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Relevance of Ocean Thermal Energy Conversion in Maritime Applications

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ABSTRACT

In the view of alarming carbon emissions and impending danger to marine life, it is high time to find alternate sources of energy. Ocean thermal Energy Conversion (OTEC) can be one such alternate form of energy source. In this paper, the background and future of OTEC is discussed in detail. The relevance of OTEC energy to marine applications, the advantages and challenges of this energy source is discussed exhaustively. The impact of OTEC energy on environment is also presented in this paper.

Keywords: Carnot Cycle, Rankine Cycle, Thermal Energy, Environment

I. INTRODUCTION

The trend towards using renewable and alternative energy sources on land has gathered momentum over the last decade to tackle the issues of pollution, energy security and climate change. However at sea, the shift towards the widespread adoption of alternative energy is only now beginning to take shape.

Over recent years the shipping industry has begun to seriously look at ways to reduce fossil fuel consumption and operate in a more environmentally friendly way. The concept of Green Shipping or Sustainable Shipping is now becoming an important issue for ship owners, shipping lines and ship builders globally [1][2].

The usage of alternate energy sources like solar power, wind power, Ocean thermal energy sources, fuel cells have many advantages like reduce of Co2 emissions, reduction of fuel consumption on-board ships, and to improve the efficiency and performance. OTEC, Ocean Thermal Energy Conversion is an energy technology that converts solar radiation to electric power. OTEC is a source, which uses the renewable solar collector the sea, instead of an artificial collector. This can in the future be an alternative to the nuclear power and the fossil fuels. OTEC systems use the ocean's natural thermal gradient. The OTEC process consist of pumping cold ocean water to the surface and using the temperature difference between this and the warm surface water to run a thermal engine to generate electricity[3][4].

Several techniques have been proposed to use this ocean thermal resource; however, at present it appears that only the closed cycle (CC-OTEC) and the open cycle (OC-OTEC) schemes have a solid foundation of theoretical as well as experimental work [5][6][7]. In the CC-OTEC system, warm surface seawater and cold seawater are used to vaporize and condense a working fluid, such as anhydrous ammonia, which drives a turbine-generator in a closed loop producing electricity.

In the OC-OTEC system seawater is flash-evaporated in a vacuum chamber. The resulting low-pressure steam is used to drive a turbine-generator. Cold seawater is used to condense the steam after it has passed through the turbine. The open-cycle can, therefore, be configured to produce desalinated water as well as electricity.

II. LITERATURE REVIEW

A. History of OTEC

It is estimated that, in an annual basis, the mount solar energy absorbed by the oceans is equivalent to at least 4000 times the amount presently consumed by humans. For an OTEC efficiency of 3 percent, in converting ocean thermal energy to electricity, we would need less than 1 percent of this renewable energy to satisfy all of our desires for energy. However, even assuming that the removal of such relatively small amount of ocean solar energy does not pose an adverse environmental impact we must first identify and develop the means to transform it to a useful form and to transport it to the user [8][9][10].

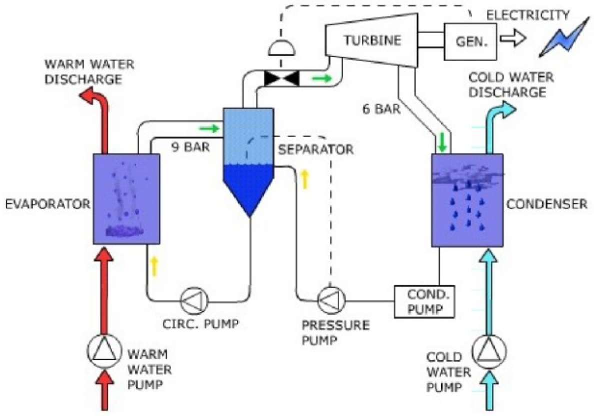

Figure 1 : OTEC schematic diagram

The first documented reference to the use of ocean temperature differences to produce electricity is found in Jules Verne's "Twenty Thousand Leagues Under the Sea" published in 1870 [11]. Eleven years after Jules Verne, D'Arsonval proposed to use the relatively warm (24 °C to 30 °C) surface water of the tropical oceans to vaporize pressurized ammonia through a heat exchanger (i.e., evaporator) and use the resulting vapour to drive a turbine-generator. The cold ocean water transported (up-welled) to the surface from 800 m to 1000 m depths, with temperatures ranging from 8 °C to 4 °C, would condense the ammonia vapor through another heat exchanger (i.e., condenser) [12][13][14].

His concept is grounded in the thermodynamic Rankine cycle used to study steam (vapor) power plants. Because the ammonia circulates in a closed loop, this concept has been named closed-cycle OTEC (CC-OTEC) [15].

Figure 2 : Mini OTEC (1979 model)

D'Arsonval's concept was demonstrated in 1979, when a small plant mounted on a barge off Hawaii (Mini-OTEC) produced 50 kW of gross power, with a net output of 18 kW. Subsequently, a 100 KW gross power, land-based plant was operated in the island nation of Nauru by a consortium of Japanese companies. These plants were operated for a few months to demonstrate the concept. They were too small to be scaled to commercial size systems [16][17].

Figure 3 : 210 KW OC- OTEC Experimental plant

B. Advantages of OTEC

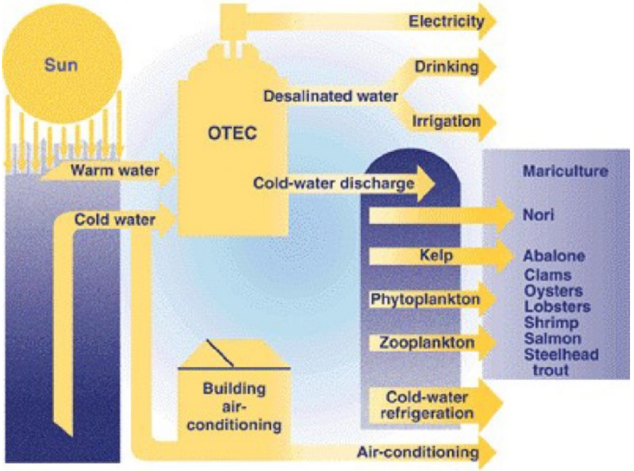

Figure 4: OTEC cycle

We can measure the value of an ocean thermal energy conversion (OTEC) plant and continued OTEC development by both its economic and no economic benefits. They are [18][19]

- Helps produce fuels such as hydrogen, ammonia, and methanol.
- Produces base load electrical energy
- Produces desalinated water for industrial, agricultural, and residential uses as shown in Figure 4.
- Is a resource for on-shore and near-shore Mari culture operations
- Provides air-conditioning for buildings
- Provides moderate-temperature refrigeration
- Has significant potential to provide clean, cost-effective electricity for the future.
- Fresh Water-- up to 5 liters for every 1000 liters of cold seawater.
- Food--Aquaculture products can be cultivated in discharge water.

OTEC's also have economic benefits, which help us achieve global environmental goals, include these:

- Promotes competitiveness and international trade
- Enhances energy independence and energy security
- Promotes international socio-political stability
- Has potential to mitigate greenhouse gas emissions resulting from burning fossil fuels.

In small island nations, the benefits of OTEC include self-sufficiency, minimal environmental impacts, and improved sanitation and nutrition, which result from the greater availability of desalinated water and Mari culture products [20][2].

III. IMPACT OF OTEC ON ENVIRONMENT

Though OTEC has many advantages to be chosen as an alternate energy source, it also has many limitations. Any change to the environment from an OTEC facility must be compliant with applicable regulations and authorities. This will most likely be determined through careful analysis of data and modeling to determine if the activities associated with constructing, installing, operating, maintaining, and decommissioning, and removing an OTEC facility impacts the environment beyond what is allowed by regulation.

In order to accomplish this, information needs associated with applicable regulations must be fulfilled to ensure a defensible assessment can be conducted. While there are numerous federal, state, and local regulations that apply to the construction, installation, operation, maintenance, decommissioning, and removal of an OTEC facility, this section focuses on those primary federal regulations that have been identified as having significant information needs. The absence of a specific regulation or authority in this section does not imply that it is not applicable, relevant, or important.

A. *National Environmental Policy Act*

The National Environmental Policy Act (NEPA) requires federal agencies to incorporate environmental values and ethics into the decision making processes by considering potential environmental impacts (both positive and negative) of their proposed federal actions and reasonable alternatives to those actions.

In order to satisfy NEPA requirements, federal agencies must thoroughly consider potential negative and positive direct and indirect impacts of any proposed federal action and prepare a detailed Environmental Assessment (EA) or Environmental Impact Statement (EIS) which attempts to determine the degree of impacts, including cumulative impacts, of any proposed federal action. EPA reviews and comments on EISs prepared by other federal agencies, maintains a national filing system for all EISs, and assures that its own actions comply with NEPA [22].

Due to the unique nature of OTEC, it is probable that a significant amount of new research and analysis and distillation of existing research would be required in order to develop the EIS. While NEPA was not separately addressed in the information gathering stage of this needs assessment, the information needs mentioned in this assessment will likely apply to the EIS. However, this does not preclude the possibility that information beyond what is addressed in this assessment would be required to develop a satisfactory EIS.

C. Clean Water Act

Water quality impairment and cooling water intake generally fall under the jurisdiction of the EPA and the Clean Water Act (CWA) sections 316(b), 402, and 403. Section 316(b) requires that the location, design, construction, and capacity of cooling water intake structures for facilities, including screening technology, reflect the best technology available for minimizing adverse environmental impact. As stated above, best professional judgment will be used in lieu of specific regulation standards.

For example, intake regulations that govern approach velocity were crafted primarily to protect the near-shore environment, but intake structures for an OTEC facility will be suspended far from the benthos. Should best professional judgment deem the impact acceptable, a higher approach velocity may be viable. In all cases, the goal is to not have unreasonable degradation of the water.

D. General Biota Information Needs

Impact to biota is a broad category that is applicable to numerous federal regulations, most notably the Endangered Species Act, the Marine Mammal Protection Act, the Magnuson-Stevens Fishery Conservation and Management Act, and the Migratory Bird Treaty Act. While these Acts are discussed separately later in this report, there are a number of general information needs that apply across many regions and organisms. While the extent of impact is not known, the physical presence, lighting, noise and EMF generated by the facility could disrupt sensitive species in the region.

The presence of the OTEC facility will likely act as a fish aggregating device (FAD), resulting in greater than normal abundance of species in the vicinity of the facility. Appendix B gives FAD location information throughout Hawaii. In addition, the presence of the cold water pipe will add a significant amount of surface area for colonization by filter feeders, potentially reducing the amount of suspended particulate matter, including eggs and larvae, in the vicinity of the facility.

Despite being shielded, high energy power cables have previously been shown to disrupt behavioral patterns of EMF- sensitive species, most notably members of the chondrichthyes class of fishes (i.e., sharks and rays).

E. Marine Mammal Protection Act

The Marine Mammal Protection Act (MMPA) places a moratorium on the “taking” of marine mammals, which is defined as harassing, hunting, capturing, killing or collecting, or attempting to harass, hunt, capture, kill or collect marine mammals. However, the MMPA allows for the authorization of the incidental taking of marine mammals that occurs during otherwise lawful activities with prior approval.

While it is unlikely that healthy marine mammals will become entrained or impinged, juvenile, sick, or injured individuals may become impinged, and alteration of the abundance or distribution of marine mammal prey species such as plankton may result in behavioural changes in marine mammals. In addition, most marine mammals are sensitive to noise.

The noise generated by the facility has the potential to result in significant behavioural changes in marine mammals, including disruption or alteration of migratory patterns and their presence in the region. Further, because sound is conducted very efficiently through water, the potential spatial impact will likely be significantly larger than other impacts. Appendix C states general acoustic thresholds (for non- explosive sounds) for use with the MMPA.

F. Endangered Species Act

The Endangered Species Act (ESA) requires federal agencies to ensure that any action that may affect threatened or endangered species that is authorized, funded, or carried out by them is not likely to jeopardize the continued existence of that species or destroy or adversely modify its critical habitat. It should be noted that many vulnerable species, most notably corals, were not listed as threatened or endangered at the time this document was prepared, but could be listed as threatened or endangered in the near future, and a common sense approach should be used to avoid impact to vulnerable species.

G. Essential Fish Habitat

The Magnuson-Stevens Fishery Conservation and Management Act (MSA) requires federal agencies to consult with NMFS if any actions authorized, funded, or undertaken by them could adversely affect essential fish habitat (EFH). An adverse effect means any impact that reduces the quality and/or the quantity of EFH. This includes direct or indirect physical, chemical, or biological alterations of the waters or substrate and loss of, or injury to, benthic organisms, prey species and their habitat, and other ecosystem components.

Areas that are deemed to be EFH Habitat Areas of Particular Concern (HAPC) are distinctly important due to the rarity of habitat, ecological function, susceptibility to human impacts, or the likelihood of development impacts. Designation as a HAPC results in greater scrutiny by NMFS and indicates that greater efforts should be made to protect the habitat. As Table 3 illustrates, the large extent of EFH and HAPC designations in the Hawaiian region make it likely any OTEC facility placed in the Hawaiian region has the potential to impact EFH or HAPC.

H. Migratory Bird Treaty Act

The Migratory Bird Treaty Act (MBTA) states that, unless permitted by regulation, it is unlawful to, or attempt to, pursue, hunt, shoot, kill, wound, capture, trap, collect, transport, or cause to be transported at any time, or in any manner, any migratory bird, nest, or egg of any such migratory bird. Note that a harassment condition is not associated with the MBTA as it is with the MMPA and ESA.

Adverse effects to EFH and HAPC may result from actions occurring within EFH or outside of EFH. The federal action agency must provide NMFS with an assessment of the action's impacts to EFH and HAPC (see Appendix D for help assessing impacts to EFH in the Hawaiian region), and NMFS provides the federal action agency with EFH conservation recommendations to avoid, minimize, mitigate, or otherwise offset those adverse effects. Federal agencies must provide a detailed written explanation to NMFS describing which recommendations, if any, it has not adopted. Impacts to EFH and HAPC could be direct (e.g., destruction of benthic or pelagic habitat

I. Fish and Wildlife Coordination Act

The Fish and Wildlife Coordination Act (FWCA) provides authority for the USFWS's involvement in evaluating impacts to fish and wildlife from proposed water resource development projects. It also requires federal agencies that construct, license, or permit water resource development projects to first consult with the USFWS (and NMFS in some instances) and state fish and wildlife agencies regarding the impacts on fish and wildlife resources and measures to mitigate any impacts

IV. CHALLENGES

A. Technical Challenges

The performance of OTEC power generating cycles is assessed with the same elementary concepts of thermodynamics used for conventional steam power plants. The major difference arises from the large quantities of warm and cold seawater required for heat transfer processes, resulting in the consumption of 20 to 30 percent of the power generated by the turbine-generator in the operation of pumps.

The power required to pump seawater is determined accounting for the pipe-fluid frictional losses and in the case of the cold seawater for the density head, i.e., gravitational energy due to the differences in density between the heavier (colder) water inside the pipe and the surrounding water column. The seawater temperature rise, due to frictional losses, is negligible for the designs presented herein. The ideal energy conversion for 26 °C and 4 °C warm and cold seawaters is 8 percent.

An actual OTEC plant will transfer heat irreversibly and produce entropy at various points in the cycle yielding an energy conversion of 3 to 4 percent. These values are small compared to efficiencies obtained for conventional power plants; however, OTEC uses a resource that is constantly renewed by the sun. Considering practical sizes for the cold water pipe OTEC is presently limited to sizes of no more than about 100 MW. In the case of the open-cycle, due to the low-pressure steam, the turbine is presently limited to sizes of no more than 2.5 MW.

The thermal performance of CC-OTEC and OC-OTEC is comparable. Floating vessels approaching the dimensions of supertankers, housing factories operated with OTEC-generated electricity, or transmitting the electricity to shore via submarine power cables have been conceptualized. Large diameter pipes suspended from these plant ships extending to depths of 1000 m are required to transport the deep ocean water to the heat exchangers on-board. The design and operation of these cold water pipes are major issues that have been resolved by researchers and engineers in the USA.

It has been determined that approximately 4 m 3 s-1 of warm seawater and 2 m3 s-1 of cold seawater (ratio of 2:1), with a nominal temperature difference of 20 °C, are required per MW of exportable or net electricity (net = gross - in-house usage). To keep the water pumping losses at about 20 to 30 percent of the gross power, an average speed of less than 2 m s -1 is considered for the seawater flowing through the pipes transporting the seawater resource to the OTEC power block. Therefore, a 100 MW plant would use 400 m3 s-1 of 26 °C water flowing through a 16 m inside diameter pipe extending to a depth of 20 m; and 200 m3 s-1 of 4 °C water flowing through an 11 m diameter pipe extending to depths of 1000 m. Using similar arguments, a 20 m diameter pipe is required for the mixed water return. To minimize the environmental impact due to the return of the processed water to the ocean (mostly changes in temperature), a discharge depth of 60 m is sufficient for most sites considered feasible, resulting in a pipe extending to depths of 60 m.

The amount of total world power that could be provided by OTEC must be balanced with the impact to the marine environment that might be caused by the relatively massive amounts of seawater required to operate OTEC plants.

The discharge water from a 100 MW plant would be equivalent to the nominal flow of the Colorado River into the Pacific Ocean (1/10 the Danube, or 1/30 the Mississippi, or 1/5 the Nile into the Atlantic). The discharge flow from 60,000 MW (0.6 percent of present world consumption) of OTEC plants would be equivalent to the combined discharge from all rivers flowing into the Atlantic and Pacific Oceans (361,000 m3 s-1).

Although river runoff composition is considerably different from the OTEC discharge, providing a significant amount of power to the world with OTEC might have an impact on the environment below the oceanic mixed layer and, therefore, could have long-term significance in the marine environment.

However, numerous countries throughout the world could use OTEC as a component of their energy equation with relatively minimal environmental impact. Tropical and subtropical island sites could be made independent of conventional fuels for the production of electricity and desalinated water by using plants of appropriate size. The larger question of OTEC as a significant provider of power for the world cannot be assessed, beyond the experimental plant stage, until some operational and environmental impact data is made available through the construction and operation of the pre-commercial plant mentioned above.

B. Engineering Challenges

The design and installation of a cost-effective pipe to transport large quantities of cold water to the surface (i.e., cold water pipe, CWP) presented an engineering challenge of significant magnitude complicated by a lack of evolutionary experience. This challenge was meet in the USA with a program relying on computer aided analytical studies integrated with laboratory and at-sea tests.

The greatest outcome achieved has been the design, fabrication, transportation, deployment and test at-sea of an instrumented 2.4 m diameter, 120 m long, fiberglass reinforced plastic (FRP) sandwich construction pipe attached to a barge. The data obtained was used to validate the design technology developed for pipes suspended from floating OTEC plants.

This type of pipe is recommended for floating OTEC plants. For land-based plants there is a validated design for high-density polyethylene pipes of diameter less than 1.6 m. In the case of larger diameter pipes offshore techniques used to deploy large segmented pipes made of steel, concrete or FRP are applicable. Pressurized pipes made of reinforced elastomeric fabrics (e.g., soft pipes), with pumps located at the cold water intake, seem to offer the most innovative alternative to conventional concepts. However, the operability of pumps in 800 m to 1000 m water depths over extended periods must be verified and the inspection, maintenance and repair (IM&R) constraints established before soft pipes can be used in practical designs.

Other components for OTEC floating plants that present engineering challenges are the position keeping system and the attachment of the submarine power cable to the floating plant. Deep ocean- mooring systems, designed for water depths of more than 1000 m, or dynamic positioning thrusters developed by the offshore industry can be used for position keeping. The warm water intake and the mixed return water also provide the momentum necessary to position the surface vessel. The offshore industry also provides the engineering and technological backgrounds required to design and install the riser for the submarine power cable.

The design of OTEC CWPs, mooring systems and the submarine power cable must take into consideration survivability loads as well as fatigue induced loads. The first kind is based on extreme environmental phenomena, with a relatively long return period, that might result in ultimate strength failure while the second kind might result in fatigue-induced failure through normal operations.

V. CONCLUSION

After extensive research by various organizations sufficient data is available that can be useful in the analysis of impacts from an OTEC facility, but in maritime scenario it is not specific enough to hold up to the scrutiny required for certain regulatory authorities. The overlying theme that emerged from the research was that the location of the facility will be a major driver of the magnitude and extent of any impacts and much of the information needs are associated with site-specific characterization of the presence, abundance, composition, diversity, distribution, and behavior of biological life, as well as the impact to water quality from water column disturbances. All data should be collected as close to the designated OTEC facility location as reasonably possible, as small variations may result in significantly different results. The duration and frequency of sampling should vary with the parameter and the expected confidence in the results.

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