ENVIRONMENTAL IMPACTS ASSOCIATED WITH OCEAN THERMAL ENERGY CONVERSION

Research Proposal

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More than one century ago French physicist Jacques Arsene d'Arsonval was the first to propose tapping the thermal energy of the ocean for producing useful energy. The relevant process was named Ocean Thermal Energy Conversion − OTEC. Surface and deep water of the ocean, which have different temperatures, can be used as a heat source and a heat sink in a thermal engine ruled by the Carnot principle. The first plant, that demonstrated the process feasibility and permitted assessing the engineering problems and financial risks stemming from its implementation, was constructed in 1930. The background of setting up diverse facilities on the basis of OTEC in different countries is provided. It is emphasized that in recent decade many countries abandoned their activities aimed at OTEC development. The USA and Japan can be mentioned as the exception, as both countries continued research in OTEC, their efforts being aimed at expansion of possible applications for deep ocean water, besides improving the OTEC processes and studying their potential impacts on the environment. OTEC impact will essentially consist of massive seawater intakes and effluent discharge, the latter having a temperature and composition a priori different from ambient values. The magnitude of this impact will mostly depend on the scale of OTEC operations (overall power generation capacity), on the spatial distribution of power plants and on the effluent discharge strategy.

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The "Club des Argonautes" is a small group of retired scientists and engineers who happened to work with French public institutions such as IRD, IFREMER, Météo France, CNES, CNRS, and MNHN

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Introduction

Ocean Thermal Energy Conversion (OTEC) has recently received renewed attention as the search for renewable, clean energies capable of replacing costlier fossil fuels has intensified. The most accessible reserves of oil, coal and natural gas have actually started to decline. Stored as heat in the surface layer of tropical oceans, solar energy can be partially converted into mechanical and electrical power by utilizing the existing thermal stratification between warm surface water and cold deep water.

The conversion process, conceived by the end of the 19th Century and tested in the 1930s, uses warm surface water and cold deep water to respectively feed an evaporator and a condenser on either side of a turbomachine operating on a so-called Rankine cycle. Operational parameters are well adapted to the small vertical temperature differences, of the order of 20 ºC, that are available in the warmest regions of the tropical oceans. Small temperature differences, however, lead to low process efficiency. Consequently, large seawater flow rates are required, of the order of several cubic meters per second per net megawatt generated. Typically, this seawater intensity would be 5 $m^3s^{-1}MW^{-1}$ and 2.5 $m^3s^{-1}MW^{-1}$ for warm and cold water, respectively (Nihous [1], 2005).

It follows that the impact of OTEC on the ocean environment will essentially consist of massive seawater intakes and effluent discharge, the latter having a temperature and composition a priori different from ambient values. The magnitude of this impact will mostly depend on the scale of OTEC operations (overall power generation capacity), on the spatial distribution of power plants and on the effluent discharge strategy. In the latter case, multiple choices are available and environmental responses will vary according to the depth at which effluents (from evaporator and condenser) are released, mixed or not. It is therefore critical to carefully evaluate impacts from OTEC seawater intakes and effluent discharge under various scenarios in order to simultaneously optimize OTEC power production and minimize its potential disruption of the ocean environment.

Such studies concern the global impact of future intensive OTEC exploitation. They are different from those necessary to evaluate the local impact of any OTEC plant construction.

Optimization itself could be based on different metrics according to possibly different objectives: e.g. to maximize power production, or to promote biological production from the artificial upwellings generated by the discharge of nutrient-rich OTEC effluents into the photic layer.

The importance of upwellings on the marine ecosystem

Natural upwellings are produced by wind stress over the ocean under certain conditions that favor a divergence of surface waters (proximity of a coastline or of the Equator). This locally induces the upward motion of deeper, colder nutrient-rich waters toward the surface.

Upwellings play an important role in the global energy balance of the ocean and of the Earth. In tropical regions, they allow an accumulation of heat that is later transferred to higher latitudes by major currents (Gulf Stream in the Atlantic and Kuro Shiyo in the Pacific). They also strongly mediate interactions between the ocean and the atmosphere by inducing meteo-oceanic oscillations that affect climate across the entire tropical belt, such as the phenomenon known for centuries as El Niño (ENSO).

Wherever they occur, upwellings boost biological productivity as well. The high nutrient concentrations generally found in deeper waters are advected upward into the photic layer where photosynthesis is promoted. This increase in primary productivity benefits the entire food chain. In certain cases (cf. below), artificial upwellings related to OTEC operations could contribute to a local increase in primary production. While seemingly positive, the consequences of such biological effects should be assessed from a long-term perspective involving multiple trophic levels.

In view of the foregoing, potential impacts of artificial anthropogenic perturbations of the thermal and chemical structures of the ocean upon ocean dynamics itself, atmospheric dynamics and marine biological processes must be evaluated carefully in the context of an ultimate and massive deployment of OTEC plants within tropical regions. Thresholds could exist beyond which such perturbations could permanently alter oceanic circulation and, possibly, atmospheric circulation as well. This could substantially constrain the acceptable scale of OTEC-related perturbations upon the environment. Such thresholds should be assessed as precisely as possible.

Problem fundamentals: energy needs and OTEC potential

World annual electric consumption in 2001 reached 15500 TW·h. It could rise to 36000 TW·h by 2040 (EREC scenario [2] to 2040). This future demand typically would be met with a total power-plant installed capacity of 5 TW (assuming a capacity factor of 80 %).

What is the theoretical amount of ocean energy that could be converted toward such a target?

Solar radiation absorbed by the oceans corresponds to an overall mean flux of 52 PW (Huang [3], 2004). References from the technical literature suggest that it should be possible to extract 10 TW of OTEC resources in a 60 million km^2 region where temperature differences between the ocean surface and a water depth of 1000 m exceed 22 ºC (Avery [4], 1994). These estimates are obviously theoretical and most likely beyond practical limits.

Beyond a strictly thermal consideration of the problem, another important limiting factor in the deployment of OTEC technologies consists of the magnitude of the process flow rates. All natural upwellings, for the most part located in the intertropical region, amount to about 30 Sverdrups (Sv). This is a flow rate equivalent to the downwelling of deep and bottom waters in the Arctic and Antarctic convective zones, so that a meridional thermohaline circulation is maintained to keep the overall system's balance as we know it today. Any perturbation of the mechanisms related to this ocean circulation, for example from artificially upwelled deep water, intuitively should remain much smaller than this background flow rate, lest the overall ocean circulation change substantially. One should keep in mind (Nihous, 2005) that the net production of 1 GW by OTEC plants would require the pumping of 2500 m^3/s of deep water (that is 25 Sv for 10 TW, a theoretical value of the same order as the magnitude of natural upwellings). In truth, even with a rapid expansion of OTEC operations, for example with 5000 plants rated at 100 MW generating 10 % of the predicted electrical power demand in 2040, the corresponding deep water flow rate would not exceed 1.25 Sv. The primary goal of this study would be the definition of optimized scenarios and the identification of potential thresholds.

Potential OTEC resource limits

At face value, a theoretical OTEC potential of 10 TW would represent an electrical power generation capacity twice as large as that predictably needed by mankind in 2040 (5 TW). This amounts to a significantly large value, but it does not take into account a number of limiting factors arising from technical difficulties, physical and geographic constraints, and environmental concerns which undoubtedly would reduce the exploitable OTEC resource. Political issues, such as a nation's sovereignty over its EEZ, are susceptible of imposing further constraints.

The exploitation of OTEC resources will therefore necessitate hard choices based on technical, economic and political parameters. Such choices will in turn influence the nature and magnitude of the environmental impacts which represent the object of this research proposal. For example, OTEC plants and their artificial upwellings located in the warm western most margins of the inter-tropical zone, where OTEC temperature differences are the most favorable, will not cause the same effects on ocean dynamics and climate as OTEC plants sited in the easternmost regions where natural upwellings occur.

Environmental impact also will depend on the selected method of effluent discharge: should effluents be mixed or not before being released into the ambient water column? at what depth(s) should the discharge take place? What are the time scales of the perturbations of the oceanic thermal structure induced by OTEC itself?

Some of these questions recently were tackled with very simplified simulations (Nihous, 2005; Nihous, 2006) that show the likely existence of a limit for exploitable OTEC resources beyond which a degradation of the oceanic thermal structure may take place. In order to sustain OTEC operations, it is necessary to preserve a sufficient vertical thermal gradient. The upper bound of sustainable OTEC power generation may be as low as 3 TW.

Beside such theoretical limits, the effects of OTEC seawater streams on the coupled dynamic behavior of the ocean, the lower atmosphere and marine biota clearly must be assessed in order to be able to quantify OTEC impacts and to determine thresholds beyond which these impacts would become unacceptable. This is the object of this research project**.**

Research project objectives

Many environmental issues arise from a prospective deployment of OTEC technologies, the more so as effluent discharge options may vary with different targeted outputs.

For a given design configuration, the following questions should be addressed:

a) How will ocean dynamics adapt to a perturbation of the oceanic thermal structure?

b) What effects perturbations of the ocean surface temperature and the onset of an artificial heat sink may have on the atmosphere and its dynamics?

c) How can marine biota respond to nutrient enrichment and different temperatures?

These questions give rise to research priorities which can be articulated along three axes, with a definite dependence on the selected effluent discharge option:

1. Study of the perturbations of the thermal structure of the ocean and of the dynamic response of the ocean as a result of OTEC operations.
2. Study of the coupling of thermal and dynamic oceanic perturbations with atmospheric behavior.
3. Study of the impact of artificial nutrient enrichment in the photic zone on the marine ecosystem.

These three research areas involve modeling as a necessary simulation tool for scenarios that cannot be tested in the field.

Boundary conditions for the proposed studies

OTEC operations rely on the existence of sustained vertical temperature differences through the water column, and therefore on elevated surface temperatures generally found in inter-tropical areas, but more precisely toward western boundaries.

A priori, one will only consider regions where temperature differences between surface and deep waters exceed 20 ºC, i.e. approximately between latitudes 20º N and 20º S. Among possible strategies to better define this OTEC zone, one could fix the deep-seawater withdrawal depth at 1000 m; this choice reflects a realistic evaluation of current and short-term technological capabilities in ocean engineering. Generally speaking, one will strive to select parameters consistently in order to facilitate the comparison of results among peers involved in this research field.

Possible tools

A) Computer simulations of the thermal and dynamic perturbations of the ocean will be performed with Ocean General Circulation Models (OGCMs) run in a predictive mode. At first, it won't be necessary to resort to high-resolution versions of these models. A horizontal mesh size of 1 to 2 degrees will help trim down the problem by allowing multiple cost-effective simulations for a few standard scenarios corresponding to an increasing overall OTEC production as a function of time. The number of power plants, their positions and rated capacity would all be input parameters.

B) The coupled effects of oceanic perturbations on the atmosphere could be studied with models currently used for seasonal forecasts. Coupled OGCM/AGCM models which deal with ENSO predictions would be a tool of choice to test the impact of artificial upwellings on ENSO dynamics along the Pacific tropical belt (regions dotted with islands where preliminary tests of OTEC plants have been performed or are under consideration).

C) The coupling between biological models and ocean-atmosphere physical models has been a strong developmental focus for many research teams. Experimental models already exist, soon to be replaced by operational models. The study of the ocean's capacity to increase its biological productivity in response to nutrient-rich upwellings is a topic of current interest that recently prompted international panel of experts to draft a specific resolution (Bergen Declaration [5]).

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