PAPER

Economic and Social Benefits from Wave Energy Conversion Marine Technology

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ABSTRACT

This paper summarizes the energy resource, the energy conversion technology, and the economic and social benefits of using wave energy technology. The Electric Power Research Institute (EPRI) estimates that the U.S. wave resource potential that could credibly be harnessed is about 6.5% of the 2004 U.S. national electricity energy demand (the total 2004 demand was about 4,000 TWh). Wave energy conversion (WEC) is an emerging technology; ten WEC devices have been tested to date in natural waters worldwide over the past 10 years. The economic opportunities are significant. A relatively minor investment by government in the public good today could stimulate a worldwide industry generating billions of dollars of economic output and employing thousands of people, while using an abundant and clean natural resource to meet our energy needs. Wave energy is potentially more easily assimilated into the grid (compared to wind and solar) because it may be more accurately predictable two to three days ahead and sold as firm power. Given proper care in siting, deployment, operations, maintenance and decommissioning, wave power promises to be one of the most environmentally benign electrical generation technologies. The primary barrier to the development and use of these technologies in the U.S. is the cumbersome regulatory process. We recommend and encourage the development of an effective regulatory system that fosters the application of this environmentally friendly electricity generation technology for our society.

Resource

The power of ocean waves is truly awesome. Aside from thrilling surfing enthusiasts and enthralling beachgoers, their destructive potential has long earned the respect of generations of fishermen, boaters, and other mariners who encounter the forces of the sea.

Ocean waves can be harnessed into useful energy to reduce our dependence on fossil fuel. Instead of burning depleting fossil fuel reserves, we can obtain energy from a resource as clean, pollution free, and abundant as ocean waves. The technology, though young, *exists* to convert the power of ocean waves into electricity.

The worldwide wave energy resource, stated in kW power per unit meter of wave crest length, estimated by Dr. Tom Thorpe (Thorpe, 1998) is shown in Figure 1. The highest energy waves are concentrated off western coasts in the 40°–60° latitude range north and south. The power in the wave fronts varies in these areas between 30 and 70 kW/m with peaks to 100kW/m in a few locations.

EPRI estimates that the U.S. wave resource potential which could be credibly harnessed is about 6.5% of 2004 U.S. national electricity energy demand (EPRI WP-009-US). The U.S. wave energy potential is about 2,100 TWh/yr (see Figure 2) and composed of four (4) regional wave energy climates, each with their own characteristics. Assuming an extraction of 15% wave to mechanical energy (which includes the effects of device spacing, devices which absorb less than all the available wave energy and sea space constraints), typical power train efficiencies of 90% and a plant availability of 90%, electricity produced is about 260 TWh/yr, which is about equivalent to the total 2004 energy generation of conventional hydro power.

In order to effectively use wave energy, the variability over several time scales—namely: wave to wave (seconds), wave group to wave group (minutes), and sea state to sea state (hours to days)—must be understood. The time scale of seconds to minutes is important for continuously "tuning" the plant to changing sea states. The hours to days time scale is important for providing firm power guarantees into the day ahead electrical grid market. Being able to accurately forecast changes in wave energy in response to the

FIGURE 1

Worldwide Wave Resource (Thorpe, 1998).

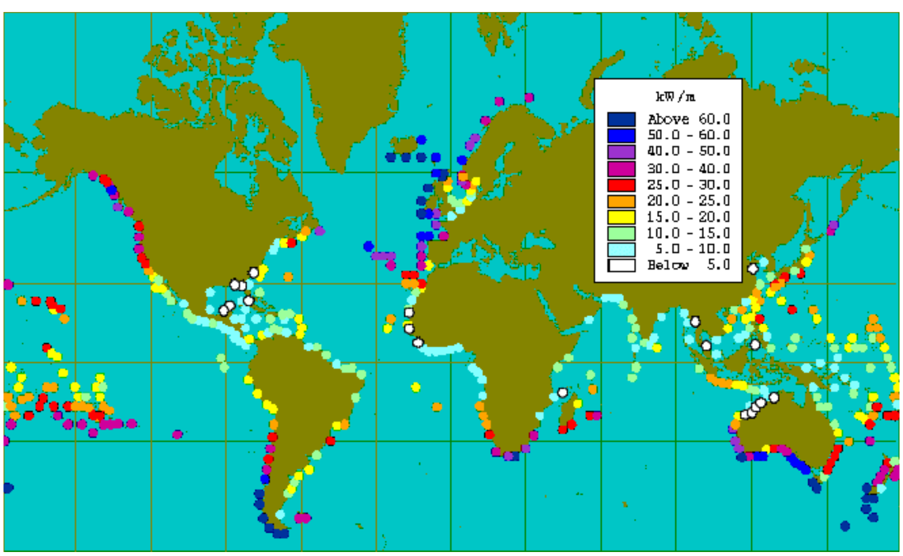


FIGURE 2

U.S. Wave Resource.

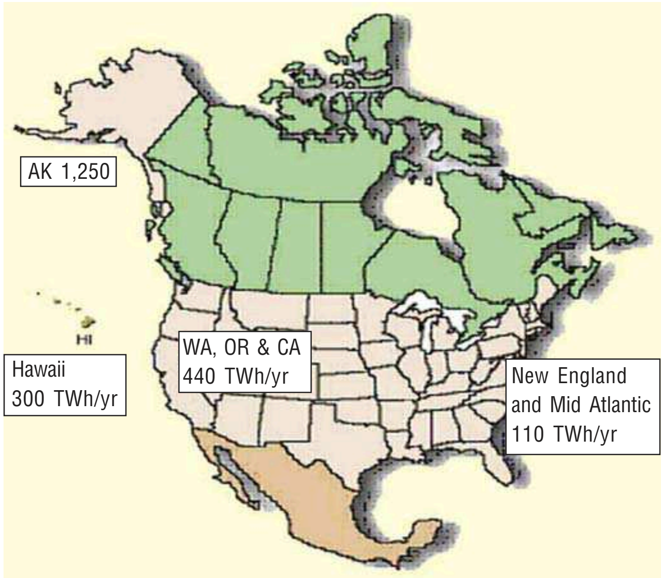
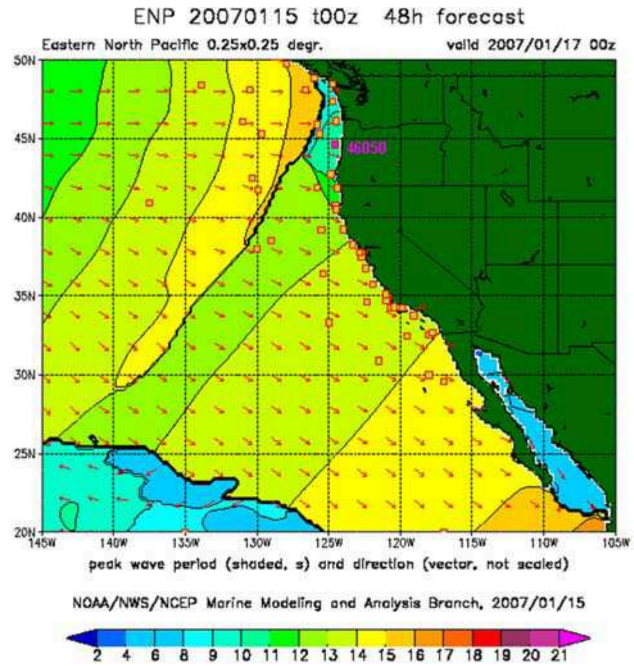


FIGURE 3

East Pacific Wave Forecast.



evolving sea and swell conditions over a time scale of hours to days is important to utility dispatchers concerned about unpredicted variability in plant output for load balancing.

Using the Washington, Oregon and Northern California region as an example, the two primary sources of wave energy along these coasts are seas built up by local winds and swell generated by storms far offshore in the North Pacific Ocean. These storms are born in the northwestern Pacific Ocean as prevailing dry, westerly winds off the Asian continent pick up heat and moisture from the Kuroshio Current. These low-pressure systems typically develop sustained wind speeds up to 50 knots (25 m/sec), blowing over a 1,000 km stretch of water for two to three days, as they follow northeasterly tracks into the Gulf of Alaska. Such storms are most frequent and intense from November through March, although they occur throughout the year. In order to take a quick look at what sort of accuracy might be expected at different forecast time horizons using the existing NOAA WAVEWATCH III implementation in the East North Pacific (ENP) region, we used the peak period forecast map for the "ENP West Coast Zoom" for 17 January 2006 at 00:00 GMT for every 24 hours, starting five days in advance of the target date and time. The forecast significant wave height was then compared with measurements at one deep-water forecast/measurement location; namely, Stonewall Banks, 20 nautical miles west of Newport, Oregon (NDBC buoy 46050). In this quick-look example, the peak period prediction had stabilized by 72 hours in advance (3-DAY forecast time horizon), and the significant wave height prediction had stabilized by 48 hours in advance (2-DAY forecast time horizon). The 2-DAY forecast map is shown in Figure 3. In 2007, EPRI will perform a study to quantify wave forecasting accuracy as a function of the forecast time horizon.

EPRI Feasibility Studies

In 2004, EPRI performed an offshore wave power feasibility definition study examining five locations and two WEC technologies (EPRI WP-006-HI, WP-006-OR, WP-006-ME, WP-006-MA, WP-006-SFa, WP-006-SFb). Design, performance, cost and economic assessments have been made for sites in Hawaii, Oregon, California, Massachusetts, and Maine. Designs have been developed for both demonstration-scale and commercial-scale power plants. All wave plants are based on the Ocean Power Delivery (OPD) Pelamis WEC device shown in Figure 4a. A typical Pelamis-based wave farm power plant configuration is

FIGURE 4

Ocean Power Delivery Pelamis (a) and Farm (b) (courtesy Ocean Power Delivery).

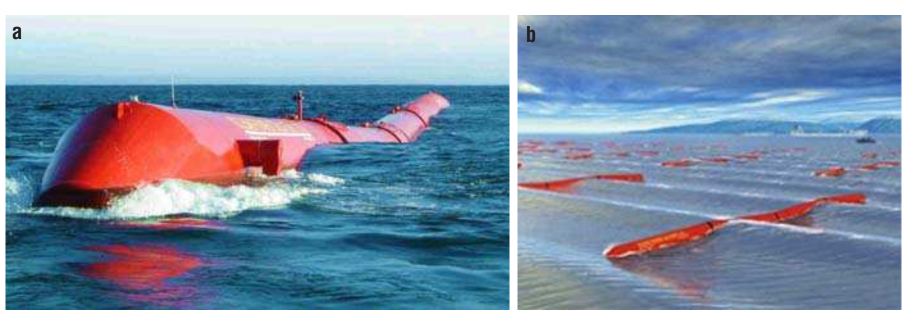


FIGURE 5

Energetech Oscillating Water Column (OWC), Australia (courtesy Energetech).

TABLE 1

WEC Costs and CoE in end-of-year 2004 current dollars (see EPRI WP-002-US Rev 4 for financing and incentive assumptions; each state has different tax rates and incentives)

	HI	OR	CA1	CA2	MA	ME
Number of Units 300,000 MWh/yr	180	180	213	152	206	615
Total Plant Investment (2004$M)	270	235	279	238	273	735
Annual O&M Cost (2004$M)	11	11	13	11	12	33
10-Year Refit Cost (2004$M)	24	23	23	15	26	74
CoE (cents/kWh)	12.4	11.6	13.4	11.1	13.4	39.1

illustrated in Figure 4b. A second study was performed for the San Francisco, California site with an Energetech oscillating water column (OWC) device shown in Figure 5.

The estimated investor-owned utility (IOU) generator busbar levelized cost of electricity (CoE) of the commercial-scale plants; each sized to provide 300,000 MWhr/yr, is shown in Table 1 with the California Pelamis design as CA1 and the California Energetech as CA2. The economic assessment methodology including financing and incentive assumptions is described in Report EPRI WP-002 (EPRI WP-002-US Rev 4).

WEC Technology Status

There are literally thousands of different conceptual ocean energy conversion devices patented. However, only a hundred or so have progressed to rigorous subscale laboratory tow- or wave-tank model testing, only 25 or so have progressed to short-term (days to months) small-scale tests in natural waters and only 10 or so have progressed to long-term (>1 year) large-scale prototypes in natural waters.

In addition to the OPD Pelamis and the Energetech OWC, other devices which have progressed to testing in natural waters during the last 10 years are listed in Table 2.

The time period for a technology to progress from a conceptual idea to deployment of a long-term full-scale prototype in natural waters is historically in the order of 5 to 10 years. The technology is in its emerging stage and it is too early to know which technology will turn out to be the most cost-effective in the future.

TABLE 2

WEC Device Developers in Natural Waters

Developer/ Country	Device Name	Deployment Location	Size & Grid Connection
AWS Energy UK	Archimedes Wave Swing	Portugal	700 kW in ocean grid connected
Ecofys Netherlands	Wave Rotor	Denmark	1:10 subscale in ocean and grid connected
Energetech Australia	Uiscebeathe	Australia	500 kW in ocean grid connected
Fred Olsen Norway	FO Research g “Buldra”	Norway	1:3 subscale in ocean not grid connected
Ocean Power Delivery Scotland	Pelamis	Orkneys, UK	750 kW in ocean grid connected
Ocean Power Technologies USA	PowerBuoy®	Hawaii, USA	40 kW in ocean, not grid connected
Renewable Energy Holdings UK	CETO	Australia	Subscale, not grid connected
Wavebob Ltd Ireland	Wavebob WEC	Ireland	1:4. subscale in ocean, Not grid connected
Wave Dragon Ltd Denmark	Wave Dragon	Denmark	1:4.5 subscale in ocean grid connected
Wave Star Energy Denmark	Wave Star	Denmark	1:10 subscale in ocean and grid connected

European Marine Energy Center

The European Marine Energy Centre (EMEC) (http://www.emec.org.uk/index.html), established in 2003, is a testing center in Orkney, UK that aims to stimulate and accelerate the development of marine power devices. The wave center's facilities include four test berths situated along the 50 m water depth contour off Billia Croo on the Orkney mainland (approximately 2 km offshore). Armored cables link each berth to a substation onshore. These cables link to an 11kV transmission cable connecting to the national grid and to a data/communications center located in nearby Stromness. The main elements of the facility are:

- **Four Test Berths:** Four individual armored cables (electrical conductor rated at 11kV/2.5-MW, two fiber-optic cables, and two control wires) connected to the onshore substation. The first wave energy device installed was the OPD Pelamis in 2005 and the next device planned for deployment is the Archimedes Wave Swing in 2008.
- **Substation:** Containing switchgear, metering equipment, power factor correction equipment, communications equipment, emergency generator, and the grid isolator.
- **Observation Point:** Containing two video cameras and a wireless communication link to the test site, linked back to the Value Center.
- **Weather Station:** Stand-alone solar-powered meteorological station linked to the Data Center.

American Marine Energy Center

The U.S. National Center (www.eecs.orst.edu/msrf) is proposed by Oregon State University (OSU) to be established in the next few years, located at a research/demonstration site in Newport, Lincoln County Oregon where land-based facilities would be integrated with the ongoing activities at the Oregon State University (OSU) Hatfield Marine Science Center (HMSC). The main elements of the facility would be similar to that at EMEC. The National Center will advance wave energy developments through a number of initiatives such as testing existing ocean energy extraction technologies, research and development of advanced systems, investigation of reliable integration with the utility grid and intermittency issues and development of wave energy power measurement standards.

Environmental Assessment

Given proper care in siting, deployment, operations, maintenance and decommissioning, wave power promises to be one of the most environmentally benign electrical generation technologies (EPRI WP-007-US). We anticipate that wave power projects will require coordination with local, state and federal agencies and may include field studies. Baseline assessments can frequently be accomplished through review of existing information and databases and through consultation with appropriate agencies and stakeholders. During the environmental permitting process for each project, it is expected that agency staff, other stakeholders, and developers will discuss concerns regarding potential project effects, project operational characteristics, and how effects can be avoided or minimized. Because of uncertainty about environmental effects, ocean wave plants will most probably be deployed first in pilot arrays and "built out" to commercial plant sizes using an adaptive management approach of monitoring to assure the promise of minimum environmental effects.

Societal Cost of Electricity Generation

Electricity is a critical "backbone" in sustaining the Nation's economic growth and development and the well-being of its inhabitants. Nearly 70% of the U.S. electricity is generated using fossil fuels. Electric power plants that burn fossil fuels emit several pollutants linked to environmental problems such as acid rain, urban ozone, and global climate change. The economic damages caused by these emissions are viewed by many economists as "negative externalities" and an inefficiency of the market when electricity rates do not reflect, nor ratepayers directly pay, the associated societal costs. There is much debate about the true value of these costs, but certainly the cost is greater than the zero cost currently applied by our society. Renewable power production from solar, wind, wave and tides usually has a lower environmental impact due to lower externalities, which represents a societal benefit over more traditional fossil fuel generation options.

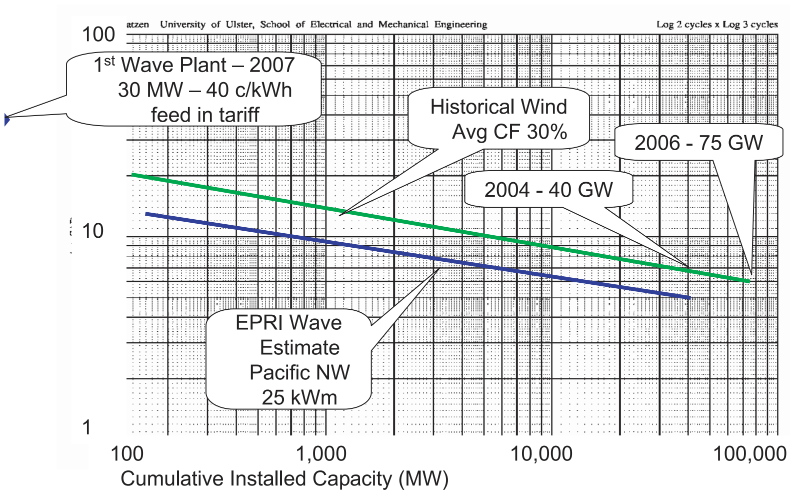
For planning new power generation, should regulators favor technologies with lower capital cost but higher emissions than technologies with higher capital cost and lower emissions? We will NOT attempt to answer that question; however, we will present data that will enable the reader to be able to weigh the costs, both capital and emission cost, of alternative electricity generation technologies. At the end of the day, society, through its politicians and regulators representing the will of the people, will answer this question.

Over two decades ago, as wind technology was beginning its emergence into the commercial marketplace, the CoE was in excess of 20 cents/kWhr. The historical wind technology CoE as a function of cumulative production is shown in Figure 6. Over 75,000 MW of wind has now been installed worldwide and the technology has experienced an 82% learning curve (i.e., the cost is reduced by 18% for each doubling of cumulative installed capacity) and the CoE is about 6 to 7 cents/kWhr (in 2006$ with no incentives) for an average 30% capacity factor plant. Wave energy technology today is about where wind was 20 years ago; just starting its emergence as a commercial technology. There are only a few MWs of wave energy capacity installed worldwide and the first commercial plant is being installed in Portugal at the 30 MW size and is receiving a feed in tariff of about 40 cents/kWh. The EPRI estimate for wave energy CoE in the Pacific Northwest, after applying a production tax credit (PTC) equal to that of wind energy is shown in Figure 6.

EPRI wave energy feasibility studies performed in 2004/2005 (EPRI WP-006-HI, WP-006-OR, WP-006-ME, WP-006-MA, WP-006-SFa, WP-006-SFb) showed that wave energy will enter the market place at a lower entry cost than wind technology did and will progress down a learning curve that is similar to that of wind energy (82% learning curve).

FIGURE 6

Actual Wind and Projected Wave Energy Cost of Electricity (assuming a PTC equivalent to wind energy).



A challenge to the wave industry at the very high installed capacities will be to assure that the inherently higher cost of offshore O&M compared to on-land wind O&M allows the wave technology total capital plus O&M CoE to be economically viable.

In order to quantify the monetary value of the emissions displaced by using wave energy instead of coal (whether wave will displace coal, gas or some other fuel and at what percentages is a question whose answer is unknown today), we take the pragmatic approach of monetizing SOx, NOx, Mercury, and CO_2 coal emissions at rates being paid in some areas. How much is being paid to avoid emissions provides an imperfect but explainable approach in estimating how great a harm the emissions are causing. The value of avoided emissions is shown in Table 3.

For a standard 500MW pulverized coal (PC) plant, monetizing the SOx, NOx and Mercury emissions above would increase the CoE from the 4.8 cents/kWh CoE of that standard PC plant to about 5.0 cents/kWh. Adding $15/ton CO_2 would increase the CoE of the plant from the 5.0 cents/kWh to 6.2 cents/kWh.

The avoided emissions at a deployment level of 4 GW of wave plants operating at 40% capacity factor, using a proxy coal fired plant with emissions at the New Source Performance Standard (NSPS) limit of what can be permitted (actual plants may be less), is shown in Table 4 (note that the emissions rate for mercury is for Bituminous coal and the NSPS for mercury varies with coal type).

Social Benefits of Wave Energy

The benefits to society offered by wave energy include: 1) providing a new, environmentally friendly and easily assimilated grid-connected option for meeting load growth and legislated Renewable Portfolio Standard requirements, 2) avoiding the aesthetic concerns which plague many infrastructure projects, 3) reducing dependence on imported energy supplies, increasing national security and reducing the risk of future fossil fuel price volatility, 4) reducing emissions of greenhouse gases by displacing fossil fuel-based generation, and 5) stimulating local job creation and economic development. Each of the five benefit areas are discussed in the following paragraphs.

1). Providing a new, environmentally friendly and easily assimilated grid-connected option for meeting load growth and legislated Renewable Portfolio Standard (RPS) requirements

EPRI believes that there is no panacea to our energy needs and that a diversified and balanced portfolio of energy supplies alternatives is the foundation of a reliable and robust electrical system. This means building and sustaining a robust portfolio of clean affordable options ensuring the continued use of coal, nuclear, gas, renewable and end-use energy efficiency. Wave energy is but one of the options, albeit a sustainable and environmentally friendly option, that we believe should be investigated as a potential new supply option for our national portfolio.

Wave energy is potentially "easily assimilated" into the electrical grid because we believe it may be accurately predictable two to three days ahead and sold as firm power and used for load balancing. The "ease of assimilation" statement is made compared to wind and concentrating solar thermal options.

A RPS is a state policy that requires electricity providers to obtain a minimum percentage of their power from renewable energy resources by a certain date. Currently there are 20 states plus the District of Columbia that have RPS policies in place. Together these states account for more than 52% of the electricity sales in the United States. Nearly 55,000 MW

TABLE 3

Emissions Avoided

	CO_2 $/ton	SOx $/ton	NOx $/ton	Mercury $/lb
Value	10-20	500-1,000	3,000-4,000	10,000-25,000

TABLE 4

Emissions Avoided

Pollutant	Emissions Rate (lbs/MWhr)	4,000 MW Wave Plant (tons/year)
2	1,600	11,000,000
Mercury	2.1 X 10^{-6}	0.014
Particulates	0.2	1,400

of new renewable capacity will be added in the U.S. by 2020 if the current RPS mandates are achieved.

2). Avoiding the aesthetic concerns which plague so many infrastructure projects

Wave energy may avoid aesthetic concerns that have plagued many infrastructure projects. WEC devices are sited many miles offshore and have a low profile above water (like an iceberg, much of the device is submerged). The submerged transmission cable will be buried and will be landed under the beach using horizontal directional drilling.

3). Reducing dependence on imported energy supplies, increasing national security and reducing the risk of future fossil fuel price volatility

The United States consumes 25% of all the oil produced in the world, yet we control just 3% of the world's oil reserves. As a result of this imbalance, we've become heavily reliant on foreign oil, much of which comes from the conflict-ridden Middle East. In 1974, our country imported 1 million barrels a day from the Persian Gulf; today, that figure tops 2.5 million. This dependence means our economy is highly vulnerable to changes in the price and supply of oil—a fact that's become all the more unsettling since the September 11, 2001, terrorist attacks in New York and Washington.

In the 1970s and early 1980s, oil and gas prices skyrocketed, making utilities and their customers keenly aware of their reliance on fuel sources. Oil and gas prices then plunged to low levels in the 1990s, resulting in construction of more gas-fired power plants. Prices to electric utilities fluctuated from about $2 to $3 per 1000 ft3 for most of the late 1980s and 1990s. In 2000, however, gas prices started to climb, and reached over $8 per 1000 ft3 by December 2000. Prices peaked at $9.47 per 1000 ft3 in January 2001, but by December 2001 had collapsed down to $3.11 per 1000 ft3. Such fluctuations are likely to continue in the future; no one knows just when and how much. Electricity systems using natural gas are exposed to this large fuel price risk; a risk that carries a cost. Renewable energy technologies, in contrast, are not subject to this risk as they don't use fossil fuels. It is a sound strategy for a utility to minimize fuel-price risks by taking low-cost steps to ensure a suitably diverse resource mix.

4). Reducing emissions of greenhouse gases

Electricity generation is the leading source of U.S. carbon emissions, accounting for over 40% of the total carbon emissions. Use of emission-free ocean energy instead of conventional pulverized coal energy to generate electricity means that 0.8 tons of carbon per MWhr of electricity produced is not released into the atmosphere. For a 300 MW PC plant that is almost 2 million tons of carbon per year. Of course, other emissions such as sulphur oxides, nitrous oxides, mercury and particulates are also reduced.

5). Stimulating local job creation and economic development

The economic opportunities are significant. A relatively minor investment today by government could stimulate a worldwide industry generating billions of dollars of economic output and employing thousands of people while using an abundant and clean natural resource.

Ocean energy is an indigenous energy resource. By harvesting this indigenous resource, jobs will be created and local economies will be improved. Construction and operations of wave energy plants would bring significant positive economic impacts to coastal states. As an example, EPRI estimates that the operation and maintenance activities alone will create about 25 direct local jobs per 100 MW wave power plant and these jobs are permanent for as long as the plant is in operation.

The U.S. economy would benefit from the large export potential of a strong domestic renewable energy industry.

Barriers

The primary barrier to the development and use of wave energy in the U.S. is the cumbersome regulatory process. The regulatory process being applied today was designed over a half century ago for conventional hydroelectric plants and does not fit the characteristics of today's wave and tidal in-stream energy conversion technology (EPRI WP-008-US). Extensive regulation applies to even small pilot projects whose purpose is to investigate the interactions between the energy conversion devices and the environment in which they operate. The impacts of these pilot demonstration projects are expected to be minimal given the small size of the projects. Developers cannot gather data on potential impacts through installation and operation of a short-term pilot demonstration project without going through the same license process that applies to 30 to 50 year licenses for major conventional impoundment or dam-type hydro projects. There is a provision whereby FERC will waive the requirement for a license for a small, experimental, short-term pilot plant as long as the developer does not realize revenue for the electricity that is generated and pays the local utility for the electricity displaced by the pilot plant's generation; a condition which many developers find unacceptable because it denies them revenue during the pilot phase. In addition, licenses are still required from many other regulatory agencies.

In the absence of information on how projects operate in real-world conditions and how they affect the environment in which they operate, ocean energy developers cannot attract capital. This existing regulatory situation is hampering and will continue to hamper the progress of the ocean energy industry in the U.S. The cost of these delays to American business is significant. While many countries in the world move forward with this technology, the U.S. remains on the sidelines neither benefiting its own industry nor benefiting itself in taking the steps necessary to overcome its addiction to fossil fuel-based energy.

Once regulatory barriers are removed, the next largest barrier may be the leveling of the playing field for ocean energy vis-à-vis fossil fuel and those renewable technologies that rely on government incentives. It is very difficult for a new technology to overcome market introduction barriers compared to established technologies even with a level playing field. The playing field is not level compared to fossil fuel generation technologies because these technologies are not made to account for negative externalities. The playing field is not level compared to wind and solar generation technologies because these technologies are the sole renewable recipients of production tax credits. An uneven playing field slanted away from ocean energy will hamper the progress of the ocean energy industry in the U.S.

While no technology barriers are evident, further technology advances are essential to achieving reductions in electricity cost from wave power plants. Therefore, the lack of U.S. government R&D funding is also a barrier, but this is offset by substantial funding from other governments and from private investors.

EPRI will continue to work to help the electric utility industry develop and demonstrate new renewable options for diversifying and balancing their generation portfolios and will continue to work to knock down the barriers that are impeding the investigation of these renewable generation options. We have a dream of an affordable, efficient and reliable power supply and transmission system that is environmentally responsible and economically strong. This electricity system is supported by an effective regulatory system that fosters the application of the best electricity generation technology for the good of society as a whole. EPRI will continue working to try to make this dream a reality.

As we in North America live in an increasingly global society, it is up to us, each and every one of us, to work together, not only to dream about our desired energy future, but to actively work together to make it happen.

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PAPER

Fresh Water from the Sea and Other Uses of Deep-Ocean Water for Sustainable Technologies

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ABSTRACT

Everyone and everything needs fresh water, and many sources of this precious commodity are in peril. In coastal areas, desalination of ocean water is an option, but it can be expensive, consume power, and generate waste. In recent times, the idea that the oceans can provide an "endless bounty" has been called into serious question with such evidence as the collapse of many fisheries and the growth of "dead zones" from waste and nutrient runoff. However, one resource of the ocean that may be practically inexhaustible is its reservoir of cold. Drawn from a thousand meters or more from the surface, Deep Ocean Water (DOW), barely above the freezing point, can be used in many ways, among them condensing fresh water from humid air in tropical environments. This fresh water resource requires little energy to produce, requires no chemicals, and produces no waste. It is most suitable for use in tropical islands and coastal deserts, which are generally near a source of cold ocean water, have warm, humid air, and little available fresh water. Further, there are other uses for the cold of DOW, enhancing agriculture in some surprising ways, and even supporting aquaculture. The Common Heritage Corporation of Hawai'i is investigating economically feasible development of this resource and other DOW technologies around the world.

Background

Fresh water is a vital commodity, and one in short supply in many places around the world. Production of fresh water where none is otherwise available generally involves some kind of desalination process (removing salts and other chemicals from seawater), either through distillation or a filtering process called reverse-osmosis. These and other techniques require significant consumption of energy, production of heat, use of chemicals, or production of waste products in some measure. Is there another way?

Most industrial processes, including the production of fresh water, use heat to drive the activity that yields the product. But it is not really the temperature that is important; rather, it is the temperature difference between hot and cold parts of the system that drives heat transfer. This temperature difference can be between hot and ambient surfaces, or between cold and ambient; either way, heat transfer can drive a process.

The depths of the world's oceans are cold. Close to the deep-sea floor, the temperature of the ocean ranges between 34 and 39 °F (1 and 4 °C); in fact, in the deep abyssal plains of the world's major ocean basins, the temperature can be below the freezing point of fresh water, leading to the whimsical term "liquid ice" for the cold, pressurized fluid found there. So, can we use the temperature difference between cold Deep Ocean Water (DOW) to drive some process?

The answer to this question was first explored through a system called OTEC, or Ocean Thermal Energy Conversion. The 60 million square kilometers (23 million square miles) of ocean surface in the tropics absorbs enough solar radiation every day equal to about 250 billion barrels of oil, yet the temperature difference between surface and bottom is relatively constant. OTEC systems use this natural thermal gradient to drive a power-producing cycle.

Like any major power plant, the OTEC process favors large systems and corresponding capital investments to achieve efficiencies of scale. Thus, in spite of the promise of OTEC as a renewable alternative energy resource, the economics of this current era of cheap oil have not yet favored its development on any significant scale. Is there a simpler way to make use of the oceans' reservoir of cold?

One idea put into practice back in the 1990s is very simple—just condense fresh water out of the atmosphere. In 1992, Eli Hay of Nisymco Inc., in Montreal, Canada and colleagues from the University of Nottingham built a prototype system designed to generate 1,000 gallons per day of fresh water from atmospheric condensation, using chilled water at around 50°F (10°C). Hay explored the relationships between cold-water temperatures, atmospheric humidity, flow rates, and types of materials used for condensing surfaces, among other critical parameters. Given a source of cold DOW, this process required little energy (just a circulating pump and fans), generated no waste materials, required no chemicals, and yielded pure fresh water.

Around the same time, in 1991, the Common Heritage Corporation (CHC) was founded by Dr. John P. Craven to develop a broad range of sustainable technologies surrounding the use of DOW. The original facilities and demonstration systems of CHC were built at the site of the Natural Energy Laboratory of Hawai'i Authority (NELHA), at Keahole Point near Kailua-Kona on the Big Island of Hawai'i. As co-founder of NELHA in 1974, its president for nearly two decades, and chairman of the board for its first decade, Craven led the development of DOW systems technologies at this unique research facility.

At NELHA, CHC was able to use DOW collected from pipelines laid at a depth of 2,000 feet, and experiment with cold seawater temperatures below 45°F (7°C). During the 1990s, CHC and NELHA explored a number of uses for DOW, including fresh water production, energy conversion, agriculture, aquaculture, and even human physiological treatments. The fresh water production component matured into a patented process called SkyWater; the agricultural process, also patented, became known as ColdAg™. As we shall see, pure, clean fresh SkyWater is sufficient unto itself, but ColdAg™ is both an irrigation technique and a thermodynamic process that affects crop growth in remarkable ways that are still being studied.

DOW Installations

In the tropical oceans, to obtain cold DOW at 45°F (7°C) or below, one must generally draw the water from a depth of more than 2,000 feet. A number of installations exist around the world that have used non-corroding high-density polyethylene plastic, essentially sewer pipe, to bring the water to the surface. Plastic pipe has many advantages, including availability, ease of assembly, and durability. Also, the insulating properties of the pipe help reduce heat loss from the DOW while ascending to the surface.

The pipe is laid by first "welding" sections together on shore (that is, heating and fusing the ends of segments) and feeding them out to a sheltered bay or lagoon. As they are fed into the water, concrete weights are added that will be used to anchor them to the bottom when placed on site. With the water end sealed, the flotation of the air-filled pipe is sufficient to keep the growing continuous pipe from sinking. The completed pipe is then towed into position (usually at night when conditions are calmer), and sunk in place by allowing air to escape and water to flow into the pipe. Meanwhile, a landfall section is prepared, which may require burial or even tunneling to be sure that the pipe can survive weather, tides, and currents. The job is complete after an underwater inspection of the critical landfall section using divers and/or robotic vehicles (ROVs). As expensive as these piping systems are, they should last decades if properly designed and installed.

It is important to site the system near deep water, to minimize the run of piping. Longer pipes are more expensive to build and install, develop more "head loss" requiring larger circulating pumps, and allow the DOW to warm more before reaching the plant. Also, sites should be at a low elevation so that the DOW does not have to be raised before use, again requiring more pumping. Fortunately, there are many tropical island and coastal desert locations around the world that meet these criteria.

In most DOW applications, the seawater itself is never touched, and simply returned to the ocean slightly warmer than when collected. Since this water is distinctly different from the near-shore water, both in temperature and nutrient content, it is wise not to discharge it directly offshore, but rather to return it at some intermediate depth. For this reason, a second (shorter) pipe is needed. Annular designs involve placing the source pipe inside a larger return pipe, with the return water flowing through the annular space. This not only simplifies installation, but helps further insulate the DOW from the warmer surrounding surface waters.

A typical recent installation was performed (by Makai Ocean Engineering, Inc. of Hawai'i) on the island of Bora Bora in Tahiti. Designed primarily to support seawater air conditioning (SWAC) of the island's Intercontinental Hotel, the pipeline is 2.3 kilometers long (7600 ft) and has a diameter of 400 mm (16 inches). It supplies frigid 41°F (5°C) DOW from a depth of 2950 feet (900 meters). The water is circulated using a 15-kilowatt seawater pump, providing cooling that would otherwise consume 300 kilowatts of electricity from a traditional air conditioning plant. Still, only half of the capacity of the system is used, allowing the addition of other DOW technologies drawing from the same resource.

Fresh Water Production

Fresh, potable water literally falls from the sky with SkyWater technology. In coastal desert communities, where rainfall is scant and humidity high, the interplay between the atmosphere and the surface of pipes filled with cold DOW yields pure drinking water under controlled, pristine conditions. There are few processing steps and moving parts, and SkyWater can be produced less expensively than other water processes, such as reverse osmosis and desalinization, which have heavy energy demands.

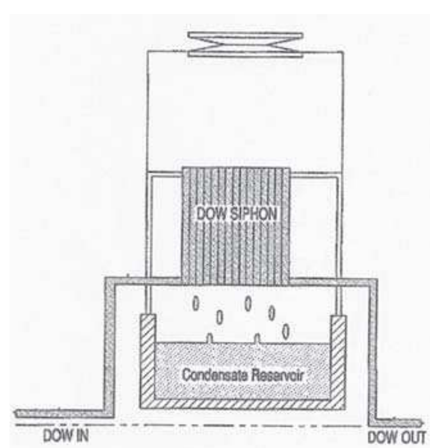
The key to the system is that the cold resource is not manufactured, but instead comes from a natural-occurring and inexpensive resource. CHC's technology takes advantage of atmospheric vapor conditions, cold deep-sea water, and dew point temperature. At Keahole Point in Hawai'i, the dew point (DP) temperature averages 60-68°F and relative atmospheric humidity averages 65-80% (RH). Any surface material below dew point temperature will condense pure freshwater from the atmosphere. A simple sketch of a SkyWater unit is shown in Figure 1.

Traditional solar distillation processes require a large humidification area to heat seawater to near vaporization temperature. Solar distillation produces freshwater vapor that rises to the top of the solar collector, where it condenses and, thereafter, is collected. SkyWater uses DOW as cooling fluid plumbed to a fluid-to-air surface condenser, greatly increasing the freshwater condensing capacity and reducing the overall collection area compared to traditional solar still designs.

Since the water is condensed from the atmosphere, there is no filtering as with reverse osmosis, and no risk of contamination from source fluid or chemicals.

One of the key factors in the performance of a SkyWater system is the design and material selection. One of the original demonstration systems in Keahole Point simply used coils of PVC pipe suspended over a collection barrel. Although the steady flow of moisture from the coils was impressive, much could be gained from design improvements.

FIGURE 1



PVC is a poor material for heat transfer, but it is inexpensive and non-corrosive. Many seawater heat exchanges are made from titanium, which also has good corrosion performance and better heat transfer, but is very expensive. The system built by Hay and Brewer at the University of Nottingham (the Brewer model) took advantage of new techniques for manufacturing roll-bonded aluminum heat exchanger flat panels to achieve much better rates of water production. The heat transfer comparison is best illustrated by assessing the physical properties as shown in Table 1; numbers vary for different alloys and manufacturer's performance data. Heat conductivity is given both in Watts per meter per degree Kelvin, and in English units of BTU per hour per degree F per foot.

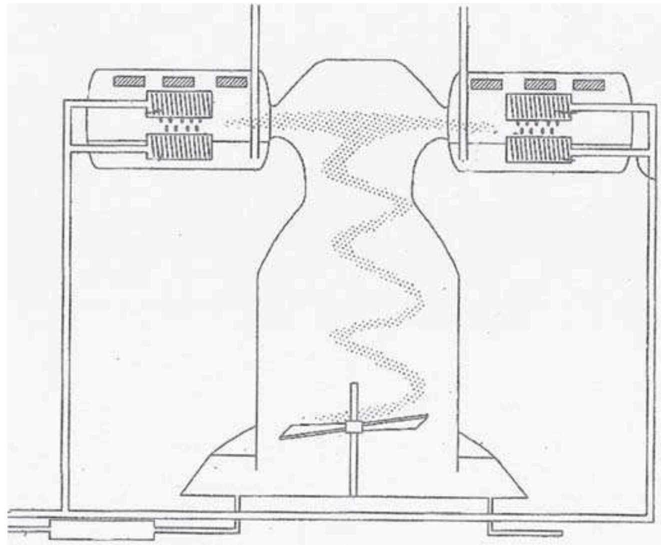
TABLE 1

We can see an enhancement in heat transfer of an order of magnitude between titanium and aluminum, and more than two orders of magnitude for PVC. The Brewer model showed that aluminum heat exchangers could be built with reasonable economy, and future production systems will probably be made this way.

A simple condensing system is effective, but there are more efficient ways to use the DOW cold in conjunction with available solar heating, which is in abundance in most tropical areas suitable for DOW technology. One device that takes advantage of this is known as a "Hurricane Tower."

The device consists of three or more stages, the first being a dehumidifying (condensing) stage as described above. The rate of fresh water collection from the heat exchanger can be increased by vibrating the heat exchanger to increase the rate of dripping. But rather than returning the warmer DOW back to the sea, some of it is directed by a gravity siphon to stage two of the device: an evaporation tower, heated by the sun, which vaporizes some of the DOW. The tower is configured as a chimney and includes a vortex generator that operates to maximize the flow of the vapor up towards a collection structure above the tower. Another condenser cooled by DOW is placed in the path of the vapor to be condensed. The fresh water condensate that is collected has been cooled by the DOW and is itself available for use through a gravity siphon feed into a third stage. A vibrator, as in stage one, may be used here to increase the level of condensate collection.

FIGURE 2



A simple sketch of a Hurricane Tower is shown in Figure 2. It is also possible to enhance the sea water evaporation process with an evaporation pool, heated by the sun, feeding additional humidity into the system.

Additional stages of condensate collectors can be stacked one upon the other and use additional siphons and heat exchangers to feed the cooled freshwater by gravity to successively higher elevations to condense the atmospheric water vapor present in the surrounding region. In theory, these vertical stages may be stacked to higher elevations until the atmospheric pressure becomes too low and/or the temperature of the collected water is greater than a dew point of the surrounding region.

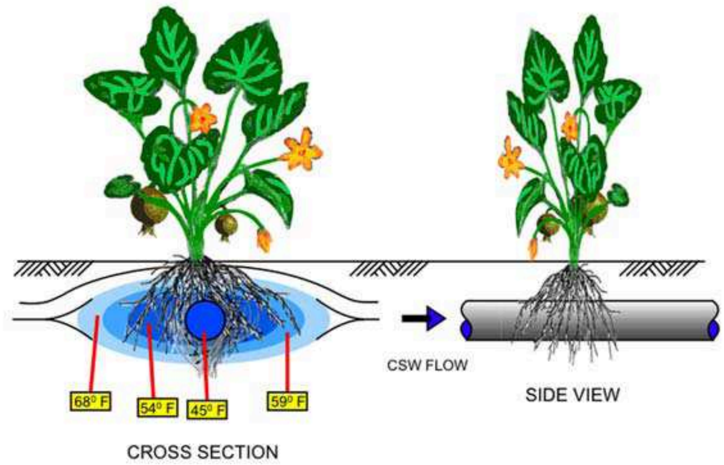
Cold Agriculture

The same fresh water condensing process can take place in the soil. Dubbed the "Blue-Green Revolution," this agricultural technology uses cold DOW to create a healthy soil environment suitable for many plant species to grow and thrive in the harshest of tropical, coastal conditions. At Keahole Point, rugged, inexpensive PVC piping was laid in crushed lava covered with composted soil as a medium for plant growth. Chilling the soil causes moisture to condense in the vicinity of root growth, pinpointing delivery of water to the plant without evaporative or drainage losses. In fact, plant roots will grow towards this source of water, and even encircle the piping, maximizing the effect.

But that is not all. It seems that the plants actually become part of the DOW system. The cooled soil creates a constant springtime condition, promoting vigorous growth of fruits, vegetables, flowers, and herbs associated with virtually any climate zone. This innovation allows for soil temperature control and plant dormancy, enabling multiple crop production per year. And it requires little, if any, irrigation, as the cold pipes produce abundant freshwater condensation. A sketch of a typical plant using a cold agriculture system is shown in Figure 3.

There is relatively little research available on crop production using cold-water agricultural systems. Most of the research has been carried

FIGURE 3



out by CHC at its NELHA demonstration site. In 2004, a summary of progress was prepared by Marc M. Siah & Associates, Inc., in collaboration with Common Heritage Corporation. Dr. Kent Fleming, an Agricultural Economist at the College of Tropical Agriculture, University of Hawai'i at Manoa, was instrumental in this study. The following, paraphrased from the report, gives a good overview of the ColdAg™ process and its far-reaching applications.

CHC scientists have evaluated about 100 different crops over the past 12 years with varying results. Most of the crops tested grew at least fairly well. The relatively few exceptions were primarily those crops, such as watermelons, that require exceptionally high amounts of irrigation. Although traditional irrigation does not work well with cold-water agricultural systems, CHC has experimented with specialized systems that enable growth of crops requiring additional water supplies.

Some high-quality crops have already been identified using these methods; these include fruits and vegetables that are harvestable in a relatively short period of time. Much of the early work was derived using anecdotal information on the role of cold in plant sugar and protein production. For example, it was observed that, in temperate climates, most fall fruits have a surface that is ideal in color and texture for heat rejection to a cold atmosphere and that the colder the atmosphere, up to the point of freezing, the sweeter the fruit. It was also noted that cacti, which are not exposed to night cold, do not flourish, and that high quality straw mushrooms require a significant period of exposure to extreme cold in the range of 4-6°C (40-43°F).

Further, many hydroponics systems are found to require cold nutrient fluids, and lettuce is known to thrive in 38°C (100°F) temperatures as long as the soil is kept cool. At a 1992 workshop sponsored by the University of Hawai'i Sea Grant program and CHC, the significance of the use of low cost cold in agricultural production was explored with particular examination of the effect of temperature differentials between roots and surface on plant physiology. Based on the theories and information from that workshop, CHC experimented with application of cold to the roots of strawberries in its demonstration garden.

Through trial and error and a fortuitous, though unplanned-for, period of neglect, the strawberries thrived and the roots particularly sought the cold pipes around which to grow. Subsequently it was discovered that the initial belief that only spring crops would be successful in a microclimate most closely resembling spring was erroneous, and that spring, summer, and fall crops of almost every species enjoyed high quality, unusual sweetness, and rapid growth from the ColdAg™ process. Asparagus plants, for example, were brought through three cycles of growth in less than nine months, a reduction by more than a year of the period between conventional planting and harvesting.

It is now recognized that the thermodynamic processes in plant growth play a major role in the transport of phosphates and nitrates to the fruiting and vegetation areas, and that the production of high energy products such as sugar is highly dependent upon temperature differences along the transport path of these nutrients.

A simplified model would note that the photosynthesis process begins with the transfer of photon energy to various phosphagens at the site of formation of the biological molecules. The energy of the phosphagens is released as required to anabolic and catabolic enzymes that cut the water molecules and fix carbon and nitrogen. Thus, the sugars that are composed entirely of carbon, hydrogen, and oxygen can be manufactured from constituents present in the atmosphere at the level of plant growth. Indeed, nearly all of the energy required for plant production comes from the photons in a process that is essentially isentropic, i.e., frictionless. Thus, the higher the temperature, the greater will be the photosynthetic activity.

Even so, only a small portion of the solar insolation is employed in plant growth. One of the limiting factors is the presence or absence of phosphagens at the production site. Phosphorus, which is non-existent in the atmosphere, must come from the soil. It must acquire its potential energy from a thermodynamic process that extracts energy from the differences in temperature in the various process fluids. The one scientific observation of the temperature structure and plant response in the demonstration garden was made for the simple root crop, the carrot. A pipe embedded at approximately 28 cm (11 inches) maintained soil temperatures of 10°C (50°F). Other pipes embedded at about 10 cm (4 inches) established soil temperatures of 14°C (57°F). Daytime surface temperatures were high and in the vicinity of 37°C (98°F). Carrot seeds employing their own internal energy projected initial root and stem structures above and below the ground. The root filaments then very rapidly grew until they reached the point of maximum cold. Thereafter plant production consisted of enlargement of the root and the production of foliage.

FIGURE 4

™ System.

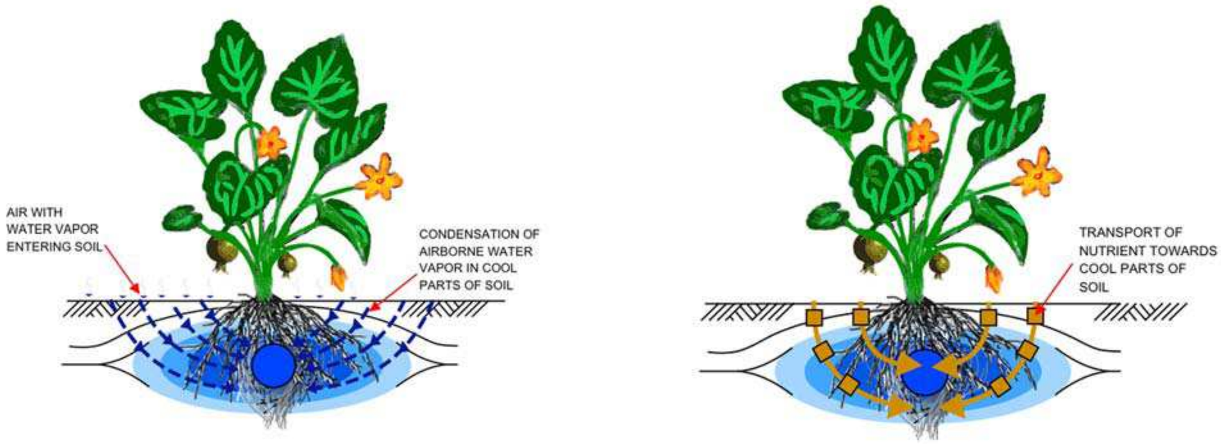


FIGURE 5

If the surface temperatures are below the dew point, condensate will appear. This moisture will migrate to the point of maximum density (i.e., the coldest spot in the soil). During the migration, the water will dissolve soil nutrients and carry them in the solution to this coldest spot. There the root acts as a wick carrying heat from the top of the plant down to the root, producing a thermal convection whose flow rate will be a function of the difference in temperature between the root and the plant extremities. If this is the predominant mechanism of transfer of phosphates and nitrates, then this process should be equally beneficial to spring, summer, and fall crops. In particular, the total energy process should lead to the production of high-energy sugar and aromatic molecules. This result was confirmed by taste tests. A few preliminary comparisons of sugars from coldwater agriculture with those from conventional gardens confirm this observation. It is now well established that the application of cold to the root area of crops produces unusually sweet fruit not only in annual but also fall fruits.

The grapes shown in Figure 5 were grown at the demonstration garden at NELHA using the ColdAG™ process and crushed lava as a soil substrate. This is one of many examples of success in growing crops that ordinarily do not thrive in tropical climates.

It should be noted that while condensate supplies the vast majority of water used by plants, some fresh water is necessary in arid coastal areas like Kona to wash salt spray from the ocean off the plants to prevent sun and salt burn on the leaves. However, surface application of water must be done with great care to ensure that the thermodynamic behavior of the ColdAg™ process is not disturbed, that is, a continuous temperature gradient must be maintained between the "fruit and the root."

Other DOW Technologies

Unfortunately, although DOW is free and essentially inexhaustible, there is a cost to moving it from the deep ocean to places it can be used. By far, the biggest cost is the pipe, which is a large capital expense in any system. Fortunately, a well-designed installation can last for decades with little or no maintenance. There is a modest cost in moving the water through the pipe, to overcome heat losses from fluid friction. To make the best use of the resource and to reduce the payback period for the pipe expense, a practical and economic system would include multiple uses of the same flow of DOW.

Certainly, if a large OTEC system were built, a subsidiary use could begin with freshwater production, possibly using the "waste DOW" of the energy generation process, depending on the temperature and environmental conditions.

In many locations, the first use would be seawater air conditioning (SWAC). As mentioned earlier, SWAC has been used effectively in locations such as Bora Bora. In fact, one of the early applications of this technology is still in operation in the city of Halifax, Nova Scotia. In 1983, a system was installed to cool a group of office towers on Purdy's Wharf at the city harbor. Drawing cold water through a 36 cm (14-inch) pipe directly from the harbor at temperatures as low as 2°C (36°F), the system (including an upgrade in 1989) provides almost all of the cooling needs for the complex's two 22-story towers and 700,000 sq-ft of space. Titanium heat exchangers are used, handling a maximum cooling load of 2 MW. The system cost $500,000 to develop and install, and saves $250,000 per year in electricity. (Capital costs in this case were low, since the pipe only needed to be laid to a depth of 23 m (75 feet) to get below the 15 m (50 foot) thermocline. Also, a backup conventional air conditioning system is sometimes needed in the fall when the seawater temperature is at maximum, but this use is generally minimal.)

In 1998, Eli Hay (collaborator in the development of the Brewer model) built a prototype aluminum heat exchanger, which was tested in place of one of the titanium units. It provided two-thirds of the performance of the titanium unit for only one-tenth of the pressure drop. This means substantially less circulating pump power required for the equivalent performance.

The temperature rise in the DOW upon exiting a SWAC system may be small enough that it is still suitable for a SkyWater plant, or depending on design, some fresh DOW can be blended to lower the temperature to an optimum level. After its use in fresh water production is exhausted, the DOW may still be cold enough for ColdAg™, which in some cases can usefully work with input temperatures as high as 16°C (61°F). Thus, a series use of the same DOW can maximize the extraction of cold from the resource before it is returned to the sea.

Even further uses are possible, such as aquaculture. DOW is uncontaminated by surface pollutants, nutrient rich, and colder than surface waters, making it ideal for aquacultural use. It is possible to reduce the use of biocides and feed, improving the health, environmental impact, and economics of the process. Some of these techniques have been under investigation at NELHA.

Finally, there are direct human uses of DOW. It has been suggested by Dr. Craven, founder of CHC, that application of cold to the body under controlled conditions can have health benefits; research is being conducted to substantiate and quantify these claims. And at the Intercontinental Hotel at Bora Bora, one can relax in a spa filled with pristine, nutrient rich (and substantially warmed!) DOW.

Current Developments

Under a research grant from the U.S. Department of Energy, CHC is currently working on the island of Saipan in the Commonwealth of the Northern Marianas to investigate the economic feasibility of a DOW system in that location. It is fitting that such research should be taking place there, near the site of the Marianas Trench, the deepest spot in the world's oceans.

In February of 2007, a CHC team visited Saipan to validate site selection for the investigations, to work with on-island researchers who will set up and operate the experiments, and to meet with local government officials to assess the level of support for such an endeavor. On the latter issue, the team was met with resounding enthusiasm from all parties, including the Governor and the legislature. The need for fresh drinking water is keen, and the ability of farmers to grow new crops that could provide economic opportunities was recognized. Saipan is a key tourist destination for travelers from Korea, China, and Japan, so there is an interest by resorts for specialty garden crops, and even for golf course turf (all of which must be imported for now).

In support of this effort, crops are being planted in test gardens both on Saipan and in Hawai'i (Oahu), using chilled water to simulate DOW under controlled conditions. Data from this research will add to the body of knowledge on ColdAg™ and demonstrate the feasibility of growing such crops in the particular conditions of the island. If the capital can be gathered to lay one or more pipes, Saipan can become a great success story in the development of sustainable DOW resources.

Meanwhile a success story is already being told in Bora Bora, where DOW is flowing and return on the initial capital investment is growing. Richard Bailey, the far-sighted developer of this system, is encouraging the spread of this technology, and CHC hopes to enhance his SWAC system with SkyWater and ColdAg™ capabilities in the near future. An interesting short video describing the Bora Bora system can be found on http://www.youtube.com/watch?v=zTGvPrrkVAA.

Conclusions

The promise of Deep Ocean Water applications is exciting, especially as other resources become scarce, energy costs increase, and environmental impact concerns grow. Once a source of cold DOW is established, a number of uses can be set up in series, using the ocean's cold to generate fresh drinking water, enhance agricultural products, and support aquaculture with little cost of operation. Initial demonstration programs over the last decade have shown that these technologies are possible; now, investigations are underway to assess the feasibility of developing full-scale systems in suitable areas of the world. Included in these studies are economic factors, weighing the high capital and low operating costs against other means of production. Another factor, harder to compare, is the sustainability of DOW technologies, since the resource they draw upon is essentially inexhaustible. Possibly the advent of "carbon credits" and related measures of assessing the impact of technology on the environment will help show the merit of DOW applications in this regard. It is expected that the next few years will see large-scale implementations of DOW system, initially focusing on air conditioning with ancillary ColdAg™ gardens and small fresh water units. In time, success of these installations could lead to specialty farms in coastal deserts, and larger arrays of water production systems. Ultimately, Dr. Craven's vision of a sustainable coastal village integrated with DOW and related technologies could be a reality.

Author's Note

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