TECHNOLOGICAL CHALLENGES TO COMMERCIAL-SCALE APPLICATION OF MARINE RENEWABLES

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INTRODUCTION

Marine renewable energy has many attractive qualities, including high energy densities for ocean wave and tidal power generation, and a high capacity factor for ocean thermal power generation. However, due to the corrosive and occasionally violent nature of the marine environment, marine renewable energy faces many technical challenges related to cost-effective, commercial-scale deployment. This paper explores some of the technical challenges being faced in developing marine renewable technologies for commercial markets.

Figure 1. Wavebob advanced development model testing.

WAVEBOB

Technology Description

The Wavebob is a highly innovative, self-reacting, oscillating point absorber designed to convert ocean wave energy into low-cost electricity (Figure 1); it represents a major technology breakthrough, given the fact that it can be tuned and controlled to closely match the prevailing wave climate, even on a wave-by-wave basis. It can respond well to long-period waves that typify ocean swell, something that was previously considered nearly impossible for a self-reacting point absorber. Its absorption bandwidth can be adjusted, and the power take-off (PTO) stroke length may be controlled. It is ideally suited to

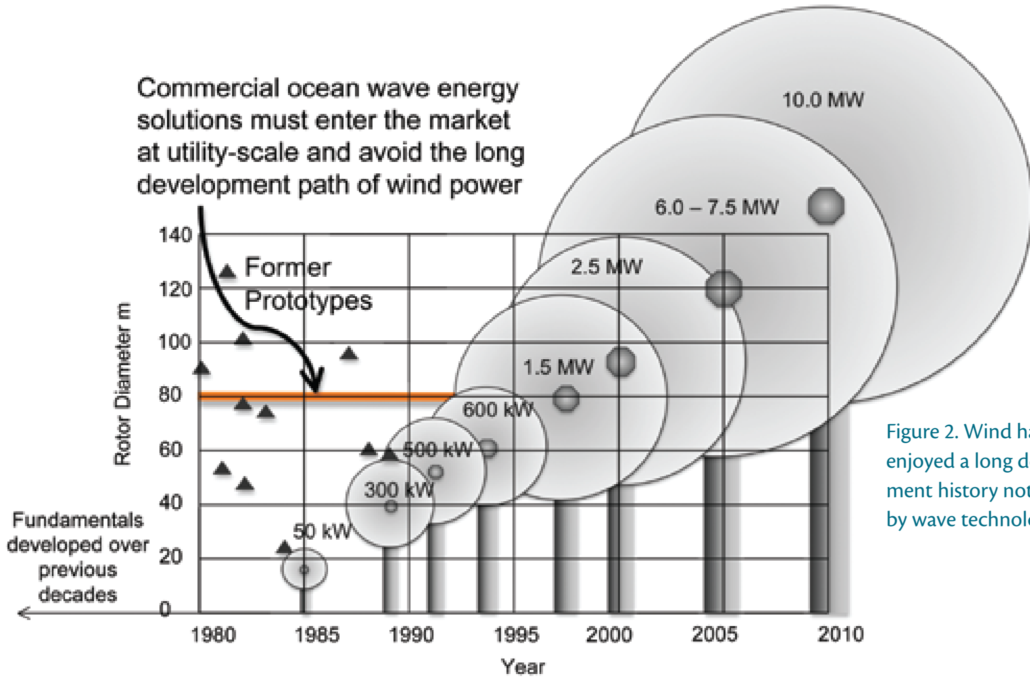

Figure 2. Wind has enjoyed a long development history not enjoyed by wave technology.

on-board autonomous control and intelligent responses within an array. At full scale, the device is capable of producing in excess of 1 MW of energy with average output of over 500 kW at sites in the North Atlantic and Pacific oceans.

Technical Challenges

To more fully understand the current position of wave energy device developers, it is instructive to examine the development history of wind power. From early grain-grinding applications to wind-powered water pumps for rural farms, wind power enjoyed a unique role as a pre-industrial source of power. Between 1850 and 1970, over six million mostly small (1 horsepower or less) mechanical output wind machines were installed in the United States alone, and the first large electricity-producing wind generator was built before the end of the nineteenth century. Wind power ultimately enjoyed decades of investment and technical development before attaining significant power output (> 1 MW) and high operational availability.

Comparatively, ocean wave energy technology was not a serious focus for research and development until the UK began its Wave Energy Program in the 1970s in the aftermath of the oil crisis, and then later development of the first utility-scale wind farms. Wind power has matured to the point that it is moving further offshore, but wave technology companies do not enjoy the significant advantage of developing and sustaining their first product lines on more convenient and accessible land-based sites. This particular circumstance significantly raises the cost of development and demands a more carefully structured approach to the commercialization of technology. Figure 2 highlights the scope of the challenge.

Future Research and Development

Robust operations and maintenance (O&M) concepts are critical to a successful outcome as operational costs will undoubtedly prove to be the most

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significant factor in determining the levelized cost of energy from ocean waves (an economic assessment of total lifecycle costs to include initial investment, operating costs, and cost of capital). Among target markets, variation in the seasonal profiles of dominant wave characteristics will have a significant impact on both operational and service availability. For any given O&M strategy, which may include maintenance actions on the device, conducted either from a tender or in port, the peculiar engineering requirements for one location may not suit another.

We simply cannot complete the design and engineering of marine energy devices without retirement of key technical risks and without having developed an intimate understanding of the complete product lifecycle. Nonetheless, what we aim to do is achievable with current standards of maritime technology. The prize is hard to overestimate—a vast untapped supply of renewable energy.

AQUAMARINE POWER

Technology Description

Aquamarine Power is the owner and developer of Oyster, the world's largest working hydroelectric wave energy converter. Oyster is designed to harness the abundant natural energy found in nearshore waves.

Oyster is a simple mechanical hinged flap connected to the seabed at around 10-m depth. Each passing wave moves the flap, driving hydraulic pistons to deliver high-pressure water via a pipeline to a conventional onshore electrical turbine. Multiple Oyster devices are designed to be deployed in utility-scale wave farms typically of 100 MW or more.

The first full-scale Oyster 1 device was deployed at the European Marine Energy Centre (EMEC) in Orkney, Scotland, in the summer of 2009. The 315 kW device is grid connected and producing power.

The company has secured US$8 million of UK government funds to develop and install the 2.5 MW Oyster 2 at EMEC in 2011. Oyster 2 will comprise three linked devices connected to a single onshore plant.

Oyster's defining characteristic is its simplicity. The device combines a simple and robust mechanical offshore component with innovative use of proven conventional onshore hydroelectric components. Oyster's offshore component has minimal submerged moving parts: no underwater generator, power electronics, or gearbox. All complex power generation equipment is easily accessible onshore.

Technical Challenges

There are three main technical challenges related to the Oyster device—installation, survivability, and operations and maintenance.

Installation

Oyster is a nearshore device and installation takes place in energetic waters of around 10-m depth (Figure 3). These parameters place particular requirements on any Oyster-specific installation methodology.

When Oyster 1 was installed during the summer of 2009, the company used a jack-up barge to drive piles into the

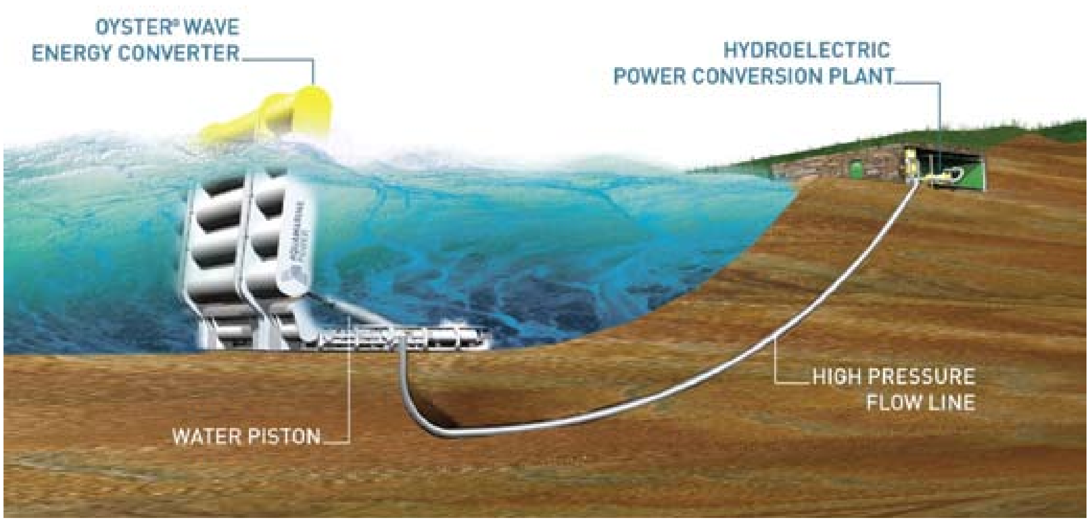

Figure 3. Aquamarine's Oyster.

seabed and a shearleg crane to lower the Oyster device onto its subsea frame. This technique, although effective, was costly and time consuming and required a significant weather window for the installation to succeed. Thus, Aquamarine Power is intending to use a novel anchor solution for the installation of Oyster 2.

There remains an industry-wide requirement for continued research and development into deployment vessels and installation methods.

Survivability

Survivability is an issue that will affect all ocean energy devices. For offshore wave energy converters, a common approach to survivability is to design the device to be self-reacting so that its moorings are compliant enough to "ride out" the 30-m (100-ft) waves that occur at highly energetic sites.

Nearshore deployment means that the largest, most damaging waves do not reach the Oyster device due to the natural filtering mechanism of the seabed, which causes the larger waves to break, thereby dissipating their destructive capabilities, while allowing the smaller waves (maximum 10 m, or 30 ft) used for energy production to pass relatively unaffected.

In addition, the Oyster device "ducks under" the largest waves—an inherent characteristic of the design that results in a 75% reduction in maximum loads. This attribute also enables Oyster to produce power in the largest seas.

Operations and Maintenance

The key O&M challenge for offshore wave energy converters is to reduce O&M costs. Substantial long-term O&M cost reduction can be achieved by increasing device and component reliability so that less maintenance is required while the device is deployed. Also, to further reduce O&M costs and ensure high plant availability, it is necessary to design the device so that offshore maintenance activities can be completed efficiently across a broad range of energetic sea states.

> "DUE TO THE CORROSIVE AND OCCASIONALLY VIOLENT NATURE OF THE MARINE ENVIRONMENT, MARINE RENEWABLE ENERGY FACES MANY TECHNICAL CHALLENGES RELATED TO COST-EFFECTIVE, COMMERCIAL-SCALE DEPLOYMENT."

The smaller maximum wave heights, together with the closer proximity of the seabed, mean that a nearshore wave energy converter can be attached to the seabed, thereby eliminating the requirement for compliant moorings and flexible electrical cables. Also, deployment in the nearshore environment means that complex electrical generating equipment can be located onshore, connected to an offshore module of limited complexity. This arrangement will increase plant availability and lower O&M costs due to improved onshore accessibility.

Future Research and Development

The above notwithstanding, there is a strong requirement for industry-wide research and development to be conducted on a shared IP basis. Recent industry-wide collaboration has identified the following broad themes:

Components, PTO, and New Concepts

Although many components used in ocean energy are standard, their application is not. Experience shows that components, or their integration in ocean energy systems, and not so much ocean energy concepts, are one of the main reasons for previous failures in ocean energy. Thus, versatile platforms to test components and subsystems at sea for extended periods, and also laboratory rigs to test components and systems, should be funded.

Deployment and Installation Methods and Tools

Deployment of ocean energy devices requires vessels that most often are also used by other offshore industry. These vessels may be very expensive and, moreover, their costs are very volatile, depending on offshore peak demands. Thus, it is important to address the requirements for vessels to be used in ocean energy deployments and how these requirements may be configured to reduce the costs of these vessels and, simultaneously, affect technology development (e.g., the specification of maximum lift capacity for these vessels may affect the mooring design). In parallel, a key issue is the financing of these vessels in the first phase of ocean energy deployment, where the number of orders is expected to be limited. Conditions need to be created that will encourage companies to invest in these types of vessels.

Existing offshore technology provides solutions for moorings and seabed foundations; however, many of the solutions were devised for offshore platforms with very different economics and usually much stricter safety constraints. The development of cheap, reliable, and safe solutions for moorings and seabed foundations for different sea bottom conditions (e.g., sand and rock) and environmental conditions is critical to the success of ocean energy, and research on this technology should be funded. These proposals may include the development of installation methods and tools (e.g., submarine robots).

Design and Operation Tools

O&M represents a significant share of offshore energy cost. Thus, the development of tools to assist in the design and operation of ocean energy farms is a research priority. This development should address energy production and forecasting, the cost of electrical cables and moorings, access to devices, survivability, failure estimation, maintenance, and safety.

Control must be efficient but also able to cope with faults in the device. Any control system must incorporate features such as failure identification and system diagnostics, and it also must have auto-reconfiguration capabilities to cope with the identified failures. Projects addressing these topics and projects that integrate experience from other areas such as aeronautics and the automobile industry should be encouraged.

RESOLUTE MARINE ENERGY

Technology Description

Resolute Marine Energy (RME) is developing several different wave energy converter (WEC) designs; however, oscillating wave surge converter (OWSC) designs have outstanding commercial promise because they can cost-effectively satisfy a wide range of offshore and onshore power supply requirements. Figure 4 shows a diagram of RME's SurgeWEC.

OWSC-type WECs are bottom-mounted and capture energy from water-particle movements excited by surface waves that pass overhead. Such water-particle motions generally occur in a horizontal plane parallel to surface-wave-propagation direction. One key advantage of OWSC-type WECs is that they have less exposure to highly energetic surface waves that can easily damage equipment.

Technical Challenges

Materials/Coatings

WECs are exposed to extreme forces that severely strain load-bearing components. One solution is to "overbuild" or "armor" WECs, but weight and volume quickly become constraining factors because WECs that are heavy and bulky are more expensive and dangerous to manufacture, transport, and deploy. Advanced composite materials have a high strength:weight ratio and resist corrosion, and manufacturing techniques are being developed that allow high-volume production of complex shapes. However, composites are significantly more expensive than more traditional materials like mild steel and concrete. In addition, although lightweight, high-strength rigid materials that deflect energy are needed, materials that are durable, flexible, and absorb energy in controllable ways are also required.

Corrosion and biofouling are processes that start the moment a WEC is exposed to saltwater. Much more work is needed to fully understand the effects of physical, chemical, and biological factors

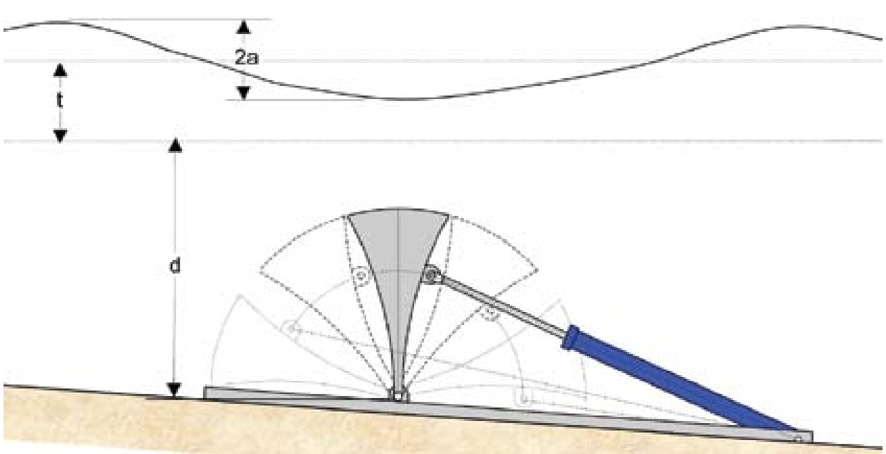

Figure 4. Resolute Marine Energy's SurgeWEC (WEC = wave energy converter) is deployed in shallow waters outside the surf zone and comprises an energy-absorbing "paddle" and a power-take-off mechanism. a = wave amplitude, t = tidal range, d = depth at mean low water

present in the marine environment and to devise materials and coatings that provide cost-effective protection. Similar to how the aerodynamic performance of an airplane wing is affected by ice accumulation or pitting, unless aggressive measures are taken to prevent it, WEC performance will quickly degrade as marine organisms accumulate and corrosion occurs. A daunting challenge specific to WECs is protecting water-tight glands and seals around sliding or rotating shafts from being compromised by calcareous deposits that, if left alone, will inevitably cause serious leaks.

Choice of Power Take-Off Scheme

Because there are many means of harvesting energy from ocean waves, there are several potentially viable PTO schemes to choose from. Despite the many options, a common challenge to all WEC PTO systems is how best to efficiently convert high-torque, low-speed energy input into electricity or other more-usable forms of energy.

A common solution is to employ linear generators for the task, but at such low speeds, the amount of iron, copper, and magnetic material required creates problems related to size, weight, and cost. In addition, maintaining air-gap tolerances for such big machines requires bearings and seals of incredible strength and durability. Other options include compressing and storing air or pressurizing hydraulic fluid, water, and other liquids, and using it to drive a rotary generator at high speed, thus greatly reducing weight and size. Potential drawbacks to this system include system interface losses and leaks. Direct-drive geared systems (e.g., rack and pinion) have durability problems similar to those encountered in the wind turbine industry with speed-increasing gear boxes. In addition, because maintenance and repair operations at sea are more difficult, dangerous, and expensive, development of a PTO that can endure millions of cycles between scheduled repairs or replacement is required.

"MUCH MORE WORK IS NEEDED TO FULLY UNDERSTAND THE EFFECTS OF PHYSICAL, CHEMICAL, AND BIOLOGICAL FACTORS PRESENT IN THE MARINE ENVIRONMENT AND TO DEVISE MATERIALS AND COATINGS THAT PROVIDE COST-EFFECTIVE PROTECTION."

Future Research and Development

RME is focusing its R&D efforts in several areas:

1. Advanced materials that increase the durability and reduce maintenance costs associated with PTO systems
2. Cost-effective means of protecting WECs from extreme loading conditions
3. WEC array performance optimization
4. Integration of WEC with other offshore technologies (briefly discussed below)

Because the ocean is a difficult and expensive place to work, it is important to maximize the utility of a given piece of ocean real estate. Collocating wave energy farms with aquaculture, mining, drilling, or other energy projects should, therefore, be carefully considered.

Of particular interest is the idea of deploying WEC within and around offshore wind projects. Shared power collection, conditioning, and transmission infrastructure are certainly one potential benefit. Because waves are a more predictable and consistent energy resource than wind, some investigation into how the terms of a power purchase agreement might be restructured as a result would be appropriate. For example, in summer months, early evening thermal changes can temporarily curtail wind activity at exactly the time when electricity demand is highest. Can offshore energy project developers somehow benefit from the fact that the WEC will still be steadily producing power? A final potential benefit is that when WECs are deployed around the perimeter of an offshore wind farm, wave energy around the towers is attenuated, thereby allowing maintenance personnel safer access more days of the year.

In conclusion, the economic, social and environmental benefits of wave energy need to be considered in a mixed-use context, and there are significant engineering challenges associated with creating productive and cost-effective combinations of offshore commercial activities.

VERDANT POWER

Technology Description

Verdant Power's Kinetic Hydropower System (KHPS) uses three-bladed, horizontal-axis turbines (see Figure 5) deployed underwater to convert the energy of tidal and river currents into electricity. The KHPS operates unattended and automatically, with the tidal version allowing for passive turbine yawing to capture energy from both ebb and flood tides at equal efficiency. Designed for simplicity and scalability, the KHPS can be used in a wide range of distributed generation settings, from nearshore placement in population centers to remote offshore sites.

Since 2002, Verdant Power has worked to develop, demonstrate, and commercialize the KHPS, utilizing the world's first array of kinetic hydropower turbines at its Roosevelt Island Tidal Energy (RITE) Project in New York City's East River.

Technical Challenges

Through a demonstration at the RITE Project, Verdant Power successfully proved many of the technological premises for the wide-scale deployment of the KHPS, achieving a number of milestones, including:

- Grid-connected, multiturbine array
- Automatic power control and effective passive yaw
- No significant biofouling or debris problems
- Hydrodynamic, mechanical, and electrical performance with excellent load-matching efficiency and power following
- Excellent overall water-to-wire efficiency of approximately 40%
- Tidal site capacity factor of approximately 30% with power generated 77% of the time
- A total of 9,000 turbine-hours of operation with over 70 MWH delivered to the grid
- Effective environmental monitoring, with empirical evidence of safe fish interaction

Moving beyond demonstration, the commercial-scale implementation of the KHPS—and other kinetic hydropower technologies—will require solutions to the following key challenges:

1. A cost-effective science-based solution to operational environmental monitoring
2. Cost-effective O&M through engineered solutions to:
   a. Reliable long-term (~ five years) unattended turbine operation
   b. Several new foundation designs that permit more lower-cost deployment and retrieval operations in a range of sites

With regard to environmental monitoring, developers must have active and bilateral awareness alongside the regulatory agencies to develop monitoring plans with reasonable economic boundaries that support both the environmental and operational integrity of commercial projects. Siting and operating arrays ranging from a few to hundreds of devices to achieve a commercial-size project will require a major leap in environmental science and policy, as occurred to allow for the aggressive development of wind farms.

Toward more cost-effective O&M, Verdant Power has enhanced its system reliability through next-generation turbine development that includes new, stronger composite rotor blades and enhanced turbine sealing. In parallel with this effort, the company is developing new foundation designs that allow for simplified, rapid, and low-cost KHPS deployment and retrieval. The broad experience of marine contractors and

Figure 5. Verdant Power's Kinetic Hydropower System (KHPS) turbines.

the offshore industry has been and must continue to be leveraged to arrive at such solutions. This will form the cornerstone of the commercial success for the kinetic hydropower industry.

R&D includes the areas of sealing, and materials for corrosion and biofouling resistance, for long-term reliable performance. With support from the US Department of Energy (DOE), its national laboratories can provide the fundamental research necessary to develop material improvements that would benefit all kinetic hydropower device developers.

"FOR KINETIC HYDROPOWER DEVELOPERS TO BE SUCCESSFUL AND ACHIEVE MEANINGFUL CAPACITY AND ENERGY PRODUCTION, A ROBUST PROGRAM OF RESEARCH, DEVELOPMENT, DEMONSTRATION, AND DEPLOYMENT (RD3) FOR TECHNOLOGY ADVANCEMENT MUST BE IN PLACE."

Future Research and Development

For kinetic hydropower developers to be successful and achieve meaningful capacity and energy production, a robust program of research, development, demonstration, and deployment (RD3) for technology advancement must be in place. Such an RD3 program should provide two types of support—basic and applied—and cover devices, materials, environmental issues, and a set of industry-wide performance standards. Monetary support for early commercial projects must also be provided, especially in the United States, to jumpstart a kinetic hydropower industry that has had far less investment to date than those in the UK and Canada.

Basic R&D

In addition to applying established science developed for the offshore oil and gas industry, the kinetic hydropower industry will need to be advanced by new basic material science R&D. This

Applied R&D

Applied R&D includes testing, standards setting, and macroenvironmental studies. Under its Advanced Water Power Projects program, DOE has provided Verdant Power funding for testing under a project entitled "Improved Structure and Fabrication of Large, High-Power KHPS Rotors." In this project, the technological challenge is to design, analyze, and develop for cost-effective manufacture, next-generation KHPS rotors capable of larger sizes, higher powers, and long life. This project will also result in the fabrication and in-water testing of a full-scale prototype rotor. The project is being conducted through a partnership among Verdant Power, DOE's National Renewable Energy Laboratory, and Sandia National Laboratories, along with the University of Minnesota's St. Anthony Falls Laboratory. Many more collaborative activities like this one must be supported for a domestic kinetic hydropower industry to take off.

With regard to standards setting and macroenvironmental studies, Verdant Power sees the importance of engaging kinetic hydropower developers as participants in any program of academic research at the applied level. Supported research at demonstration and pilot sites, coordinated with advancement of commercial operations, will jumpstart the industry by answering specific questions of environmental interaction with machine and array operation.

Although technological challenges remain, the overall success at the RITE Project provides momentum, lessons learned, and nascent partnerships that must be leveraged for commercial success as an industry. Verdant Power welcomes further collaboration in this manner as a required step toward realizing the full potential of this industry.

LOCKHEED MARTIN CORPORATION

Technology Description

Ocean Thermal Energy Conversion (OTEC) is the extraction of solar energy stored in Earth's ocean. At its most basic, OTEC is simply a heat engine that exploits temperature differences between warm surface seawater and cold deep seawater. Most designs assume a simple closed-loop Rankine cycle with a low-boiling-point working fluid. As Figure 6 shows, warm seawater is used to boil the working fluid in the evaporator. The vapor is then expanded through a turbine to drive a generator to

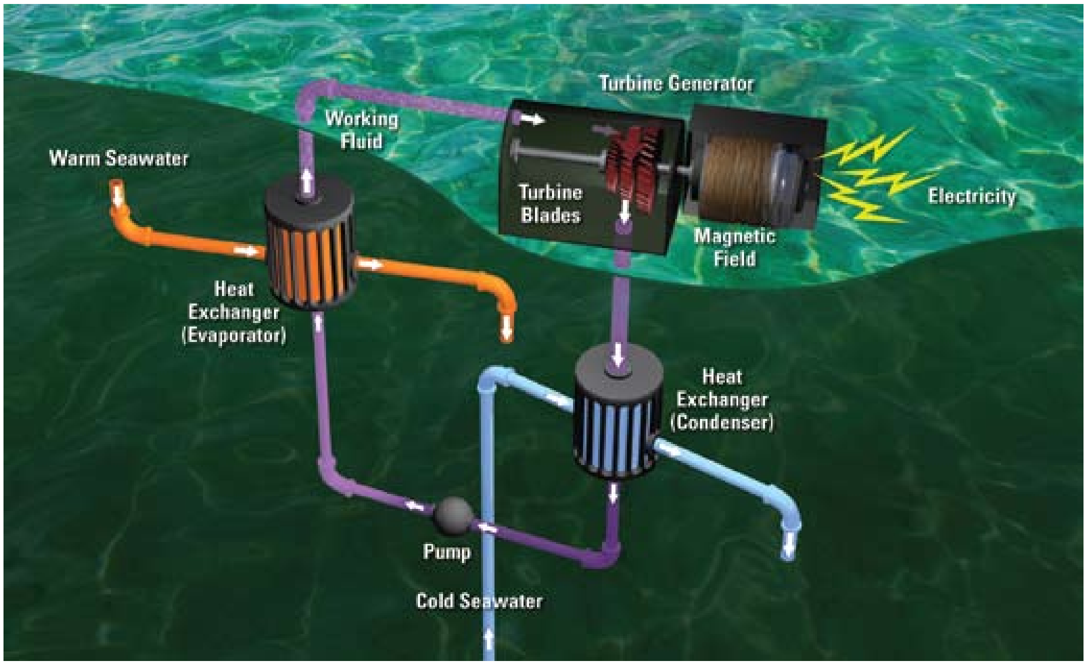

Figure 6. Ocean thermal energy conversion (OTEC).

produce electric power. The expanded vapor is converted back to a liquid in the condenser using cold deep seawater. The working fluid pump returns the liquid back to the evaporator to complete the cycle. Ammonia is one attractive choice for the working fluid due to its favorable thermal properties at the seawater temperatures.

The ocean is the solar collector in an OTEC power system. Because this large ocean thermal mass normally remains relatively constant in temperature over the course of a 24-hour period, an OTEC power plant can provide a baseload power generation capability that is very attractive to utility companies.

Technical Challenges

As described above, an OTEC system is fundamentally quite simple and has been successfully demonstrated at small (sub-MW) scales. Net power production from an at-sea closed-cycle OTEC was demonstrated successfully in 1979 with the operation of Mini-OTEC off the coast of Hawaii. This plant generated approximately 50 kW of gross power and about 15 kW of net power. The principal technology challenges are generally the very long cold-water pipe (CWP) required to reach the deep cold water, and affordable, high-performance seawater- and working-fluid-compatible heat exchangers. The required tremendous scale of a commercially viable OTEC power plant exacerbates the challenges of these two system components. The low thermal differential exploited to produce power in an OTEC cycle results in requirements for a very large heat exchanger surface area and very high seawater volumetric flow rates. These size constraints, in turn, translate into requirements for very large cross sections for seawater intakes if flow velocities are to be kept low (desirable to minimize pressure drops as well as environmental impacts). Resulting requirements for CWP and heat exchangers for commercial-scale OTEC systems are:

- CWP: large diameter (multiple meters); ~ 1000 m in length (to reach ~ 4°C water); capable of being reliably assembled and deployed to a mooring site and connected to the rest of the OTEC system (this has proven to be the Achilles heel of many prior OTEC attempts); capable of withstanding the at-sea environment (fatigue, corrosion) for the typical duration of a commercial power purchase agreement (25–30 years); capable of withstanding pressures along entire length
- Heat Exchangers: very large overall heat exchanger surface area; made from material compatible with seawater and with ammonia (or alternative working fluid); minimal

seawater side pressure drop; manufacturable in large sizes and quantities; made from affordable materials and processes

The offshore oil and gas industry has addressed most of the technology challenges that were identified in the 1970s for OTEC operations in deep water. Although in 1980 there were only a few floating drilling or production vessels operating in shallow water, there are over 150 floating production units in operation today, of which more than 50 are in water depths over 500 m. We are now drilling in 3000 m of water, and a floating production platform is operating in 2500 m. Floating production has proven a safe and reliable approach. Today's state of offshore technology ensures stable, low-motion floating platforms; a variety of reliable anchor and mooring solutions; reliable high-voltage dynamic and static subsea power cables and connectors; and a variety of specialized installation and maintenance vehicles and processes. The challenge that remains for OTEC is one of tailoring these solutions for better overall affordability. At smaller power capacity sizes, the platform and associated moorings and anchors can exceed 50% of the total cost of an OTEC project.

Finally, one additional technology challenge for OTEC commercialization must be mentioned. The largest floating OTEC system demonstrated to date was Mini-OTEC, which only produced 15 kW net and was only operated for a planned few months. Most OTEC designers, future customers, financiers, and regulators believe that there are risk-reduction objectives that can only met by building and operating a scaled-up OTEC system pilot plant for a reasonable demonstration period of two to three years. The primary objectives of such a pilot plant include:

- validation of economic models for construction, installation, and operation of an OTEC system
- validation of design adequacy for addressing unique OTEC environmental considerations such as ensuring that seawater intakes minimize impacts to marine organisms, that the method of seawater return adequately controls the thermal plume from the plant, and that noise pollution is minimized
- collection of a multiple-year environmental baseline prior to OTEC plant installation, followed by multiple years of plant operations and continued monitoring to give regulators the necessary data and confidence for licensing future commercial OTEC plants.

Future Research and Development

Based upon internal research and development to date, the technical challenges presented above do not appear to be insurmountable barriers to commercialization. Ongoing investment by industry and the federal government will ensure solutions for the critical CWP and heat exchange technologies. However, the construction and operation of a pilot plant to more fully assess risks associated with building and operating commercial OTEC plants will necessitate a large capital investment well beyond the levels currently being made available. Obtaining this funding represents the largest barrier of all to commercialization of OTEC.