NEW SYSTEMS IN OCEAN THERMAL ENERGY CONVERSION

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BACKGROUND

Ocean thermal energy conversion (OTEC) is an idea of the nineteenth century which was proven to work in the twentieth century and will likely become a significant reality of the twenty-first century. Jaques-Ars`ene d'Arsonval realized in 1881 that the same thermal gradient that over several thousand kilometers horizontally powers the global weather is also available over only one kilometer vertically in the tropical ocean (D'Arsonval, 1881). His former student, Georges Claude, gave engineering expression to OTEC with an installation in Cuba in 1930 and another in 1935 off Brazil (Claude, 1930). Both projects had to be abandoned because of difficulties with the cold water supply pipe. In the mean time global electrification and transportation systems had become thoroughly established on the basis of fossil fuels. Not until the 1970's did the limitations of this degree of dependence on fossil fuels start to become obvious. These limitations are now manifesting themselves in international conflicts, in economic uncertainties, in limitations of supply, and especially in environmental consequences.

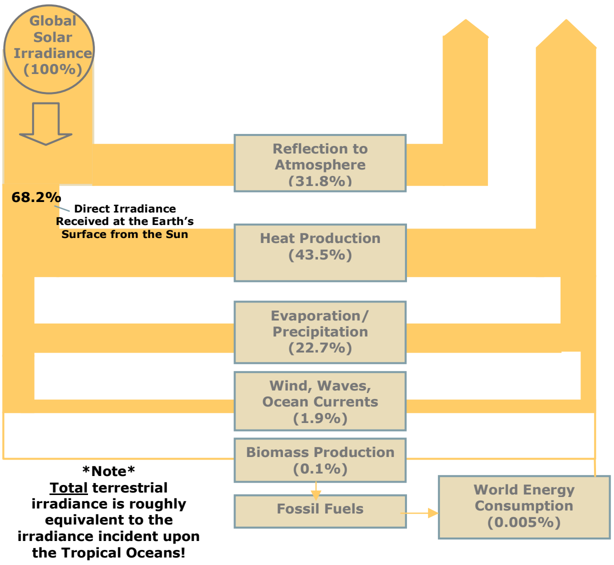
Since the "oil crisis" of the 1970's there has been a significant effort in the industrial countries of the world to find a renewable substitute for fossil fuel. Hawaii became the center of the effort in the United States to update ideas of D'Arsonval and the design of Claude with respect to developing a practical OTEC plant. By the end of the 1980's this effort had succeeded in; demonstrating net power production using a closed cycle OTEC plant, solving the biofouling problem, reliably deploying both down-slope and vertical cold seawater supply pipes, and identifying a number of other products (besides electricity) that could be commercially viable as part of an OTEC 'system'. This research and development effort in Hawaii included participation by the US Department of Energy (DoE), two federal laboratories (Argonne and SERI), several agencies of the State of Hawaii, the Natural Energy Laboratory of Hawaii Authority (NELHA), the Pacific Center for High Technology Research (PICHTR), the University of Hawaii, the University of California at Berkeley, and several private companies (notably Westinghouse and Lockheed). The several meters of book shelf space worth of reports, articles and other publications from this effort clearly demonstrated the technical feasibility of OTEC.

Many of the key points of the Hawaii based experience are included in the book written by William Avery of Johns Hopkins University and Chih Wu of the United States Navel Academy titled 'Renewable Energy From The Ocean – a guide to OTEC', published by Oxford University Press in 1994 (Avery, 1994). This book also includes the significant contributions by OTEC researchers throughout the world and describes several realistic plant designs. Notably, these designs include a 40 to 50 MW closed cycle OTEC plant for Kahe Point on Oahu and a series of 500 MW floating OTEC plants (proposed by Lockheed) to produce liquid hydrogen to be used as transportation fuel in California. These projects were not realized primarily because the economic conditions at that time were not favorable to such capital intensive projects and the price of oil had come down significantly from the high levels of the late 1970's. An economic evaluation (Huang, 1991) conducted by PICHTR and the Hawaii Natural Energy Institute (HNEI) of the University of Hawaii at that time concluded that OTEC, although technically feasible, was not likely to ever be economically viable. This evaluation used an interest rate of 10 to 15% for the capital of the OTEC plant and compared the project cost to an oil fired plant using oil at $11 to $13 per barrel. Largely as a result of this negative economic evaluation further funding for OTEC related research and development in the United States ceased.

In Hawaii only the author and his students, along with a few colleagues elsewhere, continued to work on developing practical and economical OTEC systems. This presentation will outline the new OTEC systems designs that have resulted from this work and place these systems in the context of present economic and environmental conditions.

ENVIRONMENTAL CHANGES

The amount of solar energy that flows through the earth's atmosphere and ocean is around 20,000 times greater than all the energy flow used by human societies. As shown in Figure 1, most of the incoming solar energy first gets absorbed by the upper layer of the ocean and is stored there in the form of heat and then gets redistributed through the hydrologic cycle and the global weather engine by thermal gradients. Prior to the industrial revolution the outward flow of energy from the earth's atmosphere very closely matched the incoming solar energy and the world was approximately in thermal equilibrium. Changes in climate were due to such generally slow natural phenomena as orbital variation, variations in solar output, tectonic processes, large scale volcanism and releases of methane hydrates from deep ocean reservoirs. As indicated by the observation that seven of the ten warmest years on record occurred in the last ten years, the present rate of global climate change is very rapid. Indicated in Figure 2 are the major influences, both negative and positive, on the flow of energy through the earth's atmosphere. It is clear that many of these influences are anthropogenic and are primarily related to our growing use of fossil fuels.



Note
Total terrestrial irradiance is roughly equivalent to the irradiance incident upon the Tropical Oceans!

Figure 1: Solar Energy Flux

The best record of the carbon dioxide content of the atmosphere in the northern hemisphere is from the island of Hawaii (Figure 3). This record shows that the present CO_2 content is about 375 ppm, or around a third higher than the pre-industrial revolution value of 280 ppm. Global carbon budgets have indicated that the atmosphere should have an even higher CO_2 concentration and there has been much speculation regarding the 'missing carbon'. Comparative measurements of gas exchange rates in seawater and fresh water made in the mid 1980's by my students and I at the University of Hawaii indicate that gases exchange about 20% more rapidly in and out of seawater (Krock, 1989). This observation was used to design more efficient open-cycle OTEC plants and fresh water production processes. It also indicates that the sink for the 'missing carbon' is the surface layer of the ocean. Additionally, this indicates that the greater CO_2 content of the ocean surface layer, especially in the tropical zone, leads to a lower pH. This greater acidification is the probable cause of the recently documented widespread damage to coral reefs.

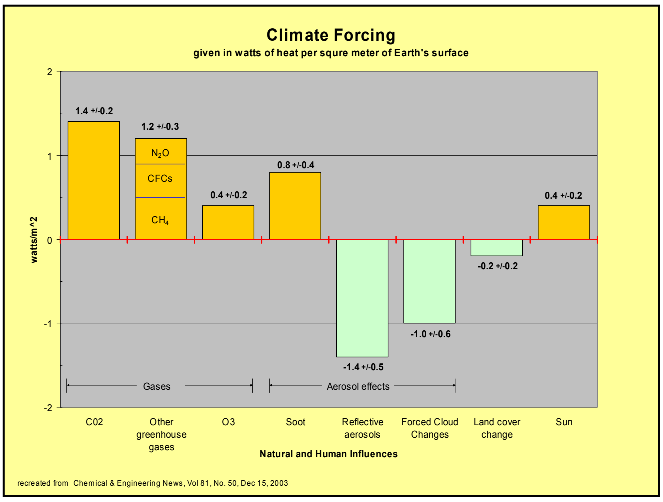


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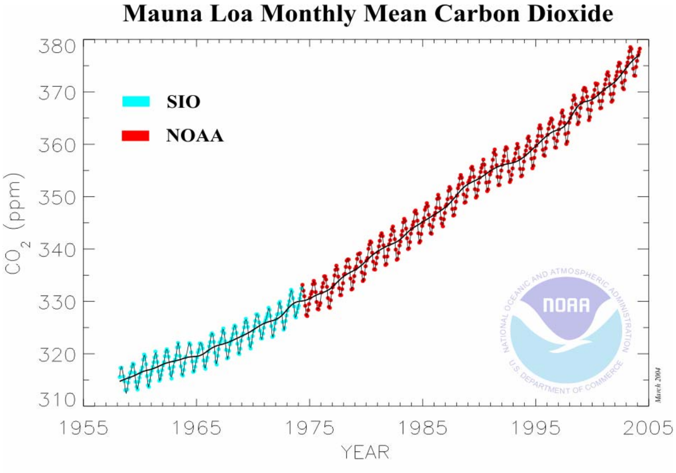
Figure 2: Global Warming - Cooling Factors

Although global warming observations are most often reported as changes in the temperature of the lower atmosphere the temperature of the ocean is a more significant indicator because of the much larger heat capacity of water. There is as yet no consensus on the average temperature rise in the ocean surface layer. The deep ocean appears not to have changed in temperature likely because its response time is in units of several centuries rather than several years. A rough approximation of the amount of the surface layer temperature change can be obtained by comparing reliable historical data with contemporary data. Such a comparison was part of an evaluation of the OTEC potential in the vicinity of Cape Verde in the tropical Atlantic. The average surface temperature of this part of the ocean measured by the German Atlantic expedition of the research vessel Meteor in 1925-1927 was about 0.6 degrees C cooler than that measured by NOAA in the 1990's. This means that the *extra* heat stored in the tropical ocean surface layer due to global warming over the last 70 years or so is enough to supply all of human society's energy



Atmospheric carbon dioxide monthly mean mixing ratios. Data prior to May 1974 are from the Scripps Institution of Oceanography (SIO, blue), data since May 1974 are from the National Oceanic and Atmospheric Administration (NOAA, red). A long-term trend curve is fitted to the monthly mean values. Principal investigators: Dr. Pieter Tans, NOAA CMDL Carbon Cycle Greenhouse Gases, Boulder, Colorado, (303) 497-6678, pieter.tans@noaa.gov, and Dr. Charles D. Keeling, SIO, La Jolla, California, (616) 534-6001, cdkeeling@ucsd.edu.

Figure 3: CO2 Concentration

needs for several hundred years. There is every indication that global warming will continue to add heat energy to the ocean through this century. The development of large scale OTEC systems takes advantage of this large energy resource while replacing the fossil fuel based system that causes the imbalance.

OTEC taps directly into the only energy resource that is large enough to replace fossil fuel. This energy resource is not intermittent so OTEC systems can be designed to operate at near 100 % capacity all the time.

ECONOMIC CHANGES

Current economic conditions are generally favorable for OTEC systems in that interest rates are low and oil prices are relatively high. The best way to evaluate the relative economics of alternative projects is on a total project basis over the useful life of the project. This means including both the initial construction costs as well as the projected operation and maintenance costs over the next 20 to 30 years. For multi-product OTEC systems it also means including the projected revenue streams for electricity, fresh water, air conditioning, and other products. A historical analogy of this type of economics is found in comparing a hydroelectric dam project with a fossil fuel fired generating station. The initial cost of the dam project is much higher than that of the fossil fuel fired generating station but the operation and maintenance costs are much lower- primarily because the fuel is ‘free’. The dam project might also have a revenue stream from the sale of water. Experience has shown that electricity rates from hydroelectric generation are lower than from fossil fuel generation. The rates are also steadier from hydroelectric generation because they do not depend on the vagaries of the price of oil. The economics of OTEC systems are similar to those of hydroelectric projects. This analogy does not carry over to environmental impacts in that OTEC systems do not significantly change their immediate environment.

A major economic aspect of the present fossil fuel based energy system is the balance of payment problem for oil and gas importing countries. This problem could be solved if each country produced its own energy supply. Such a scenario is possible using large scale floating OTEC hydrogen production platforms located on the high seas outside of any country’s 200 nm exclusive economic zone (EEZ). Even countries that are landlocked, such as Switzerland, or countries with no significant EEZ in the tropical zone, such as China, could deploy under their own flag OTEC-LH_2 production platforms on the tropical high seas and supply their own energy needs in perpetuity. The ocean thermal energy resource is large enough to support the global demand thereby freeing the remaining oil and natural gas resource for the longer term purpose to supply valuable materials (plastics) for future generations. Countries that presently have deep ocean production platforms for oil and gas in their tropical zone EEZ, such as the United States, could convert these platforms to OTEC-LH_2 production when the oil runs out.

There is presently no generally accepted method for calculating the economic benefits that would flow from a large scale switch from fossil fuel to OTEC-LH_2. However, the general elimination of most air pollution, a reduction in and eventual reversal of the anthropogenic greenhouse effect, a significant reduction in oil spills, a reduction in conflicts over limited energy resources, more stable economic systems, a significant increase in marine construction and related job and wealth creation, all point to substantial economic benefits for the world.

TROPICAL ISLAND BASED MULTI-PRODUCT OTEC SYSTEMS

Since the early 1990's, when the last significant economic analysis of OTEC was conducted, there have been several relevant technical and engineering advances in the field. These advances include:

- The successful design, construction and operation of an open-cycle OTEC pilot plant at NELHA which produced net base load power and potable fresh water. (PICHTR)
- The solution to the non-condensable gas problem in open-cycle OTEC Systems and other fresh water production plants. (OCEES)
- The successful deployments of deep cold water supply pipes. (Makai OE)
- The development and commercial application of the Kalina cycle for low Delta T applications. (Recurrent Resources)
- The design of a 1 MW turbine for open-cycle OTEC application. (ALSTOM Sweden)
- The design of reliable honeycomb concrete marine structures. (Al Yee & Assoc.)
- Systems engineering for optimizing multi-product OTEC applications. (OCEES)
- Commercial aquaculture related to cold seawater. (NELHA)
- Development of cold seawater agriculture. (Common Heritage)
- Deep ocean oil and gas production platforms. (The oil industry)
- LNG infrastructure and LH_2 tankers. (The gas industry)
- Hydrogen powered vehicles. (The auto industry)

Recently the US Navy sponsored a project to develop a computer program to optimize the design of multi-product OTEC systems for tropical island applications. This was successfully done by OCEES International, Inc. and applied to several candidate locations in the Pacific and Indian oceans. The program required mathematically describing several of the technologies listed above with respect to processes and design and site specific economic factors. The possible products from an OTEC system were divided in primary and secondary categories as illustrated in Figure 4. Primary products were those with interactive design parameters. It should be noted that all components and processes included in the model are proven technology – some with several years of commercial application.

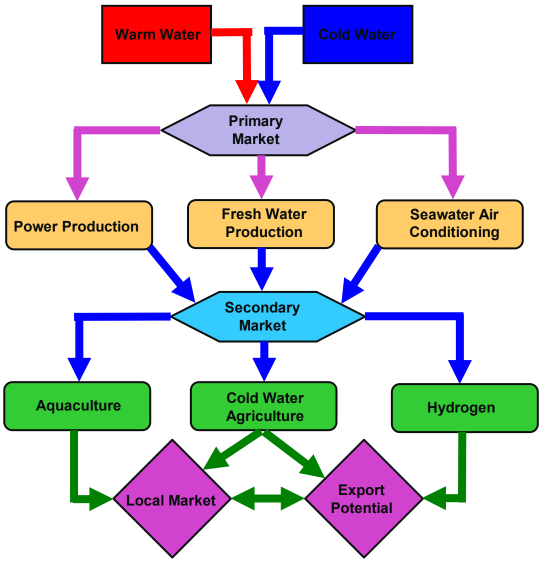


Figure 4: NOTEVAL Model Structure

The first application of this process is the preliminary design for an OTEC system for the US Navy base on Diego Garcia BIOT. This OTEC system will supply base load electric power, potable water and chilled water air conditioning at an expected overall saving of about 30% in comparison to the present fossil fuel based system. A sketch of the floating OTEC system being considered is shown in Figure 5.

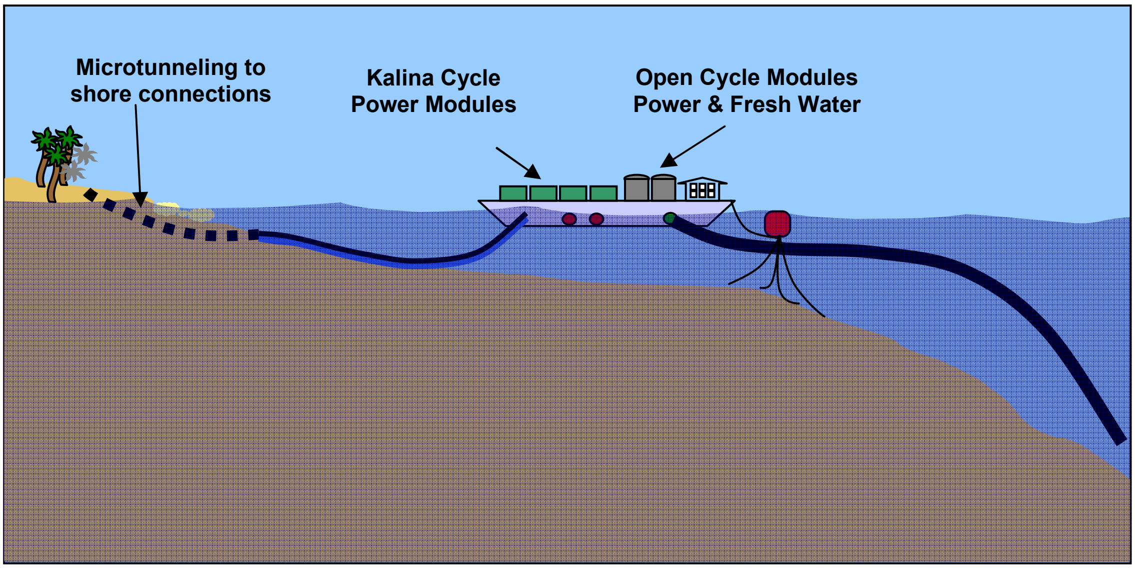


Figure 5: Diego Garcia OTEC

The design approach used by OCEES and the other companies involved puts emphasis on the ocean engineering aspects of the project. This is because all past failures related to OTEC have been in the area of interaction with the ocean.

It is expected that after the initial successful applications at selected tropical island locations with optimum physical and economic conditions the multi-product OTEC system approach will become more generally available to most tropical island communities. The advantages of self sufficiency using locally available resources will be readily apparent.

LARGE SCALE OTEC-LH$_2$ PRODUCTION PLATFORMS

Most of the tropical ocean thermal resource is located in the open ocean far from land (Figure 6). The most likely storage and transport medium for the energy produced from this vast resource is liquid hydrogen. All of the technologies required to establish this approach to future energy production exist. Some, notably the cold water supply line, will require upscaling. This is a do-able engineering design problem not to be confused with a fundamental science question such as, for example, the reliable

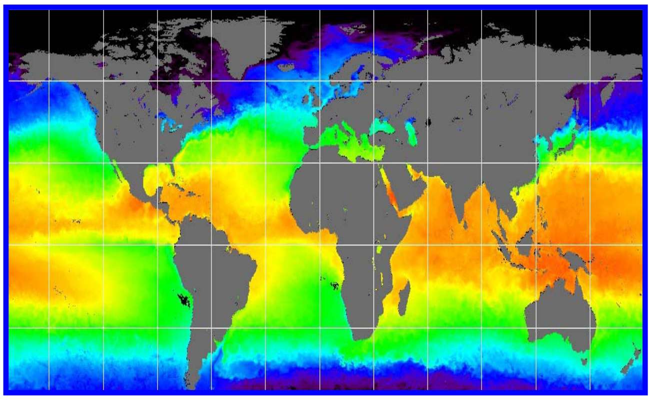


Figure 6: Ocean Surface Temperature Map

containment of a fusion reaction.

There have recently been significant advances in the design of large floating platforms. The potential uses for such platforms in the tropical zone could include: product processing from fisheries and aquaculture, satellite launching facilities, fuel production and fuel depot for ships, manganese nodule or crust mining and processing facilities, and OTEC-LH_2 production, storage and trans-shipping. All of these types of platforms can be powered by OTEC. Additionally, fresh water can be produced and cold seawater air conditioning can be supplied to support both the commercial activities and the personnel.

Deep offshore oil platforms in the tropical zone, for example in the Gulf of Mexico, are designed to withstand hurricane conditions. Recent experience with hurricane Ivan showed that these designs have been generally successful but that improvements can still be made. The frequency of hurricanes is very low in the immediate vicinity of the equator making this the best place to deploy OTEC-LH_2 production platforms and other similar platforms.

Large scale use of the tropical ocean heat reservoir will eventually require several thousand large floating platforms. This will mean a significant increase in the marine construction industry and in the development of LH_2 storage and distribution infrastructure. Presently there is a lot of activity related to the expansion of LNG related facilities globally. These LNG facilities can in the future be modified to handle LH_2.

It is clear that switching from one type of energy system to another takes both time and investment. It can be done smoothly with good planning and cause minimal disruption.

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