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ARTICLE *in* MARINE POLICY · MARCH 2012

Impact Factor: 2.62 · DOI: 10.1016/j.marpol.2011.05.008

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Marine Policy 36 (2012) 463–465

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

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ARTICLE INFO

Article history:
Received 2 April 2011
Accepted 20 May 2011
Available online 18 September 2011

Keywords:
Renewable energy
Ocean Thermal Energy Conversion (OTEC)
Small island developing states (SIDSs)

ABSTRACT

Increasing concerns regarding oil spills, air pollution, and climate change associated with fossil fuel use have increased the urgency of the search for renewable, clean sources of energy. This assessment describes the potential of Ocean Thermal Energy Conversion (OTEC) to produce not only clean energy but also potable water, refrigeration, and aquaculture products. Higher oil prices and recent technical advances have improved the economic and technical viability of OTEC, perhaps making this technology more attractive and feasible than in the past. Relatively high capital costs associated with OTEC may require the integration of energy, food, and water production security in small island developing states (SIDSs) to improve cost-effectiveness. Successful implementation of OTEC at scale will require the application of insights and analytical methods from economics, technology, materials engineering, marine ecology, and other disciplines as well as a subsidized demonstration plant to provide operational data at near-commercial scales.

The search for renewable, carbon-free energy sources has intensified in recent years for a number of reasons. Many countries continue to need more energy to fuel economic development and improve human welfare. Meanwhile, awareness of the current and potential consequences of climate change has increased, as has the price of fossil fuels. Moreover, the Deepwater Horizon oil disaster in the Gulf of Mexico has highlighted other costs of fossil fuel extraction and use, adding impetus to the search for clean alternatives. Some countries have spurred interest in renewable energy with financial and tax incentives [1].

Many kinds of clean, renewable sources of energy have the potential to address these concerns. A wide variety of energy sources will be needed to meet the twin challenges of alleviating global warming and poverty. The focus has so far been on wind power, because costs have been comparable with those of oil or gas fired power plants [2] while costs associated with other renewables have been higher. Now that fossil fuel prices have tripled in the last 20 years [3], other types of renewables may become cost-effective and even prove to have advantages over wind under certain conditions.

Ocean waves, currents, and offshore winds tend to provide power more continuously than wind over land; unsteady supply and storage issues continue to constrain wind farms [2]. Steadier still is Ocean Thermal Energy Conversion (OTEC), which conceptually can provide base-load power almost continuously [4,5]. OTEC converts the difference in temperature between the surface and deep layers of the ocean into electrical power. Warm surface water is used to vaporize a working fluid with a low boiling point, such as ammonia, and then the vapor is used to drive a turbine and generator. Cold water pumped from the deep ocean is then used to re-condense the working fluid [6,7]. The temperature differential must be greater than approximately 20 °C for net power generation [8]. Such differentials exist between latitudes 20° and 24° north and south of the equator (e.g. tropical zones of the Caribbean and the Pacific) [8]. The global distribution of temperature gradients between these latitudes is shown in Fig. 1. The actual distribution of feasible sites for OTEC will depend on other factors as well, such as proximity to shore and the potential to increase the temperature gradient by other means (e.g., by applying waste heat from other industrial facilities).

OTEC may have numerous other advantages in addition to stability of power supply. OTEC power production potential should be the highest during the summer months in warm latitudes, when

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doi:10.1016/j.marpol.2011.05.008

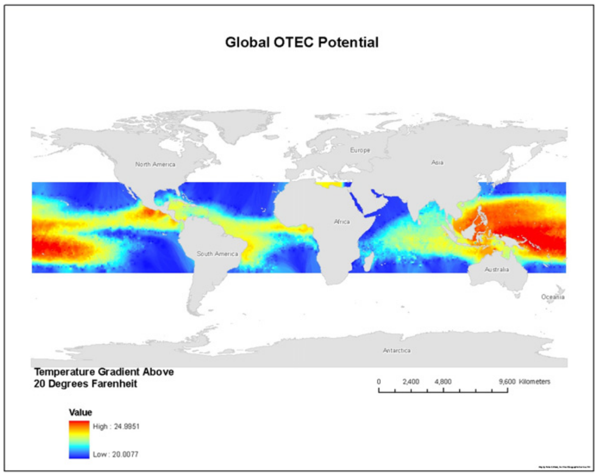

Fig. 1. Distribution of ocean temperature gradients in excess of 20 °C.

demand is typically also at a maximum in the tropics due to air conditioning [9]. At the pilot scale, OTEC plants have produced significant amounts of freshwater (through condensation on the cold water pipes) with very little power consumption and without producing brine or other pollution [6]. OTEC has also provided refrigeration and air conditioning without much additional power consumption, replacing much more energy-intensive air conditioning and refrigeration systems [10]. Moreover, several kinds of valuable aquaculture crops including lobsters, abalone, and microalgae for the production of nutritional supplements have been produced in the effluent of pilot OTEC plants, potentially improving OTEC's economic feasibility [11].

While OTEC sounds like a panacea, clearly it is not – there may be serious environmental risks associated with OTEC, and there are certainly significant technical and economic obstacles that stand in the way of further progress. However, increasing fossil fuel prices, increasing demand for clean and renewable energy, and the potential for OTEC to help alleviate increasingly urgent food and water security issues suggests that the time may be right to revisit OTEC. Much has changed since 1881, when this technology was first conceived of by French physicist Jacques-Arsene d'Arsonva, and later advanced by George Claude during the 1930s [6].

Claude attempted to construct an OTEC plant in Cuba in the 1930s, but abandoned the effort due to technology and infrastructure constraints [6]. In the late 1970s, joint ventures between the United States Department of Energy (DOE), the Natural Energy Laboratory of Hawaii, and various private companies resulted in a "mini-OTEC" barge deployed off Hawaii and also a land-based OTEC plant on Hawaii. These produced net power of 18 and 103 kW, respectively [6]. Also notable are the joint ventures by private Japanese companies and the Tokyo Electric Power Company, which resulted in an OTEC plant on the Pacific island of Nauru, generating 120 kW of gross power [12] and 30 kW of net power. This plant was used to power a school and other buildings on Nauru [13].

The majority of these projects have been considered successful because they generated significant amounts of net power. Although these plants can be considered "proofs of concept", they did not generate enough operational data to enable a scale up to a commercial plant [6]. Efforts to scale up OTEC stalled in the 1970s in large part because the cost competitiveness of OTEC relative to fossil fuel combustion was low due to the relatively low prices of oil and other fuels and the large capital costs of OTEC. Several technological and deployment failures also impeded progress [6,14]. However, recent increases in fossil fuel costs and technological improvements to OTEC that promise to reduce costs and increase efficiency may be changing the economics of energy production in favor of OTEC.

Land-based OTEC plants appear to be most cost-effective where deep water is very close to shore. This is because a large fraction of the capital costs arises from the construction and emplacement of the pipes that bring deep seawater to the plant [15]. This limitation is being addressed through the development of cheaper, lighter, and more durable materials for the seawater pipes [16], improved emplacement methods [17], and new concepts for basing OTEC plants on ships that can access cold, deep seawater with a vertical pipe. These improvements have the potential to greatly broaden the applicability of OTEC.

Many efforts are now underway to increase the efficiency of OTEC energy production, including the use of new materials for heat exchangers [17,18] and novel ways to increase the temperature differential, e.g., by using waste heat from other industrial processes [19] or passive solar energy [16]. Efficiency gains may help broaden OTEC applicability by decreasing its dependence on strong natural temperature gradients.

In addition to these efforts to reduce OTEC costs and increase efficiency, efforts are also underway to increase the economic benefits associated with OTEC in order to attract financing and meet multiple social goals, and to reduce environmental risks. Pilot scale research has shown that OTEC can support a number of the secondary benefits mentioned above (freshwater production, air conditioning, refrigeration, and aquaculture) while still producing net power. It remains to be seen whether revenues and cost-savings associated with these services will offset or exceed the additional operating costs (including the acquisition of land to accommodate these additional facilities) that will be required. In some cases – for example, small island developing states or remote locations – shortages of energy, water, food, or refrigeration may make OTEC an appropriate technology even if profit margins are low.

While OTEC is sometimes touted as an energy technology that is virtually free of environmental impacts [20], few studies have been conducted to test this claim. Several potential impacts could arise from OTEC and other ocean energy technologies if they are not mitigated [21]. For example, OTEC requires large flows of deep seawater, which could result in the entrainment of large numbers of organisms and larvae with unknown effects on deep-sea ecological processes and biodiversity [21]. Transporting large volumes of seawater from depth to the surface may also transport carbon that had been trapped for relatively long periods of time in deepwater to the atmosphere as carbon dioxide; this effect is thought to be small; however, robust estimates have not yet been made [6]. Deep seawater is much richer in nutrients than are most surface waters [22,23] and many nearshore ecosystems are very sensitive to nutrient input, particularly in the tropics [24,25]; hence, discharge would be expected to cause eutrophication. Many tropical marine ecosystems are sensitive to temperature as well [24,25], and so coldwater discharge could result in coral bleaching and other severe impacts. Coral reefs and seagrass meadows, typical of nearshore tropical environments, are also sensitive to turbidity [26,27] and thus may well suffer from the discharge of deep seawater, which would be expected to be more turbid than the clear surface waters typical in these regions due to phytoplankton growth.

Adverse impacts of entrainment (and of measures, such as chlorination, required to keep pipe openings free of fouling organisms) may be difficult to prevent or mitigate since they will occur at depth. However, discharge of cold, nutrient-rich, seawater from OTEC plants can be avoided and is the key to generating the secondary benefits of aquaculture production, freshwater production, and refrigeration/air conditioning. By routing the cold seawater through facilities designed to yield these benefits, the water can be gradually warmed, perhaps to near-ambient levels. Moreover, the cultivation of macroalgae for human consumption and for agar and carrageenan production may be a viable and revenue-positive way of removing nutrients prior to discharge [28,29].

OTEC has the potential to provide energy free of air pollution (including greenhouse gas emissions), freshwater, seafood and algal products, and refrigeration/air condition at least in some areas of the world. These attributes make OTEC especially appealing to small island states facing water shortages, food shortages, and pollution associated with fossil fuel combustion. The World Energy Council reports that many countries, primarily small island developing states but also including India and Indonesia have expressed interest in OTEC [30]. While pilot scale OTEC plants have performed admirably, all attempts to move OTEC from the pilot scale to commercial scale have failed so far. Some have been hampered by technical problems, such as the failure of the cold water pipes [31]. Others have run into gaps in financing [6,31]. A pre-commercial OTEC plant, perhaps at the 5 MW scale, that takes advantage of recent technical improvements and financing from countries and firms participating in carbon offset programs, would provide valuable operations and economic data that could help overcome the technical, psychological, and financial impediments to OTEC commercialization.

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