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OTEC: A Clean Energy Whose Time Has Come

Introduction

In Madrid in November last year, the governments of more than 90 nations agreed that man-made global warming was already underway. Although sceptics (mainly groups and nations with a stake in the fossil fuel business) still claim the available evidence is inconclusive, the majority of the world's policy makers and scientific community now accept that increasing concentrations of carbon dioxide and other greenhouse gases in the atmosphere have resulted in an accelerated temperature rise of a degree not seen in more than 10,000 years. But like an alcoholic diagnosed with a terminal illness, the world's nations seem unable to mend their ways. This is perhaps even more true of the booming economies of developing Asia (notably China and India) who are excluded from a plan by the developed economies to stabilise carbon emissions at 1990 levels by the year 2000. It would appear that now, more than any time in history, would be an appropriate time for renewable energies to be taken seriously as a major source of energy and for long term investment. Of course the catch, as it has been in the past, is the lack of short term economic motives to invest on a large scale in appropriate renewable energy technology and applications. This is generally true throughout the world as the price of oil remains fairly stable with no significant price rises likely in the near future. An economic case can, however, be made for the development of renewable energy in certain countries where a combination of physical conditions and government policy make some forms economically feasible. Leading the field in the past have been solar, wind and biomass energy sources.

Although generally not familiar to the layman, OTEC (or *Ocean Thermal Energy Conversion*) has been hyped at various times as a source of limitless, cheap and clean energy. A NASA report published in 1972[1] predicted that by using OTEC to tap the thermal energy of the Gulf Stream, the electricity needs of the US could be provided for. However,

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despite over one hundred years of research and development activity around the world, OTEC has not yet been commercialised. At first glance, the technology appears almost deceptively simple and of massive potential. Beneath this simplicity lies engineering and economic hurdles that need to be addressed before OTEC will be available as a viable energy source. This article looks at the state of the technology today, recent OTEC developments and the potential for OTEC in the future, notably in crucial energy markets of the developing nations of Asia: India, Indonesia and the Philippines.

A Brief History and Background to OTEC

The theoretical basis of OTEC as a source of energy lies in the thermal energy stored in the earth's water as a result of solar heating. About a fourth of the 1.7×10^{17} watts of solar energy reaching the earth's surface is absorbed by the oceans and seas. This solar radiation does not distribute itself evenly within the water, but rather, is concentrated in the surface layer of about 100 metres. There is thus a temperature difference between the upper and sub-surface layers of the ocean, from which useful energy can theoretically be extracted using a simple heat pump. This is the basis upon which French Physicist and inventor of OTEC *Arsene d'Arsonval* began his research in the late nineteenth century. The first to attempt to put d'Arsonval's ideas into practice was by one of his students, *George Claude*, who conducted a series of experiments in the 1920s and 30s. Claude constructed a 22 kW open cycle on-shore OTEC plant in Mantanzas Bay, Cuba in 1930. The plant did not succeed in generating net power and suffered from poor site selection and engineering difficulties. Subsequent to the widespread exploitation of crude oil in the Mideast and other areas, world-wide interest and investment in OTEC (and other renewable energies) remained dormant. The next significant activity also originated in France, in 1956. The interest this time came from within the French government, which produced a number of designs and a feasibility study for OTEC plants in various locations. Cold water pipe deployment tests were carried out in the Ivory Coast for the construction of a 3MW plant, but a lack of financing meant the project did not get beyond the design stage The next attempt to develop OTEC was made by *Hilbert Anderson*, a American engineer who formed a company (*Sea*

Solar Power) specifically to promote OTEC, and began a series of design and feasibility studies. Most of Anderson's work centred around the construction of off-shore closed cycle OTEC plant designed to produce 100MW of power and utilising a cold water pipe of length up to 1200 metres. In the early 1970s, two trends combined to greatly increase the level of interest in OTEC and other renewable energies. In 1973, the OPEC countries trebled the price of oil overnight, causing a sudden surge of interest in alternative energy sources. In addition, public and government awareness of the environment was beginning to emerge as a real issue. Interest in OTEC in the US was coming from government departments, academic institutions and corporations such as *Carnegie Mellon University and* the *Universities of Massachusetts, Texas* and *Hawaii.* The US government first began to fund research into OTEC in 1972, when the *National Science Foundation* allocated $84,000 to various institutions. By 1977, this had been raised to the not insignificant sum of $36mn, provided by Department of Energy's newly created *Energy Research and Development Administration.* Much of the money was given to large US corporations (such as *Lockheed, Westinghouse, Bechtel*), who provided designs for plants and components for OTEC systems. The prevailing thinking in the early 1970s was that floating platform based plants would be the most feasible, and a great deal of time and money was spent trying to overcome the problem of the stability of the suspended cold water pipe of length up to 1500 metres. Government-sponsored and private research into the feasibility of OTEC resulted in the construction of two experimental OTEC plants, both in Hawaii. In 1980 the US government passed the *Ocean Thermal Energy Conversion Act* during the Carter Administration, which made both commercial and experimental OTEC plants eligible for government funding and simplified the patent procedures for OTEC applications. The Act also established goals of achieving a 100MW OTEC plant by 1986 and a 10,000MW plant by 2000. Following the change in administration, these goals were modified and set at constructing a 40MW on shore closed cycle plant in Hawaii. The design work was carried out but not implemented due to a lack of funding. During the 1980s the level of activity in the US was reduced, reflecting the government policy of non-intervention in industry. Without this crucial support, OTEC became little more than a interesting "pipe dream" for the companies and individuals who had been active in the 1970s. Activity and interest in OTEC in Asia has been restricted largely to Japan and Taiwan. In 1973 Japan relied on Mideast oil for 90% of its energy needs and was thus profoundly affected by the oil crisis. The Japanese government responded by launching the *Sunshine Project* to promote and develop renewable energy. This project included OTEC and was managed by the *Ministry of Trade and Industry* (MITI) as a highly cohesive and focused way of developing the technology. A MITI backed group led by *Tokyo Electric Power* and *Toshiba* established a 120KW gross, 35KW land based plant on the South Pacific island of Nauru in 1981. The Japanese programme is now very much geared towards a complete OTEC system, whereby the cold water is used for a number of applications such as air conditioning, fresh water generation and seafood production as well as electricity generation. In its *New Sunshine Project*, announced in 1993, MITI has not prioritised OTEC, but an industry consortium, OTECA, is currently trying to seek funds for a "multi purpose OTEC system" for a South Pacific island.

Various studies have been conducted and plans devised as to the future of OTEC in Taiwan, and for the past ten years, it has continually been suggested that the government was on the verge of investing up to US$300mn on a comprehensive OTEC programme. Most of the current research is conducted by the state owned power company, *Taipower*, who would like to build a large (300MW) plant, and the government's Energy Research Laboratories who are promoting the more modest goal of starting with a smaller scale experimental unit. As yet there has been no practical demonstration of OTEC in Taiwan.

State of the Technology and Latest Developments

The means of thermal energy utilisation that is thought to have the most potential and is the most developed is the utilisation of the binary cycle heat pump to generate electricity. OTEC energy generation using such a heat pump can divided into two main types in terms of the development of the technology - open cycle and closed cycle OTEC. Variations involving combinations of both have also been suggested. Essentially, however, all OTEC systems require a method of bringing large amounts of cold sea water to the surface where it can interact with warm surface water in order to generate energy. In addition, the cold surface water has other useful applications (air-conditioning, breeding environment for aqua-culture and fresh water generation if an open system OTEC is used).

OTEC power systems basically operate in the same way as conventional power stations. They use steam to drive a turbine and generate electricity. A major difference between OTEC and "conventional" thermal power stations is the temperature of the steam. In OTEC systems the warm water at the surface of the ocean is at a maximum temperature of 25° C, well below the boiling point of water. In an open system OTEC, a low pressure environment is created and the water vaporises at less than 100°C and drives a turbine. The vapour is then condensed by the cold water from the sea depths to complete the cycle (the condensing water is essentially distilled water and in some cases can be used as a valuable by-product). The closed cycle OTEC system employs a secondary fluid, such as ammonia or freon, with a lower boiling point than water, and involves the same simple binary heat engine cycle. Closed-cycle, 50MW shore based OTEC plants are within the reach of current engineering and designs have been completed. Such plants would use ammonia as a secondary fluid, and chlorination is needed to prevent bio-fouling of the aluminium heat exchangers. Without fresh water production, this plant would require the price of oil to be around US$40 a barrel to be competitive. The use of an open cycle in conjunction with this to produce fresh water would improve the economics. The operating theory of both open and closed cycle OTEC systems is simple. The engineering realisation, however, still presents some challenges. For example, an open cycle 100MW OTEC plant would require about 450m^3/s flow of water through the pipes. Pumping water at such a rate from up to 1,500m below the surface of the ocean represents a leap in marine engineering technology. Both open and closed cycle OTEC have their merits. Open cycle, while inefficient, is easier to design and build than closed cycle and does not have to withstand as high a pressure. In addition there is the option of fresh water generation. Closed cycle is more efficient and enables the use of smaller turbines. Moreover high pressure ammonia turbines have been developed for use in the refrigeration industry. On the downside, costly heat exchangers are necessary for closed cycle and there are problems with corrosion and bio fouling. A hybrid system, combining both an open cycle and closed cycle has been suggested. This would use a closed cycle system to generate electricity, and then pass the water through an open cycle system to generate fresh water. There is also an ongoing debate as to whether OTEC will develop as a land based system or is more feasible as a floating system. Numerous designs of floating based OTEC systems have been proposed, many pre-empted in the early 1970s by the emergence of the off-shore oil industry in the United States. The advantages of off-shore based systems are two fold. Firstly, the design of such a system can be fairly generic, i.e. the sole specification is that there be a temperature difference in an appropriate depth of water. The thinking is that, in time, OTEC plants can be built from a standard design, as many conventional power stations, and this economy of scale will make a crucial difference in OTEC's commercial viability. The second advantage in having an off-shore plant concerns the cold water pipe. Proponents of off-shore systems claim that it will be feasible to suspend a cold water pipe from a floating platform, thus eliminating the need for a costly shore based pipe. However, no-one as yet has built an off shore OTEC plant, and it seems unlikely that existing oil platforms can be used with ease as a base for OTEC systems. Another problem with floating OTEC systems is the need to transport the products of the system to shore, but perhaps the key engineering problem is securing the cold water pipe. The concept of OTEC will function as long as there exists a temperature difference of 20°C or more. Under the systems so far described, this temperature difference exists between the surface ocean layer and the depths. However, this need not be a limiting factor. It is conceivable that the temperature difference is provided by hot waste water from a power station and cooler water from the ocean surface, thus eliminating the need for a long cold water pipe. Another system being proposed by *GEC Marconi* in the UK utilises "solar ponds" to trap the sun's rays and increase the temperature of water in the ponds to up to 60°C. The planners claim that the use of solar ponds can double the efficiency of the OTEC system, thus reducing the cost per KWhr calculated over the plant's lifetime. The logistics and economics of creating solar ponds of sufficient size have yet to be worked out. The variety of engineering choices available illustrates the necessity by those developing OTEC to keep an open mind with regards to the best way forward. There are numerous choices and the operating environment and market will determine which is feasible.

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For most OTEC configurations the two engineering problems remain the cold water pipe and the heat exchangers. The most challenging of these is the cold water pipe. In open cycle OTEC applications, the diameter of the cold water pipe must be substantial (0.5-25m) in order to achieve a reasonable flow of water. The world's only operational OTEC plant (an open cycle OTEC experimental plant in Hawaii) utilises cold water pipes of diameter 30cm to 1m). Whether the pipe is suspended from a floating OTEC platform or fixed to the seabed and running on-shore, the engineering, installation and operation present significant challenges in terms of cost-engineering. In the early 1980s, the US *Department of Energy* began a *Cold Water Pipe R&D Programme* specifically for OTEC to try to solve the engineering problems of bring large quantities of water ($2.5m^3/s/MW$) from the depths of the sea to the surface. The only sector which uses technology anywhere close to these requirements is the oil/gas industry, with the largest pipes in use today having a diameter of around 1m (on-shore) and 50cm underwater. A pipeline currently being planned between Oman and India will span 1000km and be on average 60cm in diameter - this is considered to involve groundbreaking engineering and sub-sea construction skills. Almost all OTEC proponents accept that further development work will be necessary to perfect an economically and technically feasible cold water pipe to the necessary levels. Suggestions put forward for the construction of the pipe include a composite materials pipe and a flexible pipe held taut by water pressure inside. *Don Lennard*, a leading UK OTEC authority, regards the perfection of the cold water pipe as the key to commercial OTEC development. He is in favour of a composite pipe mounted on a floating OTEC platform, incorporating a technique to repair damaged pipe segments without removing the entire pipe. Most OTEC experts consider the most likely commercial configuration of OTEC will be on an off-shore platform. This will eliminate the need for a cold water pipe attached to the ocean floor and spanning perhaps 10-20 km, depending on the sea floor topography, and also allow the facilities to be mobile (the current plans by *Sea Solar Power* envisage towing a pre-constructed plant from the US to India for the supply of electricity).

The other key engineering challenge for OTEC has been the construction of highly efficient heat exchangers at low cost. Both open and closed cycle OTEC require heat exchangers with a large through-put of sea water.

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Due to the limited temperature difference of 25°C or so, a high efficiency is required to achieve any net power output at all. The conventional choice of material has been titanium. The drawback is cost; titanium heat exchangers in OTEC units swallowed up over half the cost of the entire facility. A breakthrough came in the mid 1980s with the development of a "mini-OTEC" experimental unit in Hawaii by a consortium including the *University of Hawaii*. *Alupower* (a subsidiary of *Alcan Aluminium*) and UK power firm *GEC-Marconi* used the occasion to test their newly developed *Roll Bonded* aluminium heat exchangers. The key selling point was that the material used was resistant to corrosion in brackish water (the major difficulty with the use of most materials thus far). Heat exchanger cost was reduced by a factor of up to ten. The technology in general has advanced considerably in the last decade, driven in part by a drive to utilise excess or waste heat from conventional power stations. Additional development work is necessary on heat exchanger technology to reduce size and cost further.

An important point to realise about OTEC is that any pilot or initial commercial plant will be constructed from components using proven technology. The key engineering challenge will be the detailed design and practical optimisation of the assembly and a true analysis of the major hurdles will only come with practical experience. Dr Luis Vega of the *Pacific International Center for High Technology Research* was responsible for the construction of the world's first operational open cycle experimental plant in Hawaii in 1993. He stated that the main problems encountered were in constructing an experimental facility using existing components which were usually not designed for the specific application in question. Component manufacturers are often reluctant to custom build components for one-off facilities. The rigorous conditions under which the OTEC plant was operated (low pressure, corrosive environment, high water flow rate) meant that much trial and error was necessary before the plant could operate effectively.

The Benefits of Deep Ocean Water

There is another school of thought which views on-shore OTEC plants as preferable, chiefly because there is the added benefit of being able to easily access the large amounts of deep ocean water from the process. Cold water brought up from the ocean depths has two qualities that make it a valuable resource for the cultivation of marine organisms. Firstly, deep ocean water is rich in nutrients and is free from man-made pollutants and organisms that could be harmful to marine life. Thus it is a source of nourishment. Secondly, its temperature of about 4°C makes it possible to reproduce the environment of the sea floor and hence cultivate organisms such as lobsters which flourish there. The fact that OTEC utilises large quantities of such water has created an opportunity to cultivate useful marine life. Such activity is currently underway in Hawaii and in Japan. In Hawaii, the cold water is a by product of an OTEC plant, and in Japan, in Shikoku, the cold water pipe was constructed for the sole purpose of marine farming. The potential of large scale marine farming can be illustrated by the fact that over 40% of the world's fish catch is produced in regions where natural upwellings of cold water occur, which represents only 0.1% of the world's ocean area. An example is the extremely fertile fishing ground present off the coast of Peru, produced by the natural welling known as "El Nino". The cultivation of micro-organisms which thrive off the nutrient rich deep ocean water looks set to be a promising industry. Another important use of the deep ocean water generated from open cycle and hybrid OTEC configurations is fresh water production. This application of OTEC is often cited as being the most important, in parallel with energy generation, and indeed, in future scenarios may be the motivating factor behind the development of OTEC. The high through-put rate (450m^3/s for a theoretcial 100MW open cycle plant) means that fresh water can be generated at rates comparable to municipal requirements. In areas where fresh water is at a premium, such as islands in the South Pacific, initial studies indicate that OTEC generated fresh water is cheaper than water generated by other means, such as reverse osmosis, (a 50MW hybrid plant could produce fresh water at $0.80 per barrel compared with about $2 for reverse osmosis in a situation where oil is about $30 per barrel).[2]

Recent Developments in OTEC

The United States

The bulk of the OTEC development activity undertaken in the last few years has originated in the United States and Japan. Both nations undertook large renewable energy programmes following the oil shocks of the 1970s (only Japan's was sustained into the 1990s). With funding provided by the *Department of Energy* (DOE) in the 1970s and 1980s, OTEC research and development in the US emphasised large, closed cycle OTEC power plants that would float off-shore. In 1979, the DOE jointly sponsored with the State of Hawaii a closed cycle 15kW OTEC plant, and in 1981 conducted experiments at sea to evaluate certain components of closed cycle OTEC with the use of a vessel called OTEC-1. The purpose was to test the operation and effects of the heat exchangers, cold water pipe and power generation equipment at the MW level. As a result of this work, the DOE believes closed cycle OTEC to be sufficiently developed for industry to commercialise and is now concentrating its funding on open-cycle OTEC, with initial work aimed at shore based systems in the range 2-15MW.

US government funding of OTEC declined steadily during the Regean/Bush administrations and current activity is now centred on the Big Island of Hawaii. Two organisations play key roles: *The Natural Energy Laboratory of Hawaii Authority (NELHA)* and the *Pacific International Centre for High Technology Research (PICHTR)*. PICHTR is part of the University of Hawaii and NELHA operates a combined R&D centre, the Natural Energy Laboratory of Hawaii and a business park, the *Hawaiian Ocean Science and Technology Park* (HOST). These facilities host a variety of R&D and commercial projects performed by governments, universities and private groups. The attraction of the NELH to OTEC research lies in the laboratory's location. The offshore slope is steep and provides relatively easy access to deep cold water and the tropical climate provides the necessary temperature difference. Deep sea water pipes have been constructed by NELHA to pump cold water from a depth of 600m (the average temperature of the cold water is 5.5° C and the surface water varies from 24.5°Cto 27.5°C over an annual cycle). In 1982 a 30cm pipeline was constructed to provide 100 litres of cold water per second from a depth of 600m. There are currently 11 deep water pipes supplying both cold and warm water from various depths, and ranging from 30cm to 1m in diameter. The first pipes were constructed from concrete while recent pipes were made from fibre reinforced polypropylene. The pipes were originally constructed for OTEC related research, but the cold water is currently used, some of it on a commercial basis, for a range of applications such as air-conditioning and marine farming.[3] Using these facilities there are currently two major OTEC projects underway. In December 1992, PICHTR completed construction of the world's only operational OTEC plant and it is currently undergoing trials in preparation for a two year continuous operation period which commenced in June 1993. The project is formally known as the *Net Power Producing Experiment* (NPPE) and was funded by the US Department of Energy and the State of Hawaii at a cost of about $12mn. (It should be noted that this cost did not include the construction of a cold water pipe - NPPE utilised NELH's existing pipe). The pipe NPPE used is a 1m diameter, 1900m long, high density polyethylene cold water pipe which brings up 6°C water from 675m at a rate of $0.4m^3/s$. A similarly constructed pipe of 71cm diameter provides the warm water for the open cycle OTEC plant. The power equipment consists of a single 210KW turbine placed at the top of a 8m diameter concrete vacuum chamber, with generator placed above the turbine.

NPPE represents the first operational open cycle OTEC plant and has experienced some technical problems. The NPPE was built on a fairly limited budget and utilised many components not specifically designed for the application. Pump and turbine equipment suffered sea water corrosion and incompatibility with other components. In general, PICHTR reports that its component suppliers were not willing to custom build or even properly service their components, due to the experimental nature of the project and limited budget. Due to the inherent low efficiency of open cycle OTEC and the small scale of the project, the net power output is a relatively small 25kW. Indeed, the Director of the project feels that the future of OTEC lies in large scale closed cycle plants. The US Department of Energy was reluctant to fund a closed cycle plant as it deemed the technology to be developed, while open cycle OTEC technology it considered still in the research phase. The NPPE is significant in that it is the world's only operating OTEC plant, and as such provides a stimulus for continued investment and can be used for promotional purposes. The benefits in terms of technical knowledge remain uncertain, as it is unclear as to how far the operational behaviour of a 210kW plant can be extrapolated. Previous studies into closed cycle OTEC by the Department of Energy showed that for many components, a prototype of up to 40MW would be necessary to predict the behaviour of larger systems. The second of the two OTEC projects underway at the NELH in Hawaii has also been funded by the State of Hawaii, and involves a number of companies: the *Hawaii Electric Company, GEC Marconi, Alupower* (a subsidiary of Alcan Aluminium) and *Makai Ocean Engineering*, a Hawaii based company specialising in marine engineering design. Construction on the project began in March 1993, and the plant began operations in 1994.[4] The plant will be a 100kW closed cycle OTEC using, as with the PICHTR plant, the existing pipes of NELH to obtain the cold sea water resource. The plant itself originates in experimental work conducted by Alupower and GEC-Marconi at NELH since 1986. At the core of this research is the testing of Alupower's new *Roll Bond* aluminium heat exchangers in a marine environment.[5] The two companies began testing various alloys with slightly chlorinated ocean water and produced a corrosion resistant material. Conventional industrial heat exchangers are of the so-called tube-and-shell type, and consist of a cylindrical shell encasing a number of tubes through which the heat exchanging fluids flow. The closed cycle OTEC currently being assembled by the group of companies is the first to utilise the new heat exchanger technology. The plant will use four heat exchanger modules with an input of 200litre/s. The cold water will be distributed to other facilities in NELH (air-conditioning, marine farming) after use in the OTEC plant. The turbine generator was previously used by the mini-OTEC offshore plant in 1979. By using existing components and as a result of the low cost of the heat exchangers, the cost of the entire project has been kept down to $1mn, of which $725,000 has been provided by the State of Hawaii. The plant is scheduled for a one year operation. Both Alcan and GEC-Marconi are involved in the design of conventional power stations, and they hope the technology can be transferred. The *Roll Bonded* exchangers can be beneficially used within conventional power stations that use sea water as a coolant. GEC-Marconi has tested the heat exchangers in a Rankine cycle engine which uses the hot water from the power station cooled by surface sea water to drive a turbine in a secondary fluid.[6] Both companies believe there is a large market for the new heat exchangers and intend to pursue non-OTEC applications.

Japan

The development of OTEC in Japan has followed the country's general pattern of development and market realisation of technologies. A key characteristic of this pattern is long term planning, funding and guidance by the Japanese government. As such, alternative energy, and within this, OTEC, is viewed by the Japanese from three angles. Firstly, the Japanese economy is heavily dependant on imported resources for its energy needs and the government is continually exploring ways of reducing this. Secondly, the Japanese government realises that the possibility of widespread commercialisation of OTEC exists and wants to ensure that Japanese companies will be ready to participate in this market. Lastly, Japan recognises the environmental benefits of OTEC, both as part of its own energy efficiency programme and also as part of the recent push to internationalise Japan's environmental profile. Each of these driving forces has, and continues to play a part in OTEC activity in Japan. Within the Japanese government, the ***Ministry of International Trade and Industry*** (or MITI) has played a dominant role in the research and development of industry sectors. In the past MITI has targeted important sectors where it deemed success by Japanese companies was vital for the prosperity of the national economy. Examples of such sectors are the steel, machine tool, automotive and consumer electronics industries - and the results are self evident. MITI's involvement with alternative energy began seriously after the oil shock of the 1974, when it initiated its ***Sunshine Programme***. The aim of this programme was to co-ordinate the development of alternative energy in Japan, and a large part of this task involved researching the feasibility of various energy forms to determine which to prioritise - the aim being energy generation rather than environmental considerations. The energy forms prioritised by MITI were solar thermal and geothermal electricity. However, MITI also noted the US government's interest in OTEC and allocated budget to OTEC research. Initially, MITI stated its desire to build an offshore, closed cycle OTEC plant of 10 to 40MW. This was followed by ten years of research by Japanese companies and MITI laboratories into closed cycle OTEC development. Plans switched to an on-shore based closed cycle OTEC system in 1980 due to difficulties with off-shore engineering. In 1983 a consortium of companies built and operated a 100KW OTEC plant on the South Pacific island of Nauru.[7] The operational data from this pilot plant provided the companies involved (Tokyo Electric Power, Toshiba and others) and MITI with enough data to design a 2.5 MW plant, although this was never realised. As with groups in the US involved in OTEC at the time, the Japanese OTEC group experienced problems associated with the high capital cost of plant, especially the heat exchangers and the cold water pipe. To reduce these high costs, the Japanese began to research the feasibility of open cycle OTEC and more seriously, the possibility of improving the economics by using the cold water for a variety of applications. This development represents the main thrust of Japan's current OTEC programme. In January 1993, MITI announced its *New Sunshine Program* which is designed to exploit the advances made through the Sunshine Project and realise renewable energy generation. The new program also incorporates an energy efficiency programme (*Moonlight Project*) and the *Global Environmental Technology Program* of 1989 which promotes the idea of sustainable development with regards to energy generation. The priority energy technologies are solar, geothermal, fuel cell and coal conversion. Budget for OTEC has been reduced compared to the 1974 Sunshine Program, and this reflects several factors.

- Research and development has been conducted for twenty years, and it is not obvious that OTEC is close to realisation. Many of the cost engineering difficulties such as the cold water pipe remain unresolved.

- There are few regions in Japan where the marine environmental conditions would suit a large scale OTEC plant - there is a lack of an adequate temperature difference in most regions of Japan. One area where OTEC would be feasible is the southern Japanese island of Okinawa.

- One route the Japanese explored was to link the construction of an OTEC plant with its ODA (Overseas Development Aid) programme, which is largely limited to the Asia Pacific region. It has been trying to attract interest from developing island nations in the South Pacific as site for an experimental OTEC plant but has encountered difficulties.

Current research and development into OTEC in Japan is in a latent stage. Activity is being carried out by MITI, companies and universities at a low level, the aim being to maintain expertise should the technology suddenly become feasible due to, for example, a doubling of oil prices. OTEC activity in Japan is centred around a consortium of private companies, institutions and government departments know as OTECA (OTEC Association of Japan). Prominent members include Tokyo Electric Power, Toshiba, Kyushu Electric Power, Hitachi and MITI's Electrotechnical Laboratory. Another notable member is the Import Export Bank of Japan.[8] OTECA was established in 1988 to co-ordinate OTEC activities in the private sector, as government involvement was reduced. OTECA's aim is to promote OTEC as a core technology for island nations, around which they can build up a number of industries aside from power generation - desalination and marine farming are two examples. It is currently proposing to build a 1MW closed cycle, land-based plant and has four working groups dedicated to what it deems are the most important issues and problems associated with OTEC.[9]

- One group is devoted to the cold water intake pipe construction and installation. The group has been simulating a pipe associated with a 1MW plant by a 1/100 scale model. Initial results indicate that a feasible layout may be a "floating pipe", suspended above the ocean floor and anchored at both ends at points in between. The group hopes to reduce installation costs and allow the 1.2m diameter HDPE (high density polyethylene) pipe flexibility.

- Another group is concerned with aspects of the OTEC power plant. These include flow speeds of water, the fluid cycle and heat exchanger technology.

- In keeping with the theme of OTECA, one working group is concerned with finding new applications associated with an OTEC system. The group recently looked into the recovery of minerals from the deep sea water. It was found that vanadium is commonly found in trace quantities in invertebrates found in deep sea water. In 1992, the group found that fresh water recovery by condensing the saturated air above the sea surface could be feasible with the closed cycle system under consideration.

- OTECA is studying the feasibility of associating an oceanographic/environmental research centre with an OTEC plant. The research conducted at such a centre would be based around the cold water recovered by the OTEC system (similar to the NELH in Hawaii, although the Japanese centre would not be commercially orientated).

Following the above research and a site survey exercise involving islands in the Pacific region, OTECA produced a basic plan to build a multi-purpose OTEC centre on the island of Viti Levu in Fiji. The system would contain a power generation unit (1MW closed cycle OTEC) which would produce cold water for applications in marine farming and building cooling as well as power generation. The plan calls for the location of an oceanographic research centre at the site. The initial business plan predicts the scheme will produce profits of over 600mn yen (£4mn) per year after 10 years, with the bulk coming from building cooling and marine farming (under this plan power generation would continue to lose money after 10 years). The project would involve US150mn of capital costs and OTECA admits these costs are not accounted for in the business plan. It hopes to receive funding from the Japanese government to complete the project. These funds are unlikely to come from MITI in the foreseeable future, and OTECA is hoping to obtain funding as part of Japan's aid programme. ODA planners are increasingly sensitive to accusations of subsidising Japanese industry abroad and are reluctant to spend large sums on environmentally orientated projects unless specifically requested by the target country. Thus a major task for OTECA is to convince nations such as Fiji of the benefits of a multi-purpose OTEC system bearing in mind that such nations may fore-go other aid packages by accepting an OTEC system.

Taiwan

Taiwan is considered to be perhaps the most suitable location for large scale OTEC development. A temperature difference of at least 20°Cexists throughout the year on the east coast of the island, where the ocean floor drops off rapidly, facilitating cold water pipe construction for shore based plants. In addition to physical environmental conditions, Taiwan has experienced substantial economic growth in the last fifteen years and its power needs have increased sharply. The price of oil is controlled by a state monopoly at $40/barrel, and the cost of electricity generation is roughly twice that of the mainland US. Taiwan's energy planners are unsure as to where the shortfall in the nation's energy supply will come from. Nuclear power was once though to be the solution, but environmental pressure caused a delay in the planning of the nation's fourth nuclear power station. Taiwan's natural coal and oil reserves are minimal, and the country's power generation monopoly, *Taiwan Power Company*, is looking to mainland China's huge reserves of brown coal as a source of long term power, although, again, there are environmental problems with this source.

Taiwan's OTEC programme began in 1981 and since then the government has spent over $3mn on research and feasibility studies. The key players in Taiwan's OTEC programme are the *National Taiwan Ocean University, National Taiwan University* and the Taiwanese government (*Energy Commission, National Science Council*). The key industry player involved is the state owned *Taiwanese Power Company* (or Taipower). Like the Japanese programme, Taiwan's OTEC programme is influenced by activity in the US. In 1989, the Taiwanese government commissioned Hawaii based PICHTR to prepare a development plan for the construction of a 5MW OTEC pilot plant. The scheme was known as *Multiple Product OTEC Project in Taiwan* and outline the steps necessary for the commercialisation of OTEC in Taiwan.[10] The first recommended step was the building of the 5MW plant and associated aqua-culture, fresh water generation and air-conditioning facilities. The development plan built on work conducted previously in Taiwan and elsewhere and concluded that Taiwan's first OTEC plant should be of a closed cycle configuration due to the relatively advanced state of the technology. The cost of the recommended development plan was $79mn over seven years, after which the plant would be handed over to Taipower. A commercial size plant could follow, based on the pilot plant operational data, within a further nine years. Funding for this scheme has yet to be forthcoming.

A recent proposal, backed by Taipower, calls for a national scheme for Taiwan's OTEC development to be undertaken, rather than a limited one-project study. This would thus be similar to a national energy policy plan for nuclear or hydroelectric power, and has been dubbed *Master OTEC Plan for ROC* (MOPR).[11] It envisages the initial construction of a 200MW

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demonstration unit followed by a number of 500MW plants, with the "master plan" optimising location and use of deep sea water resources on a national scale. Critics of this approach wonder how Taiwan can construct a full size operational OTEC plant in one step and certainly a lack of engineering expertise will be an issue. On the positive side it is rumoured that the government is contemplating investing up to $300mn in OTEC related projects in the near future.

Future of OTEC in the Developing World

It remains true that geographically, most of the sites which are suitable for OTEC plants are in the developing world. To be economically viable, sites suitable for OTEC should have some or all of the following characteristics:

- suitable geographic conditions: tropical/sub-tropical climate, proximity to sea, necessary marine depth;
- economic conditions to suit OTEC generated energy: lack of cheap indigenous energy source, consistent market for OTEC electricity and by-products.

The second criteria is key. Many OTEC projects have targeted small tropical island nations. Japan's initial OTEC scheme concentrated on looking for a suitable site in Fiji for its experimental OTEC facility. It failed to attract support and funding ultimately because the local economic conditions did not warrant a prototype new energy generation plant. The introduction of new and perhaps untested technology into such regions presents possible social and cultural impacts. In a largely rural and agrarian society, the environmental benefits of an OTEC plant to the local population may not be as obvious as they are to a scientist from Japan or the US. Local populations may resent the intrusion of the infrastructure associated with a commercial or even experimental plant. In reality, technical and engineering labour would have to be imported, with the local population initially conducting manual labour. Thus the economic benefits of employment may not be immediate and this could be a source of friction.

Most leading OTEC and renewable energy experts acknowledge that the regions most suitable for OTEC energy generation are the developing and growing economies of Asia. OTEC has been considered seriously by Taiwan and it looks likely that the country will develop a variation of OTEC in the near future. By the year 2010, expanding economies and living standards will see the region use 133% of the energy it does at present, and 162% more electricity (according to the Honolulu based *East-West Center*). Given that there are severe energy shortages throughout the region at present, it is difficult to see where the extra energy will come from. Even oil rich Indonesia is set to become a net importer of energy resources by the year 2003. It is thus clear that Asia's energy resources in their current form will not be able to keep pace with its growth and many are seriously looking at renewable energy options to supplement fossil fuel and nuclear options. The reasons for doing so are not always based on economic issues. Most of the developing nations of Asia have strong central governments from which long term public sector planning is possible. Indeed most infrastructure projects in developing Asia are initiated and financed by the public sector. (There is a trend towards private sector investment in large energy and infrastructure projects; but these tend to be the exception at present). The motivation to develop renewable energy sources such as OTEC comes from a desire to diversify and be as energy-self sufficient as possible. There are also emerging environmental movements throughout Asia, especially in the Philippines and Indonesia, although the effect this has on government energy policy is minimal at present. More crucial is the significant amount of international (notably from Japan) funding in the form of soft loans and grants to developing Asia for environmentally benign projects. Japan alone provides over US$3bn in what can be classified as environmental financial support to Asia each year. A key motivation is to reduce the levels of air pollution emissions from China, but its also has a significant CO_2 reduction assistance programme.

While various studies have been conducted which indicate that the price of oil will have to roughly double (to $40 per barrel) to make OTEC favourable to private investors in the free market, combinations of certain circumstances (such as those mentioned above) make OTEC feasible at present. The following outlines the potential and significance of OTEC and its related applications for some fast developing nations in Asia: the

Philippines, Indonesia and India. Taiwan has been considered in detail previously and is considered also to be a leading candidate for OTEC commercialisation.

Indonesia

Energy policy has been very much in the news recently in Indonesia. The country's energy needs are predicted to skyrocket in the next ten years as it strives for industrialised nation status. Although Indonesia possesses significant reserves of oil, gas and coal, it also has the world's fourth largest population and a booming, energy intensive manufacturing sector. Energy demand is expected to increase by an average 7.5% per year to 2010 to around 1 billion barrel-oil equivalent. Presently the country relies heavily on its oil reserves for its domestic needs and its also a major exporter; it will become a net importer by 2003 given production and consumption forecasts. The government thus has a stated policy of encouraging non-oil energy sources. The country has 36 billion tonnes of coal reserves, (of which 60% is of low quality) and coal is expected to account for 20% of energy demand by 2015, up from 11% in 1995. The use of natural gas is also being encouraged. The wild card is nuclear power; there have been mixed signals recently as to whether Indonesia plans to go ahead with construction of its first nuclear power plant. There is strong lobbying against the nuclear option from influential environmental pressure group *Walhi*, and Science and Technology Minister Habibe has labelled nuclear the "last option" in the country's energy policy. Despite these somewhat confusing signals, Indonesia appears to have most of the right ingredients for a successful market for OTEC:

- geography: Indonesia has the longest coastline in the world, all of which is in tropical waters; there are thus countless possible locations for an OTEC plant;
- economic conditions: the country's demand for electricity is increasing at 10% per year; the country will have to consider alternatives to its dependence on oil and coal;
- Indonesia is effectively an autocratic state, with political and economic power concentrated in the hands of President Soeharto and his allies. Under this regime, it has been possible to develop and commercialise industries (such as aerospace and automotive) which may not have developed so quickly if left to market forces. Indonesia could do the

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same for its nuclear industry, or could decide to opt for developing a renewable energy industry. Whatever the choice, the mechanisms are in place for the government to channel funds and nurture its policy choice to fruition.

- Indonesia's fledgling environmental movement is unlikely to have a serious impact on economic policy at present. However, of great importance is international funding, particularly from Japan. The Indonesian government would find it fairly easy to raise international finance for a large scale renewable energy programme at present given the concern over the environmental impact of Asia's newly developing economies.
- Indonesia has a need for some of the other products and applications associated with OTEC: fresh water (shortages all over Asia); air conditioning and deep ocean water (whether this will be economical to use for aqua-culture at present is debatable).

Whether Indonesia will opt for a major renewable energy programme in the near future is unclear. The signs are not promising. In the past, the country has not taken many risks with regards to development of new technology, preferring instead to import proven technology and then develop its own expertise. There are many foreign industrial concerns who are pressuring Indonesia to develop nuclear power and can offer straightforward technology transfer. Indonesia has often opted to develop prestige sectors (such as aerospace, automotive) ahead of more practical but perhaps less export driven sectors. Government planners may feel that Indonesia needs a nuclear industry to maintain its place as one of Asia's leading powers. It is clear that the development of nuclear power would effectively shut out a major renewable energy programme as much of the country's human and financial resources devoted to the energy sector would be allocated to this.

The Philippines

The Philippines has many of the same characteristics as Indonesia in terms of appropriate conditions for the development of OTEC. The Philippines especially lacks domestic sources of energy (unlike its neighbours Indonesia, Malaysia and Vietnam, it is not blessed with reserves of oil and gas). Electricity shortages are common. Further more, the Philippines has the strongest environmental movement in Southeast Asia, and perhaps the only one which actually affects government policy. In October 1995, plans to construct four coal fired power stations in Quezon, to cater for critical shortages of electricity to the national grid, led to street demonstrations by a variety of environmental and special interest groups. Earlier in the month, the *Department of Environmental Protection and Natural Resources* rapped the country's leading power company (*Hopewell Power*) for unsound activities associated with its coal power stations. The fate of the nuclear industry in the Philippines appears to have been sealed when US firm *Westinghouse Electric* settled a 7 year dispute with the Philippine government concerning safety for a never-operated reactor completed by the firm in 1985. National opposition to nuclear power in the Philippines means that the plant is unlikely to operate and any new plants will not be planned. The Philippines has an active renewable energy programme underway. The chief sources of energy considered are geothermal and hydropower. These are not without their problems however. The commissioning of a US$200mn geothermal project in Mt Apo in November 1995 was greeted with protests from indigenous groups and nature conservation activists. To tackle energy shortage, the country announced a 30 year Philippines Energy Plan this year. It will add 90,000 MW of power to the country's energy capacity, with 13,000 of this already planned. The country would like to maintain its self sufficiency level at 40% over the period; it has ruled out nuclear power in favour of renewable energy sources (hydro, geothermal, solar) and coal/natural gas. It is expected that renewables will play a major part in the realisation of the country's energy needs. Private sector investment will form the major part of the 30 year plan.

Thus it is believed the Philippines presents an ideal environment for OTEC. It has a need for self-sufficient, renewabie energy due to lack of resources and environmental pressure. Current priorities (geothermal and hydro) are likely to run into opposition from NGOs in certain parts of the country. A privately funded BOT style OTEC project (such as is being planned for India by *Sea Solar Power*) would be well received by authorities in the Philippines, and its is likely that such a project may attract subsidisation from the various international organisations currently now focusing on the environmental issue in Asia.

India

India has actively encouraged its renewable energy industry in the recent past and has provided a investment-friendly environment for such projects. India relies on coal, nuclear and oil sources for much of its electricity, but over the last 15 years, has nurtured a renewable energy sector. This was done more out of economic necessity than for environmental considerations - in many rural areas, the installation of small scale wind, solar or biomass facilities was more feasible than connection to a national or regional grid. 800MW of electricity is generated by renewables and India has the largest wind energy programme after the US. A further 1,700MW is generated from waste. As a result, India has developed one of the world's largest domestic renewable energy industries. A leading solar energy firm (*Central Electronics Ltd*) was recently awarded a contract to set up a solar cell factory in Syria. The government, now driven by environmental considerations and aware that international aid will be forthcoming, has initiated a 15 year Renewable Energy Plan. India expects to be the world's second largest generator of renewable energy in the near future and has elevated the theme to Ministry status with the formation of the *Ministry for Non-Conventional Energy*. The *Renewable Energy Development Agency* was set up to disburse $195mn worth of World Bank funding specifically for this purpose. In November 1995, the state of Rajasthan commissioned a Sri Lanka-led consortium to begin construction of a 200MW solar power facility costing US$500mn (one of the largest such projects ever). OTEC has played a relatively small part in India's renewable energy programme thus far. Perhaps one reason is that many of the areas where electricity is needed are inland regions, not easily serviced by an OTEC plant. India has dire fresh-water shortages and could well utilise deep ocean water for aqua-culture applications. The US *Electric Power Research Institute* recently signed co-operation agreements with a number of influential Indian organisations on the theme of renewable energy, so there is a ready made channel for transfer of US OTEC technology to India. Thus far about 20 joint ventures have been signed between US and Indian firms in the field of renewable energy, and the *Sea Solar Power* venture looks set to be the first in a series of OTEC ventures for the country. The US firm has been discussing OTEC projects with numerous tropical and sub-tropical countries over the last decade and has found India to be the most receptive so far. It signed a Memorandum of Understanding with the *Tamil Nadu Energy Development Agencv* and the *Tamil Nadu Electricity Board*. Under the agreement, Sea Solar Power will construct and operate an offshore OTEC plant and sell the resultant electricity to local authorities. Although no commercial contract has been signed yet (as of January 1996), Sea Solar Power President *Hilbert Anderson* states that it is likely that the Indians will sign a 20 year contract to purchase electricity. Anderson states that the resultant power will be comparable in price to other local sources and the OTEC unit will also generate fresh water and the nutrients brought from the sea depths will enhance the area's fishing industry. The 100MW closed cycle OTEC plant was designed very much with economical operation in mind. The design calls for the construction of a 20,000 tonne floating "tanker" plant. Aluminium heat exchangers will be employed along with a 7.7 metre diameter fibre-glass cold water pipe. The key challenge now for this OTEC project will lie in raising the necessary funds (US$250 mn) for the project. Anderson predicts that the plant will be in operation within the next 3 years or so.

Conclusions

Ocean Thermal Energy Conversion (or OTEC) has, since its invention in the late 1800s been one of a long list of technologies with huge potential but not yet commercialised. Like many renewable energy technologies it looks destined to remain that way either until a government takes the lead or market conditions make it attractive to public and private sector investors. The former situation looks set to happen in India and perhaps other parts of Asia, particularly Taiwan, as the region begins to wake up to the fact that its economic boom cannot coexist with environmental destruction. Investment from within the region and also from the international community (Japanese aid, World Bank) is making it attractive for private sector investors to consider OTEC as a commercial proposition. The region's energy economics (energy shortages, lack of indigenous resources) and geographical conditions (tropical, sub-tropical, many island nations) point to the suitability of OTEC as one answer to the region's energy needs. By-products of OTEC can also be used for great benefit. As Southeast Asia is likely to face severe shortages of economically obtainable fresh water; certain configurations of OTEC may provide both power and large quantities of fresh water.

There has been extensive experimentation and design work done on OTEC technology. Most OTEC experts agree that what is needed now is an operational prototype plant of 100MW or so to "prove" the technology. It is understandable that few developing nations, with limited financial resources, want to be the first to commit to un-proven technology. It is likely that the first plant will be built with foreign investment and technology. One US company is already committed to undertaking such a venture in India. The successful demonstration of this plant will spur further investment and will be of great benefit to the local economics of the regions (a good precedent is India's booming solar power industry, which now exhibits 35% annual growth to provide economic benefit as well as much needed power). The investment community in Asia is extremely receptive to viable energy projects at present and with many qualified sub-contractors in the US and elsewhere, OTEC looks set to take off in the early years of the next decade.

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