2
1984	Annapolis, Nova Scotia	Canada	20
1989	Xingfuyang	China	1.3

Source: http://www.newenergy.og.cn/

In some ways, tidal plants emulate hydropower dams. That is, potential energy due to an elevation head difference on each side of the plant's barrage (i.e., the tidal dam) is converted to hydraulic energy and then to mechanical energy as water flows by gravity through conveyances and turbines. The resource is more dependable and predictable than hydropower, but it naturally varies in magnitude and timing. The power potential of a site is somewhat proportional to the square of the tidal range (R^2) and the surface area of the tidal basin (A) behind the barrage. For sites with a diurnal tidal cycle, the annual energy potential, E_p, can be approximated by the equation: $E_p = 2AR^2$, where energy potential is in units of GWh/yr when area is in square kilometers and range is in meters.

A critical factor in site selection is length of closure (L_c), i.e., the distance necessary to close off the basin. This is because of the parameter's direct effect on construction cost. Two practical rules of thumb[3] for developing an economically feasible tidal power facility are that (1) the tidal range be greater than 5 meters; and (2) the ratio: $L_c/A^{0.5} < 0.5$. More than 15 sites worldwide have been identified as economically attractive for large-scale (> 50 MW) development, but economic and environmental concerns associated with changes in hydraulic action have limited implementation at most sites. Tidal plant amenities such as cross-bay access, recreation, and fish-farming opportunities may offer sufficient offsets to soon encourage future developments.

An alternate means to recover tidal energy is with a *tidal current generator*. One such device consists of a marine current turbine mounted on a tubular steel mono-pile; essentially, it is an underwater windmill. Because of differences in the densities of water and air, a 1-MW tidal current turbine needs be only one-third the size of an equivalent-power wind turbine.[2] However, no significant commercial applications of this device yet exist.

Offshore Wind Energy. The total installed recovery capacity of wind farms worldwide exceeds 10 GW, but most existing systems are located onshore. One advantage of an offshore wind farm is that its winds are unencumbered by natural obstructions and are, therefore, more consistent and usually of greater magnitude than onshore winds. Accordingly, offshore wind farms are gaining "market share." For example, a 40-MW wind farm was installed outside the Port of Copenhagen, Denmark, in December 2000. Located 2-3 km outside the harbor, this offshore farm consists of 20-each, 2-MW wind turbines mounted on mono-piles driven into the seafloor. Also, installation of a 160-MW farm, 14 to 20 km off Horns Rev in the North Sea, will be completed later this year (2002). The latter is but one of five similar-sized offshore projects slated for Danish waters by yr-2008. Denmark's "Energy 21" Plan calls for 4 GW of offshore wind farm capacity by the year 2030, intending to satisfy 30% of that nation's energy needs.[4]

Wind energy is less predictable and more variable than tidal energy, but its potential depends on flow velocity and not on trapping (i.e., damming) a mass of fluid. Thus, construction and implementation of a wind farm is less daunting than that of a tidal power facility. Power derived from winds depends on the cube of wind speed. Theoretically, the power, P_a, available to a wind turbine [in W] may be described by the equation: $P_a = 0.6AV^3$, when the blade sweep area, A, is in [m^2] and wind velocity, V, is in [m/s]. However, since the most perfectly-designed wind turbine can extract at most 60% of the energy available, a more practical result for the conversion potential is given by: $P_c = a \cdot P_a$, where the coefficient a ranges between 0.2 and 0.4.

One would argue that there are few wind power amenities other than power generation, while concerns include farm noise, land-use restrictions, and (line-of) sight issues. Such impediments are common to land-based facilities but, in a practical sense, are mitigated by offshore developments. This suggests a unique opportunity for offshore wind farms.

Besides Denmark, wind farms exist off the coasts of Sweden, the Netherlands, and Great Britain; see Table 2. Offshore farms are also are planned for Belgium, Finland, Germany, and Ireland. The Swedish government seemingly initiated the recent foray into the sea when it installed a 300-kW demonstration windmill, 350 km off the shores of Nogersund in 1990. Sweden later installed a 2.75-MW demonstration farm off Gotland in 1998, a 10-MW farm off Oland in 2000 and yet another in 2001. This nation anticipates expanding its offshore capacity to 650 MW by yr-2005. The Netherlands has a 2-MW farm in the Ijsselmeer and a 14-MW farm off Dronten, while Great Britain installed its first offshore farm outside Blyth Harbour in yr-2000. The British farm, consisting of two pile-mounted 2-MW turbines, complements a set of 9-ea, 300-kW wind turbines set atop the harbour's constructed seawall. Although the latter facility is not technically classified as "offshore," it nevertheless captures renewable offshore wind energy.

Table 2. Active Offshore Wind Farms (March 2002)

Year	Site	Country	Dist Offshore	MW
1991	**Vindeby, Lolland**	**Denmark**	**1.5 - 3 km**	**5.0**
1994	**Lely (Ijsselmeer)**	**Netherlands**	**800 m**	**2.0**
1995	**Tuno Knob**	**Denmark**	**6 km**	**5.0**
1996	**Dronten (Ijsselmeer)**	**Netherlands**	**30 m**	**11.4**
1998	**Gotland (Bockstigen)**	**Sweden**	**4 km**	**2.8**
2000	**Blythe Harbor**	**UK**	**1 km**	**4.0**
2001	**Middelgrunden, Copenhagen**	**Denmark**	**2-3 km**	**40.0**
2001	**Utgrunden, Oland**	**Sweden**	**12 km**	**10.5**
2001	**Yttre Stengrund, Oland**	**Sweden**	**5 km**	**10.0**

Source: http://home.wxs.nl/~windsh/offshore.html

The U.S. has yet to install an in-water wind farm, although there are installations of modest capacity on offshore islands such as San Clemente Island, CA, and Block Island, NY. This year, the State of Massachusetts is reviewing a proposal to construct a 420-MW wind farm, consisting of 170 wind turbines, on Horseshoe Shoal in Nantucket Sound.[5]

Wave Energy. Ocean waves are the most visible form of ocean energy, and concepts for wave energy recovery are also the most numerous. Wave energy conversion (WEC) concepts have been proposed for locations on shore, on the seafloor in relatively shallow waters, mounted on offshore structures or moored barges, or moored submerged or floating on the sea surface. In a random sea (consisting of variable waves), the power per unit width of wave crest may be expressed by an equation of the form: $P\ [kW/m] = 0.5T_zH_s^2$, where T_z [sec] is the average time interval between successive wave crests and H_s [m] is the significant wave height, i.e., average height of the highest 1/3 waves. The distribution of wave power worldwide is not uniform; more favorable magnitudes are found between 40º and 50º degrees N & S latitudes, where the westerly winds interact with the sea surface.

Most WEC devices are designed to transform the wave kinetic energy to mechanical or hydraulic energy by using turbines or hydraulic pistons, respectively. The most productive system was installed in a cliff at Toftestallen on the west coast of Norway. This device used the concept of an oscillating water column within a chamber to compress air and drive a pneumatic turbine. Its capacity was 500 kW when installed in 1985, but the system was destroyed by storm in 1988. In yr-2000, the United Kingdom and Portugal installed similar-concept wave energy converters of 500-kW and 300-kW capacity, respectively. The U.K. has also developed and model-tested a wide range of floating devices including the well-known Salter Duck and Sea Clam. Japan has a variety of modest-sized (< 50 kW) operational systems, including the Masuda Buoy that has been employed at over 300 sites with low power needs (~ 100 W) such as for navigational lights.

A unique installation off the coast of Norway concentrates wave energy through a tapered channel resulting in increasing wave heights. The waves subsequently spill over into a reservoir three meters above sea level. The collected water is returned to the sea through an energy-producing turbine. This “Tapchan” facility has been operational since 1986 with a rated capacity of 350-kW, although power production is naturally intermittent. Similar-concept commercial-sized power plants have been proposed for Indonesia and Tasmania. Compared to existing tidal and wind power facilities, WEC devices have been of very modest capacity. A list of current, more significant wave energy production systems is provided in Table 3.

U.S. initiatives in wave energy conversion include the Delbuoy that was developed by researchers at the University of Delaware. It uses the vertical motions of a moored buoy to gain sufficient pressure to force seawater through a semi-permeable membrane. The result is the production of fresh water rather than electric energy. While at the U.S. Naval Academy, Professor M. E. McCormick initiated the design of a wave energy conversion device known as the Hydam Articulated Raft. Its motions are transformed into hydraulic energy that is also used to produce fresh water. A prototype device is currently moored in the Shannon Estuary of Ireland.

Table 3. Active Wave Energy Production Systems

Year	Name/Location	Country	MW
1984	**Toftestallen**	**Norway**	**0.35**
1989	**Sakata Port**	**Japan**	**0.06**
1990	**Isle of Islay**	**Scotland**	**0.075**
1991	**Vizhinjam, Kerala**	**India**	**0.15**
2000	**Pico Island, Azores**	**Portugal**	**0.30**
2000	**Isle of Islay**	**Scotland**	**0.50**

Source: http://www.newenergy.og.cn/

Ocean Thermal Energy. Ocean thermal energy conversion (OTEC) takes advantage of the solar energy stored in the surface waters of the ocean. The temperature difference between the warm surface waters and much colder bottom waters can drive a heat engine, which produces electric power. Power output is somewhat proportional to the square of the temperature difference ($?T^2$) and the mass flow rate of cold water. Recovery of the bottom waters from depths of 1000 meters (or so) necessitates an initial power deficit. But, theoretically at least, a temperature difference of 20ºC is sufficient to produce net power. Because of warmer surface waters, tropical regions located between 20º N & S latitudes offer sites with the greatest energy potential.

OTEC systems are of two basic forms. In a *closed-cycle* process, the warm seawater is used to vaporize a working fluid of low boiling point in a heat exchanger, i.e., the evaporator. The expanding vapors turn a low-pressure turbine connected to an electric generator. The colder seawater is used to liquidize the vapors in a second heat exchanger, i.e., the condenser. This fluid is then returned to the evaporator in a closed-loop cycle. In the alternate *open-cycle* process, the warm seawater serves as the working fluid and is flash evaporated in a vacuum chamber. The resulting vapors drive the low-pressure turbine and are condensed back to liquid in the condenser. Although less energy efficient than closed-cycle, the condensed water of this open-cycle process is free of salts and may be used to supplement fresh water supplies.

Previous OTEC developments include a 50-kW demonstration plant aboard a Navy-barge in 1971. It provided proof-of-concept closed-cycle feasibility by yielding a net 15 kW. The Japanese later installed closed-cycle plants at Nauru and Tokunoshima that yielded a net 10 kW and 32 kW, respectively. The National Energy Laboratory of Hawaii (NELH) installed an experimental 200-kW open-cycle facility in 1993 that yielded a net 50 kW. A subsequent expansion increased the net output to 500 kW, but the facility has since been dismantled.

Although shown to work on research scale, no commercially viable OTEC system has been built due in large measure to high capital costs, i.e., approximately $100 million for a 10-MW plant. However, besides electric power production, potential bi-products such as fresh water, cooling water, and nutrient-rich feed water may eventually serve to improve the economic competitiveness of this ocean resource. The governments of Indonesia, Malaysia, Puerto Rico, and Palau have sought technological agreements with different universities and private industry to develop commercial-sized power-generating facilities that will make use of their nations' ocean thermal energy resource potential.

While there many forms of renewable energy in the ocean environ, it is not possible to do justice to all in such a short paper. I have attempted to give but an overview of the more significant developments and trends. Perhaps, this discussion will stimulate a new (or renewed) interest in such technologies. If so, readers are encouraged to review the various references at the end of this paper, particularly the texts by Charlier and Justus[6] and Seymour[7].

Renewable Energy for NSF Diego Garcia

The mission of the NSF Diego Garcia is to operate and maintain facilities necessary to support operational forces in the Indian Ocean region. This support includes air terminal operations, aviation maintenance, communications, fuel and other types of supplies. To accomplish its mission, NSF Diego Garcia requires more than 65 MWh of energy and 350M gals of potable water each year[1]. With no commercial infrastructure available, the base has been self-sufficient since 1972. Diesel generators have been used to meet electric power needs, and two freshwater aquifers are sources of potable water.

By 1996, the existing utilities were nearing the end of their service life. Substantial repairs or replacement would be required to continue reliable and cost-efficient operations. Also, reliability and costs of electricity supply and fresh water quality were concerns. The Navy concluded that the best alternative for future utility provision was to contract with a private entity to install, operate and maintain new facilities that could provide the necessary power and water facilities for a unit fee based on usage. In the latter half 1997, prospective contractors were invited to submit proposals for this “Diego Garcia Repowering Project.” The formal “Request for Proposals” included some encouragement to use renewable energy resources. Four proposals were subsequently received and a utility contractor was selected in late 1998.

During the spring semester of 1998, three teams of four students (1st-class midshipmen in our ocean engineering major) were assigned the Repowering Project as their capstone design, with one modification. Their task was to develop plans for an ocean energy conversion system that could provide the approximate 10 MW of power and 1M gpd of potable water required. Each team’s design plan was to address aspects of functionality, structural and environmental integrity, constructibility, maintainability, and economic efficiency. A site visit would have been ideal, but such was deemed impractical given the Academy’s rigid academic schedule and travel impracticalities. Alternatively, the teams settled for the author’s shared memories and videos of earlier times and as much current information as they could discover.

Using the two principal reference texts noted earlier[6,7], the design teams considered many forms of ocean energy for Diego Garcia implementation. These included offshore wind, wave, and ocean thermal energies. Decision matrix techniques were used to evaluate the alternatives. Evaluation criteria included capital and operational costs, environmental impacts, constructability, and functionality, i.e., the ability to satisfy both the water and power requirements.

In separate analyses, each team concluded that the OTEC resource of Diego Garcia was the most favorable. However, that was the extent of similarity in their competitive designs. One design team proposed an offshore, moored floating plant using an open-cycle process to produce both electrical power and freshwater. The two commodities would be transferred to shore by submarine cable and pipeline, respectively. A second team proposed a closed-cycle OTEC system mounted on a fixed, shelf-mounted platform with a submarine cable for power transmission to shore. This team reluctantly (but properly) recommended upgrading the existing freshwater production systems on shore. The third team's proposal called for a land-based, closed-cycle OTEC plant for producing power and suggested that condensate collecting on the cold water pipe could be used to supplement an upgraded freshwater production system.

Each team presented its proposal to a Review Panel consisting of Navy representatives and ocean engineering professionals. The Panel selected the land-based plant as the most practical. Specifics of its design included a 4m-dia. 75m-long warm-water intake pipe and a 5m-dia. cold-water intake pipe extending 3400 meters offshore. The cold-water pipe length was necessary to reach an approximate 700m depth so as to achieve the recommended (minimum) 20EC temperature differential. Calculations of pipe sizes and heat exchanger requirements were aided by thermodynamic software available at the Academy. Environmental aspects associated with pipeline construction, wastewater discharge, and the potential for an ammonia (the OTEC working fluid) spill were addressed in the design report. Using cost data extrapolated from other sources[8], the team concluded that power could be produced at a cost of $0.12/kWh over the anticipated 30-year life of the plant. The team also suggested that the supplemental freshwater condensate would reduce the overall cost of producing fresh water.

Incidentally, one of four commercial contractors responding to the formal Request for Proposals submitted an OTEC scheme. Its projected utility unit costs were competitive with three fossil-fuel proposals. However, the perceived risk of a critical naval base depending on such a large-scale (~10 MW) prototype power production facility precluded award to the OTEC contractor.

Other USNA Opportunities in Offshore Renewable Energies

A new environmental option within the ocean engineering major at the U.S. Naval Academy has begun to emerge. The essence of the program resides in two foundation courses: Ocean Environmental Engineering and Ocean Resources Engineering. The former course has its principal focus on marine pollution - its causes, its effects and its remediation. The second course focuses on effective management policies for ocean resources of many kinds. These include renewable ocean energies, deep-ocean oil and gas recovery, desalinization, dredging and beneficial use of dredge spoil, mineral exploitation, ocean depositories, reefs, wetlands, and other coastal developments. Course instruction concentrates on resource assessment, technological recovery and utilization. This year, a major assignment will be to assess the (offshore) wind resource at Diego Garcia and to size a wind farm to meet a percentage of the NSF's energy consumption.

Our curriculum in ocean-environmental engineering is ably supplemented by elective course opportunities in other disciplines including environmental economics, environmental oceanography, environmental security, and marine environmental engineering. But, surely, the most significant learning experience comes from capstone design where students are not only challenged but also eager to approach problems that extend their minds to new horizons (and even greater depths.) Ocean resource implementation on Diego Garcia was one such opportunity.

Conclusion

It is not just book-learning that young engineers need, nor instruction about this and that, but a real-world challenge that will inspire them to give their all, to act expeditiously, to concentrate their creative energies to do one great thing – such as the system design of "A Source *of renewable energy* for Garcia!"

NSF Diego Garcia is fully fueled now, but there are other Garcias.

Numerous Navy bases have been investigated as to their potential to benefit from ocean energy implementation. Weil[9] was first to propose an OTEC system for Diego Garcia. Other potential sites for offshore renewables include the Atlantic Undersea Testing and Evaluation Center, Bahamas; USNS Roosevelt Roads and NASD Vieques, Puerto Rico; USNS Guantanamo Bay, Cuba; and, Naval Base Marianas, Guam.[10]

Since the 1998 capstone experience, another team's capstone project involved concept design of an OTEC system for USNS Roosevelt Roads. This year, a capstone team begins investigation of the offshore wind energy resource to meet a yet-unspecified naval base energy requirement. Such real-world projects provide excellent opportunity for our ocean engineering students to gain a fuller understanding of ocean energy resources and their environmental implications while fulfilling necessary graduation requirements.

"Water, water, everywhere" but not "*any drop to drink."* [11] This lament of an ancient mariner suggests both the opportunities and limitations of this world's ocean resources. As noted above, the technology for recovery of the ocean's renewable energies has limitations but, also, great potential. Engineering instructors of all disciplines are encouraged to take their students to the seas. Like the renewables to be investigated, the experiences will be everlasting.

Acknowledgments

As I endeavor to raise my teenage son to manhood and engage in daily interactions with students in my charge, I hold the deepest admiration for Mr. Elbert Hubbard and the moral lessons contained in his treatise "A Message to Garcia." [12] My sincerest apologies to this man and his followers for any inappropriate liberties and indiscretions I may have taken in adapting the style of his work to fulfill the purpose of this paper.

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Biography

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