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Potential Alternative Energy Technologies on the Outer Continental Shelf

Environmental Science Division

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for
U.S. Department of the Interior, Minerals Management Service

by
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FOREWORD

This technical memorandum (TM) describes the technology requirements for three alternative energy technologies for which pilot and/or commercial projects on the U.S. Outer Continental Shelf (OCS) are likely to be proposed within the next five to seven years. For each of the alternative technologies — wind, wave, and ocean current — the TM first presents an overview. After each technology-specific overview, it describes the technology requirements for four development phases: site monitoring and testing, construction, operation, and decommissioning. For each phase, the report covers the following topics (where data are available): facility description, electricity generated, ocean area (surface and bottom) occupied, resource requirements, emissions and noise sources, hazardous materials stored or used, transportation requirements, and accident potential. Where appropriate, the TM distinguishes between pilot-scale (or demonstration-scale) facilities and commercial-scale facilities.

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NOTATION

ACRONYMS AND ABBREVIATIONS

ADCP	acoustic Doppler current profiler
AWEA	American Wind Energy Association
BELCO	Bermuda Electric Light Company, Ltd.
DNV	Det Norske Veritas
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
EPU	electricity production unit
ESP	electric service platform
FERC	Federal Energy Regulatory Commission
FTE	full-time equivalent
HDD	horizontal directional drilling
HVAC	high-voltage alternating-current
HVDC	high-voltage direct-current
MCT	Marine Current Turbines Ltd.
NOAA	National Oceanic and Atmospheric Administration
NO_x	nitrogen oxides
OCS	Outer Continental Shelf
OPD	Ocean Power Delivery Ltd.
OPT	Ocean Power Technologies
ORPC	Ocean Renewable Power Company
OWC	oscillating water column
ROW	right of way
SMDS	scientific measurement devices station
TBT	tributyl tin
VOC	volatile organic compound
VSC	voltage source converter
WEC	wave energy conversion
WTG	wind turbine generator

UNITS OF MEASURE

d	day(s)
dB	decibel(s)
dBA	A-weighted decibel(s)
ft	foot (feet)
ft^2	square foot (feet)
ft^3	cubic foot (feet)
g	gram(s)
gal	gallon(s)
h	hour(s)
Hz	hertz
km	kilometer(s)
km^2	square kilometer(s)
kV	kilovolt(s)
kW	kilowatt(s)
kWh	kilowatt-hour(s)
L	liter(s)
lb	pound(s)
m	meter(s)
m^2	square meter(s)
m^3	cubic meter(s)
mi	mile(s)
mi^2	square mile(s)
mph	mile(s) per hour
MW	megawatt(s)
MWh	megawatt-hour(s)
rpm	revolution(s) per minute
s	second(s)
W	watt(s)
yr	year(s)
µm	micrometer(s)

1 OFFSHORE WIND TECHNOLOGIES

1.1 OVERVIEW

Wind turbines harness the kinetic energy of the moving air and convert it to electricity. Offshore wind turbines can produce more electricity than can onshore turbines, because offshore winds are less turbulent (the ocean is flat relative to onshore topography, which may have hills, mountains, and other obstructions), and they tend to flow at higher speeds than onshore winds. Because the potential energy produced from the wind is directly proportional to the cube of the wind speed, increased wind speeds of only a few miles per hour can produce a significantly larger amount of electricity. A turbine at a site with an average wind speed of 26 km/h (16 miles per hour or mph), for example, can produce 50% more electricity than can the same turbine at a site with average wind speeds of 23 km/h (14 mph) (Offshore Wind 2006).

A wind turbine can be compared to a fan operating in reverse: Rather than using electricity to produce wind, the turbine uses the wind to make electricity. Today's wind turbines have evolved into a familiar form that comprises three evenly spaced composite blades mounted to a hub. This assembly, known as the rotor, is oriented upwind from a tower on which most of the mechanical equipment is mounted. Offshore wind turbines have not yet been optimized for energy production at sea; therefore, as the technology matures, new designs may possibly deviate from this proven land-based architecture. In a wind turbine, the rotor captures approximately half of the kinetic energy of incident wind through a process of aerodynamic lift. The rotor spins a shaft that is connected through a set of gears to the center shaft of an electrical generator. A wind turbine's power output generally increases as the wind speed increases until it reaches the nameplate power level (rated power). The turbine then begins to regulate power to prevent overproduction. Most wind turbines today have a blade pitch system as the primary means for regulating peak power. This system rotates the blades about their spanwise axes to control the angle of the blades' airfoils to the relative wind. Some wind turbines use aerodynamic stall to regulate peak power, but these systems are becoming less common. Wind turbines begin production at "cut-in" wind speed, which is typically about 19 km/h (12 mph), but this can vary depending on the wind site. Power production increases as the wind velocity increases until the turbine-specific maximum performance is reached, generally around 40 to 53 km/h (25 to 33 mph). As wind speeds increase further, power production is maintained at rated power by the pitch system. Many wind turbines also use other control strategies (e.g., variable-speed torque control) to help smooth the transient wind fluctuations. At "cut-out" wind speed, typically between 89 and 97 km/h (55 and 60 mph), the turbine pitches the blades out of the wind to prevent overload and shuts the turbine down. As do land-based wind facilities, offshore facilities consist of a number of turbines operating independently and delivering their power to onshore customers through a common conduit — for offshore facilities, this is an undersea cable. The positions of the turbines are selected to ensure that each turbine operates in the wind regime for which it was designed and to minimize the air turbulence that each turbine experiences from adjacent turbines. The careful siting of turbines within a wind facility helps ensure that the facility as a whole operates with the highest possible efficiency, regardless of wind direction. In some land-based settings, this objective requires turbines to be separated by as much as 10 rotor diameters from each other. In offshore applications, where only two wind directions are likely to

predominate, it may be possible to shorten the distances between turbines arranged in a line. A spacing of seven rotor diameters between units has been used in Denmark. (Each of the 160-MW Horns Rev and Nysted offshore wind parks in Denmark covers an area of about 28 km^2 [about 11 mi^2], including the 200-m-wide [660-ft-wide] exclusion zone).

Some of the principal components of an Outer Continental Shelf (OCS) wind turbine generator (WTG) follow:

- Rotor (blades and blade hub), which is connected through a drivetrain to the generator;
- Turbine assembly, which includes the gearbox and generator and is enclosed by a shell or nacelle;
- Tower, which supports the turbine assembly, houses the remaining facility components, and provides sheltered access for personnel; and
- Foundation or structure to support the tower.

Offshore WTGs look similar to those onshore, but they may have several design modifications to accommodate the more demanding climates that exist in offshore locations. The tower is strengthened to cope with wind-wave interactions. The nacelle components are protected from the corrosive nature of sea air. An access platform is added for navigation and maintenance. Offshore turbines are typically equipped with corrosion protection, internal climate control, high-grade exterior paint, and built-in service cranes. They also typically have warning devices and fog signals to alert ships in foul weather. To minimize expensive servicing, offshore turbines may have automatic greasing systems to lubricate bearings and blades, and they may have preheating and cooling systems to maintain gear oil temperature within a narrow temperature range. Lightning protection systems minimize the risk of damage from lightning strikes, which occur frequently in some offshore locations. There are also navigation and aerial warning lights. Turbines and towers are typically painted light blue or gray to help them blend into the sky. The lower section of a support tower may be painted in bright colors to highlight the structure and help passing vessels navigate around it.

To take advantage of the steadier and higher-velocity offshore winds and economies of scale, offshore WTGs are also bigger than onshore turbines. A typical onshore turbine installed today has a tower that is about 60 to 80 m (200 to 260 ft) high and blades that are about 30 to 40 m (100 to 130 ft) long. Most offshore wind turbines are at the top end of this range. A typical offshore turbine installed today has a power generating capacity of 2 to 4 MW, with a tower that is more than 61 m (200 ft) high and rotors that are 76 to 107 m (250 to 350 ft) in diameter. A 3.6-MW turbine weighs 320 tons and is from 126 to 134 m (413 to 440 ft) tall, appoximately the height of a 30-story building. Turbines of up to 5 MW (with rotors that are up to 130 m [425 ft] in diameter) are being tested.

Wind turbines are commonly classified by their rated output at a certain rated wind speed, but the amount of time a wind turbine produces a given power output is as important as

the rated power. The amount of energy that the wind transfers to the blades increases with increasing wind speed, blade area (which determines the swept area [i.e., capture area]), and density of the air. Energy output depends on factors that include the average wind speed, speed at which the WTG begins to produce power, blade shape, stalling characteristics, operating characteristics, and component (e.g., generator and gear box) efficiencies. The capacity factor is the WTG's actual energy output divided by the energy output that would be produced if it operated at its rated power output for the entire year. For onshore WTGs, reasonable capacity factors are 0.25 to 0.3; a good capacity factor would be 0.4 (AWEA 1998). Potential capacity factors for offshore WTGs are greater (i.e., about 0.4 to 0.45, on the basis of the operating expeirence of WTGs off the coast of Denmark).

After a suitable place for the wind facility is located, foundation piles that are usually about 3.5 to 5.5 m (12 to 18 ft) in diameter are driven into the seabed to support the individual WTGs. Once the turbine is assembled, sensors on the turbine detect the wind direction and turn the nacelle to face into the wind, so that the blades can collect the maximum amount of energy throughout each diurnal cycle.[1] The wind moving over the aerodynamic blades makes them rotate around a horizontal hub, which is connected to a shaft inside the nacelle. The rotating shaft powers a generator to convert the energy into electricity. The shaft may be coupled to the generator via a gearbox (speed increaser) or coupled directly if the generator is designed to operate at low speeds and high torque levels. Undersea collection cables take the power from the individual turbines to an offshore transformer or substation that converts the electricity to a higher voltage before transmission via undersea cable to the land. The collection voltages within the facility are in the medium voltage range of 24 to 36 kV. Transmission voltages (from the substation to the shore) are in the 115- to 150-kV range.

An electric service platform (ESP) is a central offshore platform that provides a common electrical interconnection for all of the WTGs in the array and serves as a substation where the outputs of multiple collection cables are combined, brought into phase, and stepped up further in voltage for transmission to a land-based substation that is connected to the onshore grid. It also provides a central service facility for the wind park and may include a helicopter landing pad, control and instrumentation system, crane, man-overboard boat, communication unit, electrical equipment, fire extinguishing equipment, emergency backup (diesel) generators, staff and service facilities, and temporary living quarters (for emergency period or inclement weather when crews cannot be removed). These temporary accommodations will likely use waste storage tanks that would be pumped to the service vessel for proper disposal. The ESP will likely provide a central area to store insulating oil used in the WTGs. The ESP for a large wind park can store 150,000 L (40,100 gal) of insulating oil and 7,600 L (2,000 gal) of additional fluids such as diesel fuel and lubricating oil (Applied Science Associates 2006).

Currently, offshore wind facilities are connected to onshore utility transmission systems through alternating-current (AC) sub-marine cable systems. For distances of up to a few tens of kilometers and power levels in the few hundred megawatt range, AC cable connections are adequate. However, for greater distances and loads, direct-current (DC) connections might be

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[1] Diurnal wind cycles result from the differential cooling and heating rates between land and water, thereby generating wind even if there are no storm fronts in the area.

more economical, because capacitance and losses limit the technically feasible length of AC cable.

The United States has vast onshore wind resources (relative to Europe), and a number of projects have been constructed onshore; however, no commercial wind facilities operate today off the coasts of the United States. In the past few years, however, interest in offshore wind energy has increased because of a number of factors, including the following: (1) offshore wind turbines can generate power closer to high-value coastal load centers than can onshore turbines, (2) offshore winds produce more power per unit area, and (3) offshore European wind facilities have demonstrated that such offshore facilities are feasible. Figure 1 shows an offshore wind facility operating off the coast of Ireland.

FIGURE 1 Offshore Wind Facility near Arklow, Ireland (Source: Nelson 2006)

Both pilot-scale and commercial-scale European offshore wind projects have provided data that demonstrate the feasibility of offshore wind power generation. This information, combined with the fact that a large portion of the costs of developing these resources is for offshore activities that require expensive installation equipment, means that in the United States, developers would likely skip the pilot and demonstration phases and move directly to commercial operation. However, new technologies and equipment, such as new types of foundation, will require testing.

Because wind speeds tend to increase with distance from the shore, turbines built farther offshore will be able to capture more wind energy. However, as the distance from land and the water depth increase, the costs of building and maintaining the turbines and transmitting the power back to shore increase sharply. To capture the wind power and achieve the economies of scale needed to make the far offshore sites financially viable, it is generally believed that 5-MW or larger turbines will be needed. Technologies will be needed for low-cost mooring and anchor development, erecting and decommissioning in relatively deeper waters (more than 30 m [100 ft] deep), and improving accessibility and reliability. Ways to store wind energy for later use may also be required. Technologies will also be needed to develop large composite blades that are not too heavy and can withstand variations in turbulence. Reducing the weight of the blades will also reduce the structural demands placed on the towers. In early 2006, the U.S. Department of Energy (DOE) announced plans to develop an offshore, multi-megawatt wind power system over the next several years. Plans are to utilize innovative construction techniques, rotor designs, drivetrains, electrical components, and foundations designed for the harsh offshore environment while optimizing the total life-cycle cost (DOE 2006a).

The extreme requirements for tower foundations place important constraints on OCS wind resource development. Some turbines have been installed on steel monopiles, which are long steel tubes that are hammered, drilled, or vibrated into the seabed until they are secure. Other turbines in the relatively shallow waters off the coast of Europe have been attached to

gravity foundations, which are concrete structures that rest on the seafloor and are stabilized against any overturning moments by their weight or additional ballast. Although gravity foundations can be used on most seabeds, seabed preparation is required. Divers must remove silt and prepare a smooth bed to ensure uniform loading. Gravity foundations also pose greater environmental impacts because of their large diameters (about 20 m [66 ft]). Both monopiles and gravity-based foundations may need to be protected against erosion, and this erosion control can be accomplished by installing boulders, cement bags, grout bags, grass mattresses, or other corrosion-control devices. Gravity-based foundations require a shipyard and dry dock near the site to construct the massive structures (500–1,000 tons, compared with 175 tons for a monopile), and their large mass complicates transport and installation operations (they may require larger cranes for installation than other foundation types). For these reasons, gravity foundations are less suitable for the deeper waters off U.S. coasts. Platforms capable of supporting the turbines in deep water (up to 900 m [about 2,950 ft]) would allow access to offshore areas, where an estimated 750,000 MW of wind resource potential exists (Thresher 2005).

1.2 OCS WIND TECHNOLOGY DATA

Unlike offshore projects in the United Kingdom, Germany, and Denmark (where offshore development began years ago with a series of small pilot projects), the projects proposed so far for the OCS are bypassing the pilot (or demonstration) phase and moving directly to permitting for full-scale commercial development. This is because the offshore WTG technology has already been demonstrated in Europe and because, in the United States, the costs of installation make up such a high portion of the total project cost[2] that once the data from the meteorological tower indicate the economic viability of a project, developers go right to commercial scale.

In the unlikely event that a demonstration of an OCS wind project would be undertaken, information on electricity generation, resource requirements, and impacts could be estimated by scaling down the data from a commercial plant, using the per-unit data, and multiplying these numbers by the number of units in the demonstration (three to five WTGs, each with a capacity of 2 to 3+ MW). The monitoring and testing for a demonstration plant would be very similar to, if not the same as, the monitoring and testing for a commercial plant. Indeed, if the demonstration plant suggested that a commercial facility was feasible, the same meteorological tower and data that were used for the demonstration facility could be used for the commercial facility. Thus, data for a commercial meteorological tower (see Section 1.2.1) could be applied to a demonstration meteorological tower. If the demonstration facility was successful, the commercial facility would most likely be developed at the same site, and the demonstration WTGs would be incorporated into the commercial facility. If the facility was unsuccessful, it would be decommissioned in the same way as the commercial facility would be, and the data could be scaled as appropriate. The remainder of this chapter provides wind technology data for commercial facilities.

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2 Because WTGs are often larger, further offshore, and in deeper waters, special vessels and equipment are needed to transport and install turbine equipment.

1.2.1 Site Monitoring and Testing

Most of the data collected during site monitoring and testing pertain to wind speed, consistency, turbulence, and other factors that influence the efficiency of a proposed site for electricity generation. These data are generally collected by equipment housed on a meteorological tower. Data on bathymetry (the measured depth of the ocean floor), ocean bottom topography, seismic potential, and other parameters (soil characteristics, local load-bearing characteristics of the marine sediment, existence of rocks and ledges) may also be collected, since this information can influence foundation design and structure. Seismic surveys and geotechnical testing of the ocean bottom may be necessary for determining potential mooring concepts and the construction design of the WTGs.

1.2.1.1 Meteorological Tower Facility Description

To determine whether a site qualifies for a wind turbine facility, a meteorological (met) tower (also known as a scientific measurement devices station [SMDS]) is installed in the area of the proposed facility to measure wind speeds and collect other relevant data. The scientific measurement devices used consist of anemometers, vanes, barometers, and temperature transmitters on the tower. A wire to the data tower may also connect an associated acoustic Doppler current profiler (ADCP) that sits on the ocean bottom near the tower. Some facilities may use two met towers. A met tower generally consists of a foundation (a monopile or three pilings supporting a single steel pile) that supports the deck. The overall height of the structure can range from about 30 to 60 m (100 to 260 ft) above sea level, and the piles may be driven in about 8 to 14 m (25 to 45 ft) below the seafloor. The entire data tower structure can cover an area of ocean water that is approximately 84 m^2 (900 ft^2). It can take 8 to 10 weeks to construct the tower, but with specialized equipment, installation can occur in a much shorter period (about 1 week). The tower typically operates for 1 to 1-1/2 years and remains in place for fewer than 5 years. At the end of this period, the tower is removed, and the materials and equipment are usually removed by barge and transported to shore. The piles are typically cut and removed at a depth of about 1.8 m (6 ft) below the seabed. No electricity is generated from a met tower.

The expected ocean surface area occupied by a met tower would be about 84 m^2 (900 ft^2) per module, with one to two modules (or towers) expected per facility. The expected ocean bottom area occupied would be between about 26.4 m^2 (284 ft^2) (if the tower was supported by a monopole) and about 1,450 m^2 (15,600 ft^2) (if it was supported by a tripod tower). However, for the tripod tower, the area within the triangle created by the three pilings on the seabed floor would probably not be disturbed.

The tower would likely be fabricated onshore and assembled offshore from barges. Components would be sent to the site via ship. Piles would likely be installed with pile drivers over an estimated 3-day period. Expected employment for the meteorological tower would include less than 1 full-time equivalent (FTE) for construction and decommissioning. No additional FTEs would be required for operations, because data would be collected electronically.

1.2.1.2 Meteorological Tower Facility Emissions and Noise Sources

It is expected that small amounts of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions would be emitted from transport vessels and pile-driving equipment during construction. No air emissions would occur during operations, and small amounts of SO_2 and NO_x from vessels returning components to shore would be emitted during decommissioning. No water emissions are expected, and no significant amounts of waste would be generated, except possibly during onshore construction, when typical construction wastes would be produced. No emissions to water are expected, nor is any use of freshwater expected. No hazardous materials would be used or stored at the met tower. During installation, it is expected that pile driving equipment would generate noise.[3]

1.2.1.3 Transportation Requirements and Accident Potential

Components would be shipped and workers would travel on vessels during construction. An 8- to 10-week construction period (maybe less; for example, maybe 1 week if a purpose-built vessel was used) could be assumed, along with one marine vessel roundtrip per day. Components would be shipped by barge and would require an estimated three roundtrips. Transport of the tower and components from the vendor(s) to the port might also be required, with the exact modes of transportation and requirements depending on the vendor's location. Accidents and attendant fuel leaks could result from shipping components and personnel during construction.

1.2.2 Wind Facility Construction

A large portion of the costs for offshore wind facilities are for construction, transport, and installation. Highly specialized equipment is used to ship the components and assemble them offshore. The construction time depends on the number of WTGs; estimated times range from about six months to two years or more. The foundation and tower designs depend on site-specific conditions (i.e., water depth, wave height, seabed morphology). For the turbines and ESP, driving a monopole tower into the seabed is the most common and cost-effective practice in waters that are less than 15 m (50 ft) deep and that do not contain a large amount of boulders. In deeper waters, tripod towers may be more suitable. Concrete or steel gravity foundations that sit on the seabed have been used for European wind projects, but they tend to become heavy and expensive at depths more than 10 m (33 ft). Such foundations can be 15 m (about 50 ft) at the base and 16 m (about 52 ft) high, and they can weight about 1,300 tons. To provide stability against sliding and overturning, heavy-duty olivine material is used to fill the cells and shaft, adding another 500 tons to the weight. Their cost is approximately proportional to the square of the water depth (Bryne Ó Cléirigh Ltd. et al. 2000). In deep waters (more than 45 m [140 ft] deep), offshore platforms may be used. Future offshore platforms might be buoyant yet stable (with mooring anchors) — similar to semisubmersible offshore oil rigs. Other future possibilities

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[3] Estimates of noise associated with pile driving for the Cape Wind Met tower, for example, ranged from 145 to 167 dB at a distance of approximately 500 m [1,640 ft]).

include lightweight foundations that would be guyed for stability, and self-installing foundations that would allow the turbine, tower, and foundation to be floated out to a site in one piece.

1.2.2.1 Ocean Area Occupied

1.2.2.1.1 Surface. It is assumed that the construction area would have a surface diameter of 45 m (150 ft) per turbine and that the finished size of the electric service platform (ESP) would range from about 550 to 2,000 m^2 (6,000 to 20,000 ft^2). Temporary exclusion zones around construction spreads might preclude water-related recreational and commercial activities in and around the immediate area of construction.

1.2.2.1.2 Bottom. In Europe, concrete gravity foundations have been used to support WTGs. These hollow, concrete, one-piece foundations are manufactured in dry dock, floated out to the site, and then filled with sand and gravel so that they sink to the seafloor and rest at the desired location. They can be used on most types of seabed, but the seabed must be prepared first, and divers must remove silt and prepare a smooth horizontal bed of shingles to ensure uniform loading of the seabed. In many cases, protection against erosion (scouring) is required, and this is achieved by positioning boulders and rocks around the base of the foundation. Such foundations are very heavy and require larger cranes during their installation than do steel foundation equivalents.

Monopile foundations can also be used. These are steel piles, usually 4 to 6 m (12 to 18 ft) in diameter, driven 9 to 18 m (30 to 60 ft) or more into the seabed by heavy-duty pile-driving equipment. Essentially, the turbine tower extends underwater and into the seabed. No preparation of the seabed is generally required. However, if large boulders are encountered, they must be removed.

Foundations would probably have surrounding scour protection systems. Scour protection options include rubble mounds, concrete cones, and sea grass mattresses. A proposed project off the coast of Long Island, for example, calls for eight artificial sea grass mattresses per foundation. Each square mattress would be 5 × 5 m (16.4 × 16.4 ft), and the total coverage area per turbine would be about 226 m^2 (2,430 ft^2) (on the basis of the assumption that the pile diameter is 5.7 m [18.7 ft]). Installing pilings for 40 turbines and the ESP would disturb an estimated 9,270 m^2 (99,500 ft^2 or 2.3 acres) of bottom area. For comparison, the Horns Rev turbines, which also use a monopile foundation and concrete or rubble scour protection, are estimated to disturb 181 m^2 (1,957 ft^2) of bottom area per foundation.

For the inner-array cable system, it is assumed that the disturbed area would be 0.3 to 0.5 m^2 (3 to 5 ft^2) per linear foot of cable. An additional area would have to be added to accommodate construction activities. The disturbed area for the ESP-to-shore submarine transmission cable would be 0.3 m^2 (3 ft^2) per linear foot of cable, and additional area would have to be added for construction activities.

1.2.2.2 Resource Requirements

Most of the construction materials would be prefabricated on shore and delivered by barge or special equipment. Resources consumed during turbine manufacture would include electricity, heat, oil, gas, and water. Table 1 shows the estimated resources consumed per kilowatt of electricity produced at an offshore wind park over its entire life cycle.

The pilings are typically 4 to 6 m (12 to 18 ft) in diameter and made of hollow steel. When installed, they would contain bottom sediment. Energy would be required to drive the piles (hydraulic hammer or pile driver). Fuel oil for barge and other marine transport would also be required. Special ships (large and stable) are required to transport the turbines and rotors, which can approach the size of a 747's wing span. A barge used for WTG installation in Europe was fitted with a 1,200-ton crane to enable it to reach the heights required for placing the uppermost parts of the turbine and to handle the weight involved. Another example is the Excalibur jack-up barge, a 60-m (197-ft) long, eight-legged barge that can operate in 50 m (184 ft) of water (Seacore 2006).

Port facilities might need to be expanded to accommodate the equipment (e.g., large cranes for offloading and reloading components) and the sizes and numbers of vessels required to transport the components to their offshore locations. Alternative larger (but more distant) ports could be used in the construction phase, but this would increase transportation distances, fuel

TABLE 1 Estimated Life-Cycle Resources Consumed per Kilowatt-Hour of Electricity Produced at an Offshore Wind Power Plant

Resource Consumed	Amount (g)
Water (fresh)	140.010
Hard coal	0.752
Crude oil	0.635
Iron	0.419
Natural gas	0.338
Crude oil	0.550
Quartz sand	0.335
Lignite	0.334
Limestone	0.125
Sodium chloride (rock salt)	0.056
Stone	0.055
Zinc	0.041
Clay	0.031
Aluminum	0.011
Manganese	0.010
Copper	0.009
Lead	0.003

Source: Vestas (2005).

use, and construction time. For the Arklow Bank site off the coast of Ireland, the staging and assembly area was 80 km (50 mi) from the offshore site, which itself is only about 10 km (6 mi) from the coast.

It is expected that only a small amount of freshwater would be used during construction. It would be used as a fluid for directional drilling equipment to avoid potentially contaminating land areas with the bentonite that would otherwise be used in the fluid.

It is assumed that direct employment during construction would be about 2.43 full-time jobs per WTG for the manufacture and assembly of blades and other WTG components before they are barged to the project site, plus 0.58 full-time job per WTG for the construction and installation of monopole foundations, on-site assembly of WTGs, construction of the ESP, and installation of offshore and onshore components of the transmission lines. Indirect and induced employment can be assumed to be between 1.58 and 4.78 FTEs during construction, depending on the value of nonlabor purchases of goods and services.

1.2.2.3 Emissions and Noise Sources

- *Air.* Fossil fuel mobile sources (trucks, ships), cranes, and other powered construction equipment are expected to release air emissions, and the installation of onshore cables and construction of onshore substations (if needed) could generate fugitive particulate emissions resulting from land alteration activities (i.e., clearing, excavation, backfilling, grading).

- *Water.* Inadvertent releases of drilling fluids to the water could occur during the construction of the horizontal directional drilling (HDD) operation (for onshore transmission line construction) and result from accidental spills of petroleum lubricants and fuel from offshore construction equipment/vessels during project construction. These spills could result from an accident involving construction barges or support boats, a loss of fuel while it is being transferred, a loss of bentonite fluids during HDD operations, or a collision.

- *Wastes generated.* Minor quantities of bentonite in drilling fluid could enter the water as the result of an accidental leak. If an inadvertent release of drilling fluid did occur, its density and composition would likely cause it to remain a cohesive mass on the seafloor in a localized slurry pile, which would allow for relatively easy cleanup. Also, some wastes could be generated during the onshore construction of WTG components. For example, oven slag, which is produced during the steel manufacturing process, can be considered hazardous waste, a by-product used in the asphalt industry, or a bulk waste.

- *Hazardous materials stored or used.* No hazardous materials are expected to be stored or used during construction.

- *Noise.* Most of the noise during the construction phase would come from the pile-driving equipment used to install the WTG and ESP monopiles. The pile-setting operation is estimated to take four to six hours per pile. It is expected that the maximum underwater sounds produced by construction activities (pile driving) would be below 180 dB. Noise associated with cable installation would depend on the technique(s) used, which, in turn, would depend on the nature of the seabed. Such techniques could range from jet plowing and air guns, which produce low noise levels, to rock cutters or even shaped charges in areas with exposed bedrock.

1.2.2.4 Transportation Requirements and Accident Potential

Major construction activities would be supported by onshore facilities. Project materials would be staged before the expected start of WTG and ESP construction and then loaded onto vessels for transport to the offshore site. (For the 72-WTG Nysted project in Denmark, the total supply of turbines and equipment at the dock required more than 700 truck loads, necessitating a high degree of flexibility at the unloading area.) Construction personnel would be ferried by boat and/or helicopter from the shore to the facility location, depending on weather conditions.

It is expected that monopiles (6 to 10 at a time) would be loaded onto a barge to be transported to the site. The total number of barge trips would depend on the number of WTGs: one pile per WTG and one or more piles per ESP. Installation would likely be via jack-up barge with a crane; the pile would be driven into the seabed via a pile-driving ram or vibratory hammer. Installation of the WTG would most likely be done by a vessel configured specifically for the purpose. The vessel would travel from the shore and be located next to a previously installed monopile. A jacking system would stabilize the vessel in the correct location. Most of the components could be preassembled before final installation. It is expected that the installation process would take about 30 to 40 hours per WTG. The 72-WTG Nysted project called for all of the WTGs to be installed within 80 days (including downtime) – providing just over one day per turbine. To meet such demands, more onshore setup facilities might be required. Also, special-purpose transport and installation vessels could be needed. One such vessel is a modified container ship, fitted with four supporting legs and a lattice boom crane that can hold four 2-MW turbines. The vessel might also be outfitted with base plates to keep it stable during installation in high currents. They would allow the seabed to be penetrated to the maximum scour that would occur. The ESP would also be preassembled and shipped via barge to its offshore location for installation.

The inner-array cable would likely be transported to the launching area in a cable transport vessel. Line cable machines onboard the barge would pull the cables from coils on the transport vessel onto the barge, which would then be sent to the offshore location. Such cable-laying barges are specifically designed for submarine cable installation and are used for both transport and installation. The submarine cable would probably be installed by jet plowing, which uses a positioned cable barge and hydraulically powered jet plow device that simultaneously lays and embeds the submarine cable in one continuous trench from WTG to WTG and then to the ESP. The ESP-to-shore cable would be laid by following a similar process.

The amount of onshore transportation needed for materials used in steel and turbine manufacturing could be significant. Finished components would probably be transported by marine vessels. (Part of the economic advantage of offshore locations is their ability to use larger turbines; these cannot be shipped over land for onshore use.)

Marine vessels could collide with each other or with the towers. Helicopters used for installation could also collide with the towers or each other. Fuel leaks could occur in these situations.

1.2.3 Operation

An operating commercial offshore wind facility consists of (1) a number of WTGs (at least 20 to 100 now, possibly 200 in the next five years, generally in a multiple-row array); (2) one or more offshore transformer platforms or ESPs (the proposed Greater Gabbard Offshore Park in the United Kingdom calls for four separate transformers); (3) a facilitywide submarine transmission system (turbine collector cables); (4) one or more high-voltage ESP-to-shore transmission cables; and (5) a land-based, high-voltage transmission line. It is possible that a new substation would need to be built, but many facilities envision use of existing substations. A docking platform would be located near the base of the turbine, above wave level. The ESP would also likely include a helipad and possibly crew quarters for servicing.

Each WTG generates low-voltage electricity independently and transfers it to a centrally located ESP or to one of the transformers. The turbines are electrically connected by cables, trenched (typically jet plowed) in the seafloor about 1 to 3 m (3 to 10 ft) deep, and merged at the offshore transformer(s) or the ESP. The transformer(s) step up the low-voltage electricity received from the individual WTGs to a higher voltage. The higher-voltage electricity is then transmitted via one or more high-voltage (115 kV or more) buried submarine transmission cables to the shore. As would the cables used to connect the turbines to the ESP, the high-voltage facility-to-shore cable would likely be trenched into the seabed. The wind facility's output would likely be delivered to shore via a single cable design with three insulated conductors wrapped within a common outer jacket — a design used for both underwater and underground cable systems. Transmission reliability could be increased with a multiple, lower-voltage cable design, but this option could increases costs and require a wider corridor.

The most cost-effective cable transmission technology for connecting nearshore wind parks (less than 50 to 100 km [30 to 60 mi]) to onshore utility transmission systems that is available today is a solid, dielectric, high-voltage alternating-current (HVAC) submarine cable system. Capacitance and losses limit the technically feasible length of HVAC cable and can have significant economic impacts on project viability at moderate distances. New voltage source converter (VSC)-based HV direct-current (HVDC) technology may be an alternative to HVAC in the future for high voltage at longer distances, but it is not yet commercially available for offshore wind parks. For more information on cabling and transmission issues, see Wright et al. (2002) and Christiansen et al. (2006).

Onshore, the cable would most likely run underground through existing road or power line rights of way (ROWs) to an existing substation. The electricity would then be distributed to customers via the electric transmission and distribution grid.

The number of WTGs in a given facility depends on factors such as the desired output of the facility, individual WTG capacity, and area available for siting. The number of WTGs must be large enough to allow the construction costs to be spread among the WTGs and benefit from economies of scale.

It is expected that the electric generating capacities of the turbines deployed offshore in the next five to seven years would be 3 to 5 MW per turbine, or 90 to 500 MW per facility. If an efficiency of 35% is assumed, electricity output would range from 9,200 to 15,300 MWh per turbine, and from 276,000 to 1,530,000 MWh per facility. (In Europe, 2-MW turbines have been used, but 3- to 5-MW turbines are expected in the United States to take advantage of economies of scale.) Actual electricity production would depend on the selected turbine model, tower height, and siting location.

1.2.3.1 Ocean Area Occupied

1.2.3.1.1 Surface. Individual WTGs are spaced at intervals to allow for the efficient use of wind and the passage of recreational boats. The surface area occupied by the individual turbines is the area of the tower at the water line (diameter of about 3 m [10 ft] and area of about 7.5 m^2 [80 ft^2]). The area for the ESP is about 550 to 2,000 m^2 [6,000 to 20,000 ft^2). The ocean area occupied by the entire facility is generally rectangular; the size depends on the number of turbines and their spacing. A rule of thumb for spacing is to allow seven rotor (blade) diameters between units. (Each of the 160-MW Horns Rev and Nysted offshore wind parks in Denmark covers an area of about 28 km^2 [0.2 mi^2], including the 200-m [656-ft] wide exclusion zone.)

Anglers are advised to remain at least 1.6 km (1 mi) from undersea communication cables. If this advice was applied to transmission cables, there would be a 3.2-km (2-mi) wide “no fishing” area along the cable corridor.

1.2.3.1.2 Bottom. Occupied ocean bottom areas are the same as those described for construction minus the space used for actual construction activities. Scouring of the seabed at the bases of structures in offshore wind parks can be a serious concern. The danger is that the scouring action could undermine the seabed beneath the foundation. Because the diameters of gravity caissons (especially concrete) are larger than those of piled structures, the local flow immediately around the caisson foundation accelerates to a higher speed, thereby increasing the potential for scouring action over that of narrower piled foundations. If there is a danger of scouring, a ring of protective armor (usually boulders) can be placed around the base. This action results in the formation of an artificial reef.

1.2.3.2 Resource Requirements

Fuel would be required for the emergency diesel generator on the ESP, which is expected to hold up to about 1,500–4,500 gal (15,600–16,900 L). Replacement amounts would depend on use. Vessels and fuel would be required to transport maintenance personnel to the WTGs and ESP. Cables are expected to be maintenance-free during the life of the project. Turbines and turbine components might need to be serviced or replaced.

Each turbine would contain about 300 gal (1,100 L) of lubricating and hydraulic fluids and greases (which might need to be changed), and leak protection would be provided. Depending on offshore conditions, such servicing could occur at the WTG site, or the components could be shipped to shore, serviced, and returned.

Port facilities needed for dispatching maintenance boats and personnel would not need to be as expansive as those used for construction.

On average, 0.3 direct FTE of effort per WTG is expected, with more required for smaller facilities, and less required for larger facilities (because of economies of scale). Experience with European and U.S. land-based wind projects has indicated that various support jobs could be filled locally or out of state, but a local cottage industry of marine and eco-tourism is anticipated.

1.2.3.3 Emissions and Noise Sources

- *Air.* Minor amounts of NO_x and SO_2 might be emitted during testing and (if necessary) operation of the backup diesel generator on the ESP, if it is fueled by low-sulfur No. 2 oil. (The generator would provide power for aviation and boat navigation lights in the event of a grid power failure.) Estimates indicate that offshore wind projects would offset significant amounts of air pollutants. Table 2 shows estimated air emissions (including emissions from the manufacture of components) per kilowatt-hour of electricity produced from an offshore wind facility over its entire life cycle.

- *Water.* Corrosion-protective coatings might release chemicals (e.g., aluminum) to water, and the application and reapplication of such coatings might also generate unintentional water emissions. Det Norske Veritas (DNV), a classification society that helps the maritime industry manage risk, has specific recommendations for coatings to be used in the atmospheric zone, splash zone (e.g., glass-flake-reinforced epoxy or polyester, or thermally sprayed aluminum with silicone sealer), and submerged zone (multilayer, two-component, high-build epoxy or cathodic protection). Releases to water might also occur if oil was used to fuel the emergency generator or if the ESP leaked during operations, refueling, or an accident. In addition, maintenance activities may generate dielectric fluids at the WTGs and substations (both onshore and offshore).

TABLE 2 Estimated Air Emissions per Kilowatt-Hour of Electricity Produced at an Offshore Wind Facility

Pollutant Emitted	Amount (g)
Carbon dioxide	5.25E+00
Sulfur dioxide	2.22E–02
Nitrogen oxides	2.04E–02
Carbon monoxide	1.99E–02
Organic emissions to air (group volatile organic compound or VOC)	1.20E–02
Nitrous oxide	1.77E–04
Lead	1.72E–04
Hydrogen chloride	1.11E–04
Nitrogen (N_2)	1.03E–04
Hydrogen sulfide	7.45E–05
Chromium (unspecified)	5.72E–05

Source: Vestas (2005).

- *Wastes generated.* Maintenance activities could generate dielectric fluids at the WTGs and substations (both onshore and offshore).

- *Hazardous materials stored or used.* During operations, a small amount of lubricant would be stored at the WTGs (less than 300 gal per turbine). Diesel fuel oil (up to 4,500 gal) would be stored at the ESP for the emergency generator. It is assumed that cables would be solid dielectric and therefore not carry harmful liquids or materials that could leak into the environment. Each transformer on the ESP would have about 10,000 gal of dielectric fluids. (It is assumed that there would be four transformers per ESP; at some facilities, the transformers might be at separate substations.)

- *Noise.* WTG noise could be transmitted into the water via the air as airborne sound or transmitted from the WTG and foundation as structural noise. Newer WTGs produce less sound than older turbines in part because they reduce the noise from wind passing by the turbine hub and blades. Wind turbine noise is typically 50 to 60 dBA at a distance of about 40 m (130 ft) from the turbines. It is expected that levels from a typical wind park would be 35 to 45 dBA at 350 m (1,150 ft). Noise from maintenance and transport vessels and an occasional helicopter (during emergencies or times when weather conditions are poor for marine traffic) could also be expected.

1.2.3.4 Transportation Requirements and Accident Potential

It is assumed that maintenance of WTGs would require five days per year per WTG (two days for planned and preventive maintenance and three days for unplanned or forced outage emergency maintenance). Each work team would require a crew boat and a maintenance vessel, which would likely leave and return the same day. At least one trip to the WTGs per day would be likely until the requirements for offshore operation were understood. Maintenance technicians might be transported to the WTGs via helicopter when the weather was poor or waves were higher than about 1.5 m (5 ft).

There would be a need to transport fuels and other replacement material (oil and grease, spare parts). Used components would be recycled or disposed of.

There is a potential for marine vessels to collide with each other or with the towers. Also, it is possible that the ESP could be damaged or detached from its foundation during severe weather, possibly releasing dielectric fluids.

1.2.4 Decommissioning

The approximate design life of an offshore wind project is 20–25 years, after which decommissioning would likely occur. Decommissioning would entail dismantling the WTGs, ESP, and their foundations; removing the associated scour protection devices; and transporting these materials to shore for reuse or recycling. The WTGs would be dismantled in the same manner in which they were put together and by using similar equipment. The monopile foundations would likely be cut off at the mud line, then the sediment within them would be removed to a suitable depth below the level of the seafloor. Once the sediment was removed, the remaining monopole would be cut off at a depth of about 2 m (6 ft) below the surface. A major turbine manufacturer provided the estimated removal scenario described in Table 3.

1.2.4.1 Ocean Area

1.2.4.1.1 Surface. Except for the vessels used to dismantle and ship components to shore, no surface area would be occupied during decommissioning.

1.2.4.1.2 Bottom. If all materials were removed, no bottom would be disturbed once removal was complete. In some cases, some materials might remain for an artificial reef or other purposes. During the decommissioning process, the area disturbed would likely be the same as that occupied during construction. The removal of monopile and multiple pile structures would be less complex than the removal of concrete gravity-based foundations.

TABLE 3 Possible Removal Scenario for Decommissioning an Offshore Wind Facility

Material	Assumed Disposition
Steel	100% recycling (90% recovery and 10% landfilling)
Cast iron	100% recycling (90% recovery and 10% landfilling)
Stainless steel	100% recycling (90% recovery and 10% landfilling)
High-strength steel	100% recycling (90% recovery and 10% landfilling)
Copper	100% recycling (90% recovery and 10% landfilling)
Aluminum	100% recycling (90% recovery and 10% landfilling)
Lead	100% recycling (90% recovery and 10% landfilling)
Glass fiber components	100% incineration of composite material with heat recovery, glass content is then landfilled
PVC-plastic	Deposit of fractions that can be disassembled, incineration of the rest
Other plastic	100% incineration of waste with heat recovery
Rubber	100% incineration of waste with heat recovery

Source: Vestas (2005).

1.2.4.2 Resource Requirements

Fuel would be needed for the vessels that would travel to the facility and return with WTG components, ESP, and cables. Fuel would also be needed to operate equipment used in the decommissioning process, which is expected to be similar to the construction process, but in reverse.

1.2.4.3 Emissions and Noise Sources

- *Air.* Emissions from fossil-fueled mobile sources (trucks, ships), cranes, and other powered construction equipment are expected. Decommissioning of onshore cable, if conducted, would also be likely to generate fugitive particulate emissions resulting from excavation, backfilling, and grading.

- *Water.* Except for emissions from a possible oil leak during an accident, no emissions to water are expected during decommissioning.

- *Wastes generated.* Substantial amounts of solid waste, including dielectric fluids, would be generated during decommissioning.

- *Hazardous materials stored or used.* No hazardous materials are expected to be stored or used during decommissioning.

- *Noise.* Noise would be generated by vessel traffic to and from the project site and by any powered equipment needed to disassemble components.

1.2.4.4 Transportation Requirements and Accident Potential

Transportation would be needed to collect disassembled components and equipment and return them to shore, with the collection process being essentially the reverse of the construction process.

There would probably be no need for onshore transportation, unless components were reduced in size and transported for recycling or disposal. It is possible that some components, towers, and cut foundations could be used to create artificial reefs. Material not used for reefs would be transported to shore for further recycling.

Accidents and attendant fuel leaks could result from shipping components and personnel during decommissioning.

2 WAVE ENERGY CONVERSION (WEC) TECHNOLOGIES

2.1 OVERVIEW

A variety of technologies have been proposed to capture the energy from waves; however, each one is in too early a stage of development to predict which technology or mix of technologies would be most prevalent in future commercialization. Some of the technologies that have been the target of recent developmental efforts and might be appropriate for OCS applications are point absorbers, terminators, attenuators, and overtopping devices. These types of WEC technologies vary in size, anchoring method, spacing, interconnection array patterns, and water depth limitations. The following sections highlight characteristics of four WEC technologies.

2.1.1 Point Absorbers

Point absorbers have a horizontal dimension that is small compared with the vertical dimension. They use the rise and fall of the wave height at a single point for WEC. Two types of point absorbers are discussed here: The AquaBuOY™ is being considered for a demonstration project, and the PowerBuoy™ is being considered for a commercial project.

The AquaBuOY being developed by the AquaEnergy Group, Ltd., is a point absorber that uses wave energy to pressurize a hydraulic fluid that is then used to drive a turbine generator. The vertical movement of the buoy drives a broad, neutrally buoyant disk that acts as a water piston and is contained in a long tube beneath the buoy. The motion of the water piston, in turn, elongates and relaxes a hose containing seawater, and the change in hose volume acts as a pump to pressurize the seawater (Figure 2). Individual AquaBuOYs can deliver 80 to 250 kW of power each. The 250-kW AquaBuOY is about 6 m (about 20 ft) in diameter and extends 30 m (about 100 ft) into the water. It is made of steel.

AquaEnergy Group submitted an application to the Federal Energy Regulatory Commission (FERC) for a 1-MW demonstration plant off the coast of Washington. The Makah Bay demonstration will include four units, each rated at 250 kW, placed 5.9 km (3.7 mi) offshore in water about 46 m (150 ft) deep. Power levels are expected to range between 0 and 250 kW, with an estimated average output of 46 kW. The demonstration plant is expected to deliver 1,500 MWh annually for three years.

The mooring system for an AquaBuOY consists of four concrete anchors placed in an approximately square pattern on the ocean floor, with the buoy approximately centered on the surface above. From buoy to anchor, each mooring consists of a wire cable attached to a surface float, followed by a cable fastened to a chain that is fixed to float just above the seafloor (to prevent chain scouring), followed by a chain fixed to a pad eye in the concrete block. The buoy closest to shore functions as the collection buoy or hub, where the power cables from each AquaBuOY are connected to the subsea cable. Grid synchronization occurs via a variable-speed drive and step-up transformer to a suitable voltage level. Generated electricity is brought to shore

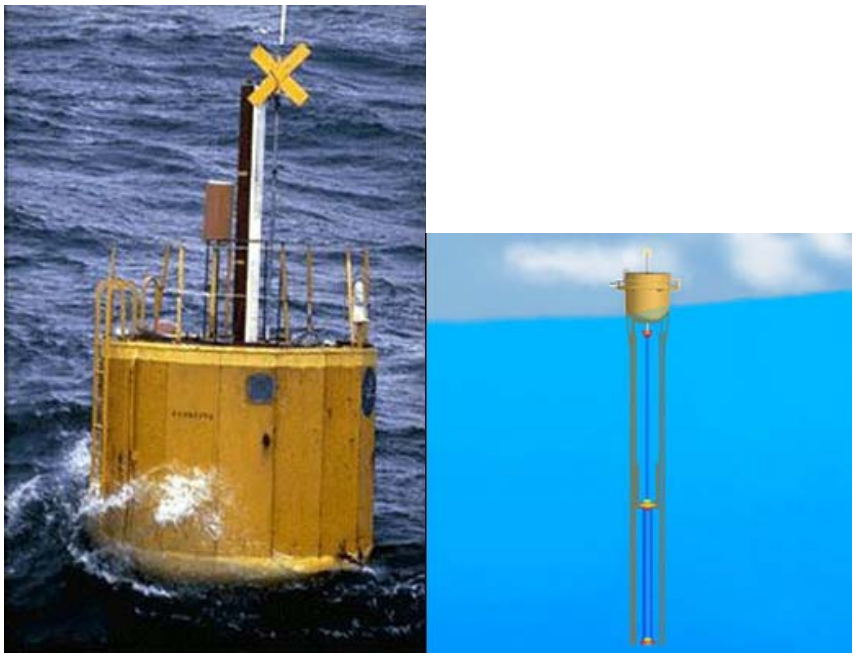

FIGURE 2 AquaBuOY Point Absorber Wave Energy Converter (Source: AquaEnergy Group, Ltd. 2006)

via a standard submarine electrical cable, along the seafloor and under the beach at the shore. An interconnection station that is about 5 × 5 m (15 ×15 ft) can connect the power to the electrical grid.

The PowerBuoy, developed by Ocean Power Technologies (OPT 2006a), moves freely up and down in response to the rising and falling of offshore waves. It incorporates a floating structure, with one component being relatively immobile and the other one moving. The movement is driven by wave motion (a floating buoy inside a fixed cylinder). The relative motion is used to drive electromechanical or hydraulic energy converters. The resultant mechanical stroking is converted via a sophisticated (and patented, proprietary) power take-off to drive an electrical generator. The generated power is transmitted to shore via an underwater power cable. Buoys are spaced to maximize energy capture. Optimum operation is achieved at water depths of 50 m (164 ft), which are typically found 0.8 to 8 km (0.5 to 5.0 mi) from shore.

An OPT power system consists of an array of PowerBuoys connected electrically in parallel to an underwater power cable, which transports the energy to the shore. The arrays are arranged in two to five rows, which are nominally parallel to the shore. Sensors on the PowerBuoy continuously monitor the performance of the various subsystems and surrounding ocean environment. Data are transmitted to shore in real time. If there are very large oncoming waves, the system automatically locks up and stops producing power. When the wave heights return to normal, the system unlocks and recommences energy conversion and transmission of the electrical power ashore. The PowerBuoys are anchored to the sea bottom with “a proprietary anchoring system that avoids any damage or threat to the sea bed or sea life” (OPT 2006a).

A PowerBuoy demonstration unit rated at 40 kW was installed in 2005 for testing offshore near Atlantic City, New Jersey. Testing in the Pacific Ocean is also being conducted, with a unit installed in 2004 and 2005 off the coast of the Marine Corps Base in Oahu, Hawaii. A commercial-scale PowerBuoy system is planned for the northern coast of Spain, with an initial wave park (multiple units) at a 1.25-MW rating. Initial operation is expected in 2007.

On July 14, 2006, OPT filed a permit application with FERC that would lead to a 50-MW commercial facility off the coast of Oregon, with an estimated total power output of 153,300 MWh/yr. It is expected that the proposed Reedsport Wave Park facility would consist of 200 PowerBuoys deployed in an array of four columns that are parallel to the beach. Each row will consist of roughly fifty-four 250-kW PowerBuoys. The power would be generated as asynchronous alternating current and converted to 60-Hz three-phase synchronous power before being fed into the substation.

The proposed facility would use an existing power substation left behind after the closing of an old paper mill (International Paper) and a 3-km (2-mi) underwater effluent pipeline (from the same paper mill) that could be used to run underwater power cables from the wave park to the shore.

The onshore transmission cable would run either within or along the existing pipe, which has an existing easement, to the interconnect point at the International Paper facility. An overhead power line runs from the outfall pipeline pump station to the local substation. It is a 13.8-kV three-phase line that is capable of handling the proposed installation of the initial units. The overhead poles used to carry this line can be re-cabled to increase capacity as needed to accommodate future park expansion.

2.1.2 Terminators

Terminator devices extend perpendicular to the direction of wave travel and capture or reflect the power of the wave. These devices are typically installed onshore or nearshore; however, floating versions have been designed for offshore applications. An oscillating water column (OWC) is a form of terminator in which water enters the partially submerged structure through a subsurface opening to the sea. The up-and-down wave action causes the captured water column to also move up and down, like a piston, thereby forcing the air that is trapped in a chamber above the water column though an opening connected to a turbine. (This contrasts with a point absorber, in which the medium acted upon by the motion of the waves is a hydraulic fluid.) A full-scale, 500-kW, prototype OWC designed and built by Energetech (2006) is undergoing testing offshore at Port Kembla in Australia (about 200 m [0.1 mi] from the Port Kembla Harbor breakwater), and a further project is under development about 1.9 km (1.2 mi) off the coast of Rhode Island. These devices have power ratings of 500 kW to 2 MW, depending on the wave climate and the device's dimensions.

2.1.3 Attenuators

Attenuators are long, multisegment, floating structures oriented parallel to the direction of wave travel. They ride the waves like a ship, extracting energy by using restraints at the bow of the device and along its length. The differing heights of waves along the length of the device cause flexing where the segments connect, and this flexing is connected to hydraulic pumps or other converters. An example of an attenuator in the advanced development stage is the Pelamis designed by Ocean Power Delivery Ltd. (OPD 2006). It has four floating cylindrical pontoons that are 30 to 38 m (100 to 125 ft) long by 3.5 to 4.6 m (11.5 to 15 ft) in diameter and are connected by two separate hinges at each segment junction, for a total of six hinges (Figure 3). Flexing at the hinged joints caused by wave action drives hydraulic pumps built into the joints. A transformer in the nose of the unit steps up the power-to-line voltage for transmission to shore. Power is fed down an umbilical cable to a junction box in the seabed, which connects the device to other devices via a common subsea cable to shore.

A full-scale, four-segment production prototype rated at 750 kW was sea tested for 1,000 hours in 2004. This successful demonstration was followed by the first order for a commercial system, which came from a consortium led by the Portuguese power company Enersis SA. The first stage, scheduled to have been completed in 2006, consists of three Pelamis machines with a combined rating of 2.25 MW to be sited about 5 km (8 mi) off the coast of northern Portugal. An expansion to more than 20 MW of capacity is being considered. A Pelamis-powered 22.5-MW wave energy facility is also planned for Scotland, with the first phase targeted for 2006. A study cosponsored by the Electric Power Research Institute (EPRI; Bedard et al. 2005) has evaluated the feasibility of Pelamis and other WEC technologies at sites off the coasts of Hawaii (2 km [1.2 mi] from shore; 15.2 kW/m [4.6 kW/ft] average annual wave energy), Oregon (3.5 km [2.2 mi] from shore; 21.2 kW/m [6.5 kW/ft]), California (13 km [8.1 mi] from shore; 11.2 kW/m [3.4 kW/ft]), Massachusetts (9.1 km [5.7 mi] from shore; 13.8 kW/m [4.2 kW/ft]), and Maine (9.2 km [5.7 mi] from shore; 4.9 kW/m [1.5 kW/ft]).

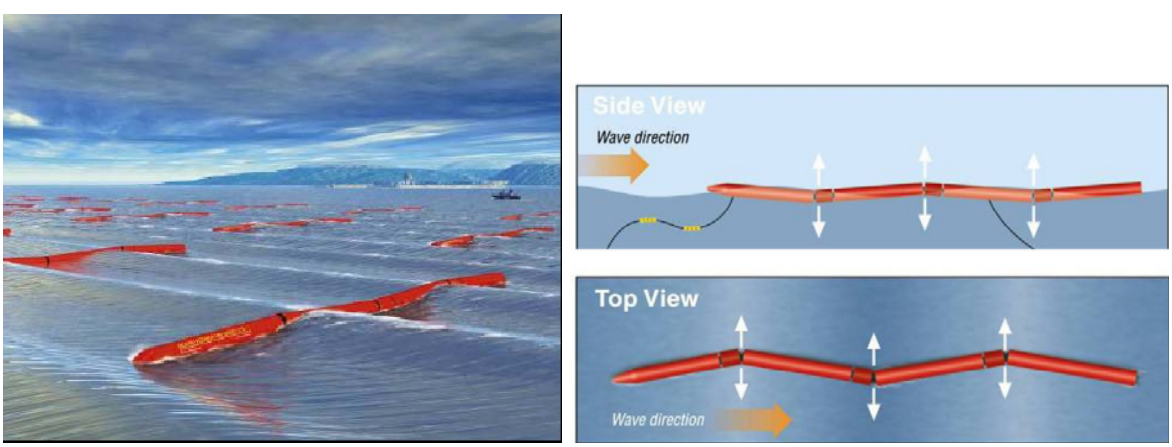

FIGURE 3 Pelamis Wave Energy Converter (Source: OPD 2006)

2.1.4 Overtopping Devices

Overtopping devices have reservoirs that are filled by impinging waves to levels above the average surrounding ocean. They are partially submerged structures consisting of walls over which the waves topple, filling the reservoir and creating a head of water. This water, when released back to the ocean, turns hydroturbines or other conversion devices at the bottom of the reservoir. Offshore devices include the Wave Dragon™ (Wave Dragon 2005), which has wave reflectors that concentrate the waves toward it and thus raise the effective wave height (Figure 4). One Wave Dragon unit is quite large (150 × 260 to 300 m [about 490 × 850 to 980 ft]), with a rated capacity of 4 MW. The Wave Dragon is designed for deployment in water more than 20 to 30 m (66 to 98 ft) deep to take advantage of high-energy ocean waves. Wave Dragon development includes a 7-MW demonstration project off the coast of Wales and a precommercial prototype project performing long-term and real sea tests on hydraulic behavior, turbine strategy, and power production to the grid in Denmark. The Wave Dragon design has been scaled up to large sizes, with a span of more than 200 m (660 ft) across the reflector arms and a capacity of about 24 MW.

FIGURE 4 Wave Dragon Overtopping Device (Source: Wave Dragon 2005)

2.2 WEC TECHNOLOGY DATA

2.2.1 Pilot Scale

It is assumed that the WEC demonstration facility would be a 2-MW demonstration wave park with 13 wave generation buoys, each 150 kW, in water that was 50 m (164 ft) deep and covered less than 1 km^2 (0.6 mi^2) in area. This scenario corresponds most closely to using the AquaBuOY or PowerBuoy, both of which are point absorbers. Smaller demonstrations might also be possible (e.g., for specific devices in specific locations).

Besides point absorbers (buoys), other offshore wave technologies that could be used for pilot and demonstration projects in the next five to seven years include terminators, attenuators, and overtopping devices. The four main types of wave devices that are likely candidates for pilot-scale demonstrations are summarized in Table 4 and described below. In the remainder of this chapter, these devices may be referred to by the manufacturer, name, or type of device. See Bedard (2006) for an illustration of the variety and status of various wave technology demonstration projects.

Many of the technologies are proprietary, so detailed technical information is limited. A few general considerations follow here. Most wave power devices under development will use frequency converters and step-up transformers to synchronize with the grid. Wave park interconnection levels will vary but are expected to be in the range of 12 to 33 kV. The onshore

TABLE 4 Candidate WEC Devices for Pilot-Scale Facilities

Type	Manufacturer	Name	Rated Capacity	No. of Units	Approximate Generation (MWh/yr) Device	Approximate Generation (MWh/yr) Facility
Point absorber	AquaEnergy	AquaBuOY	250 kW	13	150	1,950
	OPT	PowerBuoy	40 to 250 kW, 500 kW being developed	Eight 250-kW units	767	6,136
Terminator/OWC	Energetech	Energetech	500 to 2,000 kW	4	2,275	9,000
Attenuator	OPD	Pelamis	750 kW	3	1,337	4,000
Overtopping device	Wave Dragon	Wave Dragon	4 MW	1	10,900	10,900

Source: Derived from EPRI (2004b) and OPT (2006b).

transmission-related needs will vary from project to project. Some could require the construction of new conduits, substations, and overhead transmission wires, while others might make use of existing infrastructure. Most likely there will be some combination. Developers, however, do try to minimize the need for new onshore infrastructure to increase the economic viability of these new projects.

2.2.1.1 Site Monitoring and Testing

No special construction of facilities for site monitoring and for testing of WEC is expected, although individual projects might use such devices. In general, existing National Oceanic and Atmospheric Administration (NOAA) data buoys might be used.[4]

2.2.1.2 Construction

Structures would most likely be constructed on a nearby shore. Some components might be shipped via truck from other onshore locations.

[4] For example, the permit application for the Reedsport, Oregon, project refers to data collected over a period of 12 years from the nearest NOAA buoy, which is 70 mi from the proposed project demonstration site.

2.2.1.2.1 Ocean Area Occupied.

Surface. During installation, space would be required for vessels to tow the individual devices (e.g., PowerBuoy) to their offshore positions. For PowerBuoys, the area would be at least as long as the length of the buoy. For larger devices, such as the Wave Dragon, barges would be used to transport components to the offshore site. (One 4-MW Wave Dragon can be 45,000 m^2 (484,200 ft^2) and weigh 22,000 to 33,000 tons.[5])

Bottom. Each AquaBuOY is anchored by four concrete anchors; thus, 13 devices would require 52 concrete anchors. The size of the anchors is not known, but their depth is greater than 50 m (164 ft). The ocean bottom would be disturbed to install each anchor and the cables connecting individual devices to a junction box on the ocean floor. The size of junction box is not known.

The mooring configuration for the OWC terminator uses an asymmetric mooring arrangement, with six forward mooring legs and four rear mooring legs in 5 to 50 m (about 16 to 164 ft) of mean water depth. The structure is supported vertically on four mooring legs that are pinned to the structure and the seabed (EPRI 2004b). Variations within this concept may include the number and make-up of the mooring legs (e.g., wire or fiber moorings), the use of alternative anchor points (e.g., driven piles, suction anchors, drag anchors, or gravity blocks), and the number and location of vertical supports. The Pelamis is moored by using a three-point slack mooring configuration. The Wave Dragon also uses a slack mooring.

2.2.1.2.2 Resource Requirements. Most components are readily available from U.S. suppliers, and structures could be built onshore. The AquaBuOY and PowerBuoy structures are made of steel and could be built locally by following standard construction techniques and using standard technologies available in most shipyards. Devices designed for deeper (more than 50 m [164 ft] deep) waters might be more suitable for the West Coast or Hawaii; East Coast waters of suitable depth would be at a greater distance from shore, so the amount of offshore transmission cable would be greater for East Coast installations.

The job skills needed to fabricate these devices are present in most coastal communities, although some components may have to be manufactured elsewhere. Divers may be required for installation. Estimates of the specific number of employees needed were not found.

2.2.1.2.3 Emissions and Noise Sources.

- *Air.* It is likely that the marine vessels used to transport equipment to the offshore location would emit NO_x and SO_2. Construction equipment for

[5] Note that one Wave Dragon is 4 MW, twice the pilot demonstration size. However, efficiencies would be lost if the Wave Dragon was scaled down to the nominal 2-MW size.

installing onshore transmission facilities to connect to the existing grid are likely to emit particulates, NO_x, and SO_2.

- *Water.* No emissions to water are expected, unless there would be accidents that would cause fuel spills.

- *Wastes generated.* Except for possible spills of sewage discharge from barges used for installation, no waste generation is expected.

- *Hazardous materials stored or used.* No hazardous materials are expected to be stored or used during the construction of demonstration facilities.

- *Noise.* Noise sources include transport vessels and installation equipment (e.g., pile drivers for installing some anchoring systems).

2.2.1.2.4 Transportation Requirements and Accident Potential. The AquaBuOY and PowerBuoys, which are relatively small, could be towed to their offshore positions. Each device would presumably be towed separately. Installation would take about one week per device. Deployment of the OWC would likely involve more than one tugboat and a special floatation barge to properly place and stabilize the structure. Deployment and recovery of Pelamis would be relatively easy: The power and three mooring connections could be disconnected quickly from a tug. The Wave Dragon requires multiple tugs for towing.

Onshore transportation of the device's components would be via truck. Most components would come from the United States, although initially, at least, some might not be produced locally.

There is a potential for accidents that would involve maintenance vessels, possibly leaking fuel oil.

2.2.1.3 Operation

The types of WEC facilities and their operating characteristics were described in Section 2.1.

2.2.1.3.1 Electricity Generated. Electricity generation will vary with location (wave power density). For example, the annual energy production from a 150-kW AquaBuOY ranges from 81 to 124 MWh in Maine to 110 to 196 MWh in Washington. Table 4 shows estimated amounts of electricity generated from candidate WEC devices. The electricity generated by individual buoys would likely be sent by power cables to the buoy closest to the shore (the "collection" or "hub" buoy), and from there by subsea cable to the shore.

2.2.1.3.2 Ocean Area Occupied.

Surface. For each AquaBuOY, the occupied ocean surface area would be about 28 m^2 (300 ft^2). For the demonstration plant, the total occupied surface area would be less than 1 km^2. For the OWC terminator, the dimensions would be 25 × 35 m (about 80 × 115 ft), or 875 m^2 (about 9,400 ft^2) per device. If there were four devices spaced 60 to 90 m (about 200 to 300 ft) apart, the total surface area covered by the park would be about 15,000 m^2 (about 161,400 ft^2). For the attenuator (Pelamis), each unit would be about 420 to 690 m^2 (120 to 150 m × 3.5 to 4.6 m), or about 4,500 to 7,400 ft^2 (394 to 492 ft × 11.5 to 15 ft), with a centerline spacing of 150 m (about 490 ft). The total occupied surface area per device would be 18,000 to 22,520 m^2 (194,000 to 242,300 ft^2). The Wave Dragon (overtopping device) would be 39,000 to 45,000 m^2 (about 420,000 to 484,000 ft^2) for a 4-MW unit, which could not be scaled down to smaller capacities without significant efficiency losses.

Bottom. For floating devices (those being considered here), the ocean bottom disturbed area would be the area that was occupied by the moorings and any cables that were not buried. The collective area would be the per-device area multiplied by the number of devices, plus the area required for the cable. It is not clear whether the cables would lie directly on the ocean bottom or be buried.

2.2.1.3.3 Resource Requirements. Fuel oil would be required to run maintenance transport vessels and possibly maintenance equipment. The job skills needed for maintenance are present in most coastal communities. Numerical employment estimates were not available.

2.2.1.3.4 Emissions and Noise Sources.

- *Air.* The marine vessels used to transport the maintenance equipment and crew to the offshore location would probably emit NO_x and SO_2. Some devices, such as the AquaBuOY, might be brought to shore for maintenance.

- *Water.* Devices that incorporate a closed-circuit hydraulic system could spill hydraulic fluid into the water. Devices that use seawater or air as a working fluid do not have this potential. The potential impact of hydraulic fluid spills could be mitigated, to some degree, by using a water-based fluid (EPRI 2004a). Also, isolation valves that could be controlled reliably from shore would minimize the volume of any spill once a leak was reported by the plant monitoring system. For Pelamis, the hydraulics would be located in the power conversion modules at the joints, where containment and double and triple sealing would be used to prevent leaks. Environmentally benign fluids that are nontoxic to marine organisms and are rapidly biodegradable would probably be used.

All devices might need to use toxic chemicals to inhibit marine biofouling. Fouling could be controlled by divers conducting periodic cleaning or by using antifouling coatings, which would require dry-docking. If coatings were used, an organotin compound, such as tributyl tin (TBT), would probably be considered, because it has a reliably long coating interval (six to seven years) when compared with that of copper-based paints (one to two years). According to EPRI, the typical legal limit for the average TBT release rate is 5 μm per square centimeter of hull wetted surface area per day. U.S. Navy experience indicates that release rates well below this level (at 0.1 $\mu m/cm^2/d$) are fully effective in preventing hard fouling (EPRI 2004a).

Flexible reinforced rubber surfaces, such as those on hose pumps, cannot be coated. According to EPRI (2004a), this situation could cause a problem, because fouling on the interior hose walls would reduce overall conversion efficiency, and hose interiors would be especially subject to fouling during periods of summer calm. However, ocean test experience suggests that even a small amount of hose flexing is enough to prevent fouling organisms from taking hold (EPRI 2004a). If hose fouling became a problem, commercially available rubber formulations consisting of TBT could be used to line the interior (and exterior, if necessary) of the hose during manufacture. Because the TBT would be incorporated chemically into the rubber's structure, its release rates would be much lower than the problem-causing TBT paints, yet it would still be protective in preventing fouling (EPRI 2004a).

- *Wastes generated.* Maintenance activities could generate dielectric fluids at transformers and at onshore substations.

- *Hazardous materials stored or used.* Some buoys and attenuators might use hydraulic fluids. Transformers would contain an unknown amount of dielectric fluid.

- *Noise.* For PowerBuoys, noise levels are likely to be similar to those of ship traffic. Noise would probably result from the pneumatic turbine used in oscillating water column devices, but it could be reduced through careful design or muffling (EPRI 2004a). Measurements taken from a prototype OWC indicated a sound intensity of 70 to 90 dB at the seaward end of the breakwater. On shore, 650 m (2,130 ft) from the device, measured intensity is less than 60 dB. Residents likened the noise to a that of a small, single-engine airplane flying overhead. For Pelamis, underwater noise would be generated by hydraulic machinery. Within the power conversion modules in the joints of the Pelamis machine, there is equipment rotating at 1,500 revolutions per minute (rpm), but close to the device, wave noise would likely swamp any noise that might be audible from the machinery (DOE 2006b).

2.2.1.3.5 Transportation Requirements and Accident Potential. Monitoring and supervision are expected to be controlled remotely. To repair any of the submerged components (hose pumps, piston assembly, check valves), a WEC buoy would need to be floated into a horizontal position. This would require (1) bringing the counter-reaction tube into a horizontal position with a crane or (2) pumping air into sub-sea compartments. A buoy could also be towed into a nearby port for major overhauling. The OWC terminator could be accessed by boat for regular maintenance. The operations and maintenance strategy for this type of device would be to conduct as many tasks as possible on the device itself and recover the device only in case of critical structural failures. For the Pelamis, device maintenance would be conducted on shore at a pier. The device could be disconnected quickly from its mooring and towed to a nearby port for maintenance overhauls. Pelamis subsystems, such as power modules, could be lifted out with a crane and replaced.

There is a potential for hydraulic fluids to leak. In addition, there could be accidents involving maintenance vessels, with a possible leakage of fuel oil.

2.2.1.4 Decommissioning

If a WEC demonstration project was successful, additional modules could be added, and decommissioning could be postponed to the end of the project's commercial life. (If the project was unsuccessful, decommissioning would occur at the end of the demonstration period.) Decommissioning would be the reverse of the installation process, with components brought to shore and recycled or reused.

During decommissioning, space (ocean surface area) would be needed for vessels to tow the individual devices and possibly for barges to disassemble and tow components of larger devices, such as the Wave Dragon. Ocean bottom area requirements would be similar to those for construction, but they would be for removal rather than installation.

The resources required would include fuel oil to run the vessels and equipment used for decommissioning and returning components and structures to shore. (However, this might not occur for several years if commercialization followed the demonstration at the same site.) Job skills for decommissioning exist in most coastal communities. Specific employment estimates were not available.

Air emissions (NO_x and SO_2) can be expected from marine vessels returning equipment from the offshore location to onshore points. No emissions to water are expected, unless accidents caused fuel spills. No waste is expected to be generated, except for possible spills of sewage discharge from barges used for decommissioning. No hazardous materials are expected to be stored or used during decommissioning. Noise sources would include transport vessels and decommissioning equipment.

Transportation requirements for decommissioning would be essentially the reverse of the transportation requirements for construction but could also include the transportation of recycled

equipment and components. There is a potential for accidents involving decommissioning vessels and equipment, possibly involving leaking fuel oil.

2.2.2 Commercial Scale

As was the case for pilot-scale facilities, no special construction of facilities for site monitoring and testing of commercial WEC is expected, although individual projects might use such devices. In general, existing NOAA data-collection buoys would likely be used.

The construction, operations, and decommissioning of commercial-scale WEC facilities would probably be similar to those of demonstration facilities (Section 2.2.1); some summary statements are presented below.

2.2.2.1 Construction

The WEC devices would probably be built onshore and towed to their offshore locations. Divers might be required to check lines.

During the installation of the devices, an ocean surface area would be required for vessels to tow the individual devices (e.g., PowerBuoys) to their offshore positions. For larger devices, such as the Wave Dragon, barges would likely be used to transport components to the offshore site. Regarding the ocean bottom area disturbed, the transmission cable would likely be buried along the shoreline and run along the seabed under water to the mooring site.

2.2.2.1.1 Resource Requirements. Fuel would be needed to power the transport vessels. Job skills for fabrication are present in most coastal communities; estimates for specific numbers of employees were not found. Divers and local tugs would probably be used to install PowerBuoys.

2.2.2.1.2 Emissions and Noise Sources.

- *Air.* NO_x and SO_2 emissions are expected from transportation vessels and installation equipment.
- *Water.* Fuel oil or sewage could spill into water as a result of accidents involving transport vessels and installation equipment.
- *Wastes generated.* Spills and discharges of sewage from construction vessels would be possible. There might be some construction-related solid wastes. Some of these wastes might be generated at onshore support facilities.

- *Hazardous materials stored or used.* No hazardous materials are expected to be stored or used during construction.

- *Noise.* For buoys, it is expected that noise would be localized and of short duration during installation.

2.2.2.1.3 Transportation Requirements and Accident Potential. Because the buoys are relatively small, they could be towed to their offshore locations. A substation might be built along the coastline, an existing substation might be used, or a new substation might need to be located further inland.

There is a possibility that transportation vessels and/or devices could collide. Presumably installation would be timed to occur when weather conditions were good, but, by definition, offshore locations have high wave energy, so deployment could be challenging.

2.2.2.2 Operation

The commercial facility envisioned for the OCS is assumed to be a 20-MW park. It would consist of four rows, each containing twenty 250-kW wave generator buoys spaced 100 m (328 ft) apart in water 50 m (164 ft) deep. It would cover an area of 2 km (1.25 mi or 1 nautical mile) by 305 m (1,000 ft).

A commercial-scale facility would probably be a scale-up of a demonstration facility, except that the individual devices might have higher-rated powers (e.g., demonstration facility rated at 150 kW, commercial facility rated at 250 kW).

For commercialization in the next five to seven years, point absorbers (e.g., PowerBuoy, AquaBuOY) would be the most likely candidates. Operations would include activities such as monitoring, reliability management, and structural monitoring and repair. Offshore systems might need to be returned periodically to shore for maintenance or replacement.

2.2.2.2.1 Electricity Generated. The envisioned commercial facility scenario assumes that eighty 250-kW devices would make up a 20-MW wave park. However, as noted in Section 2.1, on July 14, 2006, OPT applied to FERC for a permit that would lead to the development of a 50-MW plant using two hundred 250-kW PowerBuoys. This park would have an estimated total power output of 153,300 MWh/yr.

2.2.2.2.2 Ocean Area Occupied.

Surface. According to OPT, a 10-MW power station using PowerBuoys would occupy roughly 4 acres of ocean space. OPT's permit application (50 MW capacity) states that the

approximate dimensions of the proposed site are 1.6 km (1 mi) in the east-west direction by 8 km (5 mi) in the north-south direction. It also states that the power transmission cable will be connected to approximately the north-south center of the array and run the roughly 4.2 km (2.6 mi) to the outlet of the existing wastewater discharge pipe from the now-closed International Paper Plant.

The proposed 50-MW commercial plant is expected to consist of 200 PowerBuoys deployed in an array for four columns that are parallel to the beach. Each row would have roughly fifty-four 250-kW PowerBuoys. The lateral spacing of the buoys would be roughly 100 m (328 ft), and the row spacing would be roughly 200 m (660 ft). Thus the overall size of the required area would be roughly 0.6 × 5 km (0.4 × 3.1 mi), exclusive of any required buffer area.

For PowerBuoys, the navigational aids would extend about 30 ft (9 m) above sea level.

To repair system components (e.g., hose pumps, piston assembly, check-valves), the system would most likely need to be floated into a horizontal position for access. Turbo-machinery elements would probably be accessible within the buoy hull.

The overall footprint of a large ocean energy park (e.g., Pelamis) might appear to be comparable to that of a small island. However, it is more like a transparent screen than a solid block, because the machines are designed to allow a lot of the wave energy to pass through, particularly during storm conditions (DOE 2006b).

Bottom. According to EPRI (2004b), if it is assumed that the park is composed of one thousand 250-kW AquaBuOY devices, then a mooring design that needs 2.5 mooring lines per device will require about 2,500 mooring lines and 2,500 anchors. In water 50 m (164 ft) deep, the length of the mooring line would be roughly three times the depth of the water, or 150 m (492 ft) of chain per mooring. The total cable or chain-installed length would therefore be 150 × 2,500 m (492 × 8,200 ft), or 350 km (280 mi). According to EPRI (2004b), “even at a very low failure rate, this will require a lot of intervention for O&M purposes and will critically affect the devices economic viability.” Slack moorings are commonly used in offshore applications where there is a need for the moored device to act freely without being affected by any vertical mooring forces. Flexible riser cables are expected to connect the devices to a junction box on the ocean floor.

2.2.2.2.3 Resource Requirements. Fuel would be required to power maintenance vessels. Employees would include maintenance workers (onshore and offshore) and monitors (onshore).

2.2.2.2.4 Emissions and Noise Sources.

- *Air.* No emissions are expected from the WEC devices, but NO_X and SO_2 emissions are expected from maintenance vessels (e.g., for repairs, scraping barnacles).

- *Water.* Water emissions are expected to be similar to those for demonstration-scale facilities (Section 2.1.2.4).

- *Wastes generated.* Spills and discharges of sewage from lay barges are possible. Some wastes might be generated during operations as part of device maintenance. Accidental spills could occur if equipment broke loose from its moorings. Spills could include hydraulic fluid, dielectric fluid from transformers, etc.

- *Hazardous materials stored or used.* Some buoys and attenuators might use hydraulic fluids. Transformers would contain an unknown amount of dielectric fluid.

- *Noise.* Sources of noise during operations are expected to be similar to but scaled down from sources associated with demonstration facilities.

2.2.2.2.5 Transportation Requirements and Accident Potential. Transportation requirements during operations are expected to be similar to but scaled down from those of demonstration facilities (see Section 2.1.2.5).

Regarding accidents, the WEC devices could break loose from their moorings. No data were found on the probabilities of such events, but one demonstration device (Wave Dragon) did break loose. If hydraulic fluid containers were ruptured, fluids could leak.

2.2.2.3 Decommissioning

As was the case for other offshore alternative energy development projects, decommissioning of WEC devices would likely entail the removal of equipment and return of the site to its natural state. The expected project life is about 20 to 25 years.

During decommissioning, space would be needed for vessels to tow the individual devices from their offshore positions. For larger devices, such as the Wave Dragon, barges would be used to transport components from the offshore site.

Anchors or other mooring devices, cables, and junction boxes would be removed from the ocean bottom.

Resources required would include fuel to power decommissioning vessels. Employment would include vessel operators and possibly divers.

Emissions would likely include NO_x and SO_2 from decommissioning vessels and equipment. Water emissions could result from accidental fuel leaks or hydraulic fluid leaks if containers ruptured during decommissioning. Spills and discharges of sewage could result from decommissioning vessels. Substantial amounts of solid waste, much of it recyclable, would be generated during decommissioning. No hazardous materials are expected to be stored or used during decommissioning. Sources of noise would include decommissioning vessels and equipment.

Transportation requirements would include vessels to return buoys or other devices to the shore. Once devices were returned, they might be dismantled, and their components might be shipped for other use or recycled. There is a possibility that transportation vessels and devices could collide. Presumably, decommissioning would be timed to coincide with good weather conditions, but, by definition, the offshore locations have high wave energy, so decommissioning work might be challenging.

3 OCEAN-CURRENT TECHNOLOGIES

3.1 OVERVIEW

Ocean current energy technology is at an early stage of development; only a small number of prototypes and demonstration units have been tested to date. One such technology involves submerged turbines. Energy can be extracted from the ocean currents by using submerged turbines that are similar in function to wind turbines but that capture energy through the process of hydrodynamic rather than aerodynamic lift or drag. These turbines have rotor blades, a generator for converting the rotational energy into electricity, and a means for transporting the electrical current to shore for incorporation into the electric grid. Today, two types of turbines — horizontal axis and vertical axis — are generally considered for ocean current energy.

Prototype horizontal axis turbines, similar to wind turbines, have been built and tested. Over the next five to seven years, the horizontal axis turbines are probably the most likely turbines to be installed on the OCS. The horizontal axis marine current turbine functions similarly to the horizontal axis wind turbine, but because water is 800+ times more dense than air, a 5.6-km/h (3.5-mph) current has the kinetic energy of a 161+ km/h (100+ mph) wind. Because they are relatively constant in location and velocity, ocean currents can lead to a large capacity factor (fraction of time actively generating energy) for the turbines; for nontidal flows, the capacity factor may reach 80%. Vertical axis turbines are either drag or lift designs, with the lift devices offering more potential than the drag designs. The flow of current needed to generate power economically depends on the technology; for existing horizontal axis turbines, a quasi-continuous current velocity of about 5.6 km/h (3.5 mph) is adequate. For tidal flows, more than 9.3 km/h (5.8 mph) would be needed to compensate for slack tide periods.

Various mechanisms (e.g., posts, cables, anchors) are required to keep turbines stationary relative to the currents with which they interact. Turbines can be suspended from a floating structure or fixed to the seabed. They can be anchored to the ocean floor in a variety of ways. They can be tethered with cables, with the relatively constant current that interacts with the turbine being used to maintain location and stability. Such a configuration is analogous to flying a kite underwater, where the kite is the turbine designed to keep upright and the kite flyer is the anchor. Additional components can include concentrators (or shrouds) around the blades to increase the flow and power output from the turbine. Various alternative designs have also been proposed. One would be to use a barge moored in the current stream with a large cable loop to which waterfilled parachutes would be fastened. The parachutes would be pushed by the current and closed on their way back, forming a loop similar to a large horizontal waterwheel. Figures 5 and 6 show two possible turbine and anchor technologies.

In large areas with powerful currents, it would be possible to install water turbines in groups or clusters to create a “marine-current facility,” with a design approach similar to that of a wind turbine facility. Turbine spacing would be determined on the basis of wake interactions and maintenance needs. A density of up to 37 turbines per square kilometer (to avoid

FIGURE 5 Possible Ocean-Current Turbine Technology (Source: Hammerfest Strøm AS 2006)

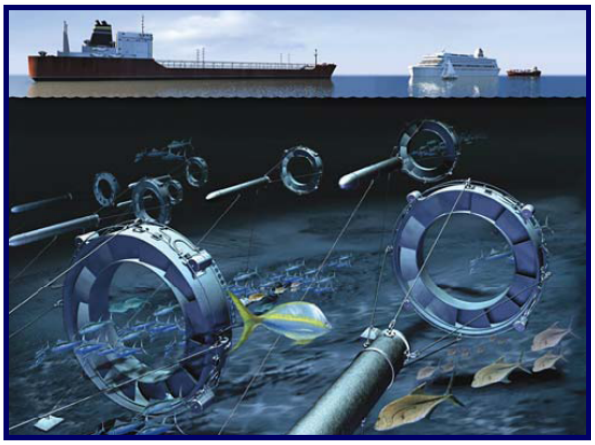

FIGURE 6 Possible Ocean-Current Device Anchor Technology (Source: Gulfstream Energy Incorporated 2006)

wake-interaction effects between the turbines and to allow for access by maintenance vessels) has been predicted (World Energy Council 2001).

For marine-current energy to be used, a number of potential problems need to be addressed, including (1) avoidance of drag from cavitations (air bubble formation that creates turbulence and substantially decreases the efficiency of current-energy harvest), (2) prevention of marine growth buildup, (3) control of corrosion, and (4) maintenance of overall system reliability. Because the logistics of maintenance are likely to be complex and the cost of maintenance is potentially high, system reliability is of particular importance.

No currently operating commercial turbines are connected to an electric power transmission or distribution grid. However, a number of configurations are being tested on a small scale. In March 2006, the Bermuda Electric Light Company, Ltd. (BELCO) announced plans to purchase up to 20 MW of alternative energy that was to be generated from ocean currents by means of a patented technology in which a large submersible device (similar to a submarine) operating within a cylindrical unit would capture the energy of ocean currents in order to power generators. It would incorporate a gearbox that would allow it to produce a large volume of electricity. The generator, which would be 46 m (150 ft) long and contain a four-blade turbine, would operate between 75 and 200 m (250 and 660 ft) below sea level (about 46 m [150 ft] above the seafloor). It would provide power to a substation on land that would connect to BELCO's power grid. The number of generators has not been determined (Jones 2006), but the 10 MW to be made available by 2007 could come from one unit (Gadbois 2006).

Several proposals for demonstration projects off the Florida coast have also been submitted to FERC. The following paragraphs describe proposals from the following three applicants: Red Circle Systems, Open Hydro, and Ocean Renewable Power Company.

3.1.1 Red Circle Systems

On May 14, 2006, Red Circle Systems filed permit applications with FERC to secure a license and perform feasibility assessments for 12 project sites along the east coast of Florida. The proposed "SeaGen" project will reportedly use technology developed by the English company, Marine Current Turbines Ltd. (MCT), which in 2003 installed the world's first 300-kW offshore turbine ("Seaflow"). According to the FERC application, the proposed project would be located about 40 km (25 mi) offshore. The twin axial-flow rotors would be about 5 to 10 m (16 to 33 ft) in diameter and made of composite. By using the flow of the current, each rotor would drive a generator via a large gearbox, similar to a hydroelectric or wind turbine. The rotors would turn at about 10 to 20 rpm (ship propellers turn about 10 times as fast). The twin power units would be mounted on a wing-like extension on either side of a tubular steel monopile, about 3 m (10 ft) in diameter, which would be set into a hole drilled into the seabed from a jack-up barge. The pile that was used for SeaGen's prototype — the single-turbine, 300-kW Seaflow — is 2.1 m (6.9 ft) in diameter, weighs 80 tons, and is 42.5 m (139.4 ft) long. These were the maximum diameter and weight that could be accommodated by the jack-up barge used for the Seaflow installation, which was the largest available at the time (2003).

The Seaflow turbine is mounted on a steel tube, or monopile, which is fixed into the seabed and carries the weight of all the other components and the operating forces on the rotor. The powertrain (rotor, gearbox, and generator) is mounted on a collar that can slide up and down the pile. With the collar out of the water, there is easy access to the working components for inspection and maintenance. Apart from the powertrain, all the other systems are housed in a pod on top of the pile (EU 2005). The turbine is controlled via an industrial personal computer in the pod, which is linked to all the systems involved in operating the turbine. Communications to the machine are carried out via a radio link to a land base; the turbine can be accessed remotely by telephone. (See Fraenkel 2004 for more information on the Seaflow demonstration project.)

The optimal water depth for the first-generation SeaGen units would be 20 to 40 m (about 66 to 131 ft). According to MCT, the device might be scaled up for depths of 50 to 60 m (160 to 200 ft). MCT says that it also has second-generation technology that "will be usable in depths possibly up to 100 m" and that it has some futuristic concepts under development that would "work in any depth of water including the Gulf Stream," but it has "not yet disclosed the details," and "such possibilities depend on success with the first generation technology to start with" (Fraenkel 2006).

The FERC application states that the capacity of each SeaGen unit would be 550 to 1,200 kW, depending on currents. It is assumed that units would be sited in portions of the Gulf Stream where the current flow maintains a speed of 4 knots. The proposed project would consist of 20 to 40 SeaGen units, or roughly 20 to 40 MW. (In general, it is expected that the MCT turbines would be installed in batches of 10 to 20. Many potential sites investigated so far are large enough to accommodate hundreds of turbines. As a site is developed, the marginal cost of adding more turbines and of maintaining them should decrease, and economies of scale should be realized as the project grows.) The actual number of units might be higher or lower, depending on further study. Units would have to be arranged so that one would not be situated in the wake of another; the precise distance required for spacing would depend on flow conditions and turbine size. Regarding transmission, individual units would feed into a grid cable for transmission to shore. The primary transmission line is expected to have a voltage of 33 kV and to be 40 to 48 km (25 to 30 mi) long. It is expected that the transmission line would be buried below the seabed to minimize possible impacts.

Because access to the turbine is critical, MCT mounts the turbine on a pile so that it can be raised above the surface for maintenance by surface vessels (Figure 7). Whether this would be possible in deeper waters (deeper than 20 to 30 m [about 66 to 100 ft]) is not known. According to MCT, there may be a few opportunities for using the first-generation SeaGen technology very close to the Florida coast or the Keys, but, as noted, MCT also has second-generation technology

FIGURE 7 Seaflow Experimental Test (Source: Robinson 2006)

that would be usable in depths possibly down to 100 m (328 ft) and futuristic concepts under development that could work in any depth of water.

3.1.2 Open Hydro

On July 12, 2004, Florida Hydro, Inc. (sold to and now known as Open Hydro) applied to FERC for a preliminary permit for a three-phase development that would include the following:

1. Demonstration of a pre-production unit (initially the testing and refining of the offshore components and then the installation and delivery of the unit's power onshore to a municipal partner),

2. Build out of additional units in the field (up to the capacity of the cable infrastructure sited in the initially used transmission corridor to the shore), and

3. Build out of other fields (depending on the identification and use of additional offshore sites, transmission corridors, and business arrangements for delivered power).

Phases 1 and 2 are expected to last three years.

The proposed project would consist of:

- A generation park containing up to eight submerged electricity production units (EPUs),

- A proposed 4.8-km-long (3-mi-long) sub-marine transmission line, and

- Appurtenant facilities.

The project would have an annual generation of 17,520 MWh that would be sold to a local utility. Work to be authorized by the permit would include economic analyses, preparation of preliminary engineering plans, and a study of environmental impacts. On the basis of the results of these studies, the applicant would decide whether to proceed in preparing a development application to construct and operate the project (DOE 2005). According to the permit application, each EPU would consist of:

- Two counter-rotating fiberglass blades, each about 21 m (69 ft) in diameter.

- An integrated turbine, generating 2 to 3 MW of electricity. It would have an open-center design, with shaped blades connected to an inner and outer hub. Materials would probably be fiberglass and carbon skins over a lightweight core, although the final material selection would depend on enhancements and scale-up (see Gulfstream Energy Incorporated 2006 for more information).

- Ballast tanks roughly 46 m (150 ft) long supporting the EPU about 60 m (200 ft) underwater.

- A mooring umbilical line to an anchor on the seabed.

- An interconnection transmission line to shore.

Systems for monitoring pressure, temperature, vibration, revolutions per minute, and power output would be located on the units and on shore. The units would be installed in groups or clusters to form a marine-current park, with a predicted density of up to about three turbines per square kilometer (eight per square mile). This grouping is intended to avoid wake-interaction effects between the turbines and allow for access by maintenance vessels.

An 80% capacity factor is targeted, producing an average of approximately 17,250 MWh per unit per year. Total capacity (number of units) would be determined later.

Transmission from the EPU cluster to shore would be by seafloor cable, about 5 km (3 mi) in length, which might be buried beneath the seabed in its onshore portion. The shore crossing for the offshore transmission line would be established through a conduit installed by HDD. Onshore underground transmission cable would carry the electricity to where it would be fed into the land-based electrical use infrastructure (DOE 2005).

3.1.3 Ocean Renewable Power Company (ORPC)

In August 2006, ORPC announced that it was undertaking a pilot-scale ocean-current generation (OCGen) project off the eastern coast of Florida that would involve the testing of a commercial-scale OCGen module in early 2008 (ORPC 2006). The design includes a “special generator” and submersible module to use with the turbine. The system floats underwater, is anchored to the seabed, and is connected to a utility company on shore. The mooring system has yet to be designed, but the unit would include a buoy connected to the module that would hold electronic monitoring devices to track currents and environmental effects. The unit would have a nominal generating capacity of 118 kW in a 5-knot current.

3.2 OCEAN-CURRENT TECHNOLOGY DATA

Because more information is available on the MCT technology than the other technologies, most of the data in this section are based on that technology and experiences with its prototype, Seaflow, which has been in operation since 2003.

3.2.1 Pilot Scale

3.2.1.1 Site Monitoring and Testing

Because offshore marine currents are relatively constant, once accurate site measurements have been taken, the water velocity and therefore the power outputs are completely predictable (World Energy Council 2001). As a result, site monitoring and testing are not likely to be continued once these initial measurements have been taken. Different vendors and technologies may use different approaches to obtain these initial measurements. For example, Open Hydro expects to conduct baseline studies by using a multibeam echosounder and acoustic backscatter to develop a three-dimensional image of the seafloor. Grab sampling and/or gravity coring in the vicinity of the anchors and transmission lines is planned to identify the seafloor composition. Seafloor mapping data would be collected and processed in the field, increasing the level of accuracy and efficiency. Additional surveys involving the use of vessel and seafloor-mounted ADCPs would be conducted to identify strength fluctuations and variations in current direction and flow in the water column. A second phase of studies would involve benthic surveys, which could include side-scan sonar, side-mounted video camera, seafloor-mounted ADCPs, and remote operated vehicles (DOE 2005). For Red Circle, which uses MCT technology, studies involving a satellite might be used if there is not enough information on flows for existing sources.

3.2.1.2 Construction

Some ocean-current components might be shipped via truck from other onshore U.S. locations or via ship from offshore locations. During installation, ocean surface area would be required for barges to transport the units and cables to their offshore positions. For the SeaGen unit, a special jack-up barge would likely be used.

The water in which the units would be installed would be deep and fast flowing. Currents impose significant drag loads on the legs of a jack up, and they can also induce vibrations in the whole structure from vortex shedding off the round legs. Seacore, a company internationally recognized for installing large-diameter monopiles, designed and installed the monopile on which the Seaflow demonstration turbine is mounted. The Seaflow demonstration (300 kW) used the largest available jack-up barge in Seacore's fleet. The installation of the monopile foundation took two months. The foundation was made by using a drill-drive technique to fix the casing into the seabed.

With the casing in place, a smaller-diameter socket was drilled for the foundation bottom spigot. The spigot was then fixed by holding it in the socket and injecting grout into the space around it. Finally, the pile was lifted into the casing, and the annulus between it and the casing was also injected with grout. After the grout had cured to achieve sufficient strength to hold the pile, the rest of the turbine was assembled. Other foundation types might employ other techniques, but no publicly available details were found for offshore installations.

3.2.1.2.1 Resource Requirements. Materials and components for the Seaflow demonstration were developed by several firms in different European countries. The technology would likely be licensed to North American companies for commercial production. (However, initial prototype components might come from overseas.)

Special installation vessels would probably need trained operators; estimates for specific numbers of employees were not found.

3.2.1.2.2 Emissions and Noise Sources.

- *Air.* Marine vessels to transport equipment to the offshore location would be likely to emit NO_x and SO_2. Construction equipment used to install onshore transmission facilities to connect to the existing grid would be likely to emit particulates, NO_x, and SO_2.

- *Water.* There could be accidental spills of petroleum lubricants and fuel from offshore construction equipment or vessels.

- *Wastes generated.* No wastes are expected to be generated, except for sewage that could possibly be spilled or discharged from barges used for installation.

- *Hazardous materials stored or used.* No hazardous materials are expected to be stored or used during construction.

- *Noise.* Noise sources would include transport vessels and installation equipment (e.g., pile-driving equipment for installing some anchoring systems).

3.2.1.2.3 Transportation Requirements and Accident Potential. Purpose-built vessels would be likely. (For the Seaflow project, a special heavy-duty jack-up barge was required for installation.) Unit components would likely be transported via truck, rail, or ship. There is a potential for accidents involving installation vessels, possibly leaking fuel oil.

3.2.1.3 Operation

The types of ocean-current facilities and their operating characteristics were described in Section 3.1.

3.2.1.3.1 Electricity Generated. The capacities of individual units being considered for OCS areas off the Florida coast range from about 500 kW to 3 MW per unit. If the capacity factor is assumed to be 80%, each unit would generate about 3,500 to 21,000 MWh/yr. A demonstration would likely involve one unit, but there could be more.

3.2.1.3.2 Ocean Area Occupied.

Surface. Open Hydro estimates that each EPU would use and modify current flows within about 300 m (about 1,000 ft) of the unit. According to Red Circle (MCT technology), the surface area depends on the shape of the current. Each turbine could sit within about 12 m (40 ft) of its neighbor if the turbines were arranged across the current, but a greater distance of about 300 to 600 m (1,000 to 2,000 ft) could be required if the turbines were upstream from one another, in order to avoid wake effects. A rough estimate is that 1 km^2 could accommodate about 20 MW (1 mi^2 could accommodate about 50 MW).

Bottom. The disturbed area would be the area occupied by the piles/moorings and any cables that were not buried. The collective area would be the per-device area multiplied by the number of devices, plus the area required for the cable. It is not known whether the cables would lie directly on the ocean bottom or be buried. No information was found regarding offshore substations. For SeaGen, the bottom disturbed would consist of the 3-m-diameter (9.8-ft-diameter) monopile, possible area needed for scour protection, and cables.

3.2.1.3.3 Resource Requirements. Resource requirements would include fuel oil to power maintenance transport vessels and possibly maintenance equipment. Maintenance would probably require skilled labor because of the new technology and difficult operating conditions; estimates for employment were not identified.

3.2.1.3.4 Emissions and Noise Sources.

- *Air.* Marine vessels used to transport the maintenance crew and equipment to the offshore location would probably emit NO_x and SO_2. As is the case for other offshore technologies, the devices themselves would not emit any air pollutants; they would, indeed, reduce the amount of emissions (SO_2, NO_x, CO, CO_2) that would otherwise be generated from using fossil fuels.

- *Water.* Devices installed in the sea can become artificial reefs, attracting a variety of marine organisms, which can cover the structures, cause significant fouling, and affect performance. Methods of preventing fouling include antifouling paints and sonic and ultrasonic devices. The paints can be toxic. Oils and fluids from gearboxes and hydraulic equipment could be released during accidents. The main potential sources of oil spillage are bearing lubricants, hydraulic fluid, and transformers. Mitigation strategies include containing oil in well-defined chambers; using biodegradable oils (esters) (but these have application limits, especially for low-temperature use); and using oil-less designs (greaseless bearings).

- *Wastes generated.* No wastes are expected to be generated, unless equipment ruptured (e.g., equipment broke loose from its mooring) and hydraulic fluid, transmission oil, etc. accidentally spilled.

- *Hazardous materials stored or used.* Non-water-based hydraulic fluids and gearbox oil are used in the devices. Transformers would contain an unknown amount of dielectric fluid.

- *Noise.* Possible sources and expected levels of noise have not been identified, but the turbines would be under water.

3.2.1.3.5 Transportation Requirements and Accident Potential. The types of vessels would depend on sea conditions. For demonstration projects, trips to units might be frequent — possibly daily during initial operations. There is a potential for hydraulic fluid or oil leaks. Also, there could be accidents involving maintenance vessels leaking fuel oil.

3.2.1.4 Decommissioning

No specific information has been found on decommissioning ocean-current devices. Presumably, if the demonstration proved successful, additional modules would be added, and the project would not be decommissioned until the end of its design life in 20 to 30 years (because of the harsh marine-current environment). If the demonstration was unsuccessful, decommissioning would occur at the end of the demonstration period. Decommissioning would likely be the reverse of the construction process, with components being brought to shore and recycled or reused. Expected aspects would include the following.

3.2.1.4.1 Ocean Area Occupied. During decommissioning, ocean surface area would be required for vessels to dismantle individual units and for barges to transport components to shore. The ocean bottom area required for decommissioning would be similar to that required for construction but would be used for removal rather than installation purposes.

3.2.1.4.2 Resource Requirements. These would include fuel oil to power vessels and equipment used in decommissioning and to return components and structures to shore. (However, if commercialization follows the demonstration at the same site, these resources might not be used for several years.) Special equipment (as was needed for installation) would likely be required. Employment requirements would be similar to those for construction but would be for removal rather than installation.

3.2.1.4.3 Emissions and Noise Sources.

- *Air.* Marine vessels used to return equipment from the offshore location to onshore points would likely emit NO_x and SO_2.

- *Water.* No water emissions would be expected unless accidents caused fuel spills.

- *Wastes generated.* No wastes are expected to be generated, unless sewage would be spilled or discharged from barges used for decommissioning or accidentally released if units became damaged during decommissioning.

- *Hazardous materials stored or used.* No hazardous materials are expected to be stored or used.

- *Noise.* Transport vessels and decommissioning equipment would create noise, but no estimates regarding the level or duration of noise are available.

3.2.1.4.4 Transportation Requirements and Accident Potential. Decommissioning transportation requirements would be essentially the reverse of construction transportation requirements and would likely include transportation of recycled equipment and components. There is a potential for accidents involving decommissioning vessels and equipment, possibly leaking fuel oil.

3.2.2 Commercial Scale

3.2.2.1 Site Monitoring and Testing

The types of offshore monitoring required during commercial operations, if any would be needed, are not known at this time. All monitoring might be conducted from the shore, but it is also possible that some units could have their own monitoring buoys. Thus, resource requirements for and potential emissions from site monitoring and testing would probably be minimal if there were any at all.

3.2.2.2 Construction

Most of the construction requirements for commercial-scale ocean-current projects are expected to be similar to those for demonstration-scale projects (Section 2.2.1.2), with appropriate scale up. These are summarized as follows: Construction of the ocean-current energy devices would occur on shore. The devices would likely be barged to their offshore locations. Divers might be required to check lines for some types of units.

During installation, ocean surface area would be required for barges to transport the units and cables to their offshore positions. Regarding ocean bottom area, transmission cable could be buried or lie along the seabed. Ocean bottom area would be disturbed for monopile installation, anchoring, or other towing.

3.2.2.2.1 Resource Requirements. Fuel would be required to power transport vessels. It is assumed that the monopile or other anchoring devices would be made of steel. For SeaGen, the following information gained from the Seaflow prototype demonstration is instructive (EU 2005):

> "The first attempt at installing the Seaflow pile failed because the ground conditions were much softer than expected. Information on ground conditions had been gathered from bores near the site and from published geological data, but it proved inadequate. A site investigation should be carried out before the foundation is designed, even though it would be expensive.
>
> The jack-up barge used to install Seaflow was at the limit of its operating capabilities, despite being one of the larger, most capable barges available at the time. The size of the Seaflow rotor and the depth at which it was installed were limited by the capacity of the barge. It is clear that larger equipment, able to work in higher currents and at greater depths, would be required for future installations. Such equipment is becoming available, as purpose-built vessels are made for offshore wind, and Seacore has a new barge, Excalibur, that extends its capabilities. However, offshore wind parks are not generally placed in areas with high currents, and further development work is needed to better understand how to work in such sites."

Divers and ship personnel would probably be required. Estimates of the numbers of employees needed to design and build the units and install them were not available.

Substations might be built along the coastline, an existing substation might be used, or a new substation might need to be located further inland.

3.2.2.2.2 Emissions and Noise Sources.

- *Air.* NO_x and SO_2 emissions from transportation vessels and installation equipment are expected.
- *Water.* Fuel oil or sewage could pollute water as a result of accidents involving transport vessels and installation equipment.
- *Wastes generated.* Sewage could possibly be spilled or discharged from construction vessels. Construction-related solid waste could be generated at onshore support facilities.

- *Hazardous materials stored or used.* No hazardous materials are expected to be stored or used during construction.

- *Noise.* Sources of noise could include the horizontal boring done to run cable from the shore and pile-driving equipment.

3.2.2.2.3 Transportation Requirements and Accident Potential. Purpose-built vessels would probably be needed for installation. There is a possibility of those vessels colliding with transportation vessels or devices. Presumably, installation would be timed to coincide with good weather conditions, but offshore locations have high flow velocities and deep water, so deployment would be likely to be challenging.

3.2.2.3 Operation

Because the ocean-current technology units are modular and are envisioned to be scaled up to provide commercial-scale power, the information provided in the sections on pilot-scale and demonstration-scale operations is expected to apply to commercial facilities.

3.2.2.3.1 Electricity Generated. The capacities of individual units being considered for OCS areas near the Florida coast would range from about 500 kW to 3 MW per unit. When an 80% capacity factor is assumed, these capacities translate to about 3,500 to 21,000 MWh/yr per unit. The number of units could range from 1 to 100 or more, with electricity output scaled as appropriate. For Florida Hydro, each unit would generate 2 to 3 MW of electricity; with an 80% capacity factor, or about 17,520 MWh/yr. Total capacity would depend on the results from further research on the optimal number of units and transmission lines and on how to avoid significant use conflicts and impacts on environmental resources. For Red Circle (MCT technology), if an 80% capacity factor is assumed, the annual energy generation for each 550- to 1,200-kW unit (choice depends on currents) is estimated to be 8,400 MWh/yr. For a 20-unit site, this would translate to 168,200 MWh/yr.

3.2.2.3.2 Ocean Area Occupied.

Surface. Relatively little ocean surface area would be occupied during operations. For each SeaGen unit, for example, the area occupied during normal operations would be the 3-m-diameter (10-ft-diameter) monopile. During maintenance, the unit would be moved to the surface along the monopile.

Bottom. The disturbed area would be that occupied by the piles and moorings and any cables that were not buried. The collective area would be the per-device area multiplied by the number of devices, plus the area required for the cable. It is not clear whether the cables would

lie directly on the ocean bottom or whether they would be buried. For SeaGen, for example, the per-unit bottom disturbed area would be the 3-m-diameter (10-ft-diameter) monopile and possibly the area needed for scour protection.

3.2.2.3.3 Resource Requirements. Fuel would be needed to power maintenance vessels and possibly to replace hydraulic fluids. MCT envisions annual inspections consisting of diagnostic tests, possible jet washing of the rotor, and fixing any detected faults. The target is to require inspections no more than once a year, with a major overhaul every five years (swapping out the power train and rotors).

Employment needs are expected to include maintenance workers (onshore and offshore) and monitors (onshore). Estimates of FTE effort were not available.

3.2.2.3.4 Emissions and Noise Sources.

- *Air.* No air emissions are expected from the devices. NO_x and SO_2 emissions are expected from maintenance vessels. (Total emissions would be less than those from fossil-fuel alternatives.)

- *Water.* Antifouling materials are likely to release toxins to water. For Seaflow, for example, rotor blades are protected with a proprietary antifouling paint that contains particles of copper in an epoxy base. The rotor hub has a different copper-based antifouling paint coating. Both paints have proved effective to date, with no signs of marine growth. Small barnacles have begun to grow on the untreated paintwork of the collar, and seaweed is growing on the pile, access tube, and ladder around the low water mark. Overall, there has become surprisingly little fouling of the turbine. The structure is protected from corrosion by zinc anodes welded onto the pile. These sacrificial anodes have become noticeably smaller and so are obviously working to prevent corrosion on the steel (EU 2005).

- *Wastes generated.* Sewage could be spilled or discharged from lay barges. Accidental spills could occur if equipment broke loose from its moorings. Spills could include hydraulic fluid, dielectric fluid from transformers, transmission oil, etc. Some wastes might be generated during operation as part of maintaining devices.

- *Hazardous materials stored or used.* Non-water-based hydraulic fluids and gearbox oil are used in the devices. Transformers would contain an unknown amount of dielectric fluid.

- *Noise.* Possible noise sources and levels are not known, but turbines would be below the water surface.

3.2.2.3.5 Transportation Requirements and Accident Potential. Transportation vessels might be required for maintenance; the types of vessels would depend on sea conditions. Regarding accidents, turbines or other components could break loose from their moorings. If hydraulic fluid containers were ruptured, fluids could leak.

3.2.2.4 Decommissioning

Decommissioning would likely entail the removal of equipment and return of the project site to its natural state. The expected project life for ocean-current technologies is about 20 to 30 years.

3.2.2.4.1 Ocean Area Occupied. During decommissioning, ocean surface area would be required for vessels or barges to tow the individual devices from their offshore positions. Ocean bottom area would be needed for the removal of anchors or other mooring devices, cables, and junction boxes

3.2.2.4.2 Resource Requirements. Resources required would include fuel, to power decommissioning vessels, and employees to operate vessels. Divers might also be needed.

3.2.2.4.3 Emissions and Noise Sources.

- *Air.* NO_x and SO_2 emissions are expected as a result of decommissioning vessels and equipment.
- *Water.* Water might become polluted from accidental fuel leaks or hydraulic fluid leaks if containers ruptured during decommissioning.
- *Wastes generated.* Sewage could be spilled or discharged from decommissioning vessels. Substantial amounts of solid waste, much of it recyclable, would be generated during decommissioning.
- *Hazardous materials stored or used.* No hazardous materials are expected to be stored or used during decommissioning.
- *Noise.* Sources would likely include decommissioning vessels and equipment.

3.2.2.4.4 Transportation Requirements and Accident Potential. Transport would be required to return units to the shore. Once the devices were returned, they could be dismantled and their components shipped for other use or recycled.

There is a possibility of transportation vessels or devices colliding. Presumably decommissioning would be timed to coincide with good weather conditions. However, offshore locations have high currents and deep water, so decommissioning work would probably be challenging.

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