Natural Cold Water District Cooling Plants Enabled by Directional Drilling

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ABSTRACT

This paper suggests an alternative method of accessing ocean and lake water to be used for sustainable energy. In particular, the paper introduces the use of Horizontal Directional Drilling (HDD) from shore, underneath the seafloor, to the point of extraction, thereby creating Protected Seawater Conduits (PSC) to transport water to be used primarily for comfort and process cooling. Initially, the paper outlines the history leading up to this technology, citing the lessons learned from pioneering projects that have led to the development of the proposed technology. Examples are given for both hydrothermal cooling and directional drilling to demonstrate how this comprehensive system mitigates the financial and environmental risks of the prior art while emulating nature in providing energy without waste. In addition to comfort and process cooling, the paper also discusses several additional benefits to be derived from this application.

INTRODUCTION

This paper introduces a sustainable approach in the field of comfort and process cooling that can be adopted by certain coastal communities to both decrease CO_2 emissions as well as increase CO_2 absorption by the oceans. This approach targets coastal communities that have deep cold water (4^oC) within the reach of horizontal directional drilling, a drilling technique that is commonly used in the oil and construction industry. When brought onshore, the cold water is utilized for hydrothermal cooling in lieu of mechanical cooling.

Projects harvesting energy from the ocean by laying down pipes dates back to 1929 in Cuba. Pioneering efforts have been made to use this deep cold ocean and lake water for space cooling since the 1980's at Hawaii's NELHA. There are four major projects around the world that use natural cold water for space cooling. These projects have exhibited remarkable savings over mechanical cooling of up to 90% and yet other coastal communities with deep cold water close to shore have proposed similar Seawater Air Conditioning (SWAC) projects but have not been able to gain traction. These projects used a process of controlled submergence of pipes with concrete collars into the body of water. This process is not without risk in installation and many potential sites have sensitive seafloor environments which must be crossed to access the cold water. Such projects may either be too costly or will not meet the rigor of an environmental assessment.

This paper introduces an innovation to overcome past deficiencies by using a mature technique used in petroleum extraction known as Extended Reach Drilling (ERD) or Horizontal Directional Drilling (HDD). This technique enables directional drilling under the surface to access deep cold water with a horizontal displacement of up to eleven kilometers from shore. Following thorough discussion of the history leading up to the innovation named Drilled Hydrothermal Cooling, the paper will then outline the several sustainable processes that can be incorporated through the access of deep cold water.

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THE PROGRESS OF OCEAN THERMAL ENERGY AND HYDROTHERMAL COOLING UP TO 2010

Early Daring Ocean Energy Pioneers

Harvesting thermal energy from the ocean traces its roots to 1881 when French physician Jacques-Arsène d'Arsonval first proposed using a heat engine based on the work of Scottish engineer William Rankine. D'Arsonval surmises that "if pumps pull enough water through two separate sets of pipes, the warm seawater will evaporate a heat transfer liquid (such as ammonia or propane) in one part of the plant; elsewhere, cold seawater recondenses the gas to liquid. But as it blows from the first point of phase change to the second, the gas stage will drive a turbine" (Chiles 2008). The physician, turned ocean scientist, knew that coastal areas close to deep cold water and warm surface water could produce power from the temperature difference.

In 1902, another innovator, named Willis Carrier, used Rankine's heat engine principle in reverse for an air conditioning or cooling application. This system employed a working fluid (such as CFCs) to aid in removing heat from where it was objectionable (evaporator), using a compressor instead of a turbine to aid in the rejection of heat (condenser), to where it was not objectionable. This led to the application of the vapor compression cycle including the chilled water systems widely used in buildings and district cooling plants today.

A colleague of d'Arsonval, Georges Claude, was enthralled with the potential of ocean energy when, in 1929, he convinced Cuban dictator, Gerardo Machado, to build ocean thermal power plants that "could light up not only the entire island and its new industry but also deliver surplus power to Florida by undersea cable" (Chiles 2008). Matanzas Bay, Cuba was selected for its relatively close proximity to cold and warm water.

Mishap No. 1 – In August 1929, six foot diameter steel pipes in 70 foot sections were welded together and floated out to sea on pontoons in three sections when a storm hit and sank most of the pipe.

Mishap No. 2 – In June 1930, a second attempt was made by building a long pipe on an adjacent river and dredging a cut in the sandbar that was separating the river from the sea. Cables from a tug boat would drag the long snake-like pipe out into the ocean. However, during the tugging operation, the pipe snagged and broke, sinking the pipe to the bottom of the bay.

Mishap No. 3 - Claude ordered more pipe from France, this time with a combination of rail-cars on land launching onto pontoon boats. This attempt also ended in a complete loss of the pipe after the pontoon boats were not well coordinated.

Mishap No. 4 – Undaunted, Claude ordered more pipe but this time from his own account and now dwindling fortune. In September 1930, the pipe was laid successfully but not as deep as planned and consequently with lower temperature differential. The power plant ran for 11 days and produced enough power to light forty 500 watt light bulbs. Investors viewed this as too little return compared to the risk.

Mishap No. 5 **–** Claude's last attempt at harvesting energy from the ocean was in the open sea off the coast of Brazil. Eight foot diameter pipes would be sunk vertically from a ship. A storm at sea during installation scuttled this project and ended Claude's ocean energy dream and drained his fortune.

Although no attempts proved to be successful, valuable lessons were learned from Claude's misfortunes. These lessons would be applied in future applications.

Ocean Thermal Energy Finds a Home in Hawaii

In 1974, the Natural Energy Laboratory of Hawaii (later named NELHA) was established by the State of Hawaii legislature on a 322 acre area at Keahole Point on the Big Island as a support facility for Ocean Thermal Energy Conversion (OTEC) research. If successful, NELHA would "prove the feasibility and usefulness of OTEC as an alternative non-polluting power source" ("Deep," 2010). In 1979, the first successful project was an at-sea, closed-cycle OTEC operation conducted aboard the Mini-OTEC, a converted Navy barge operating in waters off Keahole Point, Hawaii. This plant operated for three months and generated up to 55 kW of gross power. About 40 kW were required to pump up 2700 gallons/min of 42°F water from 2200-ft depth through a 24-in diameter polyethylene pipe and an additional 2700 gallons/min of 79°F surface water, leaving a maximum net power output of 15 kW. This preceded a shore based project by NELHA in 1980. **As depicted in Figure 1**, on the Big Island of Hawaii, the first shore based series of pipelines was constructed to draw warm surface seawater from 45 feet and deep cold seawater from 2000 feet at Keahole Point and was once used to air condition the facility. The deep ocean pipeline transitions from land under the shore break and then protrudes out the seawall where it is laid at an incline on the seabed down to the 2000 feet.

On a 2009 visit to the NELHA facilities, co-author Marie Reny learned that the cold water pipe, which protruded from the seawall under the surf break, was experiencing a warmer water temperature. This change in temperature coincided with a 2006 earthquake in the area. It was speculated that perhaps the earthquake caused a crack in the pipe at the upper portion allowing warmer water to seep in. This speculation has added to the growing concern for the vulnerability of surface laid piping. Natural disasters ranging from hurricanes to earthquakes have the potential to destroy surface laid piping. The innovation herein alleviates this growing concern.

Although there is room for improvement for the overall design of the applications, it must be known that "NELHA is 'landlord' to nearly 30 thriving enterprises which generate about $30-40 million per year in total economic impact, including tax revenues, over 200 jobs, construction activity and high value product exports. Two pipeline systems pump deep and surface seawater to shore continuously and a third, the world's largest and deepest (to a depth of 3,000 feet), is being developed now" ("NELHA," 2010). NELHA is certainly an excellent model for the sustainable future necessary in the 21st century.

OTEC Pipe In Hawaii Potentially Compromised After 2006 Earthquake

Figure 1
The deep ocean pipeline installed at NELHA Keahole Point transitions from land under the shore break and then protrudes out the seawall where it is laid at an incline on the seabed down to the 2000 feet. In a 2009 visit to NELHA, it was noted that, after a 2006 earthquake, the water from this pipe rose in temperature. It is speculated that the pipe has cracked in the upper region allowing warmer seawater to seep in.

Early Adopters of Hydrothermal Cooling

The NELHA experience spawned a group of ocean energy pioneers and, despite the US Government's abandonment of support for OTEC, they concentrated on cooling with deep lake water or deep seawater. These projects are collectively known as "hydrothermal cooling." There are currently four installed major hydrothermal cooling plants around the world. The Purdy's Wharf Complex in Halifax, Nova Scotia cooled a small office complex ("Seawater," 1992). The next hydrothermal cooling plant has a link to the 'Father of Air Conditioning,' Willis Carrier. Nearly a century after Dr. Carrier's invention changed the world, his alma mater, Cornell University, has followed suit with a Lake Source Cooling System that provides roughly 18,000 to 20,000 tons of cooling ("About," 2006). For a decade now, the Cornell campus has been cooled with 39°F water from the adjacent Lake Cayuga. The previous mechanical chiller plant at Cornell in 1999 was operating at .83 IkW/ton. The new plant is now operating at 0.1 IkW/ton or 86% less electricity, thereby providing significant savings in fuel expense and avoiding carbon emissions at the power plant. The InterContinental Hotel in Bora Bora, of the Leeward Islands in French Polynesia, is cooled by deep seawater proving 90% savings over an electric chilled water system ("InterContinental," 2007).

Taking the current lead in hydrothermal cooling, the Enwave District Cooling project in Toronto provides roughly 59,000 tons of cooling from 4°C (39°F) water from the deep water of neighboring Lake Ontario ("Enwave," 2010). The project final cost was approximately $128 million dollars but one of the key return on investment strategies was to dual purpose the water not only for cooling but also for pure drinking water. The Toronto Lake Source District Cooling project connected 3 sections of 2 kilometer long pipe and floated the 6000 meters of piping onto Lake Ontario **as seen in Figure 2.** To submerge the piping, they employed a controlled submergence technique developed by Joe Van Rysin and his team at Makai Engineering, Hawaii. As seen in the project documentary, during the installation, the wind picked up suddenly and the vast pipeline on the surface precariously flexed as a snake. The pipe was successfully submerged but there was speculation that a further increase in wind velocity and the pipe might have snapped and been lost to the bottom. Sounding eerily similar to the misfortunes of Georges Claude, this near miss has once again indicated the need to have a more robust solution in deploying pipes to access water.

Lake Source Cooling Proven Feasible But Reveals Risk of Piping Deployment

Figure 2
The 1997 Toronto Canada Enwave Deep Lake Water Cooling project is a breakthrough project in hydrothermal cooling. The HDPE pipe with concrete collars was floated out into Lake Toronto and submersed in a controlled process. The 4^{o}C lake water is used to produce more than 59,000 tons of natural cooling. The video of the historic installation told of tense moments in the installation when the wind precariously increased, perhaps risking the entire project.

THE PROGRESS OF DIRECTIONAL DRILLING

Early Pioneers in Directional Drilling

Directional drilling is defined as the ability to steer a drill-stem and bit to a desired bottom hole location. It is a technology that has flourished in the last few decades in both the oil and construction industries. Vertical drilling is common yet the practice of "drilling sideways" was started in the petroleum industry to access oil and gas reservoirs. The first horizontal well was reportedly drilled near Texon, Texas in 1929 (USDoE 1993). "Chambers (1998) noted early horizontal activity dating from 1939. In the early 1940's, horizontal wells were drilled with horizontal distances of 100 to 500 feet (Anon 1999). China attempted its first horizontal well in 1957 (USDoE 1993)" (Molvar 2003).

Beginning in 1963, a young contractor and innovator, named Martin Cherrington of Sacramento California, saw the potential of horizontal drilling as an alternative to open cut trenching in the civil construction industry. This would be an important improvement to the laying of utility cables and pipes. This Horizontal Directional Drilling, or HDD method, consisted of drilling at an angle with mud motors at the rear to clear away the excavation and keep the hole open. By trial and error, Cherrington discovered drill bit configurations that could drill initially in a downward angle and then predictably in an upward angle. **As seen in Figure 3,** this was particularly useful in placing conduits underneath rivers. The method involved penetrating the surface on one side of an obstacle, creating a tunnel of sufficient diameter underneath the obstacle and upward, penetrating the surface on the other side of the obstacle. The hole may then be reamed out to a larger diameter. The final step is to pull the required number of pipes through the drilled hole. This was later to be known as "directional crossing," starting in 1971 with Cherrington's Titan company who, under contract from PG&E, successfully drilled a crossing under the Pajaro river near Watsonville, California USA (Cherrington 2010).

Petroleum Drillers Push the Envelope of Extended-Reach Drilling

The first oil wells were drilled roughly 150 years ago on the shores of the Caspian Sea and in the state of Pennsylvania USA (Campbell and Phil 2006). Vertical drilling was the method of choice for extracting oil from the subsurface. In the past three decades, three factors have influenced the change in drilling from vertical to horizontal.

The first factor is commercial. An article in Journal of Petroleum Technology summarized the current role of horizontal drilling, "Most experts agree that horizontal wells have become a preferred method of recovering oil and gas from reservoirs in which these fluids occupy strata that are horizontal, or nearly so, because they offer greater contact area with the productive layer than vertical wells. While the cost factor may be as much as two or three times that of a vertical well, the production factor can be enhanced as much as 15 or 20 times, making it very attractive to producers (Anon 1999)" (Molvar 2003). The cost per foot of drilling a horizontal well versus a vertical well is getting much closer. According to Sarma and Ono (1995), "The 1993 Joint Association Survey of drilling costs on 845 horizontal wells indicated that, at $80.76/ft, a horizontal well was only 8% more expensive to drill per foot than a vertical well."

The second factor influencing the move to horizontal drilling is environmental. The environmental benefit of directional drilling is vividly displayed by Eric Molvar (2003) as he argues that the pipelines and access roads "destroys the wild character of primitive areas, severely diminishes the recreational value of the landscape, creates long-term scarring across scenic viewsheds, and degrades or destroys habitat for native wildlife and fishes." **Figure 4** depicts

Introduction Of HDD In The Construction Industry

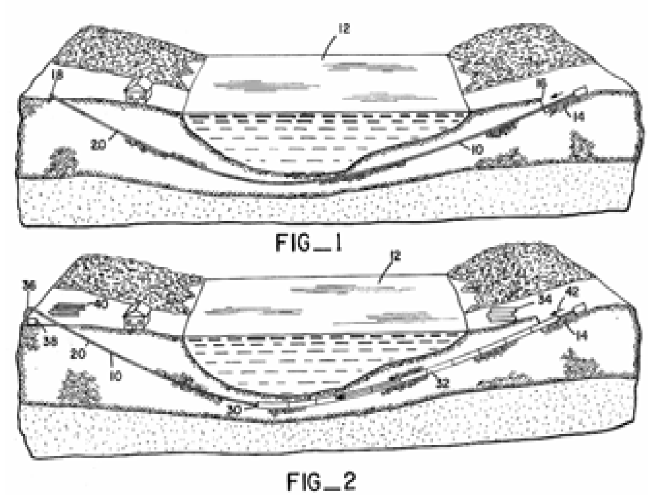
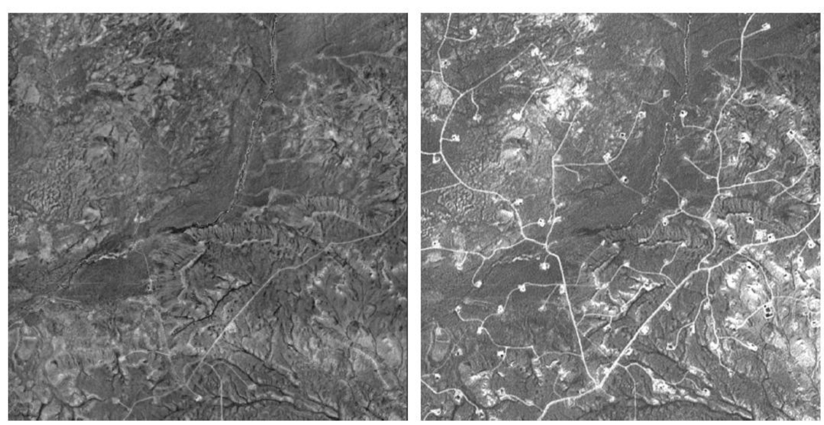


Figure 3
Martin Cherrington, author of US Patent 3,894,402, introduced a method of drilling horizontally to locate utility conduits underneath obstacles such as rivers. This foreshadowed the Horizontal Directional Drilling industry, also known as Trenchless Technology (Cherrington 1975).

Vertical Oil Wells Create An Environmental Problem For Which Directional Drilling Can Solve



Images provided by SkyTruth and the Upper Green River Valley Coalition

Recent full-field development in western Wyoming's Jonah Field as shown by aerial images. The photograph at left shows the landscape in 1994, before full-field development. By 1999 (at right), the landscape had become fragmented by roads and well pads.

Figure 4
Imported from Eric Molvar's (2003) paper, these photos illustrate the significant impact to the surface environment of multiple vertical oil wells that directional drilling techniques, such as extended reach drilling, could have avoided.

the before and after of multiple vertical drilled wells and the impact on the surface environment. Drilling multilaterally from one or a few points to several locations would greatly reduce the impact to the environment of multiple vertical wells.

The third factor influencing the movement to horizontal drilling is its technological superiority. One of the key technological advances in HDD was Measurement While Drilling (MWD), also known as Logging While Drilling (LWD). This technology gathers information at the well bit and sends it instantaneously to the drilling engineer's computer. Relative position of the bit in 3D, consistency of rock, effectiveness of the drilling fluids and other factors are evaluated in real time. This information significantly reduces the risk and relative cost of the drilling operation.

Extended-Reach Drilling (ERD) is the process of drilling relatively deep bores where the horizontal distance traveled is more than twice the true vertical depth. The ERD technique is generally a long-radius well. The wellbore shifts from the vertical to the horizontal very gradually, with only slight changes in the degree of slope over the course of the bend. BP has documented the ERD wells drilled as of September of 2006 where the horizontal step-out has reached to 11 kilometers ("K&M," 2003). This distance is well within the reach of many coastal communities with the potential for hydrothermal energy plants. The local conditions play a major role in determining the cost of an ERD project. According to Tim Boulay, Senior Drilling Engineer of the K&M Technology Group, "Costs of ERD wells can vary greatly, anywhere from $3-4million up to well over $150 million. Contributing factors are overall complexity, location, geology, formation pressures, onshore or offshore, water depth, rig requirements, and industry economics" (Boulay 2010).

In April of 2009, the Society of Petroleum Engineers sponsored a forum titled "Overcoming Barriers to Deliver ERD Wells Beyond 15 km" ("Overcoming," 2009). It appears the industry trend is to go further. These distances are being made possible with another advanced technology known as the Rotary Steerable Drives. Schlumberger, a leader in drilling equipment, participated in a project in the North Sea with their Rotary Steerable drive and saved over $140 million in development cost over previous technology ("Reduce," 2006).

Still another method making extended reach drilling

Technological Advances Lower The Cost Of Directional Drilling

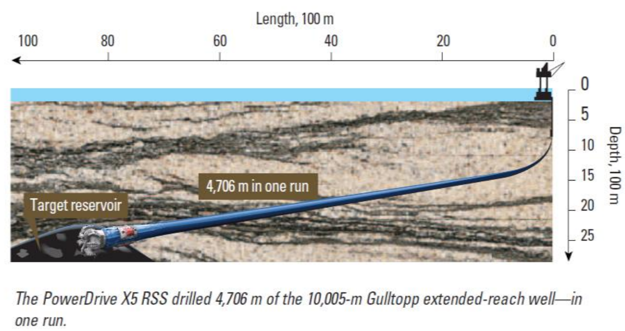
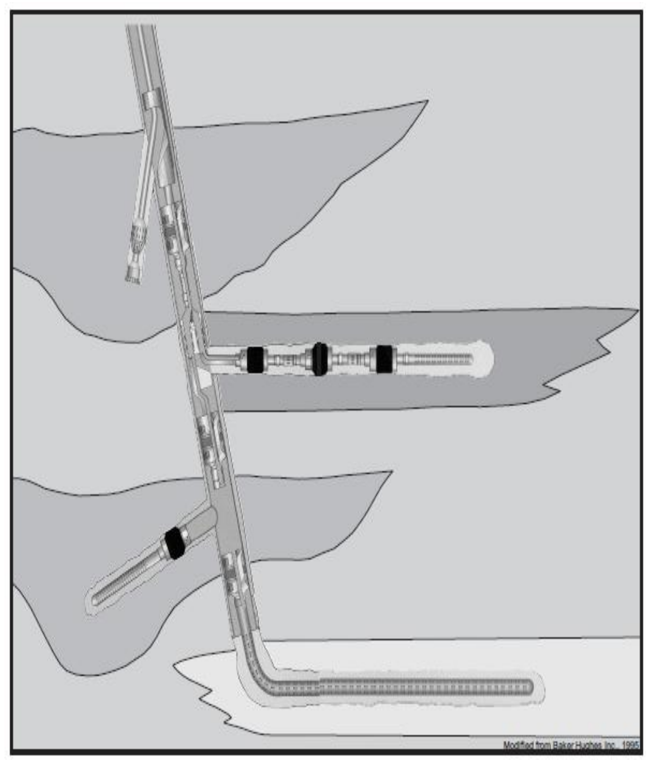


Figure 5
Rotary steerable drill bits offer faster drilling through the rock than older directional systems. This Schlumberger Rotary Steerable Drive pictured above was used at a 10 kilometer long extended reach drilling project in the North Sea. Use of this new technology was reported to save $US 140 million in development cost over previous technology("Reduce,"2006).



The above diagram illustrates a multilateral well bore. Peripherals are drilled from a main well bore. This method decreases the drilling cost per volume of extracted petroleum (Judzis et al. 1997).

technology more cost effective is multilateral drilling. This method entails drilling peripherals from a single main vertical or inclined bore. Multilateral drilling has now become an established practice within the oil and gas industry. Chambers (1998) summarized this growing role: “The implementation of multiple lateral wellbores, or multiple horizontal wells exiting a single wellbore, has gained wider acceptance in the oil industry, particularly from a reservoir management point of view. The deeper the junction, the more attractive multilaterals become. The more wells drilled, the cheaper the technology, the more laterals drilled from a well, the less the incremental cost for additional laterals. Open hole branches are very easy to create and fast to implement.” **Figure 5** gives a visual representation of a multilateral well in Alaska.

INTEGRATING OCEAN THERMAL ENERGY AND DIRECTIONAL DRILLING

In August 2005, the author and Don Murphy, then Vice President of Engineering for Marriott International, were touring Caribbean hotel properties in search of ideas for improving the efficiency of hotel energy plants. Discussions regarding the Lake Source Cooling projects at Cornell and Toronto evolved into how similar technology could be applied to tropical resort properties, many of which are adjacent to cold water. It was surmised that laying pipes in the ocean would be risky in implementation with the generally “angry” sea and sudden onset of violent weather. Moreover, the exposed pipes would be subject to damage by the violent currents of hurricanes. In addition, environmental permitting would be difficult as the Caribbean Islands are replete with sensitive sea bed habitats, such as coral reefs, that would have to be avoided. Using creative problem solving, it was theorized that a horizontal directional drilling rig could be positioned in the parking lot of the hotel. The rig could drill a diagonal “rock tunnel” of sufficient diameter to bring cold sea water of about 40°F temperature to a surface pool. Using heat exchangers between the cold seawater and the hotel’s chilled water system, 42°F to 44°F could be easily produced, thereby enabling the chillers and cooling towers to be shut down. Chiller and cooling tower operating costs represent 50 to 70% of the hotel’s energy bill. This cost would be virtually eliminated with such an innovation.

Following up on the idea, the author traveled to Folsom, California in September 2005 to discuss the application with Martin Cherrington, (the patent holder inventor of HDD) and Trenchless Technology Engineer, Dr. David Bennett (the 2005 Trenchless Technology Man of the Year). Both men were in agreement that, given that the resource is within the horizontal reach of directional drilling, such an application would be feasible. It was also confirmed that, in their experience, nothing like drilling to access ocean water for energy purpose had been done before. A provisional patent for the idea was filed on 15 September 2005.

DRILLED HYDROTHERMAL COOLING

On 11 May 2010 the US Patent Office published patent number 7,712,326 (Jagusztyn et al. 2010) which introduces directional drilling to the field of Ocean Thermal Energy. **As illustrated in Figure 6,** the hard lessons learned

Drilled Hydrothermal Cooling: An Innovation Reducing Carbon Emissions And Increasing Ocean Carbon Absorption

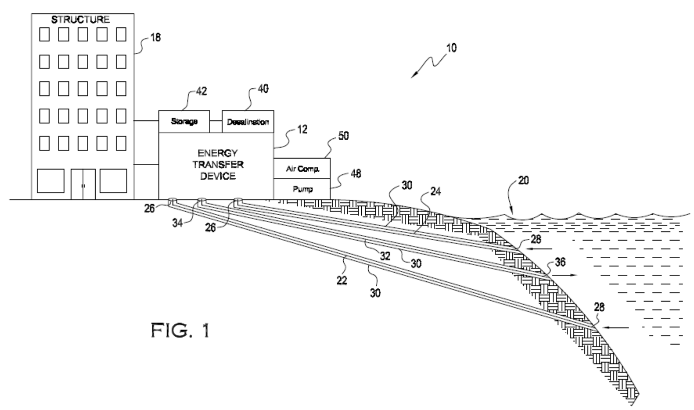


Figure 6

The above patent drawing (Jagusztyn et al. 2010) illustrates the concept of using directional drilling to access cold (4°C) ocean or lake water. This environmentally responsible method of extraction and discharge avoids disturbing coral reefs and thermal pollution, while protecting the investment from earthquakes and hurricanes. This cold water, when brought to onshore wells, will be used for space cooling and process cooling saving 90% of the comparable mechanical cooling cost. Clean low cost electric power may be generated from the temperature difference of warm surface water and deep cold water. This power may also be dedicated to generate low cost hydrogen fuel. Upon returning the mineral rich deep water to the upper layer, ocean atmospheric carbon absorption is increased, thereby mitigating climate change.

from Georges Claude were heeded and now the path is illuminated to drill 'Protected Seawater Conduits' (PSC) into the oceans or lakes. These PSC's avoid the perils of nature prevalent during implementation. The PSC's are not affected by the violent ocean currents as exposed pipes would be. An exposed pipe must transition from the earth to the open water underneath the shore break. During an earthquake, the pipe may be exposed to different stress levels, particularly at the junction. Provided that a PSC does not cross a fault during an earthquake, the pipe should move together with the surrounding rock encasement thereby decreasing the conduit's vulnerability. This enables commercial hydrothermal cooling opportunities to those coastal communities within the horizontal reach of extended reach drilling.

Lake Source Cooling Opportunity

Water reaches its maximum density at 39.16°F (3.98 °C). Below this temperature, water is less dense, which explains why ice floats. Above this temperature, water is also less dense and forms a thermocline on up to the surface. Most deep lakes have a dense boundary layer called a "hypolimnion" layer which secures a vast renewable supply of 39°F water year around. Lake Ontario is a particularly deep lake already hosting one of the first hydrothermal cooling projects mentioned earlier. Environmental scientists studying the environmental impact of hydrothermal cooling have stated that 20,000 cubic meters per second could be extracted and replaced without harming the physical properties of the lake (Newman and Herbert 2009). At a temperature difference of 10 degrees Fahrenheit (39°F to 49°F), the amount of cooling potential for natural water district cooling plants along the shores of New York State and Ontario Canada would be over 132 million tons. Lakes Superior, Michigan, and Huron have an even greater potential. Lake Erie is the exception being relatively shallow with only a small hypolimnion layer.

Many industries use a great deal of cooling and electricity in the production of their products. Flat screen TV manufacturers, micro chip manufacturing, automotive, dairy and food industry, to name a few, all use cooling in their process, the cost of which at say 1.0 IkW/ton becomes part of product cost. Coastal communities near deep cold water may consider Drilled Hydrothermal Cooling plants to attract industries to their area to increase the employment while using DHC to lower their cost.

Seawater Cooling Opportunity

Oceanographers divide the ocean into categories by depth. The broadest category is the upper part of the ocean known as the "photic" zone. This is generally regarded as the upper 200 meters of the ocean where sun light penetrates and photosynthesis takes place. The bottom part of the ocean is called the "aphotic" zone where sunlight does not add heat and cold temperatures are present. Bathymetry and oceanography studies suggest that at an ocean depth of at least 1000 meters, 4°C water temperature is assured. **Note in Figure 7,** the potential to drill for cold water in Puerto Rico is within an 11 kilometer horizontal reach of directional drilling. The area near Punta Tuna, on the south east of the island, seems to have an exceptionally close proximity from the coast to the 1000 meter depth contour line. There is also deep cold water at depths less than 1000 meters. The 1000 meter contour line should be a starting point for environmental scientists and oceanographers to confirm the location and temperature off the shore for potential projects. As an example, Dr. Vance Vicente, an environmental scientist from Puerto Rico estimated that the Marriott hotel in San Juan is roughly 2 miles, or 3.2 kilometers drilling distance, from the 4^oC cold water of the Puerto Rico Trench.

Professor Yu (2008), formerly of Purdue University, points out opportunities on both coasts of the United States stating that "it is estimated that Florida and California could reduce their peak electricity demands by about 5-10% if deep seawater is used extensively for space cooling, which would avoid CO_2 emissions by millions of tons annually." In fact, the predecessor to the US Department of Energy, ERDA, in 1975-77, funded two studies on the "Feasibility of a District Cooling System Using Natural Cold Waters" (Hirshman and Kirklin 1977). The initial report concluded that the coast of Southern Florida, from Fort Lauderdale to Miami Beach, would be the most suitable location in the US to use naturally cold water for comfort cooling. The second report made an actual feasibility study for a Miami Beach seawater district cooling plant

Puerto Rico Has Deep Cold Water And Warm Surface Water Relatively Close To Shore

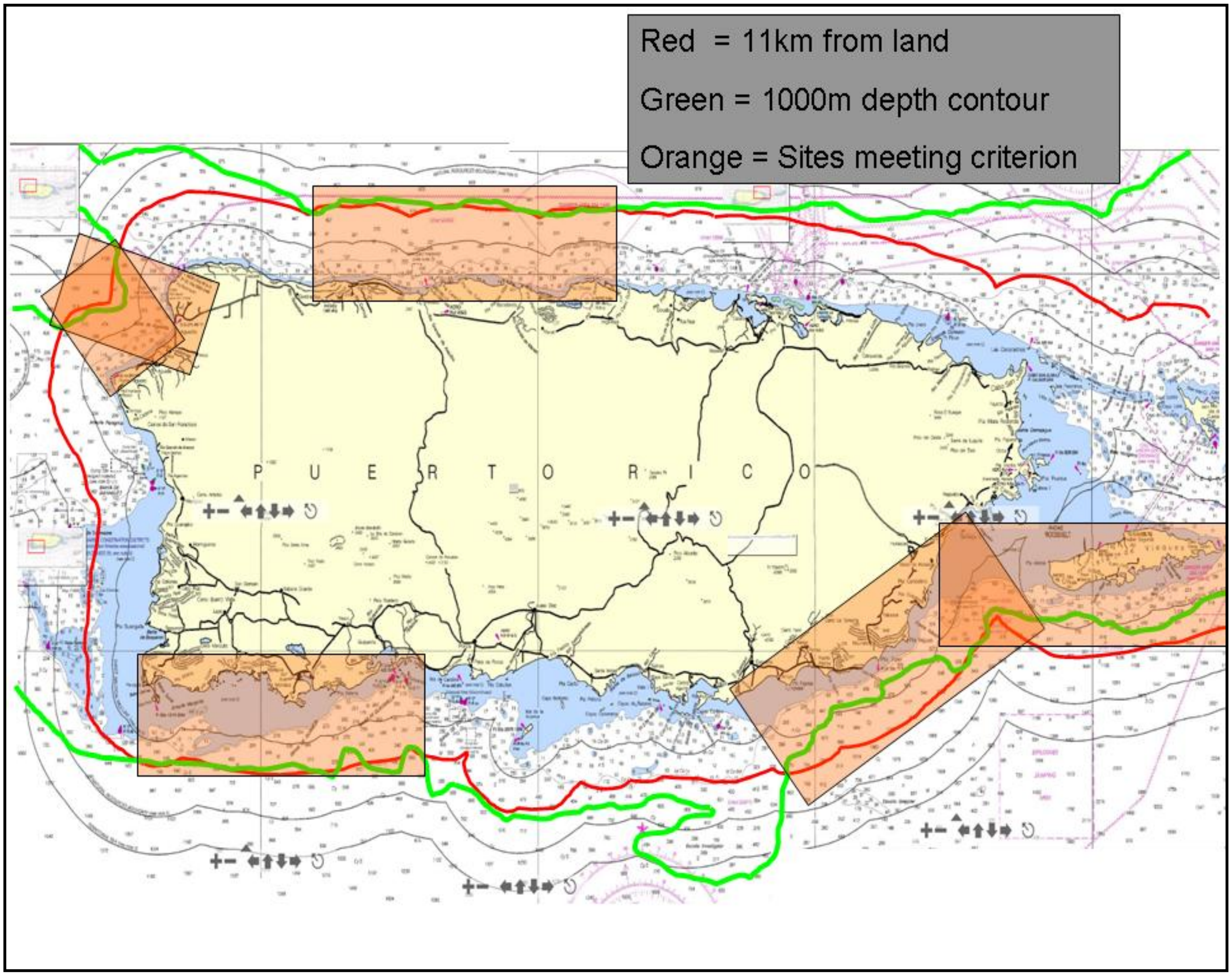


Figure 7

The above illustration is a bathymetry study of the waters off the coast of Puerto Rico identifying areas where Drilled Hydrothermal Energy can be used. At a depth of 1000 meters, the temperature of ocean water is assured to be 4 °C (39° F). ERD can reach out 11 km. These areas around the island of Puerto Rico can be used for District Cooling, Electrical Power Production and Hydrogen Fuel Production.

situated at Indian Beach Park. The conclusion of the report states that the "payoff of investment costs with energy savings is seen to be in the fifth year of operation using the recognized discount/inflation rate of ten percent and a differential energy cost escalation rate of seven percent" (Hirshman and Kirklin 1977). **Figure 8** outlines this application at Indian Beach Park. The feasibility site seems to be still available at the present time.

Miami, Los Angeles, Puerto Rico, the islands of the Caribbean and Hawaii, among many others, are all located within this accessible deep water and can therefore use directional drilling to access cold water for comfort cooling and process cooling, thereby saving 90% over the cost of electrically driven air conditioning as was experienced by the InterContinental Bora Bora application ("InterContinental," 2007). HVAC professionals, cooling customers and utilities in deep water coastal communities are well advised to consult with oceanographers to preliminarily assess the natural cooling opportunity in their locale. Once the resource is confirmed, the authors recommend that a qualified, multi-discipline team make a feasibility study.

1977 Miami Beach DOE Seawater District Cooling Feasibility Study Suggests a 5 Year Payback
The Site Seems To Be Still Available In The Year 2010

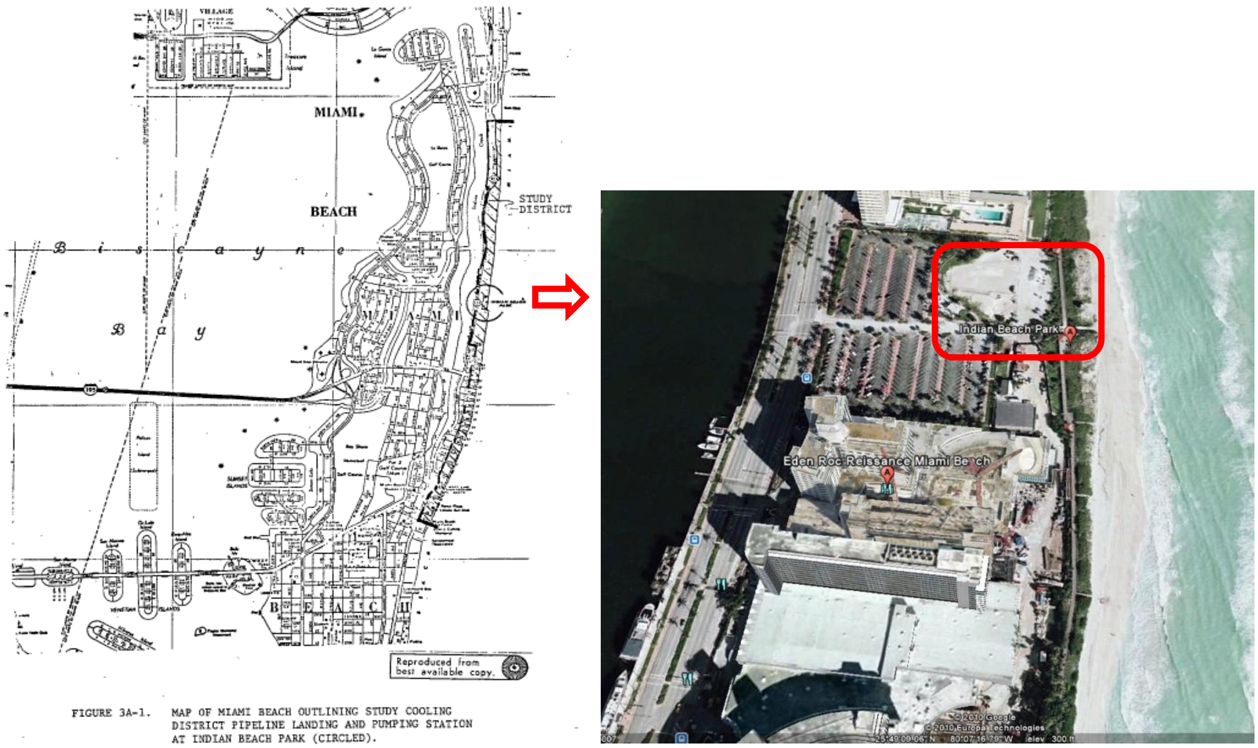


Figure 8
The map (left) is from a US Government sponsored feasibility study locating a cold ocean water district cooling plant on Miami Beach Florida at Indian Beach Park (Hirshman and Kirklin 1977). The study concluded a payback of 5 years but no action has been taken in Florida. The picture (right) shows a current photo of the same location, still relatively available, with a park and parking lot and new potential cooling customers such as the Marriott Group property next door at the Eden Rock Renaissance.

Improving Pumping Efficiency With Airlift

Ocean energy pioneer, Dr. Luis Vega (1999) of Hawaii, teaches us that typically 20% - 30% of the parasitic power of an OTEC plant can be consumed by mechanical pumping of the water. The reader will recall that Mini OTEC consumed 40 of 55 kW in pumping. To minimize or avoid this excess consumption, the authors suggest using “airlift” technology to move the water with air pressure rather than mechanical pumping. In the oil industry, air or gas is injected within the down hole about one third of the true vertical depth. The bubbles expand as they rise to the surface, thereby bringing the fluid to the surface. Airlift specialist, Dr. Sam Kondo of Dublin, Ohio, has developed and demonstrated a special version of an airlift pump which can move massive amounts of water with relatively low air pressure and low power consumption (Kroeger 2010). Taking this concept one step further, General Compression, a startup company in Massachusetts, is developing a technology to integrate an air compressor directly connected to a wind turbine to generate and store compressed air. This compressed air energy source can be used to pump water from the depths without using grid power and without the corrosion and maintenance issues of mechanical pumping of ocean water. Therefore, it becomes entirely possible to eliminate the parasitic power mentioned by Dr. Vega, particularly if wind, wave, tidal or ocean current turbines are deployed to compress the air to transport water.

Estimated Savings and Sizing of Drilled Hydrothermal Cooling (DHC) Plants

In the Middle East, companies such as Tabreed have developed an expertise in constructing district cooling plants equipped with multiple large capacity centrifugal chillers. In 2005, the author visited the offices of Tabreed in Dubai and Abu Dhabi and spoke with the engineers and then chairman, Dani Safi. It was learned that district cooling plants of total capacity, from 22,000 to 23,000 tons, seem to be the optimal size, given limits of pipe diameter sizes, that are cost effective and within the distribution system. Higher delta T is also preferable to lower pumping costs.

The actual capacity for a DHC plant would depend on the diversified load for cooling customers within the community served. An example can be derived using the empirical evidence from the before and after case of the Cornell Lake Source Cooling plant to estimate the savings of a DHC plant versus a 23,000 ton district cooling plant using mechanical cooling. Recall that the system efficiencies at Cornell were 0.83 kW/ton for the mechanical plant, including the chiller, pumps and tower fans and 0.10 kW/ton for lake source cooling. Assuming that the 23,000 ton plant in a tropical climate runs a yearly average of 50% load (11,500 tons) at .83 kW/ton for constant operation (8,760 hours per year) at a blended rate cost of $0.12 per kWh, the annual savings of such a plant are over $8.8 million as calculated below:

$$\textbf{Annual Power Cost} = \frac{\textit{System KW}}{\textit{Ton}} \times \frac{\textit{TONS}}{\textit{Hour}} \times \frac{\textit{Hours}}{\textit{Year}} \times \frac{\$\ \textit{Blended Cost}}{\textit{KW}}$$

$$\textbf{Estimated Mechanical Plant Annual Power Cost} = \mathbf{0.83 \times 11{,}500 \times 8760 \times \$0.12 = \$10{,}033{,}704}$$

$$\textbf{Estimated DHC Plant Annual Power Cost} = \mathbf{0.10 \times 11{,}500 \times 8760 \times \$0.12 = \$1{,}208{,}880}$$

$$\textbf{Estimated Annual Savings of DHC Plant} = \mathbf{\$\$10{,}033{,}704 - \$1{,}208{,}880 = \$8{,}824{,}824}$$

Island nations, such as Curacao in the Caribbean, must import oil to generate electricity. Consequently, electricity rates are relatively high at $0.32 kWh. A DHC plant of 23,000 tons in Curacao with a high loading factor would have significantly higher savings than calculated above. When the new DHC plant replaces the cooling of individual buildings, the savings will most likely be greater as the individual system efficiencies are commonly greater than 1.0 kW/ton. The Cooling Tower Institute suggests that chiller systems in the US taking a 400 ton capacity, for example, range from 0.661 kW/ton for water cooled systems to 1.21 kW/ton for air cooled systems (including fans and pumps in both cases) (Vallabhaneni 2005). Note that these figures represent new machines with clean tubes (.00025 fouling factor) and pristine condenser fins and peak load of the ARI conditions representing a temperate climate. Although chillers generally perform more efficiently at part load or at lower than design conditions, observed systems show that, as chillers age, the equipments performance deteriorates. Tropical climates, which form the bulk of candidates for DHC projects, have higher temperatures which also drive up the kW/ton. As previously mentioned, the Seawater Cooling Project at the InterContinental Hotel in Bora Bora went on record stating that their Sea Water Air Conditioning system saves 90% over a traditional cooling system ("InterContinental," 2007). Therefore the statement that a SWAC or DHC cooling plant saves 10 times the cooling cost for tropical areas is true based on empirical and theoretical evidence. These examples are given to allow the reader a perspective of the order of magnitude of the financial savings. Developers should pay particular note to the fact that there is ample room for profitability when a customer is paying 12 cents for a ton-hour of cooling and a DHC plant's raw cost is about 1.2 cent for a ton-hour of cooling.

For a 23,000 ton capacity DHC plant, assuming the availability of 39°F to 42°F cold natural water and a 12°F temperature rise, the required seawater flow would be 46,000 GPM as calculated by the formula below (ASHRAE 2004):

$$\textbf{GPM} = \frac{\textit{TONS} \times \mathbf{24}}{\textit{Delta T}} \quad \frac{\mathbf{23{,}000\ tons \times 24}}{\mathbf{12}} = \mathbf{46{,}000}\ \textit{GPM}$$

Lockheed Martin Corporation has announced the development of 4 to 10 meter diameter pipes for offshore OTEC power generation applications. These pipes entail a clever innovation of fabricating pipes while on an OTEC platform

(Varley 2010). Perhaps a vertical well can be constructed onshore with these large diameter pipes, inserted into a down hole and connected with directional drilling to the point of extraction. To access water with a single pipe for 46,000 GPM, a 48 to 60 inch diameter pipe would be required. Using ERD, multiple, multilateral conduits up to 30 to 36 inches in diameter may be drilled from the main feeder pipe to targets penetrating the sea wall at depth. Given that the target reservoir is within the technological limit of ERD (currently 11,000 meters), a seawater or lake water DHC plant of 23,000 tons capacity is within the grasp of current technology. Site specific research must be conducted with technical rigor to determine the optimum configuration and commercial viability. The authors suggest the key in initiating a DHC project is to have the right team of experts in the various disciplines assembled to perform the assessment.

OTHER BENEFITS OF DRILLED HYDROTHERMAL ENERGY

One of the lessons learned from the Toronto Lake Source Cooling project was to utilize the water for more benefit than just cooling. The Toronto project also used the deep water for drinking water. Likewise, the commercial viability of Drilled Hydrothermal Cooling plants would be enhanced if further benefits were implemented much like the $30-$40 million dollar industry that we learned grew from the NELHA pipe in Hawaii.

It is envisioned that a plant may start off supplying cooling and then gradually drill for more of the resource as the need arises. The following outlines some other embodiments or benefits that can be obtained from an initial DHC plant.

Increasing CO_2 Absorption

Currently, there is an estimated 8 billion tons of CO_2 outflow per year into the atmosphere while only 3 billion tons of CO_2 inflow is being absorbed by the oceans and land (Senge et al. 2008). The 5 billion tons of atmospheric CO_2 imbalance is a serious challenge. Returning the ocean water after using it thermally is an important part of the innovation. Refer to the middle conduit or outfall of the Drilled Hydrothermal Cooling innovation in **Figure 6**. In the preferred embodiment of this innovation, the return water, which is at a higher temperature, is discharged at a middle level in the body of water at approximately the same temperature that exists at that point in the thermocline. By introducing mineral rich deep water to the upper level of the ocean, a process beneficial to the environment is enacted. In a detailed overview of the OTEC system, Richard Crews (1997) demonstrates that "OTEC is non-polluting, in fact, it is ecologically positive since it enriches nutrient-poor surface water and tends to "sink" carbon. The nitrogen, phosphorus, silica, and other nutrients raised from the deep are combined via photosynthesis with atmospheric and ocean-dissolved carbon dioxide to produce increased biomass and reduce atmospheric carbon load." Therefore, a DHC plant is understood to not only lower carbon emissions of power generating plants but also increases ocean carbon absorption. These and other environmentally responsible applications of Drilled Hydrothermal Energy plants would hopefully speed the environmental permitting of projects. While this innovation is remarkable from a sustainability viewpoint, this perhaps is surpassed by the commercial potential as discussed in the next section.

Coordinated Drilled Hydrothermal Cooling Plant With An Offshore OTEC Plant

Offshore OTEC plants that produce electric power of 100 MW are being planned for installation in this decade (Varley 2010). Lockheed Martin Corporation, for instance, is dedicated to installing a scalable pilot OTEC plant of 10 MW capacity in Hawaii by 2015. If such offshore plants are located within the reach of directional drilling, at currently 11,000 meters, there is an opportunity for coordination between an onshore DHC plant and these offshore OTEC plants. The offshore OTEC plant must transmit the power to shore with cables. These cables must avoid sensitive seafloor ecosystems as well as the shore break. In 2010, the US Department of Energy released a report to Congress on the environmental effect of various marine technologies including Ocean Thermal Energy ("Report," 2009). The report specifically recommends HDD when "cabling" through sensitive habitats. While this is referring to offshore platforms, the same would seemingly apply to laying large pipes over the seabed. The report goes on to recommend "adaptive management" techniques or, in other words, learn by doing. A coordinated onshore DHC plant may have its drilled cold water intake proximate to the location of the offshore plant. The OTEC power cable may be inserted into the larger diameter intake pipe, thereby bringing both power and and water to shore. The onshore plant reduces the power requirement for cooling for the surrounding community while, in coordinated fashion, the offshore plant produces the power for the rest of the load. During an Energy Ocean conference, a comment from Robert Varley, the Program Manager for Lockheed Martin MS2, speculated that a power cable from an offshore plant within the 4°C cold water conduit would make the transmission slightly more efficient than riding the same cable up the thermocline because, in general, electrical resistivity increases with temperature for metals. **Figure 9** estimates about 6% better transmission for a 10 km cable at temperature gain of only 0.002 °C. These numbers, therefore, demonstrate that it is more efficient to place the power cables within the 4°C conduit rather than cabling on the seafloor. Including the robust protection and environmental benefits, there appears to be ample room for cooperation between offshore OTEC plants and onshore DHC plants.

Sample Calculation Of An Undersea OTEC Power Cable Embedded in a 4°C Drilled Hydrothermal Intake Conduit Yielding 6% Better Conductivity

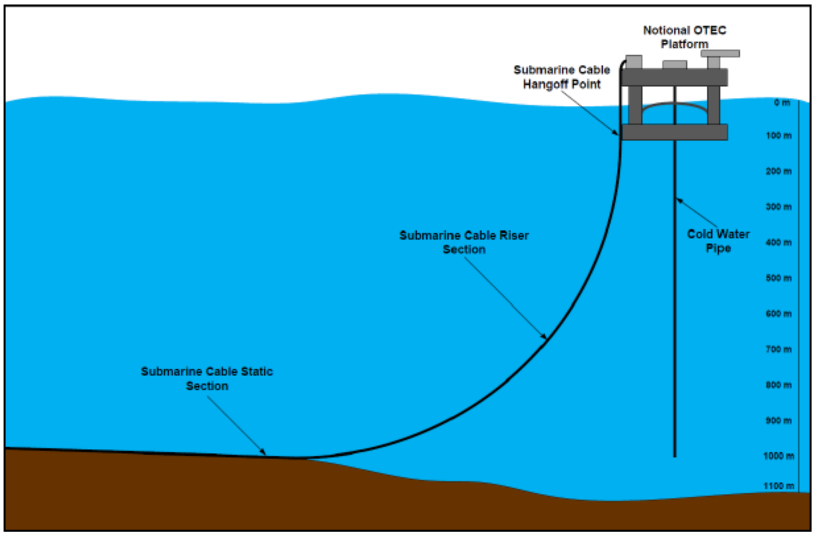


Figure 9

The above illustration (Howanski 2010) depicts a traditional power transmission cable from an offshore OTEC platform. The following calculation demonstrates that the transmission of electrical power is slightly more efficient by passing the power cable through a 4°C PSC conduit in lieu of laying the cable on the up-sloping seafloor. For the purpose of comparison, two identical 10 km long aluminum (ACSR) transmission cables are shown, except that:

1. *Cable A lays on the seafloor and experiences a temperature gradient along its length from 4°C to 35°C.*
2. *Cable B lays in the subsurface conduit without a temperature gradient and remains at 4°C along its entire length.*

If we assume a linear temperature gradient on transmission line A, then an average cable temperature of 20 °C (~ [4 °C +35 °C]/ 2) can be used for comparison. The temperature coefficient (α) of conductivity (s) for hard drawn aluminum is 0.00403 ohm/C. It has been shown that as the aluminum conductor temperature increases ($T_2 > T_1$), then conductivity goes down (s1 > s2); according to $s_1 = s_2 * [1 + \alpha*(T_2-T_1)]$. Therefore, cable B will conduct approximately 6% better than cable A due to lower average conductor temperature. This assumes a perfectly resistive transmission line and surge impedance loading (SIL) is not considered. In order to determine the temperature effects within the protected cold water conduit due to the presence of the transmission cable, all of the energy consumed by resistive heating of the conductor is assumed to be transferred to the water in the conduit (18 million joules per hour). The temperature rise of the volume of water pumped in one hour would be, collectively, $\Delta Q = c_p * \text{mass water} * \Delta T$, where the specific heat capacity (c_p) of 4 °C seawater is approximately 3990 J/kg-K. Assuming 5 million pounds (2.2 million kg) of 4 °C seawater is pumped through the conduit per hour, this would equate to an insignificant temperature rise of 0.002 °C .

Hydrothermal Power Generation (HPG)

The reader will recall Jacques-Arsène d'Arsonval 1881 closed cycle heat engine concept applied to ocean temperature difference. **Figure 10** gives the reader a visual representation of the cycle. HVAC professionals will recognize this cycle as the reverse of the air conditioning cycle. Whereas air conditioning uses electric power to produce a temperature difference, the Organic Rankine cycle uses a temperature difference to produce electric power.

Ocean Thermal Energy Conversion (OTEC)
The Closed Cycle Organic Rankine Cycle (ORC)

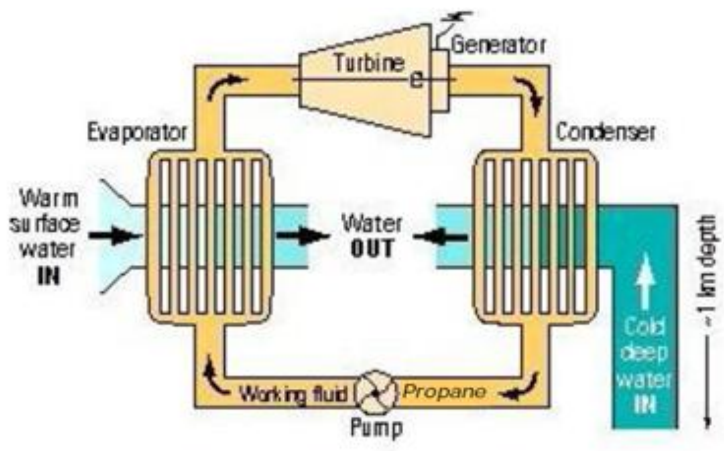


Figure 10
The above modified graphic (Inman 2009) depicts a closed cycle Organic Rankine cycle using propane as a working fluid. The cold water heat exchanger condenser functions to have the propane change state from a gas to a liquid while the warm surface water heat exchanger evaporator turns the propane into a gas. The gas, on its way to complete the cycle, gives up its energy to a turbine which turns a generator to produce electric power.

There has been some research to improve the output and efficiency of an OTEC system by integrating solar energy into the cycle. Yamada et al. (2009) of Nagaoka University of Technology, Japan and his colleagues speak to this concept in their paper "Performance simulation of a solar-boosted ocean thermal energy conversion plant." **Figure 11,** taken from that paper, illustrates two methods to integrate solar energy. The "SOTEC a" concept uses solar collectors to preheat the ocean water prior to entry into the evaporator heat exchanger thereby increasing the temperature difference and energy potential. Straatman and van Sark (2008) at Utrecht University in the Netherlands suggest a "cost optimized approach" to heat ocean water prior to entry into the OTEC heat exchanger by using an offshore solar pond. Yamada's "SOTEC b" proposes to super heat the working fluid with a solar collector to increase the energy potential.

The authors decided to take the conceptual design one step further to incorporate the aforementioned concepts but emulate the design practice of an air conditioning unit to create a Drilled Hydrothermal Power Generation Plant. Generally speaking, in designing an air conditioning unit, one of the key anchors in the design process is the capacity of the compression available. Each range and type of compressor has one "sweet spot" geometry where the capacity and efficiency is maximized with respect to cost. The innovative step in designing a cost effective ocean energy power generation system would be to start with the turbine generator by maximizing the capacity within the physical constraint of the envelope of a 40 foot ISO shipping container. This would make the turbine generator a module that could be readily duplicated and cost effectively shipped and installed. All the other parameters, such as heat exchanger size, diameter and number of drilled conduits, flow, etc. would follow around this optimum module size. **Figure 12** shows such a theoretical plant with suggested

Solar-Boosting OTEC

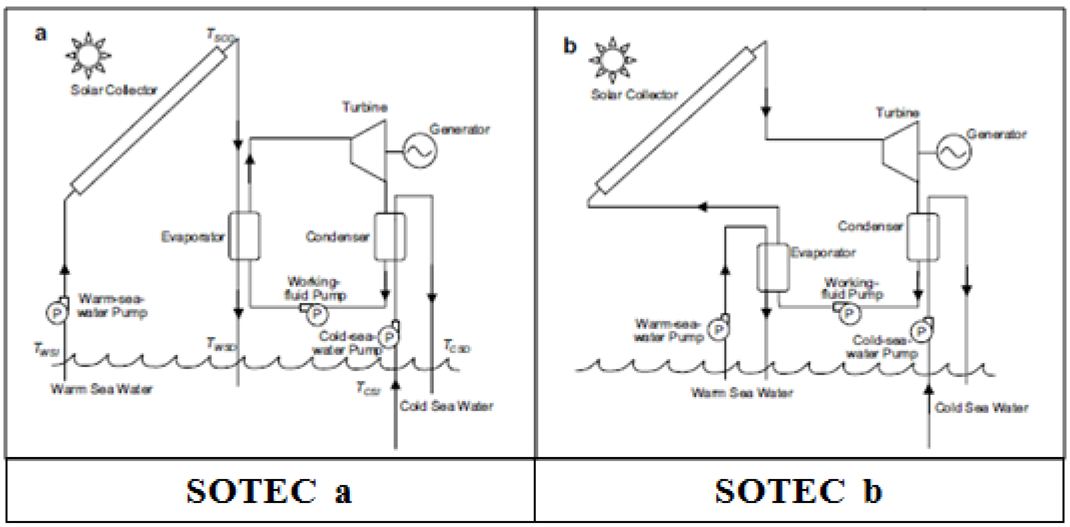


Figure 11

The above figures, taken from the Yamada et al. (2009) paper, outline an OTEC plant with two methods of solar boosting the conventional Organic Rankine Cycle OTEC system. The left diagram suggests preheating the seawater prior to entry on the water side of the evaporator heat exchanger. The right diagram suggests superheating the working fluid prior to turbine entry. This system, while only operational during incidence of solar power, uses the solar energy stored in the ocean for the changes of state of the closed cycle working fluid while the immediate solar energy boost is used to increase efficiency and power output.

conditions of 76^{o}F surface water and 40^{o}F deep cold water. Four conditions were theorized to set the turbine generator sizing. It was thought to use micro-channel heat exchangers (also in 40 foot container envelopes) to allow for a high volume of seawater, conserve temperature difference to a minimum and be able to achieve 2^{o}F leaving temperature differences. Base condition A uses no solar input and represents a 24 hour continuously operating system. Condition B has a solar booster to add 100^{o}F of superheat to the working fluid before turbine entry. In other words, solar collectors would directly heat the working fluid as in Yamada's "SOTEC b" diagram. Condition C would use Yamada's "SOTEC a" solar collector or Straatman and van Sark's solar pond to add 20^{o}F of temperature to the surface water temperature in addition to the superheat of Condition B. Condition D would enhance Condition C by maximizing the superheat beyond 100^{o}F up to the maximum that a standard size turbine design would allow.

Discussions were opened up between the Elliott Company of Jeannette, Pennsylvania USA and the author. Elliott is a renowned manufacturer of turbines and expanders especially using hydrocarbon working fluids. Elliott had manufactured a geothermal turbine generator using a hydrocarbon working fluid which was installed in the Heber plant in the 1980's in San Diego County, California.

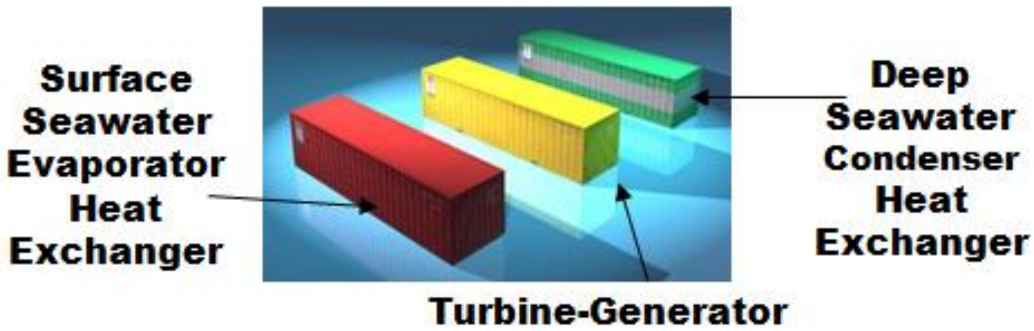
Mike Mindock, of Elliott's Engineering team, took on the challenge to theoretically size a turbine generator staying within the envelope of a 40 foot ISO shipping container. Different working fluids were discussed and evaluated and it was decided to trial size with propane R-290 and isobutane R-600a. **Figure 13** outlines the results of Elliott's theoretical sizing. We first learned that propane is a much better working fluid than isobutane at all four conditions yielding much higher output power. In fact, R-290 outperformed R-600a by two to three times in output power. We also learned that it did not seem practical to have the same size turbine run effectively at multiple conditions. In other words the same size turbine would not run effectively in Conditions A and B (with solar boosting).

Using just the energy potential of 76^{o}F and 40^o F sea water, we learned that an estimated 9.65 megawatts of power may be generated from a single stage R-290 turbine generator manufactured to fit within the envelope of the container. This then shows promise that OTEC plants, combined with directional drilling, may be modular and mass produced. Ten such modules and multiple drilled conduits would continuously produce 96 megawatts of power.

Given that space is available for solar collectors to add 100^{o}F of super heat, the power output is theoretically increased by 300% to 38.69 megawatts while using a 4 x 4 bowtie turbine, again within the envelope of the container. Condition C shows that by increasing the temperature of the seawater by 20^{o}F (76^{o}F to 96^{o}F), a maximum theoretical power output of 43.55 megawatts may be achieved from a R-290 5x5 bowtie turbine. Condition C would be the most cost effective turbine based on the amount of power generated versus manufacturing cost. Condition D of maximizing the superheat had a negative return with R-290.

This theoretical exercise suggests that 9 to 43 megawatts of power can be generated from a R-290 turbine generator built to the envelope of a 40 foot ISO shipping container. Much more work in research and development needs to be done to realize this potential but a path has been illuminated to generate power by collocating two temperature sources with a temperature difference of at least 36^{o}F or 20^{o}C. Success in this area would turn a DHC plant into a multi-tasked facility perhaps coined a Drilled Hydrothermal Energy plant.

Theoretical Sizing Parameters For A Modular OTEC Power Generating Plant



Cotherm Hydrothermal Turbine Design Conditions Date 1-Dec-09
Ted Jagusztyn

Condition		A	B	C	D
		Night time operation No solar Boost	Solar Super Heater Boost	Solar Super Heater Boost + Solar water heater boost	Solar Super Heater Maximum Boost + Solar water heater boost
Deep seawater source temperature (entry)	°F	40	40	40	40
Condenser Heat Exchanger waterside temperature difference	°F	2	2	2	2
Saturated HC Condensing Temperature oF	°F	44	44	44	44
Condenser Subcooling	°F	3	3	3	3
Surface Seawater Entry Temperature	°F	76	76	96	96
Evaporator Heat Exchanger waterside temperature difference	°F	2	2	2	2
Turbine HC Inlet Saturation temp	°F	73	73	93	93
Turbine Inlet HC superheat	°F	1	100	100	Maximum

* HC = Hydrocarbon working fluid

Elliott Co.

HydroCarbon Working Parameters		A	B	C	D
Propane					
Inlet Saturation Temperature	degF	73	73	93	93
Inlet Temperature	degF	73	173	193	300
Inlet Pressure	psia	133.3	133.3	173.8	173.8
Condenser Temperature	degF	45	45	45	45
Condenser Pressure	psia	85.6	19.3	19.2	3.3
IsoButane					
Inlet Saturation Temperature	degF	73	73	93	93
Inlet Temperature	degF	73	173	193	300
Inlet Pressure	psia	48.18	48.18	65.1	65.1
Condenser Temperature	degF	45	45	45	45
Condenser Pressure	psia	29.14	3.4	3.1	0.48

Figure 12

The above is a concept of creating a modular OTEC power plant using components confined to the envelope of 40 foot shipping containers. The author presented to the Elliott company, a US manufacturer of turbines and expanders, the above conditions to provide data for preliminary sizing of a turbine generator with fixed water temperatures and heat exchanger performance. Four conditions with and without solar boosting were considered. Two alternative working fluids were considered, propane (R-290) and isobutane (R-600a). The results of the preliminary sizing are outlined in Figure 12.

Preliminary Sizing and Power Output Parameters For
A Modular OTEC Power Generating Plant

ELLIOTT EBARA GROUP

Cotherm Propane Expander Parameters

Parameter	Units	Case A	Case B	Case C	Case D
Inlet Pressure	psia	132	132	173	173
Inlet Temperature	degF	74	172	193	300
Exhaust Pressure	psia	85.6	19.3	19.2	15
RPM	-	1800	1800	1800	3600
Flowrate	lbm/hr	5088000	3667200	3494400	1430400
Power	kw	9850	39477	44435	25044
Power	MWe	9.65	38.69	43.55	24.54
Exhaust Temperature	degF	51.7	60.7	63.9	146.2
# Stages	-	1	4+4	5+5	5+5
Base Diameter	in	41.0	41.0	41.0	22.0
LS Blade Height	in	14.5	14.5	14.5	11.0
Inlet Pipe Size	in	40	36	36	24
Exhaust Pipe Size	in	40	42	42	32

Notes: 1- Flowpath Mach numbers kept below transonic.
2- Generator losses estimated at 2%.

Cotherm IsoButane Expander Parameters

Parameter	Units	Case A	Case B	Case C	Case D
Inlet Pressure	psia	48	48	65	65
Inlet Temperature	degF	74	173	193	300
Exhaust Pressure	psia	29	3.5	3.1	3.1
RPM	-	1800	1800	1800	1800
Flowrate	lbm/hr	2342400	1008000	898560	758400
Power	kw	4055	11916	12667	13159
Power	MWe	3.97	11.68	12.41	12.90
Exhaust Temperature	degF	52.8	51.1	52.0	158.4
# Stages	-	1	5+5	6+6	7+7
Base Diameter	in	36.0	36.0	36.0	36.0
LS Blade Height	in	17.0	17.0	17.0	17.0
Inlet Pipe Size	in	40	28	24	24
Exhaust Pipe Size	in	40	48	48	48

Notes: 1- Flowpath Mach numbers kept below transonic.
2- Generator losses estimated at 2%.

Figure 13

The above are results of theoretical sizing of turbine generators based on the four conditions elaborated in Figure 12. The physical size constraint was the envelope of a 40 foot ISO shipping container. The above calculations were performed by Mike Mindock of the Elliott Company. Case A indicates that 9.65 megawatts of power can theoretically be generated from the potential energy of a 76°F and 40°F water source using R-290 as a working fluid and a single stage turbine. By boosting the potential energy with solar power, Case C, 43.55 megawatts of power are theoretically possible with a 5 x 5 bowtie turbine. These figures can form the starting point for a Drilled Hydrothermal Energy plant. A great deal of research and development remains to be done but a path is illuminated.

Water Desalination

Only one percent of the earth's water supply is drinkable fresh water. Efforts are being made to cost effectively desalinate ocean water at coastal communities around the world. At Dana Point, California USA, a pilot plant was erected to use directional drilling in a unique way to tap water from a marine aquifer. This application is called a slant well or angle well (Williams 2009). **See Figure 14** for an illustration of such a slant well. The pipe never penetrates to the ocean but has inlets and special internal screens taking water in from the marine aquifer beneath the floor of the ocean. Most of the filtration is done by the cobbles and gravel. The big advantage of this system is that entrainment of marine life is avoided. Many power plants that use Once Through Cooling (OTC) typically have some environmental issue with entrainment of marine life. Access for cooling water for power generation may use this slant well method for extraction of warm surface water. Not all areas are conducive to this type of extraction, therefore, it is suggested that a geo-science professional should be on the team to make this evaluation.

Deep ocean water at approximately 900 to 1000 meters depth is pure, mineral rich and less salty than surface water, according to Dr. Vance Vicente, an environmental scientist from Puerto Rico. After the deep water is used for cooling and HPG, a portion of the power generated can be dedicated to desalinization, thereby providing an abundant new supply of healthy drinking water. In the April 2010 special issue of National Geographic dedicated to water, an article outlines "three technologies to reduce the energy requirements of desalination by up to 30 percent" (Lange 2010). The technologies are Forward Osmosis (on the market 2010-2012), Carbon Nanotubes (on the market 2013 – 2015) and Biometrics (on the market 2013 – 2015). Again, the lesson learned from the Toronto Lake Source cooling project was to make the most use of the resource as possible. A Drilled Hydrothermal Energy plant may also be multi-tasked to include a cost effective and self sustainable water desalination plant.

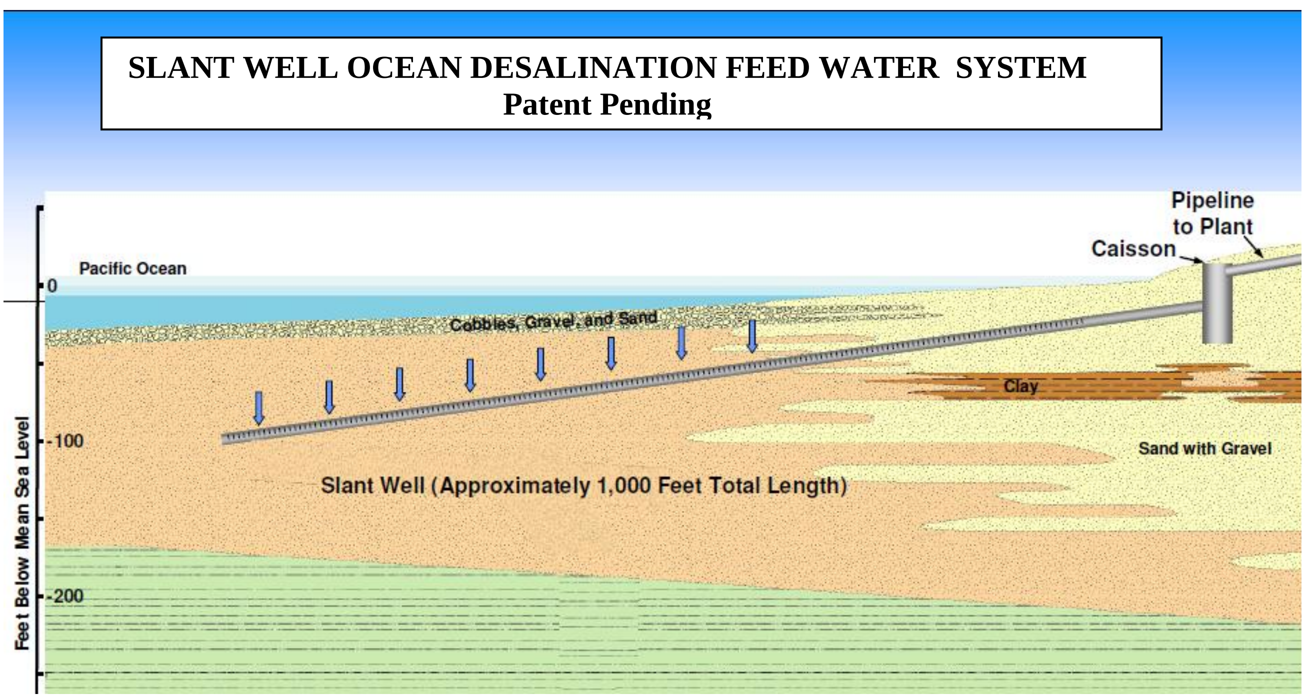


Figure 14
Dr. Dennis E. Williams proposes a slant well to tap near shore marine aquifers for naturally filtered seawater as an intake system for water desalination. This same method can be used in certain areas as a warm water intake for power generation. This avoids the problems associated with entrainment of marine organisms on ocean water intake systems. One such slant well is in operation at a pilot desalination project at Dana Point, California (Williams 2009).

Fuel Production

The authors suggest that fuel may be generated from the ocean energy. The process may be started by exposing filtered humid air to the cold seawater in a closed circuit, generating pure liquid H_2O. Through the process of electrolysis, direct current electricity from Hydrothermal Power Generation may be used to drive off the hydrogen molecules from the water. The resulting hydrogen gas may be liquefied by another dedicated ocean energy turbine, driving a compressor to produce hydrogen fuel. The downside of hydrogen fuel, however, is the relatively high cost to assure safety in transport. Alternatively, nitrogen may be sequestered from air and combined with the hydrogen gas to form ammonia $NH_{3,}$ which is an excellent fuel and relatively safe in transport. To illustrate the aforementioned process, consider these simplified 4 steps in ammonia fuel production, utilization and discharge.

1. Use the deep cold water in pipes in filtered outdoor air handling units in a humid environment to condense water vapor into liquid.

   $$\mathbf{H_2O}$$

2. Use electrical power from Hydothermal Power Generation (HPG) to separate the hydrogen and oxygen molecules.

   $$\mathbf{2\ H_2O + Energy = 2H_2 + O_2}$$

3. Use electrical power from Hydothermal Power Generation (HPG) to sequester nitrogen from the air and add it to the generated hydrogen gas from step 2.

   $$\mathbf{Energy + N_2 + 3H_2\ = 2NH_3}$$

4. Use the ammonia fuel from step 3 in a combustion engine to produce useful energy and benign byproducts.

   $$\mathbf{4NH_3 + 3O_2 = Energy + 6H_20 + 2N_2}$$

This illuminates a path to a source of fuel beyond the hydrocarbon era. Perhaps existing power plants may also be re-tasked to operate on fuel generated from ocean energy. Power plants may also be erected near to deep cold water and warm ocean water. They may burn ammonia fuel to produce power. The cold water may also be used in a heat exchanger to cool the inlet air to increase turbine efficiency in generating electric power. Island countries, such as the island of San Salvador in the Bahamas, with warm interior saline lakes inland and deep cold water just off shore may then produce all their cooling and electrical power needed and be self sufficient for fuel needs. They may export the fuel that is in excess of their needs creating a new source of wealth.

The Middle East region, while well known for fuel production and very warm bodies of water such as the Arabian Gulf, also has areas of deep cold water. The region apparently has extensive experience in directional drilling. The challenge for Drilled Hydrothermal Energy in the region is to position the two water energy sources of at least 20^{o}C side by side and transport the energy to where it is needed. This topic should be the subject of further in depth research but **Figure 15** begins to illustrate the opportunity. A close look at the bathymetry off the coast between Masqat and Sur, Oman in **Figure 16** demonstrates that, while the distances between the warm and cold water sources seem to be great, they are still within reach of current technology. An examination of the coastal waters off Gwadar, Pakistan shows the 1000 meter contour just 12,000 meters off shore.

Perhaps in the context of much more demanding piping projects such as the Trans-Alaskan pipeline which stretches 800 miles (1287 kilometers), one may begin to envision possibilities of transporting energy in the form of water, fuel or electricity. Readers are invited to use the ruler on Google Earth to assess the opportunity between two points in their region of interest. Surface water temperature data is readily available on the internet. Temperatures at depth are generally not as available. Bathymetry data is now readily available at a depth of 1000 meters where 4^{o}C temperatures are virtually assured. It should be noted that 4^{o}C temperature may also be available at depths of 500 to 900 meters. Diligent temperature studies need to be conducted as part of any feasibility study preceding a proposed project.

The Middle East Region Has Warm Surface Water And Deep Cold Water That May Be Used For Hydrothermal Power Production And Hydrogen Based (Clean) Fuel Production

Gulf of Oman Bathymetry

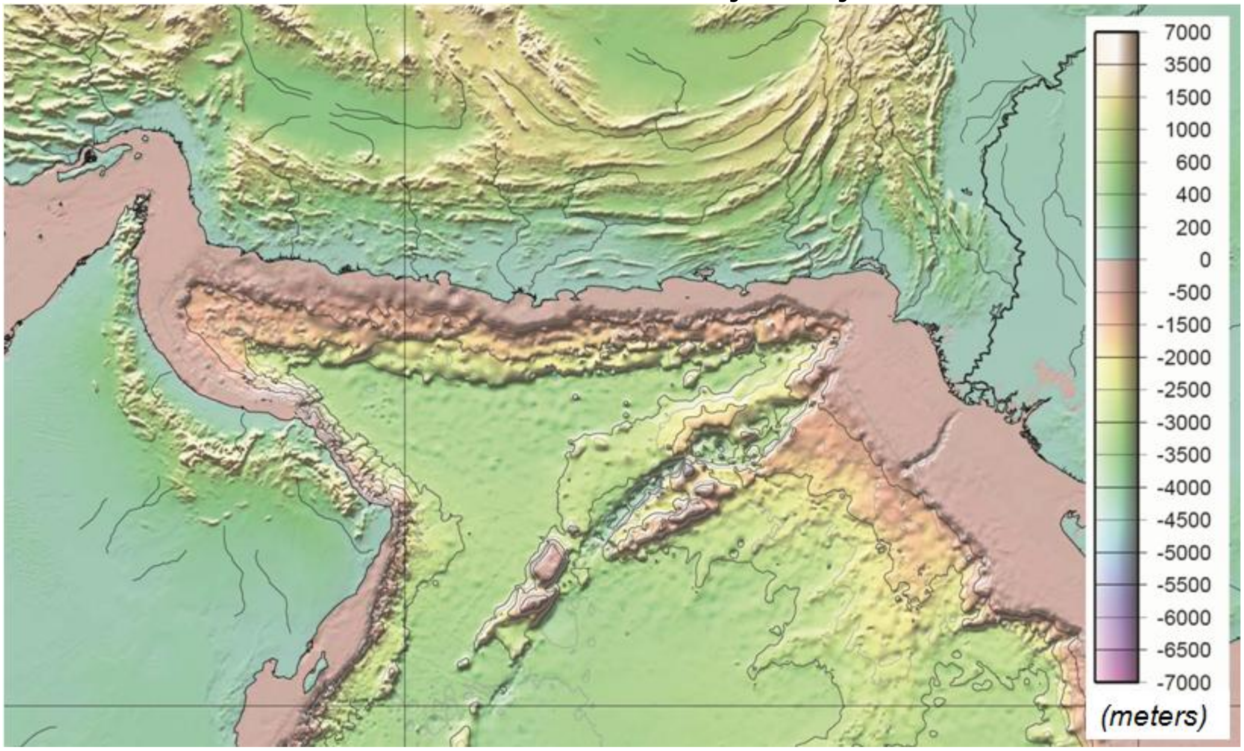


Figure 15

The above bathymetry map of the Gulf of Oman ("Global" 2009) depicts shallow warm regions of water with magenta color and deep water cold regions depicted in yellow-green approximating 4°C temperature. The bottom picture from Google Earth, with an east-west orientation, gives a closer look at the region where opportunities off the coast of Oman and perhaps Gwadar, Pakistan seem to have coast lines where directional drilling can be used to access cold water to take advantage of Drilled Hydrothermal Energy.

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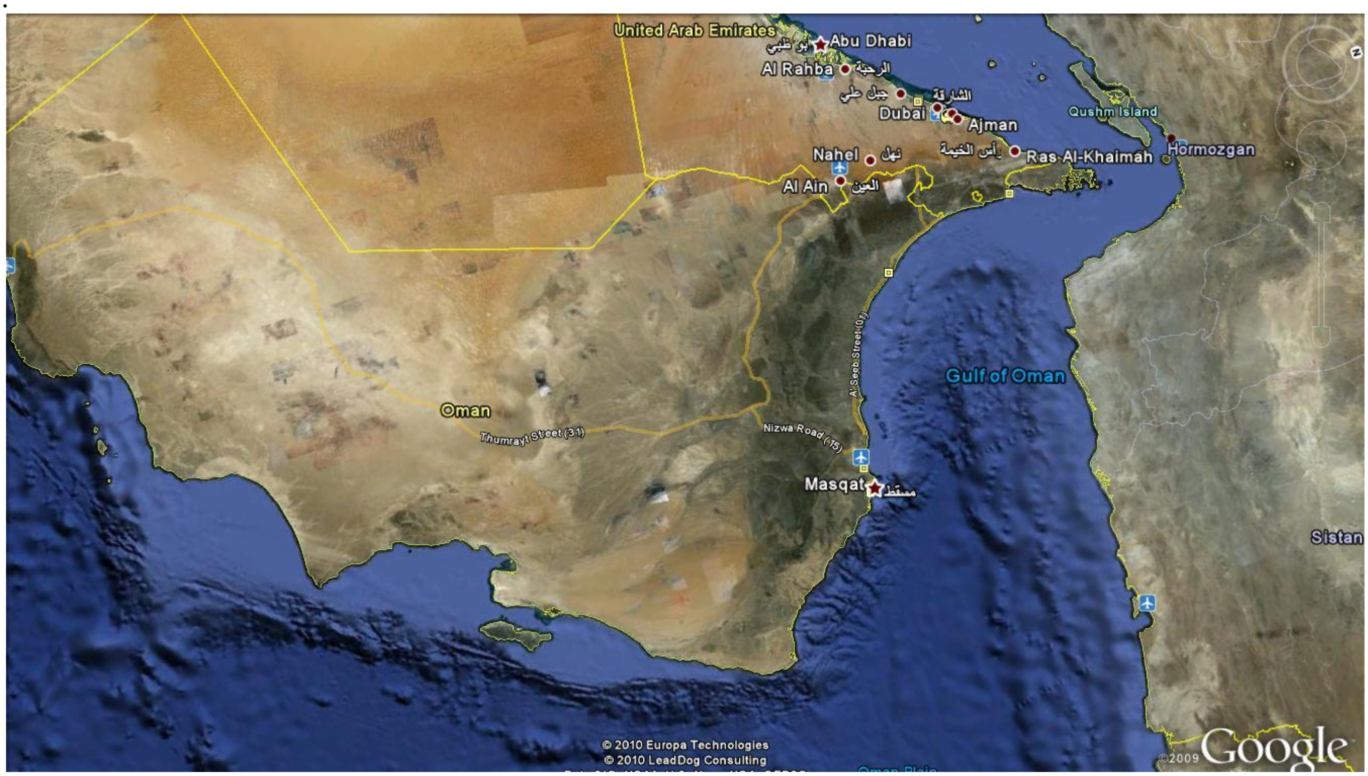

Possible Drilled Hydrothermal Energy Opportunity in the Middle East Region

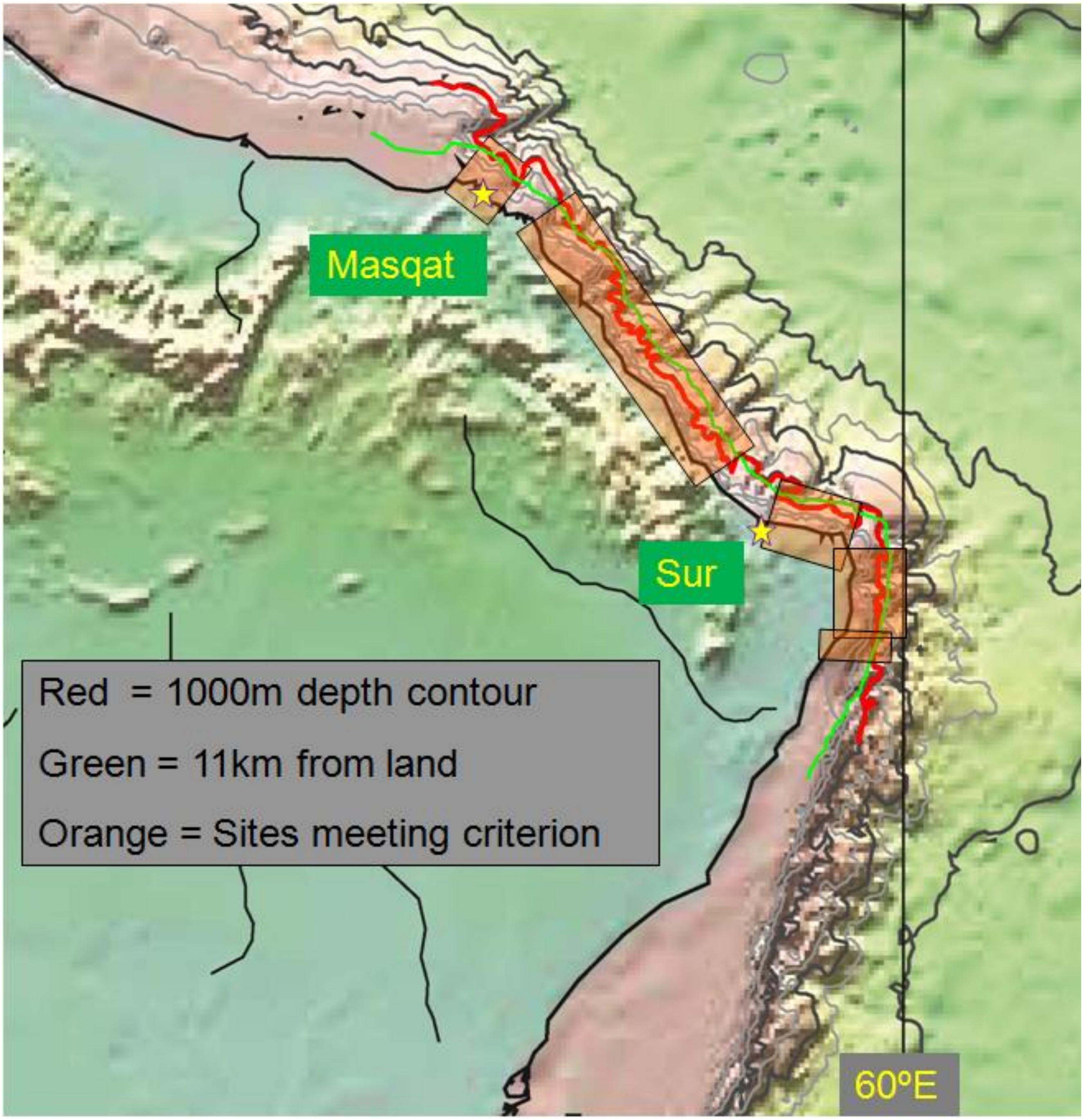

Figure 16

The above bathymetry map is a close up of the coastal region between Masqat and Sur in Oman ("Global" 2009). The offshore red line indicates a depth of 1000 meters where 4°C water temperature is assured. The green line indicates 11 kilometers from the shore which is the current horizontal step out limit of extended reach drilling. The orange areas indicate the coastal regions meeting both criteria suggesting these areas as preliminary candidates for Drilled Hydrothermal Energy plants.

Enhanced Waste Water Treatment with Pure Oxygen

Along with hydrogen production in the electrolysis process, oxygen gas is produced as a byproduct. Oxygen gas may be collected to provide an abundant source of low cost oxygen to clean waste water for re-use or for benign re-introduction to the environment. The oxygen may also be an additional revenue source. The Linde company, a renown provider of industrial gas, gives its customers guidance for utilizing industrial gases such as oxygen. Linde's paper "Enhanced Waste Water Treatment with Pure Oxygen" ("Enhanced," 2009) may serve as a good reference to use the liberated oxygen in the previously mentioned Hydrogen Fuel Generation process.

Enriched Mineral Water

The mineral rich seawater may be used to promote health in humans. Commonly used in thalassotherapy, trace elements of magnesium, potassium, calcium, sodium, and iodine found in seawater are believed to be absorbed through the skin. The therapy is applied in various forms, such as showers of warmed seawater. This treatment has become a popular favorite for many ocean side resort spas. This is a low cost revenue source that promotes human health.

Agriculture & Mari-Culture

The use of cold natural water to increase output of produce and seafood was pioneered by ocean energy expert Dr. John Craven in Hawaii. ColdAG™ has the potential to triple coastal farming output. As Dr. Craven explains in a video on Deep Ocean Water Agriculture, "cold deep ocean water is pumped through irrigation pipes embedded in the soil. No salt water touches the earth but the ground is cold (10°C / 50°F). This produces condensate on the pipes just like drip irrigation. But more than that, a temperature gradient exists between root and flower that pumps phosphates and nitrates into the plant with a Carnot efficiency that is at least three times greater than nature can provide. The results are unbelievable in terms of size, sweetness and rate of growth" ("Global," 2007). Dr. Craven's team in Hawaii has grown grapes for wine in 120 days using Deep Ocean Water Agriculture. The normal gestation period for grapes is 240 days. ColdAG™, therefore, can produce three grape crops per year instead of just one. The possibility now exists to turn coastal regions near deep cold water into very productive agricultural communities. Countries like Haiti, with deep water very close to shore, have poor soil conditions exacerbated by deforestation. Deep Ocean Water Agriculture may possibly be able to restart their agriculture industry.

Aside from the agriculture benefit, the mineral rich seawater may also be used in mari-culture farms to increase algae production for biofuels and an abundant food supply of fish and shellfish. More information on this benefit may be obtained from the Common Heritage Corporation website. This corporation was founded by Dr. Craven and is based in Honolulu, Hawaii USA.

CONCLUSION

The trials and triumphs of ocean energy from 1881 to 2010 revealed the feasibility for hydrothermal energy yet demonstrated that the application demands innovative ways to make the system both commercially and environmentally viable. Various studies point to the feasibility of natural water cooling in places such as Miami, Los Angeles and the Great Lakes. In a separate industry, the authors reviewed the development of directional drilling from 1929 till 2010. Extended Reach Drilling has reached a horizontal displacement of 11 kilometers and the industry is working toward systems surpassing this reach.

The authors then introduced, for the first time, an innovation combining these two industries in a system named Drilled Hydrothermal Cooling that can provide comfort and process cooling at approximately 10 times lower cost than mechanical cooling while reducing carbon emissions and increasing ocean carbon absorption. This method mitigates some of the risks of ocean energy extraction as was experienced by past attempts and current applications. The past technique of laying pipes in the ocean risked loss in installation and damage during the life of the pipes. This innovation creatively replaces the laying of pipes in the ocean with directionally drilled protected seawater conduits. Drilled Hydrothermal Cooling plants of perhaps 23,000 tons in size could be in installed along the Florida coast from Stuart to Miami reducing the cost of air conditioning by

90%. The coastal Canadian and US communities of Lake Ontario could have up to 132 million tons of process cooling plants using natural cold lake water to lower product cost and attract factories. This thermal energy is renewable and, according to scientific testimonies, can be applied without negatively affecting the properties of the body of water.

In addition to cooling, directional drilling to a warm water source of at least 36°F (20°C) temperature differential has the potential of generating electric power by using heat exchangers and Organic Rankine cycle turbines. Preliminary designs estimate that approximately 10 megawatts of power can be obtained from heat exchangers and a turbine generator designed to the envelope of two or three ISO 40 foot containers per module. Four times more power is theoretically possible by integrating solar energy provided space is available. This power may be used for many purposes including power generation for island communities without burning fuel, water desalination, hydrogen or ammonia fuel production and oxygen waste water treatment. A challenging yet perhaps lucrative location for this application is the Arabian Peninsula which is strategically flanked by the very warm Arabian Gulf and the deep cold water in the Gulf of Oman.

As Albert Einstein once suggested "*We can't solve problems by using the same kind of thinking we used when we created them.*" The "thinking" presented herein suggests addressing the excess amount of CO_2 that is being emitted into our atmosphere by not only reducing the rate at which we currently emit more CO_2 but by also absorbing the CO_2 out of the atmosphere and into our oceans where it can be used to improve our environment.

Government, NGO, commercial, academic and research institutions are invited to study and model this innovation in areas within 11 kilometers of 4°C water. HVAC professionals are well advised to consult with oceanographers, geologists, and directional drilling professionals to assess the natural cooling opportunity in their local community. The authors are available to assist interested stakeholders in qualifying any opportunities.

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