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Renewable energy from the ocean

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Abstract

Growing concern over the threat of global climate change has led to an increased interest in research and development of renewable energy technologies. The ocean provides a vast source of potential energy resources, and as renewable energy technology develops, investment in ocean energy is likely to grow. Research in ocean thermal energy conversion, wave energy, tidal energy, and offshore wind energy has led to promising technologies and in some cases, commercial deployment. These sources have the potential to help alleviate the global climate change threat, but the ocean environment should be protected while these technologies are developed. Renewable energy sources from the ocean may be exploited without harming the marine environment if projects are sited and scaled appropriately and environmental guidelines are followed.

Keywords: Renewable energy; Marine technologies

1. Introduction

Vast and powerful, the ocean probably stores enough energy in the form of heat, currents, waves, and tides to meet total worldwide demand for power many times over [1]. Yet the challenges facing development of ocean energy technology have been daunting, and to date, ocean energy comprises only a miniscule proportion of worldwide energy supply. Now, however, widespread concern over global climate change and other environmental impacts of worldwide reliance on fossil fuels has increased interest in renewable energy. As global commitment to renewables increases in the future, more attention is likely to become focused on the immense stores of energy in the ocean.

Increased research and development of renewable energy from the ocean may be necessary for a broad, comprehensive, and responsible energy plan. While renewable energy from the ocean would most likely improve the environment by replacing fossil fuel plants and reducing carbon emissions, we must ask the question "and then what?". It will be critically important to ensure that the development of new ocean energy technologies does not harm the marine environment, which is already subject to multiple threats such as overfishing, pollution, habitat loss, and climate change. This paper will present and compare major potential sources of renewable energy from the ocean with a view toward developing responsible development guidelines for protecting the marine environment.

2. Renewable energy development

Energy resource use is one of the most important and contentious issues of our time. Investments in energy efficiency and increased conservation may be the best way to tackle energy use. But it seems unlikely that goals for reducing carbon emissions can be met through demand-side management alone. As many as 2 billion people worldwide lack electricity today [2], and as rapid population growth in developing countries continues, demand for electricity will almost certainly rise. At the same time, rising standards of living and reliance on technology in developed countries may cause energy demand to rise faster than population, even with advances in efficiency. In the United States, for example, per-capita energy use declined throughout the 1970s and early 1980s due to improvements in efficiency, but has increased since then, and is predicted to increase in the

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next 20 years, with higher demand for energy services [3]. In order to meet demand that is anticipated despite efforts to improve efficiency, while limiting production of greenhouse gases, renewable energy sources must be developed.

In the United States, research on renewable energy has lagged in part because it is difficult for any new technology to compete economically with cheap and established fossil fuel plants. Renewables often pay off in the long term, because the "fuel"—sunlight, wind, ocean waves, etc.—tends to be free and limitless. In the short term, renewable energy plants are sometimes prohibitively capital intensive. However, proper accounting for externalized costs of energy production puts renewable energy in a more favorable light, while advances in technology and economies of scale can cause the costs of such technologies to drop considerably over time. For example, wind power cost 30 cents/kW h in the 1980s, much too high to be economically feasible; by 1999 that cost had dropped to 5 cents/kW h, making wind power cost competitive with fossil fuels [4], even without accounting for the costs of pollution and other adverse impacts associated with fossil fuels.

Renewable energy research has mostly focused on the development of solar, wind, biomass and geothermal sources. While these sources are all very promising, the best and most robust energy policy will take advantage of a full suite of renewable energy sources. With this in mind, we anticipate that governments, corporations, engineers, and scientists will increasingly look to the massive amounts of energy stored in the ocean. While ocean energy development necessarily presents some challenges, much of the infrastructure and knowledge necessary to generate energy from the ocean already exists, due in part to the offshore oil industry. Research suggests that overcoming technological challenges of ocean energy should not be prohibitive [5]. Some applications of wave, offshore wind, and possibly tidal energy may already be economically feasible for limited sites, and as research continues, costs of ocean energy are likely to drop to competitive levels.

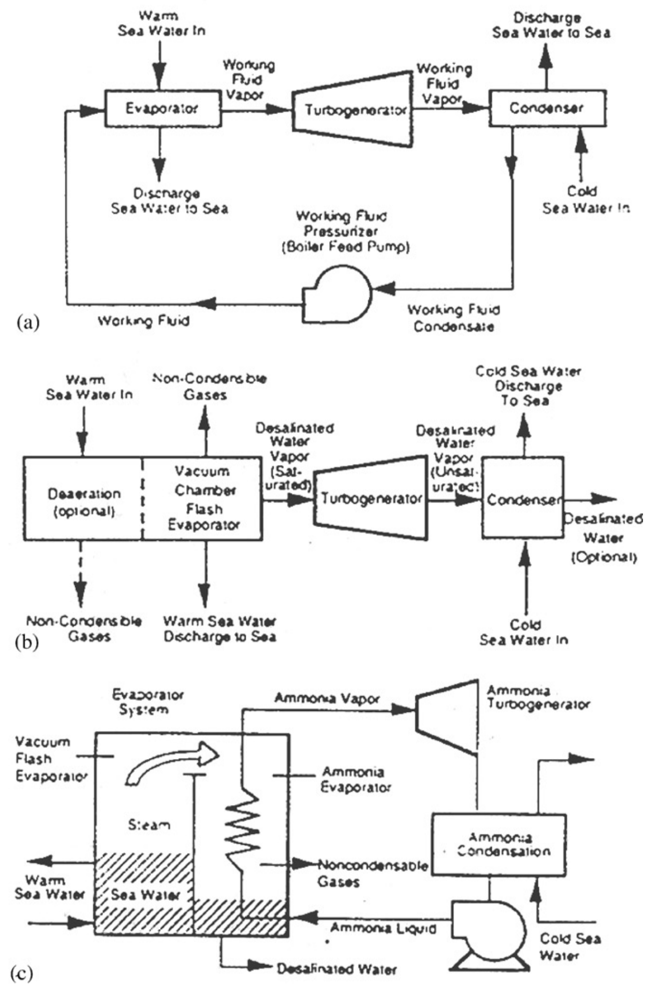

Fig. 1. Schematic of OTEC operation: (a) closed-cycle system; (b) open-cycle system; and (c) hybrid-cycle system. Reprinted with permission from [1].

3. Renewable energy resources from the ocean

3.1. Ocean thermal energy conversion (OTEC)

3.1.1. Background

OTEC produces electricity from the natural thermal gradient of the ocean, using the heat stored in warm surface water to create steam to drive a turbine, while pumping cold, deep water to the surface to recondense the steam. In closed-cycle OTEC (Fig. 1a), warm seawater heats a working fluid with a low boiling point, such as ammonia, and the ammonia vapor turns a turbine, which drives a generator. The vapor is then condensed by the cold water and cycled back through the system. In an open-cycle plant (Fig. 1b), warm seawater from the surface is pumped into a vacuum chamber where it is flash evaporated, and the resulting steam drives the turbine. Cold seawater is then brought to the surface and used to condense the steam into water, which is returned to the environment. Hybrid plants (Fig. 1c), combining benefits of the two systems, would use closed-cycle generation combined with a second-stage flash evaporator to desalinate water [1]. OTEC plants can either be built onshore or on offshore floating platforms. Floating platforms could be larger and do not require the use of valuable coastal land, but incur the added expense and impact of transporting energy to the shore. Energy can be transported via seafloor cable, a well-developed but costly technology that impacts the environment by disrupting seafloor communities, or stored in the form of chemical energy as hydrogen, ammonia or methanol. Plantships used to produce hydrogen, ammonia or methanol would "graze" the ocean slowly, store products for about a month, then transfer products to a tanker that would take the products to shore [6].

It is possible to derive ancillary benefits from both the warm and cold water cycled through OTEC plants. In an open-cycle plant, the warm water, after being vaporized, can be recondensed while keeping separated from the cold seawater, leaving behind the salt and providing a source of desalinated water fresh enough for municipal or agricultural use. The cold-water effluent can be applied to mariculture (the cultivation of marine organisms such as algae, fish, and shellfish), air conditioning and other applications. At the National Energy Laboratory of Hawaii (NELHA), once the locus of OTEC research and pilot programs, there are no longer any functioning, net energy-producing OTEC plants, but research into uses for deep seawater pumped to the surface using OTEC technology continues.

Cold, deep seawater brought up by OTEC pipes is nutrient-rich-parasite and free, and can be pumped into onshore ponds producing algae or other products in a controlled system [6]. At NELHA, private companies have already profited from raising lobsters, flounder, and high-protein algae in mariculture ponds fed by the cold water. Additionally, this cold water has been used to grow temperate crops such as strawberries in Hawaii's tropical climate [7]. Air conditioning and industrial cooling may be the most lucrative of all ancillary benefits of OTEC plants. Currently, both of the two main buildings at the NELHA lab are effectively air conditioned by cold seawater pumped through OTEC pipes [8].

3.1.2. Current status

In the United States, OTEC research has stalled since federal funding was cut in the 1980s. Though pilot OTEC plants at NELHA were able to successfully produce net power, they were considered uneconomical compared to fossil fuels. No net-power-generating plants are currently operating at NELHA, but the lab has plans for a new closed-cycle plant, scheduled for construction by summer of 2002, that will generate between 1 and 1.4 MW of power [9,10]. Additionally, the US Navy is considering building an 8 MW OTEC plant with a 2 MW gas-powered backup turbine to replace the 15 MW gas plant currently on its base on the British Island of Diego Garcia in the Indian Ocean. Because about 5 MW of the power generated by the gas plant is devoted to air conditioning, which could be replaced by cooling with water brought up by the OTEC pipes, the smaller capacity OTEC plant could replace the gas plant. The plant could also help supply the island with drinking water [10].

Sea Solar Power Inc. has developed two conceptual models for OTEC plants, one 10 MW land-based model for small islands and the other 100-MW floating platform model for mainland use. Their model is 8 times smaller than the US government design for the same capacity plant. It therefore would use and discharge significantly less water, and would cost about $\frac{1}{4}$ as much [11]. SSP believes that though OTEC power production was not economical in the NELHA experiment, the SSP design could be cost-effective [12]. Currently, SSP is involved in a 2-yr, $20 million project to test and refine each of the components of the system [9]. After optimization of the system, SSP plans to begin work on a 10 MW pilot project in Guam [12] and a 100 MW floating plant in Tamil Nadu, south India [11].

3.1.3. Potential

In total, it is estimated that about 10 TW (10 trillion W or 10 billion kW) of power, approximately equal to the current global energy demand [13], could be provided by OTEC without affecting the thermal structure of the ocean [10]. However, with the current cost of electricity generation from OTEC varying between 8 and 24 cents/kW h [1], significantly higher than fossil fuel costs, it is unlikely that this resource will be fully developed unless it is subsidized. The greatest potential for OTEC is probably for use on small island developing states (SIDS), which need both domestic power and fresh water. Full use of ancillary benefits (fresh water, aquaculture, air conditioning, etc.) is most likely necessary for economic feasibility. OTEC may not make a great contribution to worldwide power needs, but it could provide significant power to several SIDS.

OTEC is only viable in the tropical seas, in areas where the thermal gradient between the surface and a depth of 1000 m is at least 22°C. Regions of the open ocean with this temperature difference, suitable for floating OTEC plants, total about 60 million km^2 in area [6]. For a shore-based plant, an additional requirement is topography that allows access to very deep water (1 km or deeper) directly offshore, conditions that exist at certain tropical islands, coral atolls, and a limited number of continental sites. In the United States, potential sites include Hawaii, Puerto Rico, and the continental shelf of the Gulf of Mexico [6]. Areas of the world ocean with the appropriate thermal gradient are shown in Fig. 2 [1].

3.1.4. Environmental impacts

Though fairly benign in environmental impact compared to traditional power plants, OTEC poses some potential environmental threats, especially if implemented on a large scale. Data from existing electric generating stations on the coast provide insight into possible impacts of OTEC plants. These stations impact the surrounding marine environment mainly through heating the water, the release of toxic chemicals, impingement of organisms on intake screens, and entrainment of small organisms by intake pipes, all of

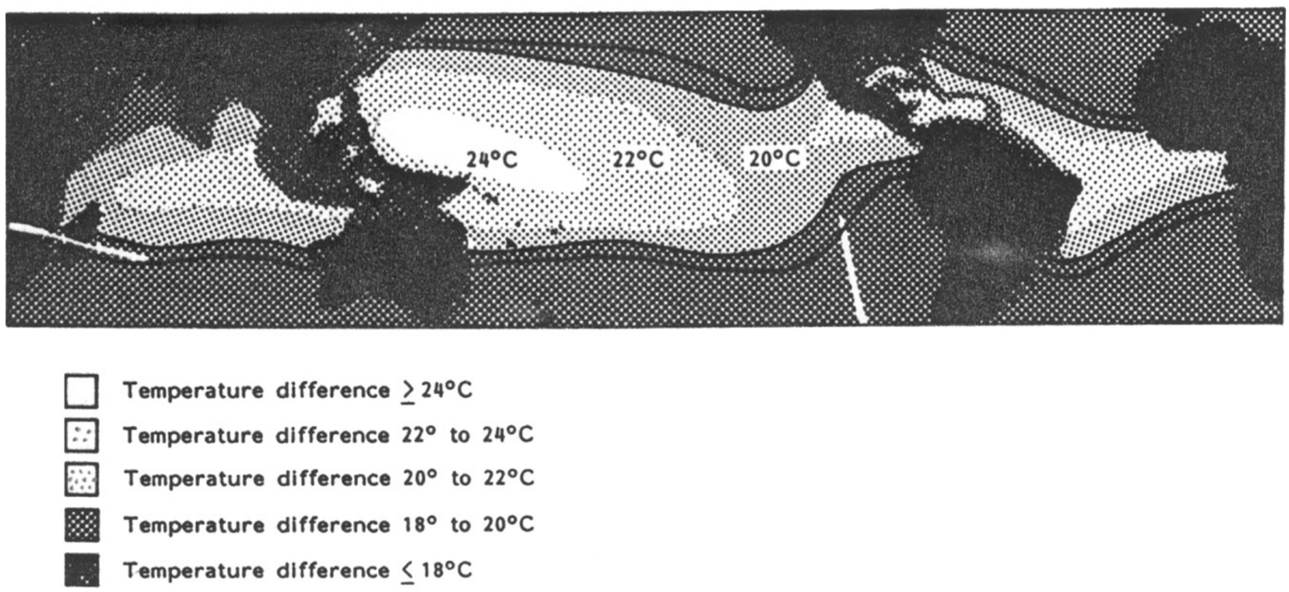

Fig. 2. Map of temperature difference between surface and 1000 m in tropical ocean. Reprinted with permission from [1].

which are concerns for OTEC. Large discharges of mixed warm and cold water would be released near the surface, creating a plume of sinking cool water. The continual use of warm surface water and cold deepwater may, over long periods of time, lead to slight warming at depth and cooling at the surface [6]. Thermal effects may be significant, as local temperature changes of only 3–4°C are known to cause high mortality among corals and fishes. Aside from mortality, other effects such as reduced hatching success of eggs and developmental inhibition of larvae, which lower reproductive success, may result from thermal changes [14]. Increased nutrient loading resulting from the discharge of upwelled water could also negatively impact naturally low-nutrient ecosystems typical of tropical seas.

Toxic chemicals, such as ammonia and chlorine, may enter the environment from an OTEC plant and kill local marine organisms. Ammonia in closed-cycle systems would be designed not to contact the environment, and a dangerous release would be expected to result only from serious malfunction such as a major breakdown, collision with a ship, a greater than 100-yr storm, terrorism, or major human error [6]. The impact of chlorine will likely be minimal, as it would be used at a concentration of approximately 0.02 ppm daily average, while the EPA standard for marine water requires levels lower than 0.1 ppm [6].

Impingement of large organisms and entrainment of small organisms has been responsible for the greatest mortality of marine organisms at coastal power plants thus far [14]. The magnitude of this problem depends on the location and size of the plant; however, if marine life is attracted to OTEC plants by the higher nutrient concentrations in the upwelled cold water, large numbers of organisms, including larvae or juveniles, could be killed by impingement or entrainment. For floating plants, victims of impingement would be mainly small fish, jellyfish, and pelagic invertebrates, while for land-based plants crustaceans would be the most affected [6].

Finally, a small amount of CO_2 is released to the atmosphere by OTEC power generation. Bringing deepwater to the surface where pressure is lower allows some of the sequestered CO_2 in this deepwater to outgas, especially as the water is warmed, reducing the solubility of CO_2. However, this carbon emission is very minute compared to the emissions of fossil fuel plants.

OTEC could significantly improve quality of life in SIDS, where the current cost of power is at a premium and the benefits of desalinated water, mariculture and air conditioning would have a major impact. Further research into environmental impacts is necessary, but if the technology is shown to be benign, the development of OTEC for SIDS should be a priority. Plants in developed tropical sites that face high power prices should also be encouraged, if appropriate sites at which environmental damage will be negligible can be found. Because the governments of the SIDS that would benefit most from OTEC cannot afford such a high capital investment, governments of developed states should contribute to the research effort and investment for OTEC in developing countries. Appropriate measures should be taken to control environmental impacts including:

- Refraining from siting OTEC plants in sensitive areas including prime fishing grounds, spawning areas, and sensitive reef habitats.

- Making use of discharge for ancillary benefits, which prevents discharges from altering local water temperature significantly.
- Carefully regulating the use of toxins such as ammonia and chlorine, and avoiding coating the plants with toxic hull coatings used on ships in harbors which are known to pollute the waters.
- Relying mainly on relatively small plants. While there may be economic benefits to scaling up, large-scale plants are more likely to damage a local community through discharge or impingement/entrainment. Also, benefits from economies of scale are likely to dwindle at the 50 MW scale [15]. Similarly, if several small OTEC plants are used these plants must be suitably spaced to prevent altering local ecology too significantly at any one site [6].

3.2. *Wave energy*

3.2.1. *Background*

Wave energy has long been considered one of the most promising renewable technologies. Not only is the energy resource vast, but it is more dependable than most renewable energy resources—wave power at a given site is available up to 90 percent of the time, while solar and wind availability tend to be available just 20–30 percent of the time [16]. There are a more than 1000 different patented proposals for wave energy devices [17], and several have demonstrated the potential for commercially viable electricity generation [18].

3.2.2. *Current status*

After several disappointing experiments dashed high expectations for wave power in the oil crisis era of the 1970s, interest waned. But interest has increased in wave energy with the introduction of several new technologies that dramatically increase the efficiency and feasibility of wave power, and a shift in focus toward smaller plants, making the initial capital costs less prohibitive. Unlike OTEC, wave power is already commercial, with recent advances continually coming from companies investing in wave energy devices around the world.

The first commercial wave plant in the world, Limpet 500, was installed on the island of Islay, Scotland, in 2000, and has been providing power to the grid for the UK since late November 2000 [19]. The Limpet 500 is a 0.5 MW capacity plant designed by Wavegen for siting on exposed shores, utilizing an oscillating water column design. Wavegen has also created a near-shore device, OSPREY 2000 (Ocean Swell Powered Renewable EnergY), a 2 MW station designed for 15 m deep water up to 1 km from shore, and the WOSP 3500, a combined OSPREY and offshore windmill unit, rated at a total of 3.5 MW (2 MW OSPREY plus 1.5 MW wind) [20].

Also on the island of Islay, Ocean Power Delivery Ltd. of Edinburgh, Scotland is installing a small offshore wave power device, which will power up to 200 homes. Installation should be finished in 2002. The plant will produce 2.5 million kW h electricity/yr. With support from the Scottish Renewable Obligation of 1999, OPDL eventually plans to install up to 900 devices, with a total capacity of 700 MW, producing more than 2.5 billion kW h/yr [21].

In the United States, the Monitor, a hybrid system designed by Demi-Tek that combines tide, wave and wind power, has been working just off Asbury Park, New Jersey since August 1990. The Monitor produces enough electricity to light the city's boardwalk and convention hall. In addition, the Monitor was deployed to help reduce wave action and protect beaches from erosion. It is anchored to the ocean floor by cables similar to those used for offshore oil drilling, and electricity is brought to shore by an undersea cable [22].

3.2.3. *Potential*

The greatest potential for wave energy exists where the strongest winds are found—at the temperate latitudes between 40° and 60° north and south, on the eastern boundaries of oceans. One of the richest nations in terms of potential for wave energy is the UK, with the north of Scotland having particularly high potential. The Science and Technology Committee of the British Parliament reports that, based on estimates from the Department of Trade and Industrys Energy Technology Support Unit, in the UK alone, wave energy devices could practicably contribute more than 50 TW h/yr [5]. In the US, a reasonable potential for wave energy development may exist off the Pacific northwest coast [21]. Worldwide, wave energy could potentially provide up to 2 TW of electricity, according to the World Energy Council [23], approximately 1/5 of current global energy demand.

The economics of wave energy power, though not yet competitive with fossil fuels, are promising, and the situation is improving with more advanced technology. Costs have dropped rapidly in the last several years, and now companies are aiming for less than 10 cents/kW h, to as low as 5 cents/kW h, for the latest designs. This price would allow wave plants to compete favorably with conventional power plants [24].

3.2.4. *Environmental impacts*

Small-scale wave energy plants are likely to have minimal environmental impacts. However, some of the very large-scale projects that have been proposed have the potential for harming ocean ecosystems. Covering very large areas of the surface of the ocean with wave energy devices would harm marine life and could have more widespread effects, by altering the way the ocean interacts with the atmosphere.

Wave power plants act as wave breakers, calming the sea. While this is often a desired effect in many harbors (in fact wave energy devices could be combined with wave break devices), the result may be to slow the mixing of the upper layers of the sea which could adversely impact marine life and fisheries. Demersal fish will probably not be directly affected; however, changes in surface productivity linked to reduced mixing could potentially reduce food supply to benthic populations. Changes in waves and currents would most directly impact species that spend their lives nearer the surface. Many fish species depend in part on currents to transport larvae, so wave energy devices that alter the currents between spawning grounds and feeding grounds could be harmful to fish populations [25].

The dampening of waves may reduce erosion on the shoreline; whether this effect is beneficial or detrimental depends on the specific coastline [25]. While dampening of waves may have damaging ecological effects, and more research is needed to determine the extent of this impact, studies show that sheltering due to wave devices will have a hardly noticeable effect on the largest waves, so that the ecological role of very large waves as a disturbance that maintains high biodiversity will be unencumbered [17].

Wave energy promoters claim the devices could enhance marine life by providing structure, acting in much the same way as artificial reefs. This claim should be critically evaluated for specific projects, because the effects of artificial structures appear to be very site specific. In areas where hard substrate is clearly limiting to production, such structures may enhance marine life. Conversely, when other factors are limiting, artificial structures may simply draw organisms away from natural habitats and potentially increase their vulnerability to harvest [26–28].

Wave energy is promising, holds a huge potential to reduce reliance on fossil fuels, and is considered to be relatively environmentally benign at this time. Further research into wave energy is recommended. For new wave plants, particularly of large capacity, siting should be carefully considered not only for the potential to generate power, but also for the ecosystem's reliance on and response to powerful waves, and wave plants should be avoided where calming of the waves would result in significant community changes or disrupt natural ecological processes.

3.3. *Tidal*

3.3.1. *Background*

Tidal power has the distinct advantage of being highly predictable, compared to solar, wind, and wave energy. The regularity of the tides along with an immense energy potential helps make tidal energy development attractive. The first tidal barrages resemble dams built across the mouths of estuaries to harness the energy of the tidal flow. Unlike a hydroelectric dam, a tidal barrage must allow water to flow in both directions, although typically, the barrage only captures the energy of the water flowing out of the estuary from high to low tide. Tidal barrage technology is fairly well developed, and offers very large potential in some sites.

Tidal barrages have been found to be potentially damaging to the marine environment (see "Environmental impacts"). More recent innovations include tidal fences and tidal turbines, which take advantage of the currents set up by tidal flows. Tidal fences consist of turbines stretching entirely across a channel where tidal flow sets up relatively fast currents. The turbines are designed to allow the passage of fish, water and sediment through the channel [29]. Tidal turbines, also installed in channels with tidal currents, resemble underwater wind turbines and require current speeds of 2–3 m/s; at lower velocities, harnessing energy from the current is uneconomical, while higher velocities can damage the turbines.

3.3.2. *Current status*

The first and largest operational tidal barrage plant in the world, built in the early 1960s, is the La Rance plant on the Brittany coast of northern France. Taking advantage of the 2.4 m tidal height at the mouth of the La Rance estuary, the plant produces 240 MW of electricity. Other operation tidal plants exist at Kislaya in Russia, Jiangxia in China, and Annapolis in Canada [30].

No commercial tidal fence plants exist at this time, but the company Blue Energy Canada hopes to develop them in the near future. It is looking toward Southeast Asia for its first commercial tidal fence ventures, most notably a planned fence across the Dalupiri Passage in the Philippines. This site, with a peak tidal current of about 4 m/s, would allow for a 2200 MW peak power plant, with a base daily average of 1100 MW. As part of a larger proposed project, Build Own Operate Transfer (BOOT), the project could help the Philippines exceed its power needs and export electricity [29]. Tidal fence projects have also been proposed for sites beneath the Tacoma Narrows bridge in Washington and between Point San Pablo and East Brothers Island in San Francisco Bay [31,32]. Tidal turbines are not yet at the commercial development stage. The industry leader in tidal turbine research, Marine Current Turbines Ltd., plans to begin commercial development in 2004 after concluding a major research and development effort [33]. By 2010, the company states, 300 MW of power could be provided by underwater tidal turbines.

3.3.3. *Potential*

It is estimated that the United Kingdom could generate up to 50.2 TW h/yr with tidal power plants, while western Europe as a whole could generate up to 105.4 TW h/yr. Total worldwide potential is estimated to be about 500–1000 TW h/yr, though only a fraction of this energy is likely to be exploited due to economic constraints [30]. The availability of tidal energy is very site specific, where tidal range is amplified by factors such as shelving of the sea bottom and funneling in estuaries, reflections by large peninsulas, and resonance effects when tidal wave length is about 4 times the estuary length, as in the bay of Fundy [34]. Major potential sites for barrages include the Bay of Fundy in Canada, which with a mean tidal range of 11 m has the highest tides in the world, and the Severn Estuary off Britain [30]. Tidal fences and turbines could be installed anywhere tidal flows and the constraints of topography create predictable currents of 2 m/s or greater.

3.3.4. Environmental impacts

Tidal plants sited at the mouths of estuaries pose many of the same environmental threats as large dams. By altering the flow of saltwater into and out of estuaries, tidal plants could impact the hydrology and salinity of these sensitive environments. Estuaries serve as a nursery for many marine organisms as well as a unique and irreplaceable habitat for estuarine organisms, and alteration of this habitat by the construction of large tidal plants should be avoided. During the construction phase for the tidal plant at La Rance, the estuary was entirely closed off from the ocean for 2–3 yr, and there was a long period before the estuary reached a new ecological equilibrium. Changes caused by the barrage include a reduction in intertidal area, slower currents, reduced range of salinities, and changed bottom water characteristics, all of which led to changes in the marine community there [34]. In the future, any new tidal barrages should be constructed taking care not to close off the estuary from the ocean during construction, and these plants should not be built until detailed environmental assessments demonstrate a minimal impact on the marine ecosystem.

Tidal fences and tidal turbines are likely to be more environmentally benign [29]. Tidal fences may have some negative environmental impacts, as they block off channels making it difficult for fish and wildlife to migrate through those channels. However, Blue Energy claims that the slow-moving turbines allow both fish and water to flow right through the structures, and have no effect on silt transport. A 20 kW prototype built in 1983 by Nova Energy, Blue Energy's predecessor, in the St. Lawrence Seaway found zero recorded fish kill [31]. In longer-term situations, some fish kill would be inevitable, but fences could be engineered so that the spaces between the caisson wall and the rotor foil were large enough for fish to pass through, and the turbines could be geared down to low velocities (25–50 rpm), keeping fish kill to a minimum [32]. Marine mammals would be protected by a fence that would keep larger animals away from the structure and a sonar sensor auto-breaking system that shuts the system down when marine mammals are detected [31]. The tidal fences would not alter the timing or amplitude of the tides.

Tidal turbines could be the most environmentally friendly tidal power option. They do not block channels or estuarine mouths, interrupt fish migration or alter hydrology [29]. Tidal turbines and tidal fences both may offer considerable generating capacity without a major impact on the ocean, while tidal barrages are probably too damaging to the marine ecosystem. Research in tidal energy should focus on turbines, fences and similar technologies. These projects should be sited and built so that major migration channels are left open. Turbines should turn slowly enough that fish mortality is minimized and nutrient and sediment transport is largely unaffected. Tidal fences should be built across narrow channels, but not blocking an entire bay or corridor.

3.4. Offshore wind

3.4.1. Background

Wind energy has received a lot of attention lately as one of the most promising and economically feasible technologies for clean power generation. Wind power is one of the cleanest types of power available, and can be currently cost competitive with fossil fuels, depending on siting. While most research and promotion of wind energy is focused on land-based sites, interest in offshore wind energy is growing. Very strong winds regularly blow over the oceans, winds over the ocean attain higher speeds and are less turbulent than winds over land, and no landforms block accessibility of the wind over the ocean.

Offshore wind power design is very similar to onshore windmills; thus much of the technology is currently well developed. Unlike land-based wind farms, offshore wind farms require high-voltage cable laid from windmills to shore to transport the electricity. In addition to transporting energy to shore, the main technological challenge involved in developing offshore wind sources is creating foundations stable enough to last in the harsh ocean environment and withstand storms, and to economically transport these foundations and anchor them offshore.

3.4.2. Current status

The majority of offshore wind power development is taking place in Denmark, which is currently planning to generate 40 percent of its power from wind plants by 2030, mostly from offshore wind farms. Denmark has already built two successful 5 MW pilot wind farms, at Tuno Knob and Vindeby [35]. Several other northern European nations are also considering investing in large offshore wind parks. The Netherlands has built two wind farms and plans to build a third park of 100 turbines, making enough electricity for 100,000 households. Sweden recently built a wind park of 5×500 kW turbines, and Swedish companies are planning a 48 MW wind farm and possibly a park producing as much as 750 MW. The United Kingdom also plans to make use of its great offshore wind energy potential in the near future [36].

Currently, offshore wind power is still more expensive than either land-based wind power or fossil fuels, but the cost is dropping and in many places offshore wind is approaching economically feasible rates. The cost is expected to drop by 50 percent in the next 10 yr, which would put it on par with onshore wind and natural gas [35]. New wind farms planned for Denmark will be more economical by using turbines rated up to 1.5 MW, 3 times larger than those at the pilot plants. The farms will consist of 100 or more of such turbines, taking advantage of economies of scale and saving on the costs of undersea cables used to transport electricity to shore [36], which comprise up to a quarter of the costs for offshore wind farms [35].

Making stable foundations that can be transported or constructed offshore and that can resist the many challenges of the marine environment is one of the most difficult and expensive aspects of offshore wind development. Recently, the Danish Energy Agency discovered that by using steel, which is lighter and easier to transport than the concrete currently used, foundation costs could be cut by one-third. This would significantly impact the overall cost of the turbines, since foundation costs may account for 23–30 percent of the total cost [35].

Recent engineering studies show that turbines may be economically built in water up to 15 m deep, allowing a much greater area of the ocean to be utilized [36]. In these deeper waters, winds are more strongly developed, allowing greater power to be generated from the same size plant [35]. Over time, with economies of scale and further optimization of offshore technology, offshore prices could be comparable to fossil fuel plants.

3.4.3. *Potential*

There is a fairly large potential for offshore wind and many possible sites. It is estimated that wind plants on the US coast alone could provide up to 54 GW of capacity, or 102 TW h/yr of energy, with most production from the northwest, northeast, and Gulf of Mexico coasts. Worldwide, the potential for offshore wind may be well over a thousand TW h/yr, with most capacity off the coast of northern Europe [37].

The technology may be especially promising if combined, as in the OSPREY model (see Wave Energy), with other large electricity-generating offshore structures such as wave plants. This innovation can significantly improve the economics of the plants by cutting down the costs of attaching them to the seabed. Models indicate that combined wind and wave energy structures could be more economically efficient, environmentally benign, and reliable than separate plants [38].

It is probable that offshore wind power will increase dramatically in the next few decades. Denmark, Germany, the Netherlands, Norway, Sweden, and the UK are continuing to research larger-scale, offshore applications [35]. While land-based wind power has been tested more extensively and generally demands lower capital investment, offshore wind power is gaining favor for a number of reasons. Offshore wind potential is vast. Wind speeds over the ocean can be up to 20 percent higher than over land. Because power varies with the cube of wind speed, this translates into a huge increase in potential—up to 70 percent higher offshore than on land. Unblocked by hills, tall buildings or other obstacles, wind power can also be more reliable offshore. Furthermore, most of the northern European nations investing in offshore wind plants are densely populated and have little remaining undeveloped land suitable for wind farms [36].

3.4.4. *Environmental impacts*

Potential impacts of offshore wind on the environment include effects on fisheries, seabed communities, and migratory birds. Additionally, vibrations from the windmills could disturb marine mammals. Currently, there is no evidence of damaging effects from offshore wind turbines, but insufficient studies on environmental impact have been conducted.

For offshore wind farms, visual impact and noise pollution should be minor if the farms are not visible from shore [39]. While most plants to date have been sited very near shore in shallow water, it is anticipated that as the economics of offshore plants improve, future plants will be built farther from shore and in deeper waters, where visual and noise impacts are greatly reduced [37].

One of the few noted environmental drawbacks of wind power in general is the potential to kill birds. Careful siting of windmills to avoid important bird migration corridors can significantly mitigate this danger. Empirical studies have concluded that diving birds at Tuno Knob in Denmark are not frightened from the sites of wind farms [36,39], and that bird mortality from collision with windmills at Blythe Harbor, UK is significantly lower than background mortality [40]. With careful siting to avoid harm to local or migratory birds and fish, offshore wind may be one of the most environmentally benign of ocean energy resources, as it has a very small footprint, does not affect currents, waves or tidal flows, and does not discharge fluids or change the ambient temperature of the waters [37].

4. Conclusions

The technologies for OTEC, wave, non-barrage tidal, and offshore wind energy are still fairly new. Further research is needed on the environmental effects as well as economic feasibility of renewable ocean energy projects. However, research has shown that these technologies hold promise, and further research and development could help address one of the most serious threats to the environment and society, global climate change, by reducing dependence of fossil fuels.

Any energy technology has some environmental impact. However, while fossil fuel plants lead to pollution and global warming regardless of their size and location, the impacts of various renewable energy technologies are likely to be highly site specific and scale dependent. Carefully choosing sites that can withstand the alterations to the environment caused by power plants will be crucial to effectively develop these technologies without harming the ocean. As with any promising but new technology, it is advisable to continue with research efforts, but proceed cautiously, prioritizing the health of the marine environment while producing clean energy.

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