Websites of Interest

US DOE:

- National Renewable Energy Laboratory: www.nrel.gov (general characterization of solar resources and technologies, including CSP)
- US DOE Solar Energy Technologies Program: http://www1.eere.energy.gov/solar/ (PV technologies)
- Sandia National Laboratories, National Solar Thermal Test Facility: http://energy.sandia.gov/?page_id=1267

International:

- Australian National University, Solar energy research: solar.anu.edu.au
- European Commission, Scientific and Technical Reference on Renewable Energy: http://re.jrc.ec.europa.eu/refsys/
- EuroSolar: www.eurosolar.de
- Solar Power and Chemical Energy Systems (SolarPACES): www.solarpaces.org/inicio.php
- World Council for Renewable Energy: www.wcre.org

Ocean Wave, Tide, Current, and Thermal Energy Conversion 14

Water, water, everywhere,
Nor any drop to drink.
—Samuel Taylor Coleridge, "The Rime of the Ancient Mariner"

14.1 Introduction

The awesome power of ocean waves and the relentless tides makes them obvious candidates for anyone's list of potential natural energy sources, while the more subtle observation that surface water is warmer than the briny deep tempts only those with some exposure to thermodynamics and the concept of heat engines. We

Table 14.1
Historical Timeline of Exploitation of Ocean Energy

BC–AD	References to use of tides in classical Greece, possibly dating back to the time of Aristotle
960 AD	Reference to tide mills at Basra in southern Iraq
1041, 1078	First references to European tide mills (around Venice)
1100–1900	Waterwheel-driven mills powered by tidal impoundments and currents operational in England, western Europe, and colonial Boston, among other places
1135–WWII	Bromley-by-Bow Tidal Mill near London
1734	Slade's Tidal Spice Mill, Chelsea, Massachusetts
1799	Girard files first patent on wave-energy device in France
1800–1900	25 tide mills cited in Britain
1871	Jules Verne's fictional Captain Nemo posits thermoelectricity from ocean water in the novel *20,000 Leagues under the Sea*
1881	D'Arsonval proposes concept of ocean thermal energy conversion (OTEC)
1892	Stahl notes 19 wave-power concepts in American Society of Mechanical Engineers (ASME) transactions
1934	Claude tests open-cycle OTEC in Cuba
1935–1977	Succession of studies of Passamaquoddy/Bay of Fundy tidal power stations
1959	First of a number of small (<1 MW_e) tidal power plants reported in China
1966	Rance River tidal power plant operational in France
1969	Experimental tidal unit constructed in Kislaya Guba, Russia
1972–1984	US OTEC program
1976–1982	British launch, then suspend, their wave-power program; revised post-2000
1977	Wells invents turbine which rotates in same direction when airflow is reversed
1978	Japanese install 125 kW_e wave-power unit off Honshu
1979	Mini-OTEC operated in Hawaii by the US and by Japanese off Shimane
1984	20 MW Annapolis tidal station operational in Nova Scotia
1985	KVAERNER wave-energy converter deployed in Norway; later succumbs to storm
1995	2 MW_e OSPREY wave-power station wrecked during installation
(1986–2000)	Decline, on the average, of fossil energy prices in constant dollars saps motivation for vigorous pursuit of the more expensive categories of alternatives, e.g., anything out at sea; then reinvigorated by post-2000 oil price escalation: see following initiatives
2003	European Marine Energy Center established in the Orkney Islands off northern Scotland
2007	Pelamis devices operational at first commercial wave-power stations off Orkney and Portugal, where more are planned
2007	Underwater tidal stream turbines installed in New York City's East River
2008	Scottish government offers \$20 million Saltire Prize for best demonstrated innovation in wave or tidal power
2009	Wave Hub project off Cornish coast in England: scheduled to test multiple concepts

Table 14.2
A Broad Survey of Oceanic Energy Resources

Type and References	Characteristics of Interest
Thermal Avery and Wu (1994); Vega (1995)	About one-third of ocean surface water is (slightly) higher than 25°C and three-quarters of its volume is ≤ 4°C (deep water ≥ 500–1000 m): sufficient to operate a low-efficiency heat engine
Waves Ross (1995); Hagerman (1995); Edwards (1998)	Wave-power averages ~ 10 kW_e/m of coastline; mechanical energy can be extracted from their periodic motion
Tides Charlier (1992); Clark (1992, 1995, 1997)	The gravitational pull of the moon (68%) and sun (32%) causes 7 m tides in several dozen coastal sites worldwide, which can be harnessed by low-head hydro
Current Wick and Schmitt (1981); Pearce (1998)	Steady flows of ~2.5 m/s at large volumetric rates are available at selected sites: e.g., gulfstream off Florida, Kuroshio off Japan; also from tidal currents; power can be extracted using large turbine rotors
Salinity Wick and Schmitt (1981); Levenspiel and de Nevers (1974); Norman (1974); Stover and Pique (2006)	Differences in salt content between freshwater (rivers) and the ocean can develop osmotic head of 240 m; Dead Sea and Great Salt Lake 3,000 m; more energy in salt of oil-trap salt domes than in the oil
Biomass Wilcox (1977); Ryther (1979/80)	Giant kelp of the type growing off California could be artificially farmed, harvested, and processed to yield biogas; similarly for algae
Unconventional hydro	Flow via canals into the Dead Sea or Qattara depression or in a sea-level canal between the Atlantic and Pacific Oceans; or even through dams across the Bering Strait or Strait of Gibraltar
Methane hydrates Suess et al. (1999)	Extensive deposits trapped in deep-sea sediments
Offshore geothermal Peltier (2008)	Geopressured reservoirs and hydrothermal vents
Mineral Best and Driscoll (1980)	Extraction of uranium for fueling nuclear fission power plants from seawater or special sediments; extraction of deuterium and lithium to fuel fusion reactors

Note: See IPCC (2011) for recent updates.

can also point to a history of past development and recent applications in each area (see table 14.1), and perhaps through them come to some understanding as to why more widespread deployment has not yet occurred. We can also draw informed conclusions about whether they can eventually compete with other candidates for inclusion in future scenarios for sustainable energy.

Wave, tidal, current, and thermal are not the only ocean-related energy prospects, as noted in the broader survey of table 14.2 (which also provides references for finding more about each entry). But they are the most likely candidates. This chapter does not include other conventional energy sources at sea that are already developed for land-based energy extraction, such as oil, gas, coal, oil shale, geothermal, tar sands, biomass, or wind (all of these energy sources are discussed in other chapters of this text). Table 14.3 gives the approximate magnitude of the potential and potentially exploitable resources of marine energy (also see table 2.6 in chapter 2). These resources and extraction technologies are also the focus of an ocean energy chapter in a recent special report on renewable energy sources and climate change mitigation (IPCC, 2011).

Table 14.3
Approximate Worldwide Ocean Energy Available

Phenomenon	Maximum Potential (in gigawatts)	Practicable to Exploit (in gigawatts)
Tides	2,500 (total dissipation)	20
Temperature difference (OTEC)	2 × 10^5 (based on total absorbed insolation in equatorial waters)	Near or onshore: 40 Offshore: 10,000
Waves	2,700 (on all the world's coastlines) 10,000 (open sea renewal rate)	500
Salinity gradients (pressure-retarded osmosis, PRO)	2,600	In early test phase
Marine currents	5,000	50
Offshore near-surface winds	20,000	1,000
For comparison:		
Total installed capacity/production of electric energy in 2008		World: 5,000/2,500[a] US: 1,050/500[a]
World freshwater hydroelectric capacity in 2005	4,000	715[a]

Note: All values are gigawatts, annual average. The powers quoted are annual-average useful mechanical (electrical) values, converted from thermal, where applicable, by a representative thermodynamic efficiency: e.g., 2.7% for OTEC.
Values are derived from similar estimates in the references at the end of this chapter or equivalent "back-of-the-envelope" calculations. Estimates in the literature vary widely, often by an order of magnitude.
Overall, the electric power grid operates at an average-to-peak load ratio of ~0.5; hence, average power is about half of installed capacity. Individual sources (e.g., hydro) may have capacity factors that are higher or lower than average.
[a] Actual installed capacity.

14.2 Energy from the Tides and Currents

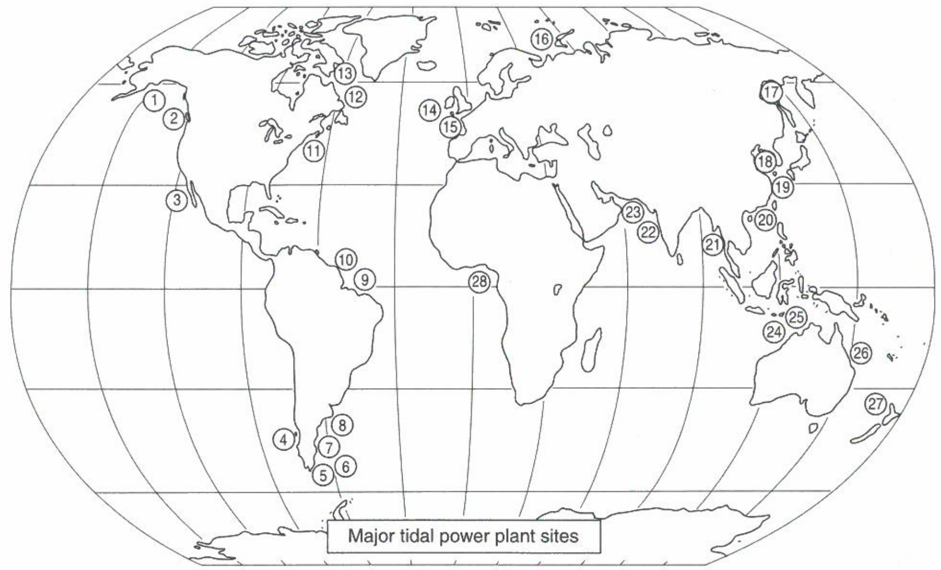
There are two different approaches to deriving tidal energy: those involving impoundment by a barrage (dam) and those involving freely flowing currents (akin to underwater wind turbines). The latter employ essentially the same technology as their counterparts in freshwater rivers (chapter 12). A brief review of current-powered systems is repeated in section 14.2.2 because prospects for their deployment appear more promising than barrage-type megaprojects. One should also note that nontidal marine currents such as the Gulf Stream and Kuroshio offer candidate sites which may employ unique technology less constrained by seafloor topography. As such, they deserve categorization as a separate type of resource.

14.2.1 Impoundment-type tidal

Wheel-type watermills powered by tide-induced flow have been employed since the late medieval period, but they were far outnumbered by their freshwater-driven counterparts. Our interest here is in more modern versions that generate electricity by employing low-head, propeller-type turbines similar to those in run-of-the-river or other low-head hydro freshwater applications. One large-scale complex of this kind has been constructed at La Rance in France.

Tides arise from the gravitational interactions of the earth/moon (68%) and sun (32%) systems, with successive high (and low) tides normally occurring twice daily. Some locations, including most of the Gulf of Mexico and the Gulf of Tonkin have only one high and one low tide in a 24-hour period (Cartwright, 1999; Clancy, 1969). Extreme tidal variation is the consequence of resonant interactions involving basin configuration, Coriolis forces, and the like, of sufficient complexity to require several dozen harmonics for accurate representation. In deep water far at sea, the rise or fall is only 0.5 m or so, which is not useful. However, tides vary greatly with location—for example, only about a meter at Nantucket Island, which is 150 km southeast of Boston, but up to a world maximum of 16 m between high and low water in the Bay of Fundy, which is 400 km northeast of Boston. It is these rare locations (several dozen sites worldwide: see figure 14.1), with shelving shores or funnel-like inlets, that are candidate sites for practical tidal power stations. Estimates are that full exploitation of such resources (5 m rise) might contribute several tens of gigawatts to the world's energy budget.

As figure 14.2 shows, calculating the maximum potential energy recoverable from a single tidal cycle is a straightforward exercise. The water impounded at peak high



1. Cook Inlet; 2. British Columbia; 3. Baja California; 4. Chonos Archipelago; 5. Magellan Straits; 6. Gallegos/Santa Cruz; 7. Gulf of San Jorge; 8. San Jose Gulf; 9. Maranhão; 10. Araguaia; 11. Fundy/Quoddy; 12. Ungava Bay; 13. Frobisher Bay; 14. Severn/Solway; 15. Rance; 16. Mezen/Kislaya; 17. Okhotsk Sea; 18. Seoul River; 19. Shanghai; 20. Amoy; 21. Rangoon; 22. Cambay Bay; 23. Rann of Kutch; 24. Kimberleys; 25. Darwin; 26. Broad Sound; 27. Manukau; 28. Abidjan.

Figure 14.1
Sites with major potential for tidal power. Source: Borgese (1985).

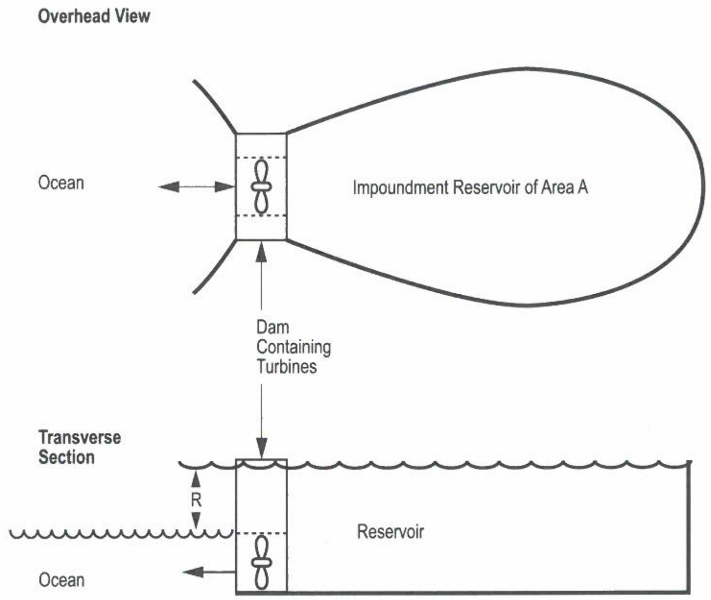


Figure 14.2
Schematic for estimation of available tidal energy.

tide is, on average, a height $R/2$ (where R is the total range) above the minimum low water point, in which case

$$\hat{E} = mg\ R/2 = (\rho AR)g\ R/2\,. \tag{14.1}$$

Substituting parameter values given in the appendix to this chapter and converting units appropriately, we get

$$\hat{E} = 1{,}397\ R^2 A,\ \text{kW}_e\text{h per cycle} \tag{14.2}$$

for R in meters and A in square kilometers. The world mean period for tides is 12 hrs 24 min; hence, there are 706 tidal cycles per year, and therefore annual average generation is

$$\bar{E} = 0.986 \times 10^6\ \text{COP}\ R^2 A,\ \text{kW}_e\text{h} \tag{14.3}$$

where we have introduced an overall coefficient of performance, COP (typically on the order of 0.2–0.35), to account for a variety of factors.

Factors affecting performance include the following:

1. Instead of single-basin one-way operation, as analyzed above, two basins could be employed and/or power could be generated in both the drain and fill phases (if reversible turbines are employed).

2. Using dual-purpose pump-turbines, by drawing power from the grid, the basin can be overfilled at the high water state and/or pumped down further at the low water mark, which allows a net energy gain later in the power generation phase.
3. Pumps/turbines/generators are not 100% efficient electromechanically, and a minimum head (~1.5 m) is needed to permit operation.
4. Instantaneous drain or fill is unrealistic, hence the difference in head between source and sink is less than the full tidal range.
5. Basin area (hence water volume per unit height) will decrease as a function of water depth if the reservoir has sloping sides.

Charlier (1992) describes the La Rance station in France (see table 14.4). Using R = 8.5 m, A = 22 km^2, and COP = 0.33, equation (14.3) predicts that it will generate 517 GW$_e$h/yr, about what is actually achieved as shown in table 14.4.

Table 14.4 summarizes some characteristics of interest from the La Rance tidal station. It is by far the largest and longest operating of modern tidal-electric power plants. Even so, note that the mean power delivered of about 65 MW$_e$ is only about one-third that of a single combined-cycle gas turbine module.

Table 14.4
Characteristics of La Rance Tidal Power Station

Fully in service	1967
Length of dam	750 m
Area of basin	22 km^2
Usable basin volume	184 × 10^6 m^3 (max)
Tidal range	13.5 m (max)
	8.5 m (avg.)
Nominal rating	240 MW$_e$
Annual mean output	~65 MW$_e$
	~500–600 GW$_e$h/yr
Range of output	Spring tides 2,940 MW$_e$ hr/day
	Neap tides 738 MW$_e$h/day
Modes of operation:	
Capability	Double effect with pumping
Practice	Not much reverse turbining or pumping
Turbine-generator	10 MW$_e$ each @ 3.5 KV
	24 units, reversible flow and pumping capability; bulb configuration axial flow Kaplan type, useful range ≥ 1.2 m head
Cost of electricity	\$0.037/kW$_e$h (1997) (around 2¢/kW$_e$h in 2011)
Track record (1967–1997)	Hours of operation: 160,000 (continues to dispatch power about 12 hours per day)
	Generation: 16 × 10^9 kW$_e$h (continues to average about 600 GW$_e$/yr).

Source: Charlier (1992).

No discussion of tidal power would be complete without mention of the much-studied and debated, but never built, Passamaquoddy/Bay of Fundy projects bordering Maine in the US and New Brunswick and Nova Scotia in Canada (Baker, 1992). The Bay of Fundy has the world's largest tidal range and a topography that could support power stations totaling 2,000 MW_e or more. Proposals for its exploitation date back to the 1930s, with periodic revivals thereafter, most recently in 2006. The principal forward progress has been the construction and operation, starting in 1984, of a 20 MW_e demonstration unit near the mouth of the Annapolis River in Nova Scotia. It generates about 30 GW_eh/yr (5% of La Rance), employing the largest straight-flow turbine in the world (7.6 m diameter). It is the only tidal station in North America.

To date, high projected capital cost and the need for Canadian-American coordination have stymied action on the Passamaquoddy project. Moreover, initiatives to exploit natural gas production offshore of Nova Scotia will create a local, low-cost alternative power source that would be tough to compete with. Thus, tidal dam power appears to be, at best, a limited localized alternative and unlikely to make a near-term impact of global significance on energy-use sustainability.

14.2.2 Current-powered systems, tidal and otherwise

The underwater equivalents of wind turbines have recently attracted increasing attention. A principal motivation is that water is about 850 times denser than air, which more than compensates for its flow rates being a factor of roughly three times lower, despite the cubic dependence of power on velocity (see equation (15.17)). Two categories of applications are of interest: tidal currents, with their successive forward and reverse flow; and unidirectional oceanic currents, such as the Gulf Stream, or free-flowing rivers upstream of their tidal estuaries (also see discussions of run-of-river hydropower in chapter 12).

As with their terrestrial counterparts, submerged water turbines have been proposed with both axial-flow and cross-flow designs. Table 14.5 surveys a range of species of varying provenance. The reader is forewarned that dozens of concepts have been proposed but few have been built and tested. There is no consensus yet on which, if any, is most likely to become cost competitive.

14.3 Energy from the Waves: Overview

Waves are created by the interaction of the prevailing winds with long reaches of open water. Strong storm-force winds create a disorganized, chaotic, local wave field, which, through a process of interactive reinforcement and interference, leads to a more regular sequence of swells propagating away from the storm zone. As waves approach shallow water (depth approximately the same as wavelength), significant changes take place: wavelength shortens, speed is reduced, and the profile steepens—to produce the surfer's delight and breakers on the beach.

Table 14.5
Representative Current-Power Concepts

Category	Principle of Operation	Examples
Axial-flow single-stage turbine, or propeller	Same as wind turbine of same configuration	Verdant Open Hydro RiverStar Snail
Eggbeater (cross-flow) type	Analogous to Darrieus or Savonius wind machines	Gorlov Helical Turbine MCT Seagen
Mechanical oscillator	Hydrofoil; wing lift Flutter vane; vortex-shedding	Pulse Tidal Stingray Schneider Hydro Engine Vivace
Ducted versions of above	Flow channeled onto rotating element	Rotech Tidal Turbine Open Hydro

Reference: Patel (2008).

As discussed in chapter 15, there is at least a weak correlation between wave-power and wind-power resources. For example, the western shores of Europe and the British Isles have high-grade resources of both. The Scottish coast is favored by waves having an average embodied linear power on the order of 50 kW_e/m of wavefront. Therefore, it is not surprising that the British have played a leading role in R&D to exploit this potentially huge resource. Other favored locales include the coasts of western Ireland, Oregon and Alaska in the US, southern Australia and New Zealand, and Chile.

Many, literally dozens, of ingenious devices have been proposed for this application, based on exploitation of wave-induced pitching, heaving, or surging motion (Hagerman, 1995). Table 14.6 summarizes some of the principal contenders. Many of these devices have been tested under realistic in-service conditions. The simplest concepts, called "over-topping devices," funnel waves to run up ramps in order to replenish a low-head hydro reservoir. Others employ surface floats with up-and-down motions that create mechanical work. In the Salter "nodding duck," a pear-shaped float cranks a hydraulic pump to create flow of a working fluid, which spins an electric generator via a hydraulic motor. The oscillating water column (OWC) devices create hydraulic pistons which force air through a turbine, again to power an electric generator. This latter scheme is the modus operandi for a Japanese buoy, and a few others elsewhere, delivering on the order of 60 watts—enough to power navigational aids.

One of the design challenges for wave-power devices is their vulnerability to damage in storms, when they may need to withstand linear wave-power densities in excess of 200 kW_e/m. This condition creates a costly design criterion.

Table 14.6
Wave-Power Device Types

Category	Principle of Operation	Examples
Pitching-motion-driven pumps	Rocking motion pumps water (or other fluid) through turbine	Pelamis Duck Oyster Stingray
Oscillating water column (OWC)	Water or air pushed/sucked through turbine	Wave Gen Limpet Osprey Pico OWC
Moored buoy up-and-down motion	Several: • pump water or air through turbine • move magnets past coil • oscillating float	Aqua Buoy Power Buoy Seadog Snapper AWS
Ramp—ashore or afloat	Wedge-shaped ramp lifts water to create head to drive turbine	Wave Dragon Kvaerner

For earlier reviews, see Cavanagh, Clarke, and Price (1993); Hagerman (1995), Sanders (1991); Edwards (1998). Note that hundreds of designs have been conceptualized and dozens tested, hence any list is somewhat evanescent.

Although wave hydrodynamics are devilishly complicated, a simplified model can give a rough estimate of wave-borne energy. Following Penner and Iceman (1984) and Twidell and Weir (2006), consider a sinusoidal wave with crest-to-trough height h (thus, the height from mean sea level to crest is $h/2$), as shown in figure 14.3. Then the average height above the levelized sea is $2/\pi$ times this value, or h/π; the center of gravity of the wave mass above sea level is $\pi h/16$. Thus, if the mass above sea level is (inverted and) dropped to fill in the below-level trough (which is its mirror image), potential energy is made available for extraction due to a total drop of $\pi h/8$. One has, per unit width of wavefront, and for wavelength, λ:

$$\Delta PE = mg\Delta h = \left[\rho\left(\frac{h}{\pi}\right)\left(\frac{\lambda}{2}\right)\right]g\left(\frac{\pi h}{8}\right), \tag{14.4a}$$

or

$$\Delta PE = \frac{1}{16}\rho\lambda g h^2. \tag{14.4b}$$

However, power is energy per unit time (here, wave period, T), and wavelength is given by

$$\lambda = \frac{gT^2}{2\pi} \tag{14.5}$$

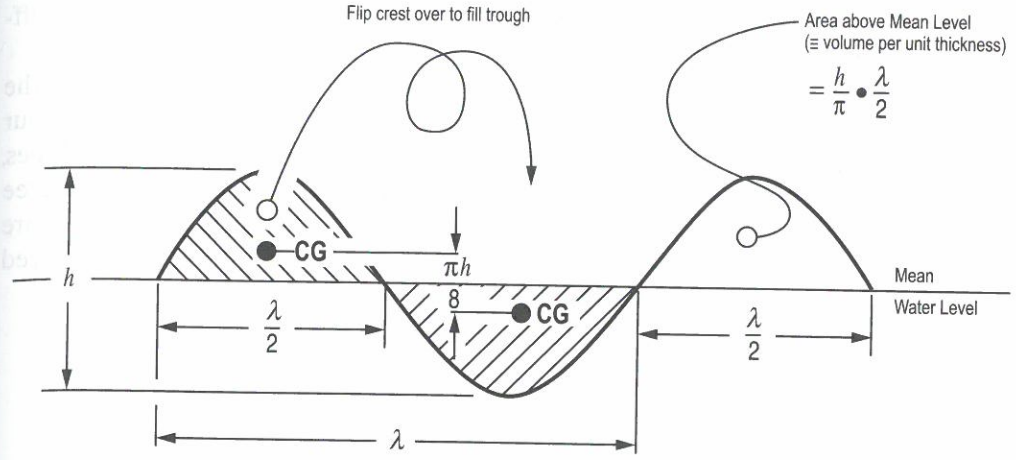


Figure 14.3
Schematic for estimation of wave potential energy.

which all combine to yield

$$P_{pe} = \frac{1}{32\pi}\rho g^2 h^2 T = 0.98h^2T\text{ , kW}_e\text{/m.} \tag{14.6}$$

where

ρ = density of seawater (1,025 kg/m^3),

g = acceleration of gravity (9.807 m/s^2),

h = crest-to-trough wave height (e.g., 2 m),

T = wave period: time for successive crests to pass a fixed observer (e.g., 10 s).

We will not derive it here, but kinetic energy equals potential energy, and hence total energy is double that of equation (14.6) (Rahman, 1995; Elmore and Heald, 1969). To estimate power, however, we should use the group velocity, which is half the phase (i.e., crest) velocity (MacKay, 2009), and therefore

$$P = 0.98h^2T,\ \text{kW}_e\text{/m}. \tag{14.7}$$

For the numerical values cited above, P = 39 kW$_e$/m, which is a high-quality resource several times the kW$_e$ per meter of rotor blade length for a representative wind turbine.

The various mechanical devices engineered to extract this energy are only of modest efficiency. Thus, the energy actually delivered is significantly less. Also note that wave energy decreases as a wave moves closer to and interacts with the offshore subsurfaces.

The dependence on wave height squared in equation (14.7) also highlights the vulnerability of wave machines to storm damage. Doubling wave height in our example would unleash power on the order of 200 kW_e/m. Unlike wind turbines, few wave-power devices have effective cut-out schemes to achieve a high degree of protection against excessive loads due to peak waves. Wave-height spectra are sometimes fit to the same type of Rayleigh or Weibull functions as are employed for characterizing wind velocity (see chapter 15).

14.4 Energy from Temperature Differences

14.4.1 Overview

As shown in figure 14.4, there is a vast belt of warm ocean water between 20° north and 20° south of the equator, some 20–25°C hotter than the underlying deep water several hundred meters below. This temperature differential is just barely enough to make heat engine operation technically feasible for the production of net electrical energy. The capital cost of an ocean thermal energy conversion (OTEC) plant varies roughly as ΔT to the minus 2.5–3.0 power. Thus, only the highest-grade resources are worth consideration. Although the total resource is immense, on the order of tens of thousands of gigawatts, practical considerations limit, or at least defer, its exploitation. First, the existence of broad continental shelves force major OTEC plants to operate far offshore, which complicates transmission of energy back to large load centers on land. There are very limited potential OTEC sites where underwater power cables might be practicable. It has been suggested that hydrogen, ammonia, or methanol could be produced at offshore sites as transportable energy carriers. This idea presupposes the existence of a viable synthetic-fuel-based economy, which is still a prospect for the distant future. A secondary niche market involves the many islands scattered throughout the Pacific Ocean, where the cold water is close offshore. Here, the small scale can also be more than offset by the sale of coproducts: distilled water, the products of mariculture and cool-climate agriculture, and air conditioning services. (For a discussion of a scenario for exploiting OTEC for future energy needs, see Savage, 1992.)

14.4.2 Performance limits

If hot and cold water are supplied to a heat engine at a rate sufficiently high that the energy processed by the engine is small compared to total throughput, then the

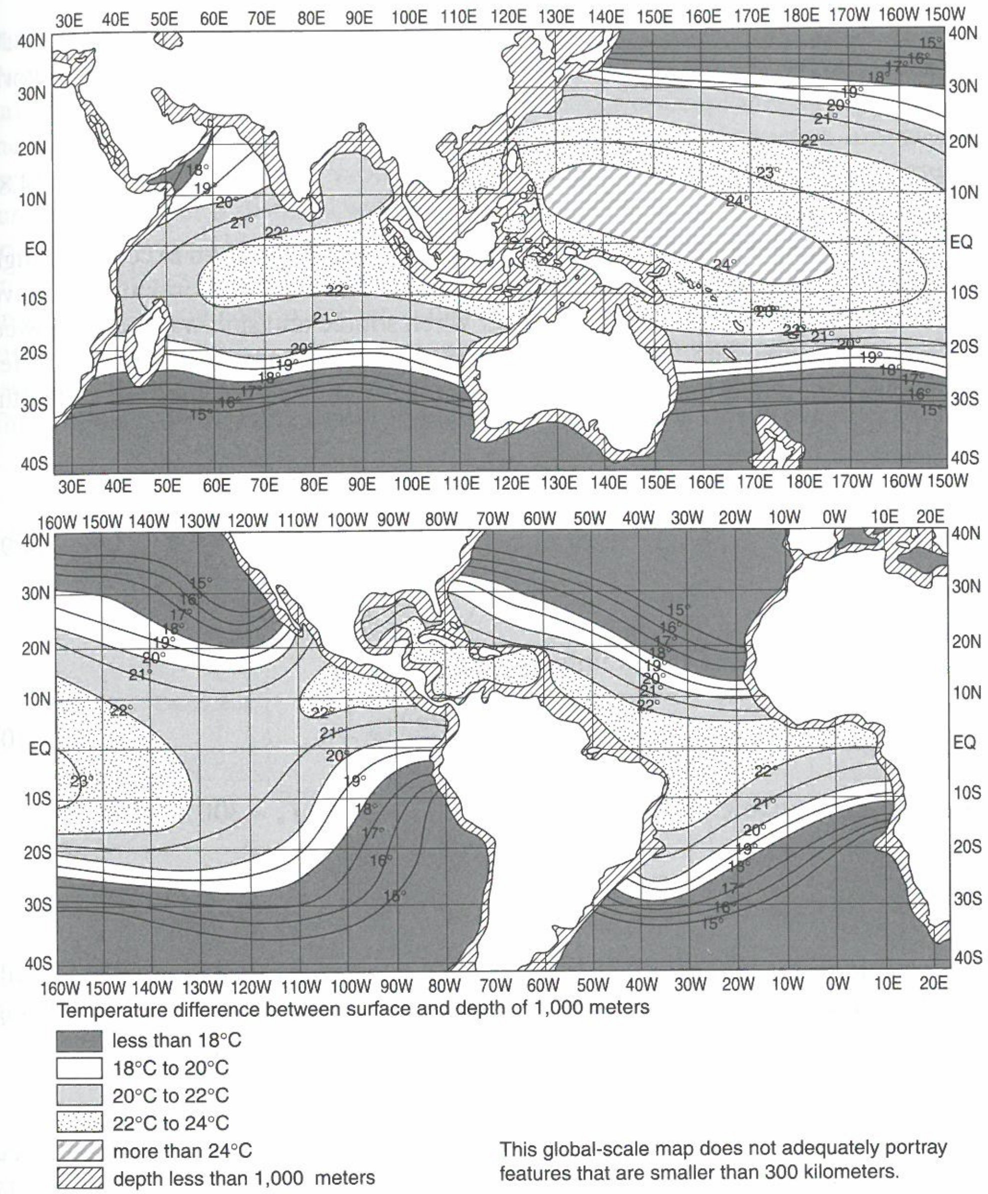


Figure 14.4
Worldwide distribution of the ocean thermal resource. Source: SERI (1990).

source and sink temperatures (T_h and T_c, respectively) are constant, and Carnot's theorem gives the theoretical maximum efficiency of conversion of heat to work (chapter 3):

$$\eta_c = \frac{W}{Q} = 1 - \frac{T_c}{T_h}. \tag{14.8}$$

However, pumping water through the hot and cold reservoirs at an excessively high rate would consume too much energy in the present instance. Several authors have optimized performance to maximize power when source and sink water are allowed to change temperature and when finite temperature differences across heat transfer surfaces are accounted for. This more practical Carnot cycle has the following efficiency (Johnson, 1983):

$$\begin{aligned} \eta_{pc} &= 1 - \sqrt{\frac{T_c}{T_h}} \\ &\equiv 1 - \sqrt{1 - \left(\frac{T_h - T_c}{T_h}\right)} \end{aligned}. \tag{14.9}$$

And for small $T_h - T_c$, as is certainly the case here:

$$\eta_{pc} \cong 1 - \left[1 - \frac{1}{2}\left(\frac{T_h - T_c}{T_h}\right)\right] = \frac{1}{2}\eta_c. \tag{14.10}$$

Under representative OTEC conditions, $T_h - T_c \approx 24°C$, $T_h \approx 300$ K, and

$$\eta_c = 8\%$$

$$\eta_{pc} = 4\%.$$

Bringing cold water to the surface from 1,000 m depth and other internal loads will typically consume 1% of the gross work output per unit of thermal energy, leaving a net

$$\eta_{pc,net} \approx 3\%.$$

This is a factor of more than 10 less than that achieved by nuclear or coal-fired plants, and 20 times less than that of the best new gas turbine combined-cycle units. Hence, while the fuel is "free," the large physical size of the OTEC unit per MW_e of rating causes it to have a high specific cost, $\$/kW_e$. Operating and maintenance costs at sea are also higher than those on land. Together, these costs require that fossil-fuel costs undergo a significant, lasting escalation before OTEC once again appears as attractive as it did in the wake of the 1973 oil crisis.

14.4.3 OTEC technology

Two different power cycles—direct (open) and indirect (closed) (see figure 14.5)—have been pursued for OTEC service. In the direct cycle, pioneered by Claude in the 1930s, hot water is flashed to steam which is passed through a low-pressure turbine, and the exhausted vapor is condensed in a direct contact condenser (or surface condenser if distilled water is a desired coproduct). Two practical problems arise. Noncondensable gases must be removed by vacuum pumps, which consume an appreciable amount of the gross energy generated. Further, the low pressure drop and vapor density available to the turbine result in conditions roughly similar to those in the last low-pressure stage of the largest commercial steam turbines used in nuclear power stations. Consequently, this delivers only a megawatt or two. Thus, open-cycle OTEC units of higher rating require development of special

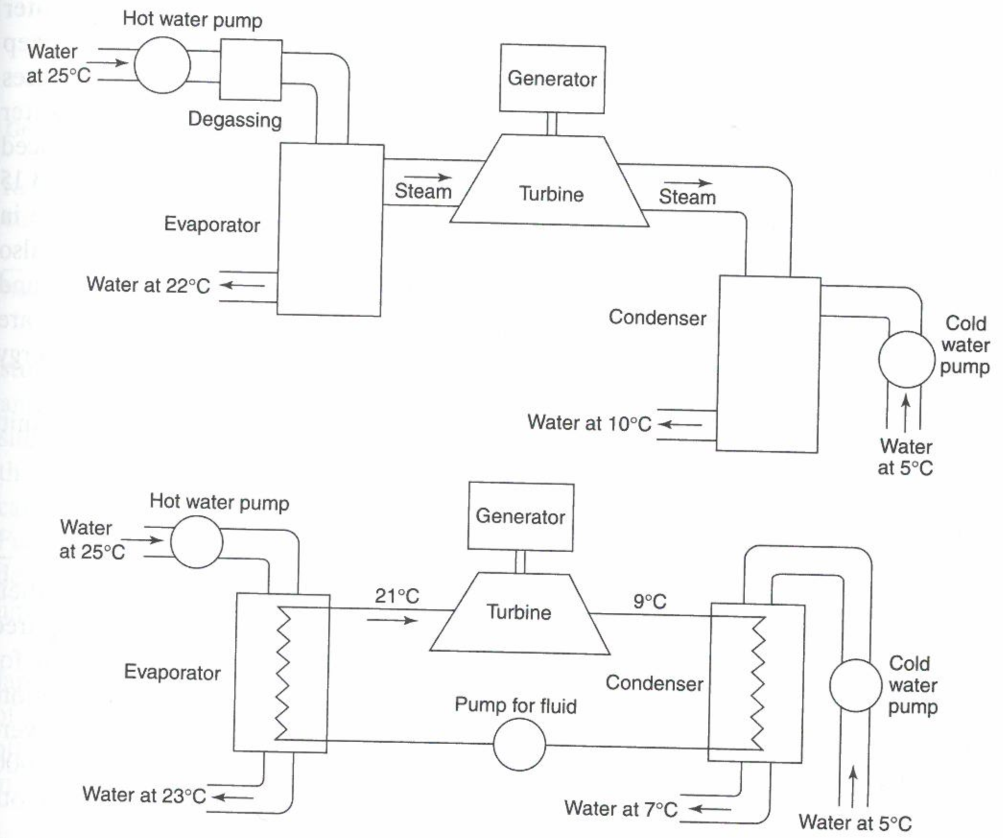


Figure 14.5
Operating principle of (a) an open-cycle OTEC plant, and (b) a closed-cycle OTEC plant. Adapted from Brin (1981).

large-diameter turbines. A 100 MW_e unit could be as large as 100 m in diameter; hence, several smaller turbines would probably be used.

Closed-cycle OTEC systems operate under conditions similar to air-conditioning and refrigeration applications, indirect-cycle geothermal power stations, and bottoming cycles appended to other power sources. Thus, working fluids such as ammonia or propane are preferred (CFCs are no longer an option due to their ozone-depleting chemistry). Their higher pressure and vapor densities greatly reduce size requirements for turbines, but with the tradeoff of adding two huge heat exchangers, each an order of magnitude larger in terms of m^2/MW_e than the main condensers of large fossil-fired or nuclear power stations.

A hybrid of the open and closed cycles has also been proposed (Patel 2008). In it, flash-evaporated seawater steam is condensed to transfer energy into the power cycle working fluid's evaporator.

OTEC concepts share another unique feature: a long, large-diameter cold-water pipe and associated pump to bring cold water for the heat engine up from as deep as 1,000 m. Diameters as large as 7 m are required for a 40 MW_e unit to keep losses in pressure drop tolerably low. Shore-based OTEC plants may require a cold-water pipe two or three times longer. Protection against damage by current-induced forces, especially during storms, is a challenge because wave heights may exceed 15 m and wave energy increases as the square of height. The best OTEC sites are in the doldrums (regions of low average wind velocity). However, these zones are also the spawning grounds of hurricanes and typhoons. Although hurricanes and typhoons expend energy at an average rate of about 3,000 GW_e, these storms are more of a threat to energy facilities than they are candidates for useful energy extraction. This is because of their limited duration and changing location.

Table 14.7 summarizes key design features of a representative OTEC power unit.

14.5 Economic Prospects

The energy technologies discussed in this chapter—current, wave, tidal, and OTEC—have the common burden of high capital-cost estimates. This is due, in part, to their one- or first-of-a-kind nature. The higher rates of return and imposed taxes required of the recently deregulated electric power industry in several Organization for Economic Cooperation and Development (OECD) nations make it even more difficult for these capital-intensive options. Thus, plans for further R&D were deferred as a consequence of the low fossil-fuel prices during the 1990s. Since 2000, however, concerns over climate change and fossil-fuel price escalation have motivated significant new initiatives.

Even with the benefit of the successful La Rance experience, and despite being technically proven, tidal power has not gone beyond successive rounds of paper

Table 14.7
Characteristics of a Hypothetical 40 MW_e OTEC Plant

Type	Closed Rankine cycle		
	Ammonia working fluid		
Nominal ΔT	23°C ± 1°C seasonally		
Platform	Concrete barge 150 m (l), 50 m (w), 30 m (d) 100,000 MT displacement Multipoint-moored plus dynamic positioning		
Cold-water pipe	Segmented, lightweight reinforced concrete 950 m long, 9 m diameter ball-and-socket joint with barge, flexible segment joints		
Hot-water intake	15 m depth		
Effluent discharge	70 m depth (below thermocline)		
Heat exchangers		Evaporator	Condenser
	Flow rate, kg/s	130,000	100,000
	m^3/s per MW_e	3.3	2.5
	m^2/kW_e	6	6
	Material	Al	Al
Gross TG output	52 MW_e Underwater power cable to shore		
Net thermodynamic efficiency	2.7%		
Cost estimates	\$4,000/kW_e 10¢/kW_eh		

Note: This table is an amalgamation of design features from several sources, most notably Avery and Wu (1994).

studies (most notably in 2007–2010, for the Severn and Mersey estuaries in the UK and the Passamaquoddy site mentioned earlier). The limited number of premium sites worldwide and the associated detrimental ecological consequences suggest that the barrage type of approach is unlikely to become a resource of global significance, although another barrage project is under construction in Korea as of 2011. Free-current-flow turbines have better prospects in this regard, but are still in a demonstration stage. In tidal power's favor, its output, while cyclical, is predictable—unlike that of most other renewable sources.

Although OTEC applications were formerly of significant interest in the US and Japan, they are also currently stymied by high capital cost and the limited number of good sites on or near shore. While global resources are immense, they are far offshore, which requires the deployment of a synfuels infrastructure for transporting energy to users.

Wave power appears to be the most promising ocean energy technology at this point, pending demonstration of a successful, long-term track record of operation. This may change over the next several years (Edwards, 1998). If any of the dozen or so units live up to expectations, wave power could be cost competitive and capable of eventually supplying 10% or so of the world's electric energy needs—and even more in favored locations, such as the UK and Ireland. As of 2011, there are over fifty wave-energy technologies at various stages of development; estimates of theoretical potential power vary widely among different sources, indicating the uncertainties in dealing with seasonal and daily variability as well as in choosing potential sites for deployment of operational wave-energy systems (IPCC, 2011).

As a rough generalization, good wave-power sites often correlate with better-grade, offshore wind-power resources. For this reason, there may be useful synergism in colocation of these two types of technology. Cost savings could arise from the sharing of power conditioning and transmission facilities, operating and maintenance infrastructure, and personnel. The ratio of lifetime energy generation to that consumed in construction and operation for OTEC is predicted to be a surprisingly large 10–15, achieved in large part by assuming a long lifetime (e.g., 50–100 years). Tidal installations come in at around 5—a bit lower than freshwater hydro. Early estimates for wave-power devices suggest 2 or lower (Spreng, 1998). Costs of electricity are projected to be higher than contemporary fossil competition: 50/100/150% for tidal/OTEC/wave, in that order. However, the lack of large-scale serial manufacturing, deployment, and operating experience introduces considerable uncertainty into all energy ratio and economics predictions.

Finally, shoreline sites are often expensive and strictly regulated because of competition for residential, recreational, nature reserve, and industrial uses.

14.6 Environmental and Sustainability Considerations

While the four major oceanic generator types of present interest are all rather benign, especially in terms of regional or global impact, there are local and regional effects to consider.

Tidal impoundment requires damming an estuary, thereby changing the regular cycle of wetting and dryout to which local flora and fauna have become adapted. Change in the mix of species is inevitable. Nonmigratory fish can be exposed, several times a day, to passage through the plant's turbines. Migratory waterfowl may be deprived of a useful way station. Here, as elsewhere, one must keep in mind that other alternatives may (and probably will) have different adverse effects.

OTEC units bring large amounts of cold, nutrient-rich seawater close to the surface. This effect is often cited as an advantage, as it would provide an opportunity for mariculture. The cold water has also been hypothesized to alter CO_2 chemistry and pH at the ocean surface, and, if near-shore, to bring up preserved pathogens accumulated during years of wastewater runoff. Only long-term operational experience, which is currently lacking, can convincingly resolve these issues. Wave-power devices remove energy from the incoming waves and thereby alter sediment transport and suspension closer to shore. This breakwater feature may be credited as an advantage in some locations. However, it is also a navigation hazard and may impede fishermen in their harvesting of bottom-dwelling fish and shellfish. For sites close to or onshore, aesthetic concerns must also be addressed.

In summary, the subject systems could all be credited with significant avoided emissions costs that may help defray the cost penalty associated with operations at sea.

14.7 The Ocean as an Externalities Sink

Another traditional de facto role of the ocean in energy generation has been as an ultimate natural sink for dispersed emissions, such as the carbon, sulfur, and nitrogen oxides created in fossil-fuel combustion. Coastally sited power stations also commonly reject waste heat into ocean water.

Several other risky ways to exploit the oceans for their properties as a sink are listed below.

- Seeding vast ocean tracts with trace-element iron, or nitrogen-rich fertilizer, to promote the growth of biota—hence increasing the rate of CO_2 uptake and sequestration (Nadis, 1998; Pearce, 2000; Young, 2007). Any such relief, however, is unlikely to be permanent.
- Capture of CO_2 at power plants and its injection into deep ocean waters or sub-seabed strata, again to reduce its buildup in the atmosphere (Herzog et al., 2000).
- Disposal of encapsulated high-level radioactive waste from spent nuclear-power-plant fuel in ocean bottom sediments overlying subduction trenches (Hollister and Nadis, 1998).

The technical and cost effectiveness of these options, and their environmental impact, are matters of contention. The ocean's legal status as a protected global commons ensures strong political challenges to the deployment of such practices.

14.8 Current Status and Future Prospects

Among the sources of ocean energy, only the La Rance tidal station provides, at present, a sizeable commercial contribution to world energy needs. A similar-sized barrage project in Korea is under construction and nearing completion as of 2011. Several other locations in Korea are in various stages of development. This situation is likely to continue for the foreseeable future at favorable sites. As always, it is a matter of choosing among alternatives. Of the alternatives having high capital cost and low (or no) fuel costs, conventional hydroelectric and nuclear fission reactors appear to have a significant advantage over tidal, current, OTEC, and wave-power installations. Thus, despite increasing concern over global warming, many analysts opine that ocean-derived power is not likely to be a highly ranked option. Experience with offshore oil and gas production offers a firm basis for estimating the significant cost penalties of offshore operations. In addition, the rough geographic correspondence of premium wind and wave resources makes it likely that wind power will be used in preference to ocean power. Finally, near-shore OTEC and good tidal sites are too few in number and in size of exploitable capacity to merit attention if one is primarily interested in options of potentially global significance. However, local contributions can be significant and should not be ignored.

From this perspective, freshwater hydro, with a 2009 installed capacity of more than 980 GW_e, is a far more important source of water power (International Hydropower Association, 2011). Compare, for example, the World Energy Conference prediction of ≤10 GW_e from tidal energy plants by 2020 under their most optimistic scenario (Clark, 1997). More recent estimates of the global theoretical power vary from 1 to 3 TW_e, with the caveat that only a very small fraction of this energy is likely to be exploitable (IPCC, 2011). This is an unlikely extrapolation from the current level of about 1 MW_e. The prospects for power from waves should become clearer with further operation of the European Marine Energy Centre (EMEC) test facility in the Orkney Islands (Knott, 2003). It is being used to test modules of a wide variety of wave-power concepts at a commercially relevant scale under realistic environmental conditions.

Appendix: Constants and Conversion Factors

Quantity	To convert from units of	→	Into units of	→	Multiply by
Energy	Joules[a]		kWh		2.78×10^{-7}
Power	Horsepower		kW		0.746
Length	Feet		Meters		0.3048
	Miles		Kilometers		1.609
Area	Square miles		Square kilometers		2.59
Mass	Pounds		Kilograms		0.454
Velocity	Knots		m/sec		0.514
Flow rate	gpm		m^3/sec		6.309×10^{-5}
	Into units of	←	**To convert from units of**	←	**Divide by**

Note: Density of seawater = 1,025 kg/m^3; gravitational acceleration = g = 9.807 m/sec^2; temperature conversion: °C = (5/9)(°F – 32); °K = °C + 273.2; °R = °F + 459.7. Also see Conversion Factors section following chapter 22.
[a] Note that 1 J = 1 Newton-meter (Nm) and 1 N = 1 kgm/s^2.

Problems

14.1

a. Estimate the total flow rate in m^3/s of hot plus cold water for a fleet of closed-cycle OTEC units generating the same amount of electric power, 1,450 MW_e, as a large nuclear power plant. The difference between warm surface water and cool deep water is 22°C, and net OTEC thermodynamic efficiency is 3%. Express your answer as a fraction of the flow rate of the Mississippi River: 16,800 m^3/s. Seawater has a density of 1,025 kg/m^3 and a heat capacity of 1.16 kWh per metric ton per °C.

b. Avery and Wu (1994) states that a medium-size OTEC plant of 100 MW capacity and a temperature differential of 23.3°C would require an intake of 300–500 m^3/s of warm surface water and an equal intake of cold deep water. Redo the estimate of part (a) using this estimate (e.g., 400 m^3/s) and explain any difference in results.

c. The nuclear reactor in part (a) requires 200 MT/yr of natural uranium to produce its required 30 MT/yr of low-enrichment fuel. Seawater contains 3.3 parts per billion of uranium. If it were possible to remove 50% of this uranium from the water streams in part (b), what fraction of the reactor's annual requirement could be satisfied?

14.2

a. It has been proposed that large underwater single-stage multiblade turbines be installed in ocean currents such as the Gulf Stream off Florida and the Kuroshio near Japan. These units are entirely analogous in their fluid mechanics to the wind turbines discussed in chapter 15. Using the relations in section 15.4, evaluate the power rating of a current turbine having a rotor diameter of 12 m and an overall power coefficient, COP, of 0.42, driven by seawater of density 1,025 kg/m^3 flowing in a steady 2 m/s current.

b. Compare the pros and cons of this approach for renewable energy generation.

c. Compare the diameter of an equal-power wind turbine in a steady 7 m/s breeze.

14.3 The winter air temperature over the floating ice sheets off the shore of Antarctica (where the emperor penguin breeds) is as low as –62°C, while the water beneath (home of the ice fish) is around –1°C. Evaluate the prospects for siting OTEC units in this environment, using the sea as the "warm" reservoir and the air as the "cold" reservoir.

a. Estimate the achievable thermodynamic efficiency.

b. Discuss other important factors that would affect a decision to select this site for OTEC units compared to the usual proposal for their operation in equatorial seas.

14.4 Before experiential evidence suggesting otherwise, concern was expressed that an OTEC plant would release CO_2 to the atmosphere by transporting cold deep water containing 2.4 gram moles CO_2/1,000 kg seawater (as HCO_3^-) to the surface, where CO_2 content is effectively 2.0 g mol/1,000 kg, and releasing the excess CO_2.

Carry out a worst-case evaluation of this scenario for an OTEC unit having a cold-water flow rate of 5 m^3/sec per MW_e. Compare the maximum hypothetical CO_2 release rate in kg CO_2/kW_eh to that of a modern high-efficiency combined-cycle gas turbine (CCGT) (η = 60%) unit burning natural gas and emitting 0.33 kg CO_2/kW_eh.

14.5 It has been suggested that wave-powered devices be moored to an OTEC barge to provide added power to help defray the large internal energy consumption by the cold- and hot-water pumps.

Estimate how long a string of wave-power converters would be required under the following conditions:

Average wave height = 2 m
Average wave period = 8 s
Efficiency of device = 50%
OTEC pumping power = 25 MW_e (for a 100 MW_e net unit).

14.6 An entrepreneur has the choice of locating underwater turbines, of a given design and number, either in the Gulf Stream, which has a steady current of 1.5 m/s, or in a tidal estuary, where peak velocity is 2.5 m/s and the velocity distribution is sinusoidal in time. Assuming equal performance in both forward and reverse flow, which siting option provides the most energy, and by how much?

14.7 Some visionaries have proposed damming the 20-mile-wide strait of Bab El Mandeb between Yemen and Djibouti to exploit the high rate of evaporation in the Red Sea (Schuiling et al., 2007).

a. If a net lowering in level of 2 m could be sustained, what is the power level achievable at 80% turbine efficiency?
b. Discuss the practical aspects of this initiative.

References

Avery, W. H., and Chih Wu. 1994. *Renewable Energy from the Ocean: A Guide to OTEC*. New York: Oxford University Press.

Baker, G. C. 1992. Current Status of Tidal Power in the Bay of Fundy. In Tidal Power Trends and Developments: Proceedings Fourth Conference on Tidal Power, ed. R. Clare, 15–28. London: Thomas Telford.

Best, F. R., and M. J. Driscoll. 1980. The Prospects for Recovery of Uranium from Seawater. *Transactions of the American Nuclear Society* 34 (June):380ff.

Borgese, E. M. 1985. *The Mines of Neptune*. New York: Harry N. Abrams.

Brin, A. 1981. *Energy and the Oceans*. Ann Arbor, MI: Ann Arbor Science.

Cartwright, D. E. 1999. *Tides: A Scientific History*. New York: Cambridge University Press.

Cavanagh, J. E., J. H. Clarke, and R. Price. 1993. Ocean Energy Systems. In *Renewable Energy: Sources for Fuels and Electricity*, ed. T. B. Johansson et al. Washington, DC: Island Press.

Charlier, R. H. 1992. *Tidal Energy*. New York: Van Nostrand Reinhold.

Clancy, E. P. 1969. *The Tides: Pulse of the Earth*. New York: Anchor Books.

Clark, R. 1997. Tidal Power. Annual Review of Energy (Palo Alto, CA): 2648–2674.

Clark, R. H. 1995. Tidal Power. In *Wiley Encyclopedia of Energy Technology and the Environment*, vol. 4, ed. A. Bisio and S. Boots. New York: John Wiley & Sons.

Clark, R., ed. 1992. *Tidal Power: Trends and Developments*. London: Thomas Telford.

Edwards, R. 1998. The Big Break. *New Scientist* (October):3.

Elmore, W. C., and M. A. Heald. 1969. *Physics of Waves*. New York: Dover.

Hagerman, G. 1995. Wave Power. In *Wiley Encyclopedia of Energy Technology and the Environment*, vol. 4, ed. A. Bisio and S. Boots. New York: John Wiley & Sons.

Herzog, H. B., H. B. Eliasson, O. Kaarstad, D. Keith, and E. Parson. 2000. Capturing Greenhouse Gases. *Scientific American* 282 (2):72–29.

Hollister, C. D., and S. Nadis. 1998. Burial of Radioactive Waste under the Seabed. *Scientific American* 278 (1):60–65.

International Hydropower Association. 2011. Activity Report. http://www.hydropower.org/downloads/ActivityReports/2011-12_Activity_Report-web.pdf

IPCC (Intergovernmental Panel on Climate Change). 2011. *Special Report on Renewable Energy Sources and Climate Change Mitigation*. New York: Cambridge University Press.

Johnson, D. H. 1983. The Exergy of the Ocean Thermal Resource and Analysis of Second-Law Efficiencies of Idealized Ocean Thermal Energy Conversion Power Cycles. *Energy* 8 (12):927–946.

Knott, M. 2003. Power from the Waves. *New Scientist* 179 (2413):33–35.

Levenspiel, O., and N. de Nevers. 1974. The Osmotic Pump. *Science* 183 (4121):157.

MacKay, D. J. C. 2009. *Sustainable Energy—without the Hot Air*. Cambridge, England: UIT Cambridge.

Nadis, S. 1998. Fertilizing the Ocean. *Scientific American* 278 (4):22.

Norman, R. S. 1974. Water Salination: A Source of Energy. *Science* 186 (4161): 360.

Patel, S. 2008. A New Wave: Ocean Power. *Power* 152 (5).

Pearce, F. 2000. A Cool Trick. *New Scientist* 166 (2233):18.

Pearce, F. 1998. Catching the Tide. *New Scientist* 158 (2139):38.

Peltier, R. 2008. Tapping Seafloor Volcanic Vents. *Power* 152 (7).

Penner, S. S., and L. Icerman. 1984. *Non-Nuclear Energy Technologies*. 2nd ed. Vol. 2 of *Energy*. New York: Pergamon Press.

Rahman, M. 1995. *Water Waves: Relating Modern Theory to Advanced Engineering Applications*. Oxford, UK: Clarendon Press.

Ross, D. 1995. *Power from the Waves*. New York: Oxford University Press.