Ocean Thermal Energy Conversion (OTEC) and Derivative Technologies: Status of Development and Prospects

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Introduction

Ever since Georges Claude conducted his pioneering work on Ocean Thermal Energy Conversion (OTEC) nearly 80 years ago [1, 2], generations of engineers have dreamt of tapping this enormous renewable resource. Considerable work was initiated after the oil price shocks of the 1970s, but these efforts waned within the following two decades under less favourable political and economic conditions. In the meantime, OTEC advocates and researchers realised that the ocean thermal gradient could be used not only to produce electricity, but also in derivative technologies like desalination, cooling and aquaculture. These other deep ocean water applications (DOWA) were often envisioned as co-products that could help OTEC break its economic glass ceiling. In time, they would follow their own separate development paths.

A good synopsis of OTEC economics was published in 1992 by Luis Vega [3], who had been instrumental in the execution of some of the most significant OTEC field demonstration projects ever conducted [4, 5]. The emphasis on economics in his brief article certainly was not meant to belittle other challenges faced by OTEC promoters, of which he was well aware, but it does reflect a fundamental need for very heavy financing. Given the sharp rise in the cost of primary energy over the past few years and a renewed interest in renewable energies, it is timely to examine the current status of development of OTEC and its derivative technologies. This summary will include a brief discussion of prospects, technological or other issues, and activities.

OTEC

Long-term opportunities

The OTEC resource covers an area exceeding 100 million km^2 across tropical oceans. Unlike most renewable energy conversion systems, OTEC could deliver power at very high capacity factors and offer baseload capabilities. The overall sustainable size of the resource is limited by the rate of formation of deep cold seawater, although unrealistically high estimates based on solar fluxes are often suggested. Orders of magnitude between 3 and 10 TW appear likely, i.e. a range approximately ranging from twice today's overall electricity consumption to about half of today's primary energy needs [6-8]. The lower bound reflects a possible degradation of the local thermal gradient under very intensive OTEC scenarios.

Favourable OTEC regions are for the most part far offshore from any land. This suggests that a substantial development of OTEC would necessitate floating systems rather than land-based plants. In either case, tropical locations with steep bathymetries remain the best candidates. They include countless small islands as well as some large, sometimes heavily populated island nations (Indonesia, the Philippines, Papua New Guinea, Taiwan). Brazil has extensive coastlines with excellent ocean thermal gradients, while the Gulf of Mexico could provide the USA with good opportunities.

Any significant OTEC development is not likely a) to take place where logistical difficulties are excessive (e.g. lack of infrastructure) and b) to be spearheaded by countries that may have difficulty bearing the risk and burden associated with novel capital-intensive technologies. In a more distant future, a systematic development of remote OTEC regions would probably require the manufacture of energy vectors such as liquid fuels rather than direct power transmission to shore.

Issues

In the standard formulation of OTEC, electricity would be produced by circulating a working fluid through a Rankine thermodynamic cycle. Because of the moderate temperatures involved, ordinary refrigerants such as ammonia typically have been considered for such systems. Available seawater temperature differences T, of the order of 20ºC, must be used not only to define the boundaries of the cycle (evaporation and condensation temperatures), but also to maintain adequate temperature differentials between seawater streams and working fluid as heat is transferred. Hence, the Carnot efficiency of OTEC cycles is based on a fraction of T, and is at most a few percent. All issues related to – and hurdles impeding the development of – OTEC stem from this fact.

OTEC systems require cold seawater flow rates of about 2.5 to 3 m^3/s per net megawatt, with usually greater warm surface seawater flow rates. Large and efficient heat exchangers are thus necessary. Because of a need to also minimise seawater pumping losses, very large conduits also must be envisioned. The Cold Water Pipe (CWP) in particular represents a technological frontier, at least for OTEC plant designs beyond 10 MW [9]. Difficulties with the OTEC power block have been tackled differently. To be able to replace costly metal heat exchangers with simple hardware, Claude invented the Open-Cycle (OC-OTEC) [1] where steam generated from surface seawater in a low-pressure chamber continuously provides the working fluid. Unfortunately, the benefits gained with simpler robust evaporator and condenser designs are offset by the needs for very large low-pressure turbines and multi-stage vacuum compression systems. This would effectively limit OC-OTEC to plants smaller than 10 MW.

More recently, there have been efforts to improve the low efficiency of OTEC Rankine cycles by using a mixture of ammonia and water through the heat exchangers. This concept is embodied in the Kalina and Uehara cycles. The behavior of the mixture during evaporation and condensation differs from that of pure fluids. It theoretically allows a better match of heat loads during heat transfer since the temperatures of working fluid and seawater can remain closer. A plant based on this cycle requires additional hardware, i.e., a separator before the turbine inlet and an absorber after the turbine outlet. Also, the heat carried by the water in the mixture can be partly recuperated through a regenerator. The Kalina cycle reportedly can boost the Carnot efficiency of an OTEC system by 50% or so, but it also imposes increased demands on the evaporator and condenser. Hence, the viability of OTEC cycles departing from the standard Rankine cycle probably hinges on the availability of better heat exchangers [10].

The greatest technological (and credibility) challenges facing OTEC remain in the realm of ocean engineering, as OTEC field experimentation critically depends on whether a CWP can be deployed and how long it survives. From Claude's hardships in the 1930s [1, 2] to recent trouble in Indian waters [11], the history of OTEC development is rife with CWP failures. The state-of-the-art for operating deep cold seawater pipelines consists of seafloor-mounted high density polyethylene (HDPE) conduits. The largest to date (1.4 m in diameter and 2.8 km long) was deployed off the west coast of Hawaii to a depth of 900 m in 2001 [12]. While HDPE CWPs would be ideal for small megawatt-class systems, OTEC plants of much greater capacity would have to rely on other choices. On the other hand, the exploitation of vast remote offshore areas with floating platforms poses specific challenges that are not addressed with land-based systems.

The most ambitious programme designed to resolve ocean engineering problems specific to large floating OTEC plants remains the comprehensive effort led by the US National Oceanic and Atmospheric Administration (NOAA) in the late 1970s and early 1980s. This included the development of computer simulation tools, model basin tests of potential platforms and pipes, and an at-sea test of a 120 m long, 2.5 m diameter CWP suspended from a small barge. (The pipeline was to be much longer for a representative 1/3 scale test; the actual length reflects funding limitations marking the end of political support for OTEC in the United States after the 1980 presidential election. The pipe was made of two layers of fibreglass-reinforced plastic (FRP) separated by syntactic foam. Manufactured in Washington State, it was shipped to Hawaii in 24 m sections. A field experiment took place for three weeks in the spring of 1983 off of Honolulu.

The large size of OTEC components and the demands imposed by offshore environments on equipment survival and power production logistics result in high projected capital costs. From an economic point of view, this is exacerbated by relatively low power outputs so that standard analyses based on the levelised cost of electricity generation have consistently resulted in uneconomical projects. Even though the cost-effectiveness gap between OTEC and the most expensive fossil-fuel power generation technologies (e.g., oil) has steadily declined, OTEC market penetration has not yet succeeded. When considering estimates of capital costs per unit power as a function of rated power, OTEC systems exhibit a considerable expected economy of scale as one would move from small pilot plants to larger commercial units. Because of a lack of experimental and operational data in running OTEC systems, however, taking advantage of this purported economy of scale has not been possible. Various strategies aimed at leveraging market resources have been attempted. A common approach has been to identify niche markets where the local cost of electricity is sufficiently high and the overall power demand sufficiently low to make OTEC potentially attractive at the modest power outputs suitable for first-generation projects (e.g. 1 to 10 MW). In the best scenarios, a Power Purchase Agreement (PPA), perhaps indexed on a high Avoided Energy Cost (AEC), may be secured with a local utility. While addressing the demand-side aspect of the problem, a favourable PPA has proved insufficient to persuade investors that the risk associated with OTEC is acceptable, with capital outlays as high as USD 300 million for power outputs of the order of 10 MW. Hence, it remains likely that any meaningful demonstration of scalable OTEC systems will be accomplished with a strong commitment of public funds.

Activities

Recent efforts have shown a widespread interest in reviving OTEC, but remain subject to formidable funding hurdles. Accordingly, a number of partnerships were established this year that seek to leverage the necessary technical and financial means to build OTEC pilot plants. In August, Xenesys Inc. of Japan and Pacific Petroleum Company formed a joint venture for the industrialisation and commercialisation of OTEC in French Polynesia. They are seeking support from local authorities to proceed. In October, a consortium of French industrial and public partners launched the initiative IPANEMA aimed at facilitating the emergence of marine renewable energy technologies. In November, Lockheed-Martin (LM) and the Taiwan Industrial Technology Research Institute (ITRI) pledged to collaborate on a 10-MW plant project in Hawaii. Significant monies have already been committed by LM on initial design and research and development activities, but the completion of the project will necessitate a substantial commitment by the US government.

Seawater Desalination

Long-term opportunities

While fresh water is a valuable commodity worldwide, the future of seawater desalination utilising the ocean temperature gradient is hard to evaluate, either in conjunction with OTEC electricity production, or as a stand-alone technology. In the former case, it depends on the development of OTEC with specific additional constraints (e.g. low vacuum components, water transmission to market). In the latter case, it must compete with other desalination technologies. On the bright side, the temperature differential sufficient to generate steam can be much smaller than for OTEC systems that require a turbine. At this juncture, it is likely that any advance in the development of this technology will hinge on the identification of specific niche markets or on some definite progress in deploying OTEC systems.

Issues

The concept of producing fresh water from seawater streams of different temperatures emerged as a logical consequence of OC-OTEC. In such a cycle, about 0.5% of the warm surface water is converted into steam in a low-pressure vacuum chamber; this steam can be recovered as potable water by condensation as long as a Direct-Contact Condenser (DCC) is avoided. From this basic idea, numerous hybrid cycles were devised to preserve advantages afforded by a DCC in OC-OTEC systems (with the addition of a freshwater-seawater liquid-liquid surface condenser), or by other more general OTEC Rankine cycles (with electricity and desalination modules in series, or in parallel with double heat exchangers). The next conceptual leap was to forego OTEC electricity production altogether. This led to the additional consideration of more typical, though more complex desalination technologies such as Multistage Flash (MSF) distillation or Multiple Effect Desalination (MED). The latter relies on using heat from condensing vapour at a given temperature in order to produce vapour at a lower temperature in a series of vacuum chambers (effects). It was identified to be potentially well suited for low-temperature applications, at least in small systems [13]. In all cases, non-condensable gases released at low pressures need to be continuously removed.

Activities

Ocean thermal gradient desalination on the floating barge Sagar Shakti has been successfully demonstrated in 2007 by India's National Institute of Ocean Technology (NIOT) [14]. The project was designed to produce 1 000 m^3/day by converting about 1% of the pumped surface seawater into steam. It extends NIOT's previous experience with smaller land-based low-temperature thermal desalination plants (e.g. Kavaratti).

Seawater Air Conditioning

Long-term opportunities

Seawater air conditioning (SWAC) is the only technology using a thermal property of the oceanic water column that has reached commercial maturity. It is essentially a land-based technology that relies on a close access to cold water from population centres on shore. Hence, cost effectiveness critically depends on favourable siting. In spite of such limitations, there remain a great many attractive locations to further expand SWAC systems.

Issues

The success of SWAC rests on the direct cooling of A/C fluids with available thermal energy rather than with the mechanical energy expended in typical chillers. It is thermodynamically efficient as long as seawater pumping power requirements remain modest. In practice, available HDPE pipes a few kilometres long are generally adequate.

Activities

Many SWAC systems are currently being considered, e.g. in French Polynesia where existing projects have already proved successful. The largest venture with a marine SWAC system to date is planned for Honolulu, Hawaii by Honolulu Seawater Air Conditioning, LLC. The 25 000 ton (A/C) project will utilise nearly 3 m^3/s of 7ºC deep seawater pumped from a depth of about 530 m via a 1.4 m diameter HDPE conduit. Planners have released their Draft Environmental Impact Statement (EIS) to the US permitting authorities in October and no roadblock is anticipated [15]. At the other end of the scale, 'mini-SWAC' systems based on small pressurised pipes conveying the coolant directly to submerged heat exchangers have recently been suggested to serve the needs of the smallest remote island communities [16].

Seawater Enrichment

Long-term Opportunities

High nutrient concentrations are found in deep seawater. Its use in land-based mariculture operations was spearheaded at the Natural Energy Laboratory of Hawaii Authority (NELHA) in the late 1970s. Many similar facilities have been developed elsewhere since then. The production of high-value nutraceuticals and additives (e.g., spirulina, astaxanthin) and of seafood for local niche markets has typically been targeted. The deep seawater needs of even modest land-based OTEC plants are projected to exceed the needs of land-based mariculture, however, especially if land availability (e.g., for raceways) is limited.

Just as long-term opportunities for OTEC lie offshore, the most tantalising prospects for seawater enrichment are embodied in the concept of Artificial Upwelling (AU). With its high deep cold seawater intensity, OTEC seems ideally suited to be a generating technology for AU. Moreover, OTEC relies on strongly stratified tropical waters where the upper layer tends to be depleted of nutrients. Hence, if large floating OTEC plants are built, it might be possible to adjust the release of the effluents to deliberately produce significant artificial upwellings. The success of this approach hinges on achieving effluent neutral buoyancy well within the photic layer. Different stand-alone AU concepts have also been formulated and partially tested, but their practical viability remains to be established.

Issues

The most obvious strategy to potentially boost the oceanic food chain with OTEC deep seawater effluents is to release them at a shallow depth (without interference with the OTEC warm seawater intake). This would generate a negatively buoyant plume that would entrain ambient water until it stabilises. The process is strongly site specific (e.g., local density stratification, cross currents) and very sensitive to scaling effects. All other things being equal, larger plumes sink to deeper waters but undergo less dilution. Time scales of minutes involved in plume stabilisation are too fast to allow immediate nutrient utilization. Instead, primary production (and subsequent trophic enhancement) would take place in the 'far field', over time scales of days. In Low Nutrient Low Chlorophyll (LNLC) waters, the upper ocean is so depleted in essential nutrients that constraints on plume dilution should be less critical than constraints on stabilisation depth.

The Japanese developed a concept that would make the stabilisation of upwelled water independent of AU scale by pumping both lighter surface seawater and deeper nutrient rich seawater in a prescribed ratio corresponding to neutral buoyancy at a targeted release depth. Successful tests were initiated in Sagami Bay, Japan in the TAKUMI experiment [17, 18]. Simple plumes released from the surface as well as the TAKUMI concept were later analyzed for oligotrophic waters [19]. It was confirmed that TAKUMI represents an optimal limit for desirable AU characteristics. It was also shown that in the presence of deep permanent pycnoclines typical of LNLC oceanic regions, the amount of surface water that would have to be pumped for a prescribed mixing ratio with deep seawater rapidly would make TAKUMI impractical for desirable stabilisation depths. Additional results suggest that the presence of moderate ambient cross currents may dramatically improve the physical behavior of AU for simple plumes, with deep seawater flow rates about an order of magnitude higher for a given combination of neutral-buoyancy depth and dilution.

The high flow rate AU configurations discussed so far rely on hard pipes and powerful pumps. There are low flow rate alternatives that would require minimal or no pumping mechanism and could possibly use soft flexible conduits. In one case, the heaving motion of a buoy induced by surface waves would control a valve in a connected vertical pipe; this would allow the upward flow of seawater within the pipe [20]. In another system, less saline deep water brought inside the pipe slowly warms up; as a result, density differences with the outside water column allow a sustained ('perpetual') upward flow of a few millimeters per second [21]. Slowly upwelled water would be quite stable near the ocean surface and therefore correspond to optimal conditions for enhanced photosynthesis. Aside from specific engineering challenges and issues of survival at sea, the low flow rates associated with these concepts would necessitate the deployment of arrays of considerable extents to be quantitatively significant.

Activities

The most significant endeavour is the sustained operation of TAKUMI since May 2003 in Sagami Bay, Japan, where 100 000 m^3/day of 200 m deep water is stabilised relatively close to the surface. TAKUMI has been organised by MARINO-FORUM 21, a subsidiary of the Fisheries Agency of the Government of Japan. Notable as well, although less successful is an attempt this year to deploy novel wave-driven AU pumps off of Hawaii during the first Ocean Productivity Perturbation Experiment (OPPEX-1) led by the University of Hawaii.

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