An Overview of Ocean Renewable Energy

Christopher D. Barry, P.E. (WA, CA) [1]
Paul Kamen, P.E. [2]

The Official 2009 Earth Day Poster

Abstract:

For at least a century, innovators have looked on wind, waves, tides, warm ocean waters, marine organisms and the salt in the sea as potential sources of energy. More recently, even use of heat from marine vulcanism has been suggested. Although there have been any number of creative technologies invented to exploit these resources and numerous trials, these sources have only provided a miniscule amount of energy. Much of the reason for this has been the relatively low cost of competing forms of energy, especially fossil fuels.

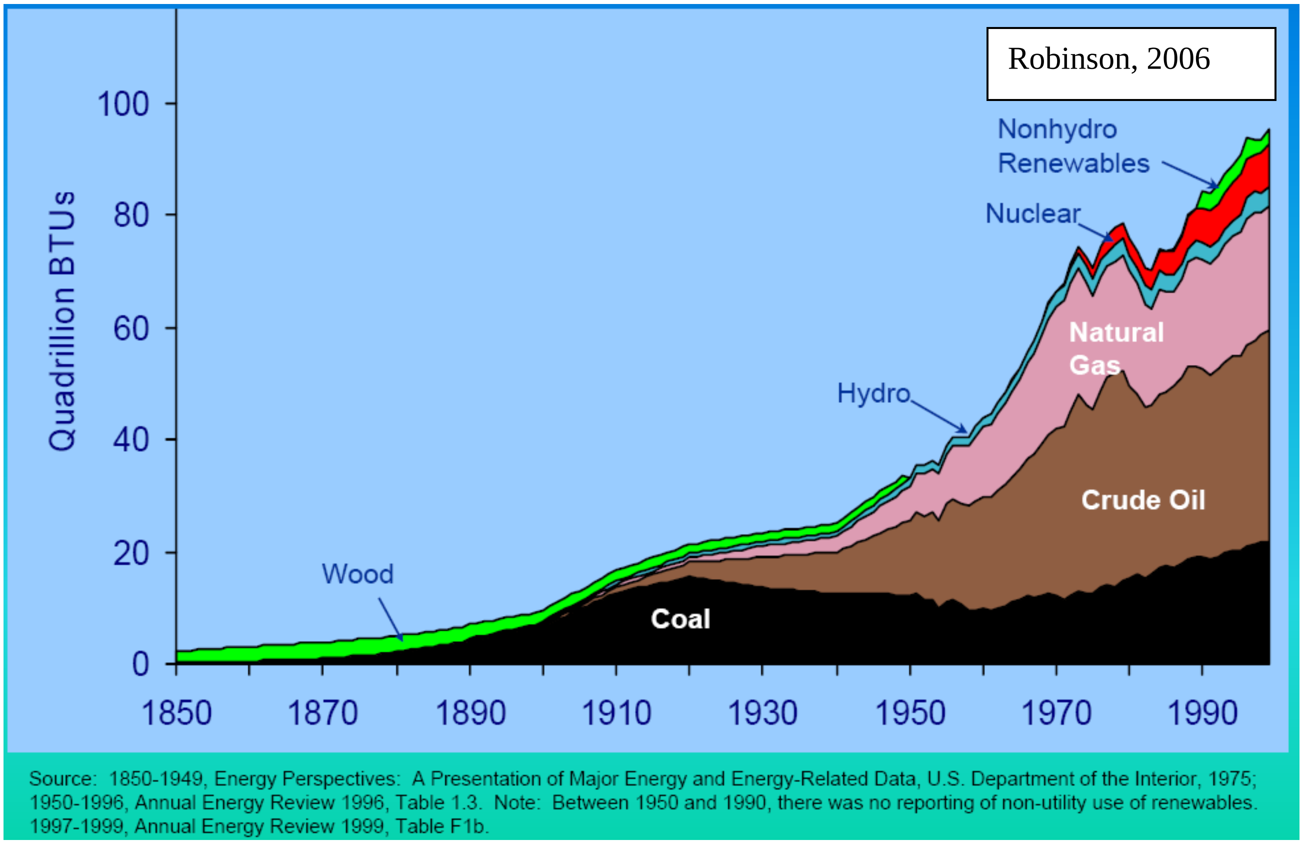
Concerns about carbon dioxide and global warming and the security and long term availability of fossil fuel supplies has led to greatly renewed interest in all forms of renewable energy. The current administration has emphasized its interest in renewable energy both as a replacement for fossil fuels and as a job creation engine, and is providing vastly increased funding for all forms of renewables, so the time may have come for ocean renewable energy as well.

This paper presents a basic review of the technology of each of the major sources including wave conversion, fixed and floating wind turbines, free flowing current turbines, ocean thermal energy, salinity gradient and marine biofuels, and discusses the magnitudes of each of the resources, and the particular technical issues each technology is facing. A history of some notable historic efforts is presented and specific current efforts are discussed.

However, many of the key issues of ocean renewable energy do not involve the technology of the conversion devices, but how ocean renewable energy sources relate to the overall system of energy, the environment, public policy and the practical and business issues of introducing such radical new systems into the existing energy and marine industries.

---

[1] Senior Naval Architect, U.S. Coast Guard Surface Forces Logistics Center
[2] Naval Architect, Surface Propulsion Analysis; Chair, Berkeley Waterfront Commission



Source: 1850-1949, Energy Perspectives: A Presentation of Major Energy and Energy-Related Data, U.S. Department of the Interior, 1975; 1950-1996, Annual Energy Review 1996, Table 1.3. Note: Between 1950 and 1990, there was no reporting of non-utility use of renewables. 1997-1999, Annual Energy Review 1999, Table F1b.

The US Energy Picture 1850 – 1999

Figure 1

OCEAN ENERGY

The frontispiece suggests that some environmentalists are beginning to discover the potential of ocean energy. Other groups are also beginning to recognize the potential of ocean energy – the state of Oregon has declared September 14-18 as Wave Energy Week, and there has been considerable attention to ocean energy concepts on television - in a recent episode, the "Planet Mechanics" on the National Geographic Channel built a wave energy conversion device out of sewer pipe.

But, why ocean energy?

The simple answer is real estate – most of the earth's surface is ocean, so most of the earth's solar energy falls on the ocean. The ocean also provides, naturally, various mechanisms to collect, concentrate and transform that energy into forms that might be more useful.

The oceans are a heat engine that transforms solar energy into the kinetic energy of wind, waves and current. (Tides, of course are mostly lunar energy, not solar, but they are still energy.): The average solar power flux onto the surface of the ocean at 15^{o} North latitude is about 0.2 kW/m^2, (annualized, over 24 hours/day) but this is typically converted to trade winds of about 20 knots, which have a power flux of 0.6 kW/m^2. Here though, the energy is over a vertical area, perpendicular to the wind. This wind energy subsequently is concentrated into a wave energy flux of 8 kW/m^2 (McCormick, 1981), but this time it appears essentially along a line of wave crests at the ocean's surface. Each stage of energy conversion conceptually drops one dimension to present the energy in a more easily accessed form.

These forms of high quality energy are very useful, but often intermittent, require more or less large collectors, and may have siting and environmental issues. On the other hand, wind and wave tend to be stronger in winter, when direct solar energy is lower, so they may provide seasonal leveling in association with land based direct solar systems.

Ocean Thermal Energy Conversion eliminates the heat collector, and provides steady power, but has practical issues and tends to be in distant locations.

Salinity gradient conversion exploits the difference between salinity of fresh water and salt water, or salt water and brines, the latter potentially derived from underground salt domes. This is very concentrated, with the osmotic pressure difference between salt and fresh water the equivalent of over seven hundred feet of water head. It is derived from retarded pressure across a reverse osmosis membrane and extracted either mechanically or electrically. The principal issue with this source has been membrane technology and expense, so proposals to exploit this resource have been very limited, with one small 4kW demonstration project in Norway.

One interesting option is ocean farming of biofuels, because biological systems make fuel directly and manufacture themselves.

The authors would like to note that developments, especially as regards legislation, ongoing projects, finance and similar issues are very fluid and change rapidly, so something that is mentioned herein may have changed substantially after this paper was written, and in addition, we claim that as an excuse for being so late in finishing it. Please refer to the resources in the “Webliography” at the end of the paper for the latest news. We would also like to note that this is a very big field, and we can neither cover every part of it here, nor mention all of the projects and concepts that are being considered. We apologize in advance to anyone we have inadvertently slighted, and invite them to communicate with us.

THE NEED

Energy Supplies and Security

In 2004 the US used almost 89 “quads” of fossil fuel derived energy, that’s 88.5 quadrillion BTU, $88.5\text{x}10^{15}$ BTU. Since 2004, we have seen an oil price shock that gave us a hint of the possibilities of real shortages of oil and at least initially spurred a lot interest in alternative energy. Now, in the depths of a global recession, energy prices have moderated, but we know that there is a good possibility that there is a clear choice – expensive energy or a weak economy.

There is also a lot of concern about the long term supply of oil. Matt Simmons, the famous oil industry financier has written and spoken extensively about his concerns for the global oil supply, most notably in *Twilight in the Desert*, (Simmons, 2005), which postulates a sudden crash in the major Saudi Arabian oil fields. T. Boone Pickens has also been speaking on the need for the United States to replace oil with other forms of energy, and in addition to speaking both have actually taken action in the renewable energy industry. Pickens has proposed a system of wind farms (though this may be a victim of the current recession). And, almost to illustrate the point of this paper, Simmons has established an ocean energy institute in Rockland, Maine to develop offshore wind and wave energy conversion systems. Though it is not clear that all petroleum reserves have reached a peak, it is generally agreed that we have seen the end of “easy” oil and the remaining oil resources will require more effort to bring to market.

The United States (and most Western nations) also import a significant amount of oil and natural gas from other parts of the world, and are therefore dependent on the stability and goodwill of other nations. The last major burst of interest in alternative energy during the Carter administration began with the oil boycott based on US support for Israel, and resulted in significant economic disruption. This was not the first such problem, though – the Japanese entrance into World War II had a great deal to do with Japan’s access to oil.

The True Cost of Energy

Basic economics tells us that we should consider all of the costs of a good to ensure that it is at the “right” price that includes all “external” costs and benefits. The “right” price then sends a signal to engage in the Pareto optimum level of activity producing that good and any competitive or substitutional goods.

Maintaining the military (and engaging in action) to ensure access to foreign supplies of oil is probably the most obvious external cost, but there are others, especially for any good that has become highly integrated into society. In the case of fossil fuels, various types of pollution and their effects on health constitute costs that do not appear at the pump or the electric meter.

In the case of coal especially, much of the effects of mining on miners and their families and on mining communities are charged to other accounts and don’t send an appropriate signal to encourage conservation or alternative sources of energy. These effects include long term health issues, loss of environment due to mining practices and workplace injuries, which are probably not fully included in the cost of the produced coal (Adeyeye, *et al*, 2009). Recent studies suggest that wind and solar energy appear to offer less risk of workplace injury and death than traditional fossil fuel industries. (Medical College of Wisconsin, 2009) However, it is likely that at least the offshore portion of operations involving ocean renewable energy will not be as safe as landside wind and solar energy.

Though sulfur pollution (acid rain) is now managed by a very successful “cap and trade” type market system, which is sending the correct economic signals regarding low sulfur coal and sulfur emissions controls, mercury emissions and fly ash are not yet in such a market system and not so well controlled. The cost of hydropower on the natural environment and fisheries is also less well charged at the electric meter, and the complex rules of water resource allotment between hydropower, agriculture, municipal users and fisheries in the U.S. West are not based on economics at all.

It is also important to note the cost of energy in a particular situation as regards choosing possible alternatives or conservation methods. For example, the Navy has recently looked more carefully at the cost of electricity that also considers the cost of transporting fuel through a supply chain to a ship in mid-ocean and providing generation capacity aboard that ship, and this better pricing information makes a big difference in the real economic viability of alternatives such as use of expensive LED lighting or absorption cooling using waste heat recovery. In terms of ocean energy, powering systems on a remote island might be much less expensive by using ocean energy compared to sending out fuel for a diesel generator periodically. Offshore platforms and aids to navigation might be another good candidate for renewable ocean energy.

In this regard, it is worth noting the keen interest in alternative energy in Hawai'i, due to the cost of transporting fuel from the mainland.

There are also even more difficult to account for costs that cheap fossil fuels have produced. The ready availability of gasoline has certainly contributed to the reshaping of most Western cities into at least partly distressed urban hubs surrounded by suburbs, and the loss of public transport.

The lesson here is that we have to be aware of the complete cost of any energy source, new or old, to be able to make a choice.

Climate Change

"It's not easy being green"
Kermit the Frog

As the frontispiece notes, the most significant externality is global warming caused by greenhouse gases, primarily carbon dioxide from fossil fuels. The costs of climate change are projected to be enormous, and even the Department of Defense (Naval Research Board, 2010) has studied that matter and is convinced that climate change represents catastrophic global disruption and potential war. A parallel threat is ecological collapse due to global toxification. Although not currently in the public spotlight, toxification of air and water on a global scale may prove to be at least as disruptive as climate change. It's not clear which catastrophic outcome may be a marker for the other.

Replacing 88 quads of fossil fuel energy seems like an enormous task, but compared to the solar resource, it is theoretically feasible. This amount of energy is the same amount that falls on just White Sands Proving Ground in New Mexico. During the recent power crisis in California, electricity use peaked to a record, but this was roughly the same amount of solar energy that fell on just Irvine, a small southern California city. Also, although these comparisons are at 100% efficiency for solar power, they are also at 100% efficiency for burning coal, oil or natural gas.

The key is economics, and it's worth looking at the comparison, again based on 2004 data. It looks like we need to be able to get alternative energy for anywhere from 40,000 to 300,000 usable Btu per dollar. These are tough goals to get alternatives competitive, but this is what engineers do. The economics of alternatives are also better if we keep in mind the real price of energy, especially any potential carbon credits. Also, we can look at economics anywhere, because energy is fungible. If we can come up with a solution that works in a Third World country with low cost labor and lots of sun, giving it to them benefits us, because we can use the energy they save – and sell them stuff that low local energy costs allow them to afford.

THE "ECOLOGY" OF RENEWABLE ENERGY

"Plays well with others"
Seen on children's report cards

Here the term "ecology" is not mainly considering environmental issues, but the overall way a technology might fit into the rest of the energy system. Environmental issues are a part of this, but by looking at how a given energy source might interact with other sources and consumers, we may find both opportunities and problems that affect decisions regarding appropriate technology.

The most important issue to keep in mind regarding alternative energy is that it is entering a complex infrastructure that has evolved over the last century primarily to manage and support a combination of fossil fuels and hydropower from dams. Completely supplanting this system rapidly is probably not feasible, at least in part because fossil fuels and hydropower are basically very convenient: Fossil fuels are readily transportable and storable, are energy dense and are already available in a form that requires relatively little processing to use. Hydropower incorporates a storage mechanism inherently, and most of the resource (water at a height) is naturally provided by rain and snow and even collected and channeled into rivers by Nature.

As a result, a system of gas stations, power plants, coal trains and barges, oil refineries and pipelines, electrical power distribution systems and on and on has evolved to support the use of fossil fuels. This means also that much of this infrastructure needs to be adapted to the use of renewable energy, or more likely, renewable energy has to adapt to this structure. For example, extensive use of plug-in hybrid or electric cars, especially with a "Smart Grid", might enable more effective use of intermittent electrical sources.

Grid Connections

Marine sources have to consider power transmission from sea to shore, and perhaps often relatively remote shore

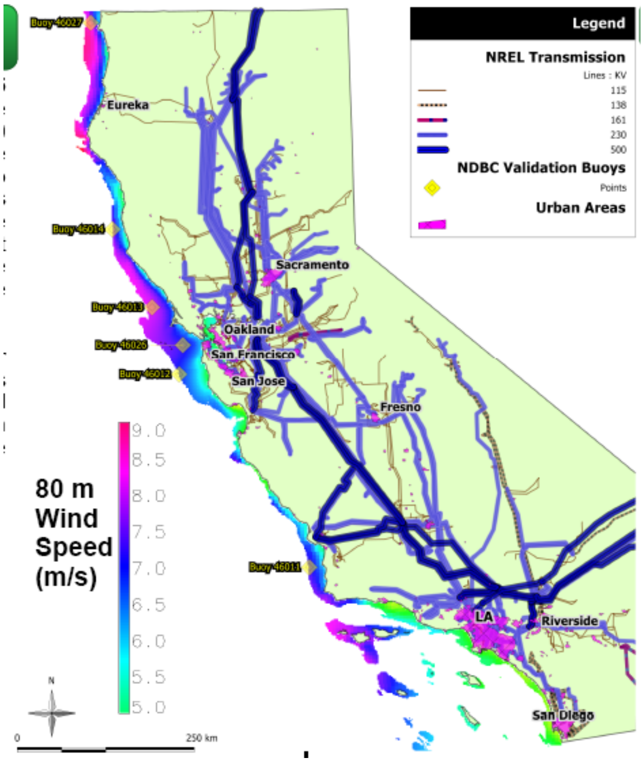


Figure 2

locations to power consumers. It seems that in many cases, the best wind and wave resources (which, of course, are correlated) are relatively remote from consumers, both ashore and at sea (though the fact that people tend to live near coastlines mitigates this a bit compared to some of the wind resources located well inland in the U.S.). In Europe, western Ireland is the best location for both wind and wave, and relatively sparsely populated. On the North American Atlantic coast, the best wind and wave (and current) resources are off Maine and Maritime Canada. Off the Pacific Coast, the best resources are generally about equidistant between consumers in San Francisco and Seattle in a relatively sparsely settled area. Dvorak et al (Dvorak, 2006, 2009), Figure 2, illustrates this problem for wind resources off the Northern California coast. All of this means that any large expansion of electrical generation from marine sources will require a substantial growth of grid infrastructure. However, it is likely that marine sources may be both closer to consumers and larger than other shoreside resources, so that the grid infrastructure to support renewable energy may tilt toward marine sources.

Intermittency / Dispatchabilty

Marine energy sources such as wind, current and wave are intermittent, so to have a robust overall energy supply, these sources have to be balanced with other intermittent sources that are counter cyclic and hopefully readily dispatchable sources, or energy storage has to be available. One key enabling technology for most sources of ocean energy is therefore energy storage, whether at sea or ashore. Fortunately, energy storage is the topic of a great deal of research, and many promising technologies are being developed. Another is a smart power grid that can connect all of these diverse sources and a market system that allows effective rapid power trading. Hopefully such a market can also be developed with appropriate regulations and oversight that prevent the gaming the system to artificially restrict power and run up spot prices.

This also means that regions (such as New Zealand or the U.S. West Coast) with sources such as dammed hydropower can more readily integrate intermittent marine sources into their energy mix, especially if direct solar resources are also available to "fill in" as needed. Integrating fossil or nuclear sources into the mix may be more of a problem, especially if they are new power plants, since it is unreasonable economically to ask fossil or nuclear power plant operators to defer recovery of the capital cost of their plants by running them as backups to intermittent renewable sources (not to mention the cost and efficiency penalties inherent in running fossil and nuclear plants at highly variable loads).

This also suggests that use of marine energy for production of hydrogen, synthetic fuels or other high energy chemicals may be appropriate, especially where energy resources are stranded far from consumers, such as at sea in Ocean Thermal Energy plants. An effective technology that uses electrical energy and some sort of biofuel precursor to make fuel might provide a favorable niche for some ocean energy resources. It might also provide local employment in some of the more remote coastal communities that have wave or current resources. We particularly like one recent development: A research team at the University of Delaware has developed a process for heating chicken feathers that results in a matrix capable of absorbing hydrogen at high density. One can imagine fleets of "poultry gas carriers" bringing hydrogen ashore from OTEC plants.

Interactions with Fossil Fuel

We should also look for possibilities to work with, rather than compete with fossil fuel sources. One interesting example is using renewable electrical sources to generate hydrogen by electrolysis. The hydrogen can be used with coal to make liquid hydrocarbon fuels with a much lower carbon load than current means, and this provides yet another opportunity to cover the intermittency problem. However, the oxygen resulting from electrolysis is also valuable: Burning coal in pure oxygen results in temperatures high enough to make Magneto-hydrodynamic (MHD) power generation feasible. This process uses a very hot, fast gas stream "salted" with small amounts of metals such as cesium passing through a magnetic field to generate electricity. The relatively "cool" MHD exhaust is still very hot and MHD generators are extremely compact so they might be retrofitted to conventional steam plants as a first “hot end” stage, thereby substantially increasing thermal efficiency. Finally, the exhaust from burning coal in pure oxygen would be almost entirely CO_2, instead of mainly nitrogen as in a conventional plant, and can be sequestered more easily. This might mean that substantial renewable energy resources would paradoxically enable clean coal.

The main point here though is that the various forms of renewable energy should not be considered competitors, but rather partners, and this has to be made clear to the public and policy makers. Developers of one particular form of energy have to avoid the temptation to offer their solution as “the best”. There are also many enabling technologies that could bring the cost of renewable energy down and increase its viability. It is also worth remarking that there are probably techniques evolved in naval architecture and marine engineering that could be applied in non-ocean systems: Note that the size, temperature and general economics of a solar concentrating steam plant in the desert are very similar to typical merchant ship steam power plants rather than large utility installations.

Jobs

One of the authors grew up in Vallejo, California, the home of the now closed Mare Island Naval Shipyard. (And he now lives near the now closed Bethlehem Steel Shipyard. Some readers might consider this journey a metaphor for the marine industry as a whole.) In the current recession, any source of jobs has attractiveness entirely independent of other considerations, and marine renewable energy systems and their supporting equipment can readily provide the type of skilled trade jobs that could help an economic recovery. The construction of wave generators, wind turbine platforms or towers, OTEC plant ships or most of the other systems that have been proposed for harvesting ocean energy will require basically traditional shipyard skills in vast quantities. The actual installation and maintenance of these systems at sea will also require labor, and more labor to build the ships, cranes and other systems required to service them. It is also worth noting that most of these systems will be substantially more standardized, and produced in larger runs than in traditional ships, which should result in better economics, and in more opportunities to improve productivity, which may in turn feed into other areas.

Standards Development and Testing

Standards for evaluation and certification of renewable energy systems is another important part of the infrastructure required for renewable energy systems. Without some standards, it will be impossible to insure or invest in offshore energy systems, or to permit them. These standards not only have to consider the survival of the systems, and their hazards to others, but have to provide standard means to reasonably predict the available resource and the capability of a system to harvest it. This is unique to renewable energy – a fossil fuel power plant can operate essentially at its nominal capacity as long as it is provided fuel, but the availability of a renewable source depends on an accurate assessment of the environment as well as the system, and the long term available power (not only on the average, but as it relates to time of power demand) will determine the value of investing in a particular system. The International Electrotechnical Committee has convened a Technical Committee (TC 114) to develop these standards for hydrokinetic sources (wave and current), with the National Renewable Energy Laboratory leading the U.S. delegation. Wind energy standards (mainly for onshore systems) are under the aegis of TC88.

Physical testing is another requirement. In addition to existing ship model basins, there are a number of facilities specifically suited to testing renewable energy concepts, most notably the MMS Ohmsett facility at Leonard, NJ. This facility was developed to test oil spill recovery techniques but comprises a large wave tank and MMS has made it available for device tests.

One problem in hydrokinetic device design is testing at an intermediate scale, larger than in a model basin, but either for single units or at less than full scale. Such a facility has to be close to the other test facilities and convenient (and appropriately permitted), but would otherwise be in a natural environment. A sheltered bay is required with “scaled down” waves well scaled to nature both in height and period, and where long period ocean waves are excluded. Testing single tidal current conversion devices mainly requires a convenient area with reliable tidal currents but relatively shallow water (to reduce test installation costs).

Ireland has such a combined test facility at the Hydraulics and Maritime Research Centre, University College Cork (with an open water site in Galway Bay), for example (Lewis, 2009), and the University of New Hampshire has established a Center of Ocean Renewable Energy with a tidal energy facility at the General Sullivan Bridge, an offshore wave test facility and a laboratory wave basin. Other regions are developing similar facilities, and the authors would like to note that such wave conditions are available off Berkeley, California (with a suitable wave model basin nearby).

ECONOMICS

> *Engineering ... to define rudely but not inaptly, is the art of doing that well with one dollar, which any bungler can do with two after a fashion.*
>
> *Arthur Mellen Wellington*

The key to effective use of ocean renewable energy resources is therefore, obviously, economics, and this is one of the most fertile areas of development. Even if we didn't actually care about profits, we should always be aware that we are interested in obtaining the largest amount of useful energy resources by expending the least amount of other fungible resources, and money is usually a pretty good proxy for resources. This in turn means that there is frequently a role for the simple, low risk, low sophistication, low cost solution even if it is less efficient or elegant in terms of physics. This also means that many economic factors, most outside of the control of people involved in the ocean renewable energy industry, have great importance in the feasibility of a project.

Evaluating Offshore Renewable Energy Systems

We believe that this point is so important that we are making a proposal that seems a bit whimsical, but is actually intended to emphasize this point. Wave energy and other marginally viable schemes are often difficult to evaluate because cost and output data are either unavailable or not clearly defined. To facilitate apples-to-apples comparisons of a wide variety of energy-producing devices, we propose a new unit of measure: The Duggle (Dgl). The Duggle is defined as peak electrical power output (measured at the device) per dollar of first-cost to build the device (not including installation and maintenance). The Duggle has the dimension *watts/dollar*. For example, if a turbine that costs $500 has a peak power output of 1 kW, then it would be rated at 2.0 Dgl. A somewhat more complex but ultimately more useful unit is the Duggleby (Dglb). The Duggleby is defined as the average power production over an average climatological year, divided by the annualized cost of the device including first-cost, installation, power transmission and maintenance. The Duggleby is also expressed as *watts/dollar*, although the annualized nature of cost in the definition implies that the cost actually has the dimension *dollars/year*. *Watts / (dollars/year)* is the inverse dimension of the more familiar *dollars / (kw-hour)*, with the appropriate non-dimensional conversion factor. For example, a device which can send electricity to the grid at $0.15 per kw-hour, averaged over a typical year, would be rated at 1.3 Dugglebies. ($/kw-hour = Dglb / 8.7). We prefer this power-per-cost form rather than the inverse (watts/dollar rather than dollars/watt) because it is clear that Duggleby ratings must ultimately be greater than unity for industrial-scale devices to be commercially feasible, and because better performance should be described by higher numbers. (As a useful comparison, a compact fluorescent light is about 25 Dglb by "generating" energy through improved efficiency.)

Oil Prices

The difference in the enthusiasm for all types of renewable energy in the last eighteen months is, though obvious, remarkable. In the day of $150/Bbl oil, the economic feasibility of any sort of oil replacement was tremendous, and the (at least hyped) interest in ocean energy was at a peak. Predictably, it collapsed with the economy as oil prices retreated to $30/Bbl. Long term stability of oil prices is an important part of the viability of any alternative. Leonardo Maugeri (Maugeri, 2009) has recently suggested that $70/Bbl is a reasonable long-term price. This would stimulate both renewable energy and the growth of domestic oil production from non-traditional sources, such as tight, thin formations, oil shale, or tertiary recovery. One proposed road to this might be through a variable import tax that set the oil price at such a level. Some parts of the Clinton administration's "Btu tax" included aspects of this approach, though it is hard to imagine the political viability of such a tax today.

Carbon Credits

One clear economic factor in any area of renewable energy is a charge for carbon emissions, either as a carbon tax or in a tradable carbon credit "cap and trade" system. Charging for carbon emissions has been shown to work especially well as regards efficiency, and presumably it will generate support for renewable energy of all forms as well in the longer term. However, the entire issue of the economics of controlling climate change at a lower cost than the effects of climate change is a complex one (Nordhaus, 2008), but from the point of view of energy developers, payments for non-emissions of carbon are a potential economic benefit that could help spur investment in ocean renewable energy.

One important question is whether carbon is to be taxed or "cap and traded". The two approaches would initially appear to be similar from the point of view of system developers, but in either case the problem is that the level and uniformity of available payments, and their future values, have to be predictable to be well accounted in the economics of any renewable energy scheme. This has not yet been the case in either scheme.

Finland was the first country to tax carbon, at €18.05 per tonne of CO_2 (€66.2 per tonne of carbon - note that carbon credits are often quoted as carbon vice carbon dioxide – a kg. of carbon is 3.66 kg. of carbon dioxide). Sweden implemented a carbon tax of $100 per ton of carbon dioxide, then increased it to $150, but there are numerous exemptions, most notably electricity generation. It is difficult to calculate the effect of this tax, (especially against what "would have happened"), but estimates suggest Sweden has reduced the growth of fossil fuel carbon emissions by 15% to 20%, (though much of this has been due to a shift to biomass heating fuels), while their economy has grown 44% in the same period. Ireland has recently proposed a carbon tax on the order of €20 a tonne, and interestingly enough the Chief Executive of ExxonMobil has supported it. Other regions have also imposed carbon taxes including Quebec, British Columbia, the San Francisco Bay area and Boulder, Colorado, but the results of these regional efforts remain to be seen.

Recent U.S. proposed legislation has also suggested carbon taxes. Starkey and McDermont proposed a tax of \$10 per ton of carbon on fossil fuels on the manufacturer of the fuels, increasing at \$10 per year until emissions are reduced to 80% of their 1990 level (H.R. 2069), and Larson has proposed \$15 per ton of carbon dioxide with a ten percent increase above the annual cost of living adjustment.

However, it appears that the U.S. will enact a "cap and trade" program, which places an absolute cap on the carbon emissions of an entity, initially giving the entity a fixed allotment. The entity can then buy additional rights to emit carbon, or to sell those it doesn't use to another entity that needs them. Meanwhile, the cap is gradually reduced. This is intended to put an accurate market-determined price on carbon, but there is significant concern that the market will not set prices high enough initially, or that prices will not be stable enough to provide a clear long term signal that encourages investment in alternative energy. There is currently a Regional Greenhouse Gas Initiative trading scheme in place in the U.S. (for Northeast and Mid-Atlantic states) as well, with the first auction in September, 2008. The price to emit one ton of CO_2 has ranged from \$2.06 to \$3.51. There is also significant chatter about setting up futures, derivatives, and other financial instruments for trading carbon credits, and this may result in an unstable market or even a bubble (Morris, 2009).

As of right now, even where there are fungible charges on carbon that could finance or offset operating costs for ocean renewable energy, either a tax or a cap and trade plan, they are widely variable and thus don't send a good quantitative economic signal that will guide investors. Considering electric power, generating a kW-hr from coal emits about one kg. of carbon dioxide and natural gas about half that. This range of carbon credits results in \$0.0265 to \$0.0023 per kW-hr of electricity (4 Dglb – 50 Dglb) from coal. The former value is quite meaningful in terms of an incentive, but the latter is much less so. Again, though, the primary need is for stability and predictability, even more than high levels of payments.

Business Models

Another issue is the form of business models for ocean energy, both for individual developers of a concept and for installations. Individual technology developers could be in the position of licensing their designs and expertise, of building components for utilities that develop the resource, of actually operating power generation plants, or something else. In the early wind power industry, individual turbines were owned by passive investors and leased to a power generation firm. The fact that wave, current and wind conversion installations comprise large "fleets" of devices may make this a viable model, especially depending on the taxation treatment of such deals. Most of us are justifiably a bit nervous about "innovative business models" at this point, but they are probably an important development.

Government Actions

Government subsidies of various kinds have so far been vital to the growth of all forms of alternative energy and are at the heart of the success of wind energy in the U.S., especially early on. The UK and New Zealand have been especially supportive of their nascent hydrokinetic energy industries. U.S. support specifically for ocean energy has been limited until recently (though there has been ongoing funding to NREL to keep ocean energy alive), but this has been changing, most recently with two grants (for \$12 M to industry and \$15 M to laboratories) announced in April (DOE 2009).

Besides direct grants for research, targeted tax advantages are probably the most common strategy. One very important provision allows 30% of tax credits to be taken out as a grant (basically, cash upfront) instead of offsetting other tax obligations, which means that firms that don't yet have profits still get benefits. The American Recovery and Reinvestment Act provides a production tax credit to hydrokinetic energy (and OTEC) through projects placed in service before 2012. One problem with tax benefits has been that they are not yet permanent, and have to be renewed. This makes it difficult to obtain reliable financing. A long term tax regime, even if it is for less than developers might like, is vital for the development of any type of alternative energy.

The other help governments have given the alternative energy industry is feed-in tariffs. A feed-in tariff is a law that obliges energy utilities to buy electricity at a fixed price, usually over a fixed period, from specified sources (though usually the term is used relative to renewable energy, it actually can apply to any generating source). These tariffs give developers and hence investors a guaranteed market and price and again ensure the long-term stability required for a secure investment.

Financing and Innovation

Every stage of finance of ocean energy concepts and projects is difficult, and, especially at the earliest stages is probably the doom of many otherwise worthy concepts.

To a certain extent, investors are probably mislead by the recent success of IT innovations and earlier, electronics. Initial development of software mainly requires a PC, time and coffee, so it was feasible for innovators to get quite far along without significant funding. This was also the case with a lot of electronics, so that two developers could build a personal computer with a wooden case in their garage. Unfortunately, this is not the case for many alternative energy concepts. Many energy concepts cannot be reliably even demonstrated at small scale, so finance requirements, particularly for early stage finance

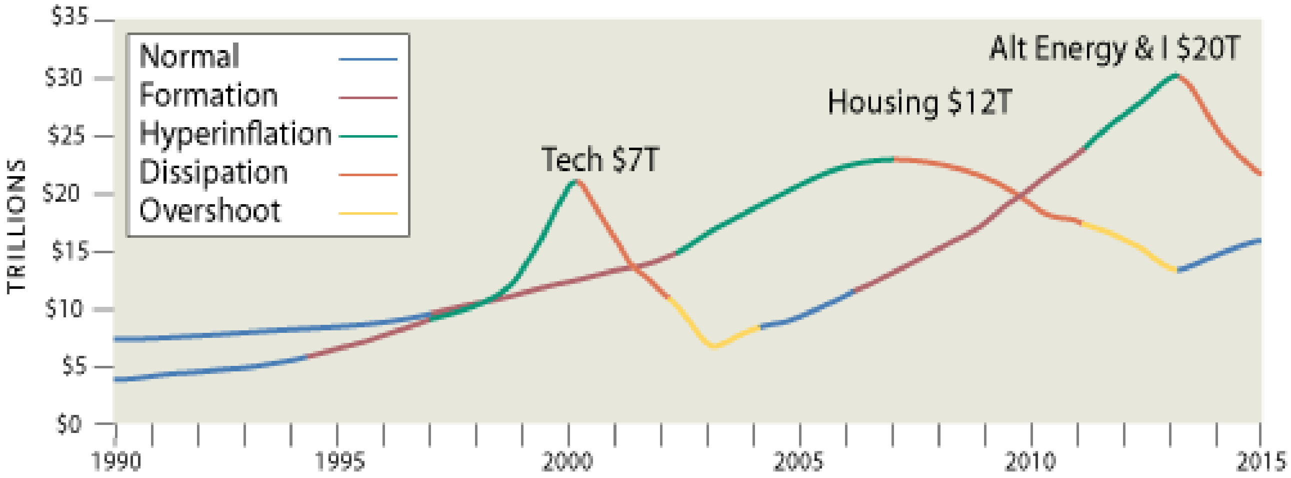


Figure 3

are much more of a problem, and hence government and not-for-profit sector investment is much more critical. One innovation that is needed to support alternative energy is better ways to put ideas in front of investors. Technical societies certainly can help here by promoting technical conferences that bring investors as well as other technical people. Stevens Institute has such a program, the Environmental Entrepreneurship (E^2) Lab, which includes both wave and current ocean alternative energy technology projects.

Not-for-profits also will have a key role to play here, (especially at early stage financing). The UK Carbon Trust has recently funded hydrokinetic projects with hundreds of thousands of pounds for demonstration and test phase work, the Abell Foundation of Baltimore has been funding early stage technology developments in OTEC, and we would like to see more small levels of funding from foundations going to the earliest stages of innovation in ocean energy – this is probably the only way they will survive.

A Bubble?

There have been a number of suggestions that alternative energy could become a financial bubble (Brady, 2009) amounting to as much as $20T (Janszen, 2009), Figure 3. However, there have been a fair number of tongue-in-cheek pleas (mostly op-ed cartoons) for a new bubble to replace housing and the Internet and thereby rescue the economy, and they are becoming a lot less tongue-in-cheek as the recession continues. One element frequently involved in bubbles is some form of government intervention that distorts the basic economics, so this might be a reasonable fear. However, it is worth noting that some bubbles have had a positive long-term effect for society as a whole, most notably the excess growth in fiber optics infrastructure, which has left the world with substantial very low cost communications capability (though it certainly hurt the investors). It is also important to note that renewable energy at its foundation does have real definitive value in the form of energy generation, and this is quite obvious, so the excesses of speculation will probably be restrained to some extent. (The authors certainly wish that renewable energy could develop a business model like the Internet boom that doesn't require profits, or even revenue, but this is unlikely.) Unfortunately, what is more likely is that fear of a bubble will restrain investment. The best vaccine against either of these is good, honest engineering information, made widely available, and this again is a role for a technical society.

OFFSHORE WIND

Wind is well established (Figure 4) and the transfer of wind power technology to sea is fairly straightforward and common in Europe at least as regards turbines, generator systems, and bottom founded towers. At the end of 2008, 632 turbines were in service offshore, with a rated capacity of 1471 MW of electricity from offshore installations, mainly in Europe, especially Denmark (29% of total world offshore wind capacity and 34% of turbines), (Kopits, 2009). Landside wind farms are cost competitive with conventional power plants now, but land based plants have issues such as limited good sites, bird and bat kills, noise, visual impact and so on. At sea, winds are stronger and steadier, so there are existing ocean wind farms off Europe and some proposed for the coast off the US.

There is a significant energy resource in the form of wind offshore of much of the United States. For example, a recent study done at Stanford by Dvorak, Jacobson and Archer (*ibid.*) suggests that there is an exploitable wind energy resource of up to 200 TWh/yr off the coast of California. Other estimates taking into account various exclusions suggest a total of 52,560 TWh/yr for all of North America. Figure 5 shows the average power off the US coasts in GW. As a comparison, the total U.S. electrical consumption in 2003 was 2800 TWh/yr.

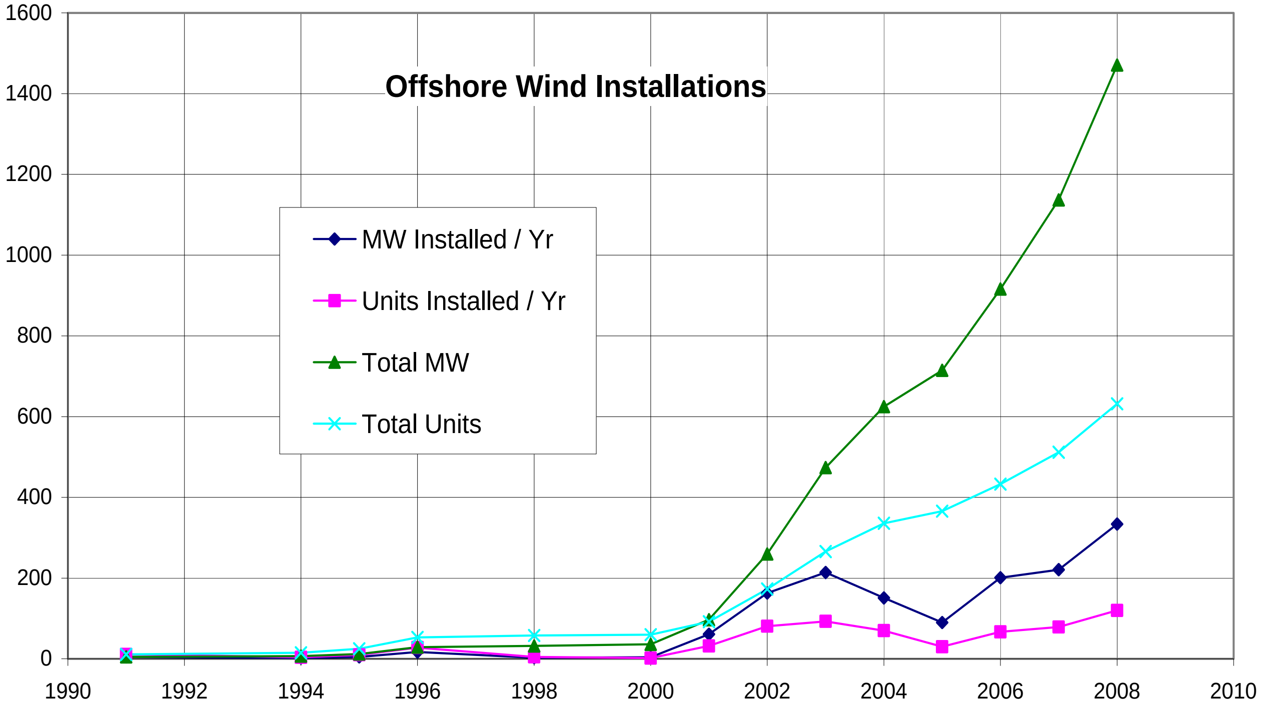
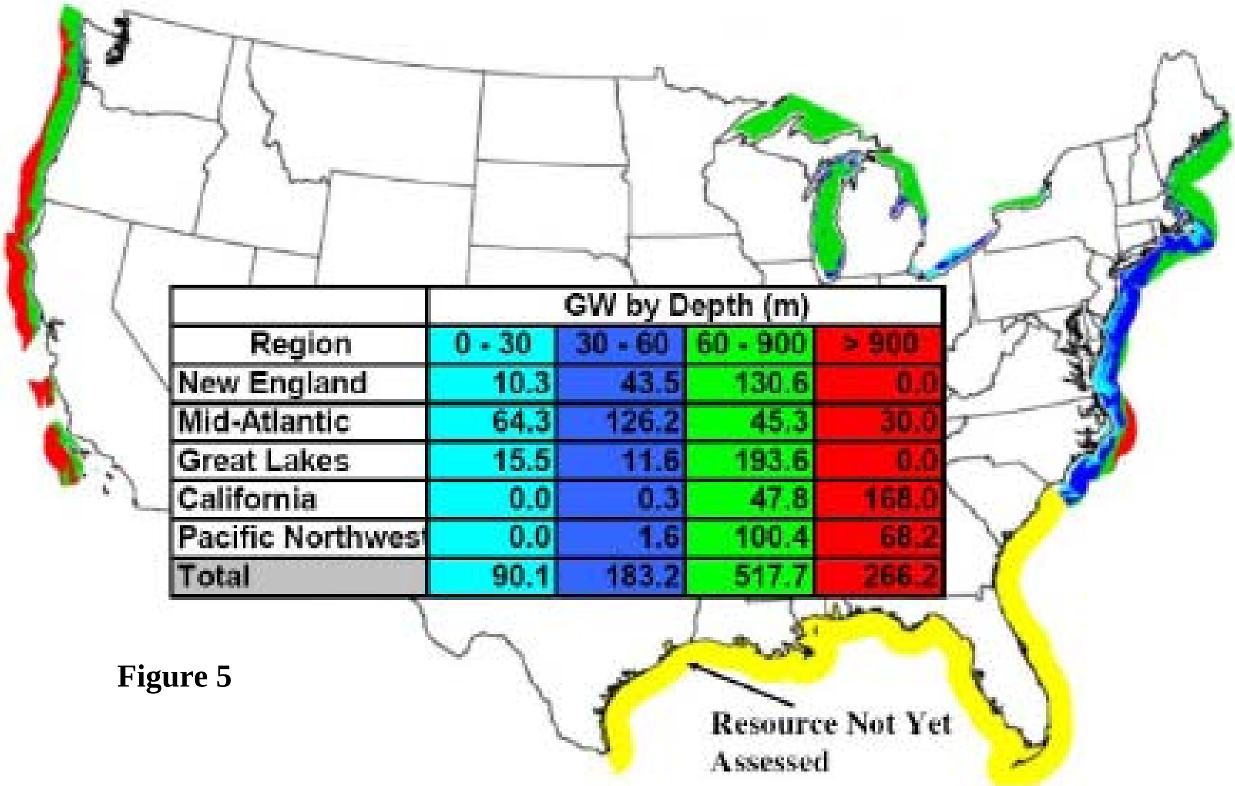


Figure 4



	GW by Depth (m)			
Region	0 - 30	30 - 60	60 - 900	> 900
New England	10.3	43.5	130.6	0.0
Mid-Atlantic	64.3	126.2	45.3	30.0
Great Lakes	15.5	11.6	193.6	0.0
California	0.0	0.3	47.8	168.0
Pacific Northwest	0.0	1.6	100.4	68.2
Total	90.1	183.2	517.7	266.2

Figure 5

This is an example of where marine people can help right away. The naval architecture community has a lot of know how in installing ocean platforms and a lot of experience that wind farmers might draw on. There are probably considerable opportunities for innovation in the details of wind turbine offshore platform design based on thinking about the installation process as well – consider the change in offshore platform design that was enabled by underwater pile drivers.

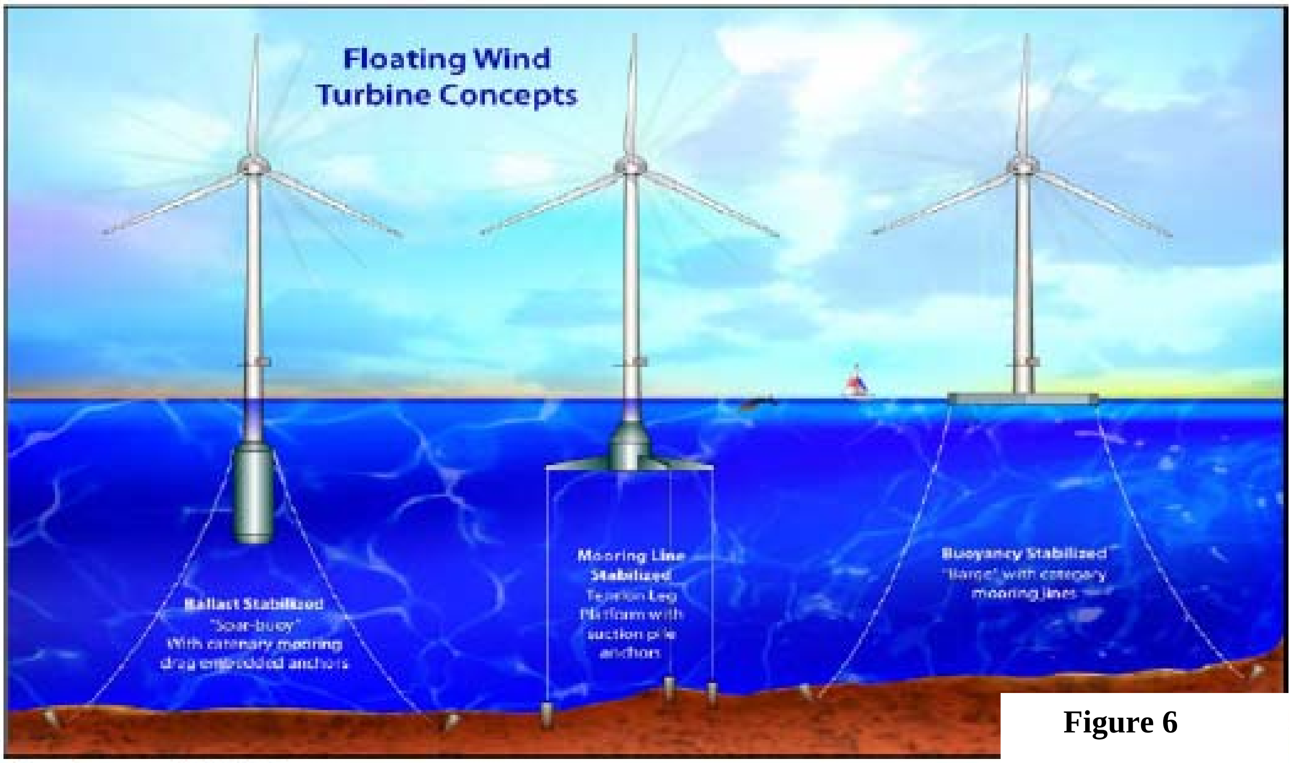


Figure 6

Courtesy of NREL

Buoyancy Support

Unfortunately, most of the wind resource, especially for steadier, stronger winds, which represent a more easily harvested resource, is in waters more than 50 meters deep, so a lot of this energy is not regarded as economically viable with the current bottom founded monopile tower technology. Figure 5 shows this as well; the largest resource (517.7 GW) is in waters deeper than 60 meters and only 9% is in waters shallower than 30 meters. For the Pacific Coast this is even more problematic – there is basically no exploitable wind resource in waters shallower than 30 meters.

In general, the offshore oil industry has found that cost of a bottom founded platform is a function of depth cubed so the cutoff depth is a function of the value of the energy asset (whether it's oil, gas or wind). This is a cubic function because if the water depth doubles, the platform height (from the bottom to the water line) doubles, so the amount of steel in it doubles. Then if the platform doubles in height, the base dimensions have to increase, roughly linearly, because the overturning arm on the base increases at least linearly. (The weight the lower section supports also increases as well, which adds some more steel cost.) As the platform gets larger, the wave forces also get larger, and the overturning force gets larger. The wave forces are largest in near surface zone, so they don't increase as much all the way down, but at the end of the day, all this tends to a rough depth cubed relationship, especially for Pacific platforms, which are also subject to seismic loads. Seismic loads don't fall off with depth the way wave loads do because in an earthquake, the base of the platform jerks sideways and the inertia ("added mass") of the water surrounding the platform uniformly tries to resist the movement of the rest of the tower.

Fortunately, the offshore oil industry faced this problem in the late 80's, especially when the price of oil fell dramatically, and developed a number of options to economically exploit small oil fields in deep water. Most of these concepts are even more applicable to wind power, because another critical problem of many oil platforms is the high payload weight (which, even worse, can vary substantially during operation) needed to support equipment to condition and control reservoir fluids. Wind turbines do not represent such high payloads, and they don't vary, so many of the concepts developed for offshore oil can be simplified. (Figure 6)

Floating platforms represent the most straight forward solution. The basic concept behind a floating system is that most of the wave load comes from the water plane, where the body pierces the water surface, but the buoyancy can be anywhere, so the motions of a platform due to waves can be reduced by having most of the body well submerged with only small members piercing the surface. To be a bit more specific, the natural period of a floating body, and hence its response to wave energy increases as the mass of the body (including the "added mass" of the water closely surrounding it, which moves with it), and decreases with larger waterplane. In addition, the acceleration of the fluid in the waves produces a force

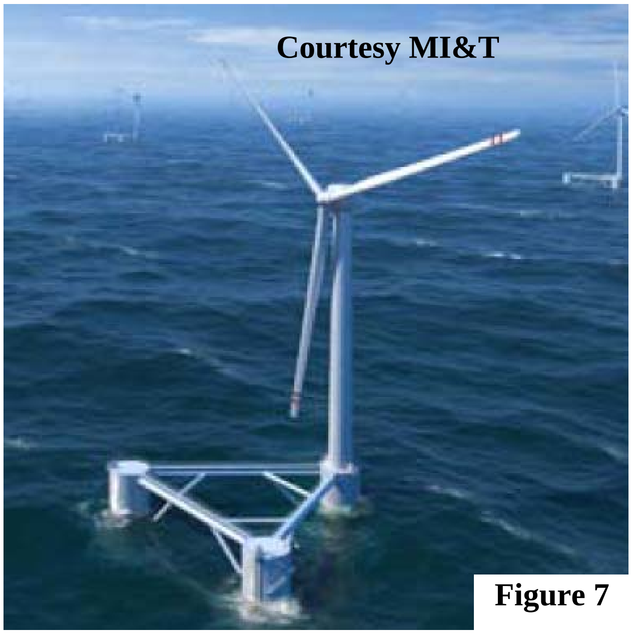

Courtesy MI&T

Figure 7

in a submerged body opposite to the rise of the wave – under the crest of a wave there is a downward component of force, and under the trough, an upward force. As a result, a body with a relatively small waterplane and larger submerged bodies has a range of wave periods where the net heave (vertical) forces are minimal or even zero. This gives us the two basic forms for fully buoyant platforms, either a semi-submersible or a spar.

A semi-submersible has two or more submerged hulls connected to the platform with multiple columns. One common configuration is a tripod of slender cylindrical vertical columns with much larger diameter shallow sections, "cat food cans", at the bottom. This configuration is now rare for offshore oil systems, because it has a limited payload, but it is probably well suited for wind turbines. The spread of the columns and their diameter produce the stability to resist overturning forces from the wind, and the volume of the "cat food cans" provides the buoyancy to support the platform and the mass to increase the natural period. It is worth noting that the shallow shape produces a large added mass as well – the water above and below the can moves with vertical motions of the cans, so it increases the effective mass without requiring a larger body. The shape also provides damping, which further reduces motions. The design of this type of platform is an optimization of required buoyancy and stability, tuning the ratio of column diameter to can shape to a period that minimizes wave motion in the typical wave environment on site, but the process is well understood.

Another alternative is a spar. This is a long single cylinder, ballasted at the bottom. The cylinder diameter generally increases toward the bottom, again to provide buoyancy without adding waterplane, which would cause increased wave forces. In this case, stability comes mainly from the ballast very low down. With the very small waterplane a lot of very low ballast is required to keep the spar vertical, so the volume of the spar is much higher than required to just support the payload, but on the other hand, the structure is strong and simple – no framing is required to interconnect columns, for example and some promoters are considering reinforced concrete instead of steel.


Figure 8

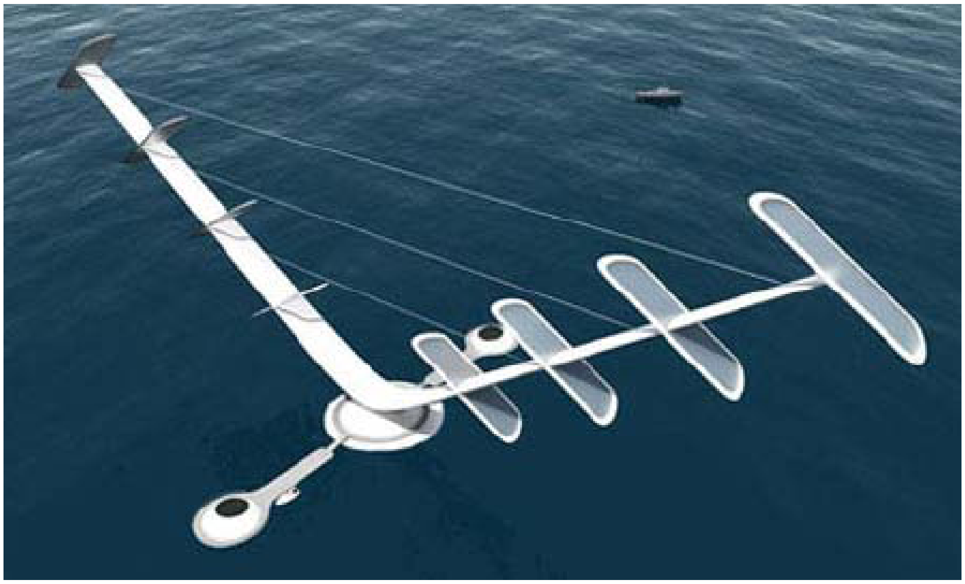
Photo courtesy StatoilHydro

In either case, the mooring system must also be considered. In general, floating systems, especially those in fields of multiple turbines will require multi-legged catenary mooring systems, and even then, the platform will still move around somewhat. The mooring system and its installation also add to costs. Floating systems will generally have more motions than bottom fixed systems, and there have been some concerns about interactions between the platform motions and turbine and rotor dynamics. Some researchers are looking into specially designed turbines that can take increased forces from relative motions of the platform and rotor.

There are also three essentially "hybrid concepts", guyed towers, buoyancy supported towers, and tension leg platforms. These generally have much reduced motions, though probably at higher costs.

Some of the problems of bottom founded towers, especially with the relatively light payloads of wind turbines, can be addressed simply by taking up the overturning forces with guy wires, also connected to the bottom. A number of guyed towers are in offshore oil service now. The amount of steel they require still goes up faster than depth increases, but they may represent a solution for specific sites, especially in intermediate depths. One advantage of guyed towers is that the relatively slender tower produces minimal wave loading. These towers are also frequently designed as relatively light truss work instead of a large diameter tube, which may reduce production costs. Another possibility is a buoyancy supported tower. In this case, the tower structure only carries a portion of the total weight, and one or more fully submerged buoyant hulls near the surface provide the remainder of the lift. The couple between the bottom foundation and the buoyancy also produces large stability to resist overturning forces. Buoyant towers are often designed with flexible links to

Duncan Graham-Rowe
guardian.co.uk, Tuesday January 29 2008



The Aerogenerator wind turbine (Photograph: Grimshaw Architects)

Figure 9

the bottom foundation. This is especially useful for seismic loads.

Taking a buoyant tower to the extreme (and actually beyond) produces a tension leg platform. In this case, the total buoyancy is greater that the weight of the system, and flexible tendons, in some cases cable, pull the platform down to a heavy foundation, usually a large concrete box, set on the bottom. The tension in the tendons produces excellent stability and reduced motions. This can even provide enough stability to allow a structurally simple spar configuration, but with minimal ballast. The tension leg platform is installed by floating out the platform and foundation separately. The foundation is flooded so it sinks, the platform is connected to it, and the tendons are tensioned. The tendons, the heavy foundation (including separate installation processes) and the excess of buoyancy over weight represent increased costs compared to fully floating systems, but the reduction in volume required for stability may balance this out. Again, the specifics of the site, including water depth, bottom conditions, available wind resources and the normal and extreme wave environment will dictate the applicability of this concept.

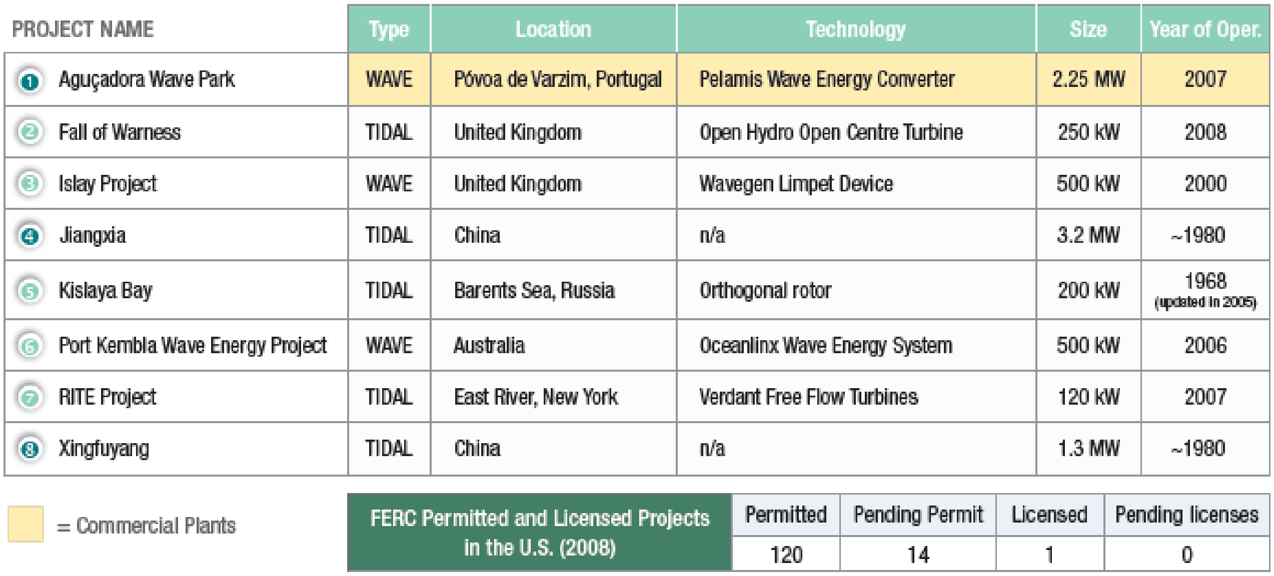
Another consideration for offshore wind is extreme wave height. It would probably be unfortunate for a moving turbine blade to be struck by a wave. In most cases, extreme waves will be associated with severe wind, such that the blades will be stopped, but occasionally, large swells can form from a distant storm. These will be long period waves, so a floating platform with a long period will be able rise and pass safely over these swells, but a bottom fixed system will not.

Developers around the world are working on various applications of these platform concepts for offshore wind energy. Some notable programs include significant research on the dynamics of various floating systems at MIT under Professor Paul Sclavounos, (Sclavounos, Butterfield, Jonkman, Lee, Withee, 2004-2007) and both TLP and semi submersible platform designs from Marine Innovation and Technology in Berkeley, California (Roddier, Zambrano, 2006, 2007, 2009), Figure 7. Blue H Group, in the Netherlands, has a set a tension leg wind turbine test platform in 108 meters of water off Italy. Technip and Statoil Hydro have installed the first major spar type installation on Sept. 8, this year, a 2.3 MW wind turbine 10 kilometers offshore of Karmøy, Norway. It is 165 meters tall of which 100 is below sea level. (Figure 8)

Finally, the power generated must come ashore. This poses two issues, cable dynamics in the case of a floating platform, and power loss. A flexible power cable is required, and it will be subject to motions from the platform at the top end, as well as effects from ocean current throughout its length, so it has to resist fatigue damage for twenty years or more, as well as marine environmental effects such as corrosion and marine growth. The technology for flexible oil hoses used in some offshore systems is available for power export cable design, but it is likely that some research effort will be required to adapt these components for the high current and voltage requirements of export power cables.

Cables with alternating current will also produce severe losses if long sections are immersed in a conductive medium, so it is likely that high voltage, direct current will be required for transmission. In any case, though, this will not be a trivial cost – some estimates suggest that the total cost of such cables might run more than a million dollars a mile.

The equipment to produce this current will have to be in each individual platform, which increases complexity of the platform, but also provides opportunities. Instead of a single large generator, offshore wind systems have been proposed with multiple smaller generators driven by a bull gear off the rotor. These would generate AC and each



PROJECT NAME	Type	Location	Technology	Size	Year of Oper.
① Aguçadora Wave Park	WAVE	Póvoa de Varzim, Portugal	Pelamis Wave Energy Converter	2.25 MW	2007
② Fall of Warness	TIDAL	United Kingdom	Open Hydro Open Centre Turbine	250 kW	2008
③ Islay Project	WAVE	United Kingdom	Wavegen Limpet Device	500 kW	2000
④ Jiangxia	TIDAL	China	n/a	3.2 MW	~1980
⑤ Kislaya Bay	TIDAL	Barents Sea, Russia	Orthogonal rotor	200 kW	1968 (updated in 2005)
⑥ Port Kembla Wave Energy Project	WAVE	Australia	Oceanlinx Wave Energy System	500 kW	2006
⑦ RITE Project	TIDAL	East River, New York	Verdant Free Flow Turbines	120 kW	2007
⑧ Xingfuyang	TIDAL	China	n/a	1.3 MW	~1980

🟨 = Commercial Plants

FERC Permitted and Licensed Projects in the U.S. (2008)	Permitted	Pending Permit	Licensed	Pending licenses
	120	14	1	0

Figure 10

one would have its own step up transformer and rectifier to produce high voltage DC which would then be combined. This might reduce cost and dynamic stresses in the drive train, and would produce redundancy and easier maintenance (an especially important consideration offshore). Another recent concept dispenses with the gearing altogether and runs the generator at turbine speeds. Though heavier than high speed generators, the absence of gearing reduces that cost and improves reliability.

There are also some possibilities for advances in turbine blade and generator design specific to offshore wind buoyancy supported systems. Two blade vs. three blade turbines may have some advantages offshore because of their lower weight per MW. Two blade turbines can also tilt to reduce dynamic forces. The wind force load will be a significant driver for platform cost, and there are techniques for blade design that reduce the thrust induced on a wind turbine (and hence the overturning force as well) compared to the power extracted. There have also been a number of proposals for vertical axis turbines, which would also tend to reduce overturning moments. (Figure 9) The motions of a floating platform may also induce significant loads in gearing and generator systems (and possibly even blades) due to gyroscopic effects. This may mean that alternatives to the single large gearset and generator used ashore would be appropriate. Fluidic speed converters running multiple smaller generators have been proposed for wind turbines at sea – they are less sensitive to motions and the use of multiple small generators and other components increases reliability and reduces the lift capability required to service components.

It is clear that there is a significant energy resource in relatively deep water wind sites offshore, and thanks to this synergy between offshore oil and renewable energy that there are many viable concepts to exploit these resources, but there are also a lot of requirements for engineering developments and design innovations. It is also clear that there is significant room for innovation and economic optimization.

HYDROKINETIC ENERGY

Hydrokinetic power refers to power extracted from the kinetic energy of moving water, rather than from the pressure head behind a dam. Wave and current power had been grouped together, with "hydrokinetic" originally referring only to the latter, (DOE, 2005) but the IEC now uses the term for both, and both are under the aegis of TC 114. One important aspect of the term is that current laws also give the Federal Energy Regulatory Commission control of electricity derived from hydropower, of which hydrokinetic energy is legally a subset. Figure 10 lists some significant hydrokinetic projects.

WAVES

The obvious power of waves has been attracting inventors for well over a century, with some wave power extraction patents going back to 1898. McCormick (McCormick, 2007) includes as an appendix some thirty different concepts illustrating the basic range of techniques, (and the authors recommend this text as the best introduction to the general field of wave power conversion).

The Resource

Figure 11 (Robinson) shows the wave energy resources for the U.S., including Alaska. Again, the available power in regions with power densities over 10 kW/m is close to the total U.S. electrical consumption.

The energy in a deep water wave of length λ and amplitude a is:

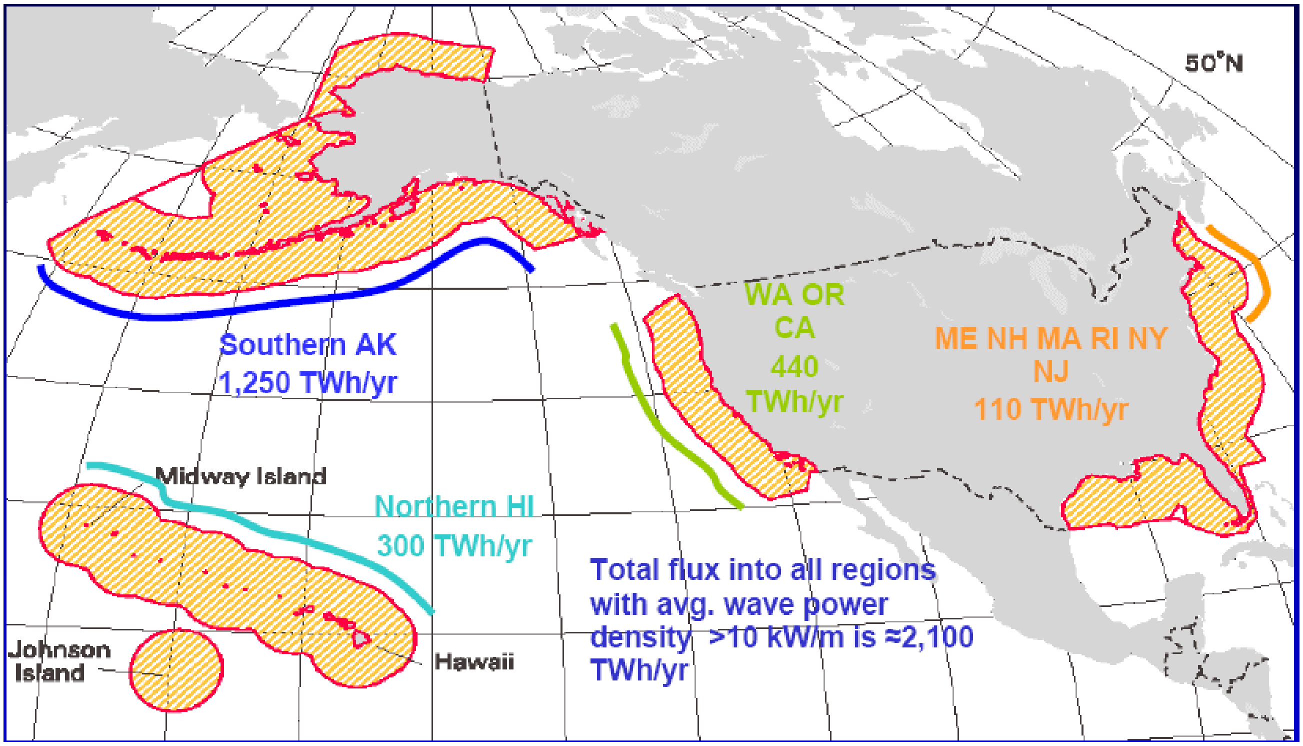


Figure 11

$$E = \tfrac{1}{2}\,\rho\, g\, \lambda\, a^2$$ per unit breadth of crest.

For a random sea of significant height H_s and zero crossing period T_z, the energy is:

$$E = \tfrac{1}{2}\, H_s^2 T_z$$ kW per meter of crest.

Half of this energy appears as vertical motion, and half as horizontal motion.

At least in deep enough water, the wave particle motion reduces exponentially with depth. The main importance of this is that a surface device can exploit the difference in particle motion between it and a deeply submerged object to extract power rather than having to be rigidly connected to the bottom of the ocean.

Devices

Wave power continues to attract innovators who have come up with a very wide range of concepts. Though some concepts are clearly intended for specific environments, such as shorelines or in shallow water, unlike wind turbines there is no “standard” concept.

The most obvious system is a vertical point absorber, essentially a buoy connected to the bottom or to a highly damped submerged body (such that it is essentially motionless relative to the sea surface). The vertical motion of the buoy is absorbed in some sort of mechanical power take off and converted into useful power, though it only converts half the available energy. The other problem with this concept is there has to be a relatively motionless “force reference” that the buoy forces can react to.

Salter’s Duck, which is often considered to have initiated the modern era of wave conversion devices, is a point absorber, but captures both vertical and horizontal wave particle motion through a “nodding” or pitching motion, rotating about a horizontal axis parallel to the wave crest. As a result, the Duck is as much as 80% efficient in a monochromatic wave at its resonant frequency. The Duck is sometimes considered an attenuator, because it is often suggested that a chain of Ducks with a common axis could be arrayed across a wave front and use their varying relative motion to derive power instead of being fixed to the ocean floor.

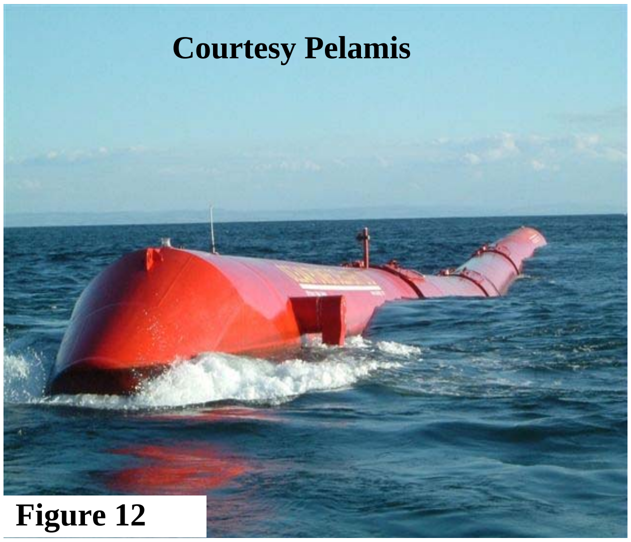
Attenuators have a principal axis parallel to the wave direction and convert wave energy to relative motion of their parts, thus avoiding the need for a force reference. The Cockerell Raft comprised a chain of linked rafts (arrayed along the direction of wave travel) that contours the wave. It derives power by the relative motion between the rafts, essentially what would hull girder bending in a ship. The popular Pelamis device (Figure 12) is precisely this concept, though the rafts are linked cylinders, (with the cylinder axis horizontal and parallel to wave travel), rather than flat barges.

A problem common to many motion based wave energy devices is that the force provided by the device for conversion is constant (and large – in the case of a point absorber, it is on the order of a significant fraction of the weight of the buoy), but quite variable in both frequency and stroke length. As a result, many wave devices use hydraulic or air compression as an intermediate power storage means. A typical scheme uses the force of the moving buoy to actuate a cylinder, which compresses air into a tank. The energy is then extracted with an air turbine. An interesting variant of this scheme captures air in a deeply submerged inverted cup, where hydrostatic pressure provides the containment and counter pressure. Another interesting variant is to use a secondary device. One scheme uses heavy sinkers, each with a turbine on one end, suspended from numerous points on a disk buoy. The sinkers are in the relatively still water well below the surface and as the disk rises, falls and pitches, the sinkers rise and fall and the turbines spin, generating power.

The natural frequency of the device relative to the waves also affects the efficiency of energy capture. One technique that addressed both the issue of frequency matching and matching to power extraction devices is latching. In this scheme the moving component is stopped at the extreme displacement, zero velocity positions and held momentarily while the wave goes by, until the wave is quite out of phase with the moving buoy. Then the buoy is released, so that the resulting motion is much faster. Appropriate controls also allow this process to in effect adjust the natural frequency of the device, and some of the most recent concept in point absorbers or attenuators incorporate a variety of mechanical, hydraulic or electrical means (adjusting the field strength of the generator components) to produce this effect.

Oscillating water columns and overtopping devices are another means of addressing the conversion issue. Oscillating water columns enclose a column of air, trapped by the water beneath. They usually have a funnel or similar converging section at the top. The rise and fall of the wave causes air to rush in and out of the device through the funnel, spinning a turbine. One of the fertile fields of invention in these devices has been clever air turbines that rotate in the same direction regardless of which direction the air flows through them. Over topping devices use the wave action to fill a reservoir with water, which is then run through a turbine. More sophisticated versions of these devices exploit the fall of the wave as well, using energy from the difference in water level. Overtopping and oscillating water column devices can be on the shoreline, bottom mounted or floating. In the latter case, the platform they are mounted on is typically much larger than the device, so its natural frequencies in heave or pitch are well away from that of the column, though some point devices use the motion of the buoy to induce air motion as a means of energy conversion.

Horizontal particle motion devices are generally bottom mounted vertical flaps, just like the wave generator flap in a model basin. The Oyster device is in this category. Another type of horizontal motion system uses water wheels, though this concept does not seem to be in use now.



Courtesy Pelamis

Figure 12

Shoreline surge devices use a variety of conversion means, but count on the transformation of wave particle motion to horizontal surge in shoaling water, especially when the wave breaks, to concentrate power. The Limpet device on Islay is a shore based sloped oscillating water column device enhanced by shore effects and is one of the first devices to actually delivery power in production to a grid (100 kW in July 2008 in the UK). (The "Planet Mechanics" device mentioned earlier is also a shoreline oscillating column device.)

Bottom pressure devices are bottom mounted devices that absorb energy from the change in water pressure as a wave passes over them. A typical scheme uses a flexible membrane over a water reservoir that pumps water through a turbine. Frequently the turbine is ashore and connected to the reservoir by pipes.

Other less common devices include sloshing devices (water channels in a raft running turbines as the water sloshes – essentially an anti-roll tank producing power) and even electrical devices that use waves to move hydrogen gas between two reservoirs and induce a charge.

Focusing / Shoaling

Inventors have also applied various focusing or shoaling schemes to concentrate the wave energy. An isolated point absorber actually collects energy from a wider crest of wave than itself (this is referred to as "relative capture width"). The wave induced by the heave motion of the device itself interacts with the incoming wave to focus energy on the point device, especially at the devices natural frequency. As a result of this effect, some early tests of Salter's Duck showed "efficiencies" as high as 150%. The design of the wave device array can exploit this effect, as can carefully designed artificial shoals. The Lockheed "Dam Atoll" device is an overtopping device comprising a large circular buoy with a carefully designed cross section that focuses waves on its center. A water turbine is mounted beneath the center to extract power. It also has guide vanes that induce a swirl in the waves so that the energy it extracts includes the velocity of the waves climbing the device as well as their potential energy. Other schemes use the submerged stationary body that provides a force reference as an artificial shoal as well. The shoaling effect increases the wave steepness, improving energy extraction. (Raftery, 2009)

Challenges – Economics and Survival

An important question is how much a wave generator might cost compared to the power produced. To get a very rough guess, a Salter's Duck matched to a design wave of for the Pacific coast of the U.S. might be about 8 meters depth, roughly the same beam and length and would average 70 kW annualized, based on wave data for Marsden Square 5 (Hogben, 1966). Assume the largest single cost is the device hull. The total volume of the Duck would be about 350 m^3. If we assume the cost of Ducks is similar to that of tank barges, recent contracts listed at Colton Company suggest a cost of \$243/Bbl or \$1529/m^3. This produces a capital charge of about \$0.02/kW-Hr, (5 Dglb) without the generation equipment inside, power transmission or anchoring systems, maintenance, overhead, etc., which should more than double the delivered cost. The authors currently pay about \$0.15/kW-Hr, (1 Dglb) to PG&E or BGE, but wholesale power prices are much less than that. Clearly this cost presents a challenge to be competitive with other sources, especially without subsidies or carbon credits, but a simple guess doesn't completely throw wave energy out (and there are a lot better estimates available). This also points out the trade off between sophisticated devices that might be more efficient and simple ones that are cheap. As regards carbon credits, it should also be noted that the carbon footprint of the device itself and its installation should be considered as well.

Though the authors don't like to compete renewable energy systems, it is worth remarking that Sorensen (Sorensen, 2004) has criticized the economics of wave power on grounds analogous to that above, suggesting that the weight of a wave device will be ten times that of wind power per kW (and the costs of power generation, transmission, etc. will be otherwise similar). Though this may be true for monopile wind turbines, it is probably not so for floating systems. However, one might note that once mooring systems, power cables, permits, and so on are all in place, it is probably worth thinking about getting both wind and wave power out of the same area. The NREL has proposed a combination platform that does exactly this (Musial, 2006).

The device also has to survive in extreme wave conditions, and a number of test devices have been lost. This also adds to the cost of the devices, especially the mooring systems. Some schemes to intentionally submerge the devices in the worst weather have been proposed, but this again adds cost and complexity.

Alternative Roles

One lesson from the history of photovoltaic systems is that at least initially, promoters should look for unique niche markets that exploit some special aspects of a device and its environment to show it off to best advantage. In the case of wave power, some devices might be well incorporated into breakwaters and enhance their effectiveness as well as deriving power. There are also roles where the ability to produce energy in a remote location such as a small island might be advantageous despite the cost (keeping in mind the alternative cost of shipping diesel fuel to a remote location for a generator instead). Powering aids to navigation (which was also an early role for photovoltaic power) comes to mind. Wave power has also been suggested as a means of powering specialized offshore oil platforms. A good opportunity here might be pumping high pressure water into an oil bearing formation for secondary recovery. It might be possible to match the device to the required pressure so no conversion to and from electricity is required.

Providing energy for environmental mitigation might also be feasible. Lovelock and Rapley (Lovelock, 2007) have proposed that wave powered devices might be used to bring nutrients from the deeps to the surface, and that this process would sequester carbon. Phillip Kithil at Atmocean has conducted experiments with the University of Hawai'i (that were also the subject of a Discovery Channel program). Another role might be pumping air into littoral anoxic "dead zones". These areas are where nutrients and other pollutants washed from the land have caused blooms of phytoplankton, which subsequently die, using up all the oxygen dissolved in the water.

CURRENTS

Hydrokinetic power in terms of tidal or current power refers to power extracted from the kinetic energy of freely moving water currents, rather than from the pressure head behind a dam. (The latter concepts are barrage systems, which while effective and frequently proposed in the past, require major expensive civil engineering works for impoundment basins that also require substantial real estate, often in expensive areas, and that have significant environmental impacts). Energy extraction from free flow is desirable because it causes less disruption of natural hydrology (no dam required), and because it appears to be readily available in a number of coastal cites with tidal action, placing the power resource near major population and industrial centers.

The disadvantage of tidal power vs. offshore wind is the speed of the medium. The advantage is the density of water. The energy available goes down with the cube of the speed and up with the density. A typical water current might be four knots, compared to a wind speed of 20 knots, but water is 800 times as dense as air, so current based devices can be smaller for the same energy extraction.

There has been considerable interest worldwide in current energy, both in coastal areas and in “run of river” projects inland.

Technologies

Conversion devices for current power mainly comprise various configurations of horizontal axis turbines, similar in principle to conventional wind turbines, though the smaller size of current devices has opened the way to other systems, so that vertical axis turbines in a wide range of configurations are also being studied. The issue of size and fluid speed has also inspired a number of devices that include nozzles or other types of converging ducts to increase flow velocity. There are a small number of especially interesting proposals involving devices that have large hydrofoils and “tack” back and forth across a current, thereby increasing the speed of the device compared to the current. Power is taken off a turbine in a nacelle on the moving hydrofoil. Finally, the fact that power per cost is the vital measure has inspired some seemingly crude devices comprising half submerged paddlewheels. These devices hope to make up what they lack in elegance by low cost.

The Resource- A Tidal Energy Reality Check

It is tempting to look at locations with strong tidal current flows and imagine a vast energy resource going untapped. San Francisco is a good example. The Golden Gate is a narrow inlet that drains 450 square miles of inland bay and estuary water surface. Typical daily peak ebb current velocity is 4.5 knots and flood current is 3.3 knots. During spring tide peaks, ebb currents of 6 knots are not unusual.

The San Francisco City government has at times shown considerable interest in developing this apparently unlimited source of local, renewable and carbon-free energy, and it is an interesting exercise to at least crudely estimate its potential. Neglecting, for the moment, the difficulties inherent in extracting power from a relatively slow-moving medium, it is instructive to calculate the maximum amount of tidal energy that is theoretically available at this site (Bauman, 2008).

- Surface area of San Francisco Bay: 450 square miles
- Average vertical tidal range: 4.1 feet, measured from mean high water to mean low water.
- The average tidal day is 24 hours and 53 minutes. One-quarter of the tidal day, or the time from high tide to low tide, is 6.22 hours.

We can calculate the potential energy in a 450 square mile layer of water 4.2 ft thick:

- The volume is: $450 \times 5280^2 \times 4.1 = 51.44\times10^9$ ft^3
- At 1.9905 slugs/ft^3, the mass is 102.38×10^9 slugs
- The center of gravity of this layer of water is 2.05 ft above mean low water.
- The potential energy is $102.38 \times10^9 \times 2.05 \times 32.2 = 6.76 \times10^{12}$ ft-lb
- Releasing all of this energy in 6.22 hours, the power output is:
- $6.76 \times10^{12} / (6.22 \times 3600) = 301.8 \times10^6$ ft-lb/sec = 549×10^3 hp = 409 mw

This estimate is at least an order of magnitude too high because it assumes 100% conversion of all the potential energy in the tidal layer. But we see that even with this level of unrealistic optimism, tidal energy could only supply about 400,000 homes, a small fraction of the Bay Area population (using a 1 kW/household rule of thumb). Assuming a more realistic, albeit still probably optimistic, 5% extraction of tidal energy, we are only supplying 20,000 homes.

The inescapable conclusion, before even considering the type of tidal energy recovery hardware to evaluate, is that tidal power for San Francisco is a very small drop in very large bucket of energy demand. Even if tidal energy could be extracted economically, it cannot scale up to more than a token contribution, even for a location perceived as having a strong and concentrated tidal energy resource.

Are there other venues that might work?

Dent Rapids, near the north end of Puget Sound, has a mean tidal current of 8 knots flood and 14 knots ebb. There is no nearby population center, but transmission lines are accessible.

Perhaps a more valuable feature is the region's supply of conventional hydro power. Both conventional pressure-head hydro (dams) and hydro-kinetic (tidal) have one distinct advantage over wind and solar: They produce "clean" power, i.e. no spikes or lulls due to gusts, clouds, calms or storms. Tidal power, although of course subject to a predictable outage at every slack tide, is even more predictable than pressure-head hydro in the long term, because it does not rely on seasonal rainfall.

A dual-source hydro system, using pressure head during slack tide and tidal hydrokinetic energy when the current is flowing, might have some potential, but if and only if the hardware for extracting the hydrokinetic energy can be built and maintained economically.

A floating device has been proposed by one of the authors and carried through the conceptual design and costing stages with this site in mind. Two major problems were identified in this project: biofouling and anchoring loads.

The approach to biofouling is to use a surface-piercing rotor design. At every slack tide, the device stops for more than enough time to allow water jets to automatically clean at least one blade that is fully out of the water. This allows the use of low-toxicity anti-fouling paint, and significantly extends the major maintenance interval, a factor crucial to real-world economic viability of all renewable energy systems.

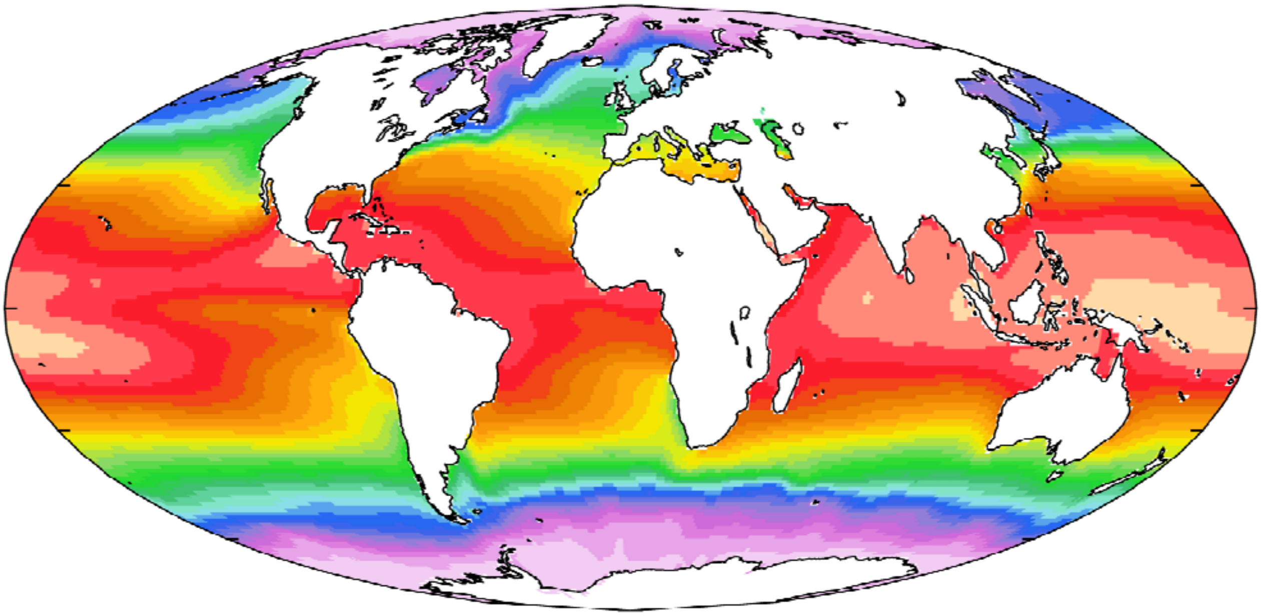
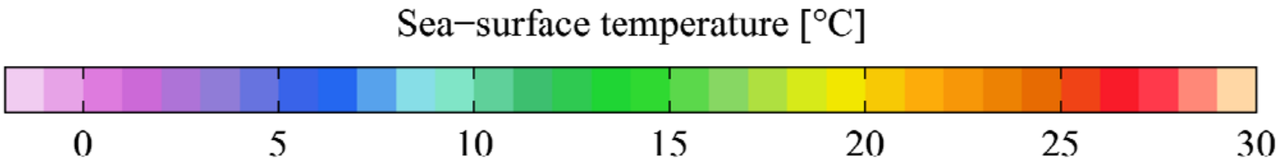


Figure 13 **World Ocean Atlas, 2005**



The problem that was not addressed is anchoring loads. Regardless of the hardware design, there is a fixed relationship between anchoring loads, power output, and current speed.

Approaching the problem as the reverse of ship propulsion, begin with one horsepower as 550 ft-lb/sec or a KW as 737.7 ft-lb/sec. Device efficiency will range from about 0.5 for the low-aspect reversible surface-piercing rotor to approximately 0.85 for an optimized water turbine with long slender blades. Choosing 0.65 (typical of efficient marine propellers) we have 737.7/0.65 = 1135 ft-lb/sec "effective drag power" per KW extracted. Anchoring load in lb/KW is then 1135 divided by current speed in ft/sec, or 672 / speed in knots.

A 5 MW extraction device in 8 knots of current will produce 420,000 lb. or 188 long tons of load on the anchoring system or support structure.

While an incremental improvement can be achieved with a high-efficiency turbine, the basic relationship is device-independent, and limits the feasibility of all extraction devices, especially in locations with low current velocity.

However, there definitely is a place for tidal power in specific locations and energy need niches. Like all other forms of renewable energy, it is a matter of “horses for courses”.

OCEAN THERMAL ENERGY

Ocean Thermal Energy Conversion (OTEC) extracts solar energy through a heat engine operating across the temperature difference between warm surface water and cold deep water. In the tropics, surface waters are above 80^{o}F, but at ocean depths of about 1,000 meters, water temperatures are just above freezing everywhere in the ocean. (So the available differential is approximately the surface temperature in ^{o}C, Figure 13.) This provides a 45 to 50 F^{o} temperature differential that can be used to extract energy from the surface waters. John Huckerby, chairman of the IEA Ocean Energy Systems Executive, has also recently pointed out that an even larger temperature differential exists between the deep ocean and deep water hydrothermal vents that might be exploited in a similar fashion.

Of course, with such a low differential, the Carnot efficiencies of such a scheme are very low; for a system operating between 85^{o}F and 35^{o}F the maximum theoretical efficiency is only 9.2% and real efficiencies will be less. Regardless, OTEC has been demonstrated as a technically feasible method of generating energy.

There are a number of different concepts for the heat engine including low temperature difference Stirling cycle engines and direct use of water vapor derived from the surface waters that is condensed with the cold water, but

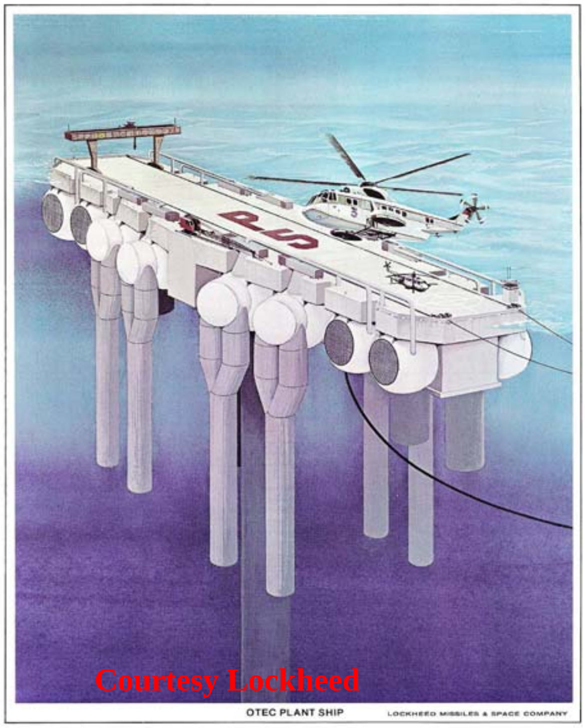


Figure 14

most concepts have a Rankine cycle using a fluid with a low boiling point.

It works like this: Warm water is used to heat a fluid such as ammonia to vapor. The vapor then runs through a turbine to generate power and the cold water is used to condense it. Let's use ammonia as an example. Ammonia boils at 85°F and 166 psi and condenses at 35°F and 66 psi. This gives us 100 psi to run a turbine. Unfortunately this cycle only provides about 7% efficiency, though it can be boosted a bit by superheating, reheating and similar strategies used in steam cycles. However the big advantage is that OTEC is a solar power system with no collector – the ocean itself is the collector. This means it also is available constantly.

There are many practical issues as well. Again, assuming ammonia, ammonia attacks copper bearing alloys, but only copper alloys resist marine fouling, and only a small amount of fouling is enough to enough to drastically cut heat transfer efficiency. Systems using ammonia have to have sophisticated waterside cleaning systems. There are also issues with the design of efficient low head turbines, very high performance heat exchangers, the long cold water pipe, and the platform, if it is floating (most OTEC designs are floating platforms, "grazing" in the open ocean – Figure 14). Finally, there is the problem of using the energy. Most OTEC plants will be far at sea, because deep water in the tropics is generally far from energy markets, so the energy is "stranded."

Since the 70's a few developers have been experimenting with approaches using different fluids, with improved heat exchanger and turbine technology and innovative platform and cold water pipe designs and materials. Other developers have been working on techniques to use the stranded energy, generally by making an energy intensive chemical at sea that can be used as a fuel or to supplant energy that would otherwise be used to make the chemical. One candidate is ammonia, which currently requires substantial energy to provide the world's need for fertilizers, and can be used as an alternative fuel as well. Another nitrogen based high energy fuel is guanidine, NH C $(NH_2)_2$. Another is sodium: PowerBalls are little coated balls of sodium hydride, made from the salt in seawater or from sodium hydroxide (eventually recycled from used PowerBalls). When placed in water the coating dissolves and they evolve hydrogen, so they store hydrogen in a relatively dense medium – twelve pounds of sodium produces about a pound of hydrogen, and the density of sodium is about the same as water. Since hydrogen has about six times as much energy per pound as gasoline, this might be a feasible solution for energy storage. These developments, plus the growing cost of energy, have people looking again at OTEC.

A more recent development proposes a modification of the Fischer-Tropsch process for making liquid hydrocarbons. The traditional process uses carbon monoxide, steam and hydrogen, generally derived from coal combustion with limited oxygen. However a recent project by the Navy (Dorner, 2009) uses carbon dioxide and electricity (in part to generate hydrogen by electrolysis) instead. The interesting point is that the plan is to obtain the carbon dioxide from seawater, since CO_2 is 140 times as concentrated in surface seawater as in air.

Other Considerations

Deep water is laden with nutrients. In the tropics, the warm surface waters are lighter than the cold water and act as a cap to keep the nutrients in the deeps. This is why there is much less life in the tropical ocean than in coastal waters or near the poles. The tropical ocean is only fertile where there is an upwelling of cold water. One such upwelling is off the coast of Peru, where the Peru (or Humboldt) Current brings up nutrient laden waters. In this area, with lots of solar energy and nutrients, ocean fertility is about 1800 grams of carbon uptake per square meter per year, compared to only 100 grams typically. This creates a rich fishery, but most of the carbon eventually sinks to the deeps in the form of waste products and dead microorganisms. This process is nothing new; worldwide marine microorganisms currently sequester about forty billion metric tonnes of carbon per year. They are the major long term sink for carbon dioxide.

Lovelock and Rapley (*ibid.*) originally suggested using wave powered pumps to bring water up from the deeps, but OTEC inherently brings up prodigious amounts of deep water. In one design, a thousand cubic meters of water per second are required to produce 70 MW of net output power.

We can only make crude estimates of fertility enhancement and sequestration, but a guess is that an OTEC plant designed to optimize nutrification might produce 10,000 metric tonnes of carbon dioxide sequestration per year per MW. The recent challenge by billionaire Sir Richard Branson is to sequester one billion tonnes of carbon dioxide per year in order to halt global warming, so an aggressive OTEC program, hundreds of several hundred MW plants, might meet this.

In economic terms, (very) optimistic guesses at OTEC plant costs are in the range of millions of dollars per MW. Since a kilowatt-hour of electricity generated by coal produces about a kilogram of carbon dioxide, a carbon tax of one to two cents per kWh might cover much of the capital costs of an OTEC plant in carbon credits alone.

The actual effectiveness of OTEC in raising ocean fertility and thereby sequestering carbon still has to be verified, and there has to be a careful examination of other possible harmful environmental impacts – an old saying among engineers is "it seemed like a good idea at the time".

The most important issue is that the deep water already has substantial dissolved carbon dioxide, (much more than surface water) and so an OTEC plant may actually release more carbon than it sequesters. Some estimates done in the 80's suggest that OTEC plants will produce roughly half the carbon dioxide emissions of coal fired power plants. Most commonly it is believed that it will just speed up the existing cycle, sending down as much as it brings up with no net effect. This question has to be answered before OTEC is implemented. It may also be possible to optimize sequestration by being selective about the depths that water is drawn from, or possibly by adding other trace nutrients, especially those that enhance species that sequester carbon in shells. This is based on recent research by Karl and Letelier, (Karl, 2008) and recent tests at sea off Hawai'i. The key question is whether a "super Redfield ratio" diatom bloom can be generated. The Redfield ratio is the ratio of carbon to nitrogen to phosphorus (106 C : 16 N : 1 P) in average marine biomass and is generally considered to govern the potential uptake of carbon dioxide in the sea, and if an induced bloom of biomass maintains this ratio, the carbon will just be cycled back and forth from dissolved carbon dioxide to biomass. Since deep seawater is already at the Redfield ratio, there would be no net take-up. However, specific phytoplankton species at various stages of their lives can vary widely away from this ratio and Karl and Letelier's work suggest that a two stage process occurs with a second "super Redfield stage" occurring. This, however, depends on a number of aspects of the biology and chemistry of the sea water. It is also worth remarking that the concentrated carbon dioxide in the deep water might be seen as an improved resource for using OTEC energy to make fuels by the Dorner process.

An OTEC plant optimized for ocean fertility will also probably be different than one optimized to generate power, so any OTEC-based carbon scheme has to include transfer payments of some sort – it won't come for free. Finally, who owns the ocean thermal resource? Most plants will be in international waters, though these waters tend to be off the coasts of the developing world.

There might be other benefits: An old saying is "we aren't trying to solve world hunger." but we may have. Increased ocean fertility may enhance fisheries substantially. In addition, by using OTEC energy to make nitrogen fertilizers, we can improve agriculture in the developing world. OTEC fertilizer could be sold to developing countries at a subsidy in exchange for using the tropic oceans. Finally, there have been a number of suggestions, including one recently by Bill Gates, that cooling surface waters might reduce the intensity of hurricanes, though one has to be a bit concerned about geo-engineering to the level of modifying the weather.

MARINE BIOFUELS

One of the more exotic possibilities for ocean based energy is marine biofuels. In a sense this is hardly new – whale oil was the first high grade hydrocarbon and the petroleum industry can be credited with saving whales from extinction. Even now, oil from processed fish is burned aboard catcher processors to provide energy for processing. However, the most promising marine biofuel is giant kelp (*Macrocytis*), which can provide the same sort of cellulosic feedstock as agricultural waste and grasses. If efforts to develop cellulosic biofuels – "grassoline" - bear fruit, it might be worth considering kelp as a feed stock. The "Ocean Food and Energy Farm Project", also during the Carter administration (Wilson, 1977) proposed that kelp is principally limited by anchoring opportunities, so submerged semi-floating frames are all that is required to generate 200-400 tons of material per acre/year, with a potential of 200-400 MBtu per acre/year.

Another more exotic possibility is farming microalgae at sea. This where most of our fossil oil came from in the first place, and a naval architect might be able to suggest why: Algae need to float, and store energy, and one strategy is to make and store hydrocarbons – so the Bathyscaphe was invented at a microscopic scale hundreds of millions of years ago. A possible yield for algae species is 100,000 liters/hectare (vs. palm oil at 6000 liters/hectare or sunflower oil at 1000 liters/hectare). Some algae even make long chain hydrocarbons instead of lipids or triglycerides. *Botryococcus Braunii*, a species of blue-green denitrifying algae, makes up to 40% of its dry weight as straight chain partly unsaturated hydrocarbons. However, we should ask why ocean farming? Again the answer is the real estate required:

Replacing the 20 million barrels per day currently imported into the US would require half of Nebraska. Fresh water is also a limited resource but many algae of interest are salt water species. Finally, as noted above, seawater represents a much greater concentration of carbon dioxide than air, so providing a high CO_2 environment conducive to algae growth might be easier with seawater. The question is how this could be done, and is left as an opportunity for the reader.

CONSTRUCTION, INSTALLATION AND MAINTENANCE

Alternative energy systems have to be built, installed, supported and ultimately decommissioned and this is another area where the marine industry has considerable experience.

Most of the technology developed by ship building productivity improvement programs such as the National Shipbuilding Research Program will be readily applicable to building wind platforms, wave devices and OTEC plant ships. This technology ranges from specialized welding electrodes to “Lean” manufacturing guides. Renewable energy devices generally will be built in much longer production runs than ships, so many of these manufacturing technologies will probably provide even better benefits.

Composites also probably have a significant role in ocean alternative energy (Greene, 2008). Wind turbine blades have been made of increasingly advanced composites for decades, but nacelles, hub components and even towers might be made of composites to reduce weight and hence floating platform displacement. For wave and tide devices, the fact that composites don’t corrode may be an important issue, and at some point, reducing the carbon footprint of device construction will probably become important, and some composites may have an advantage there. Composites will also have a prominent role in OTEC – the cold water pipe generally has to be roughly neutrally buoyant, and only composites fulfill this need with the requisite strength. A current DOE/Lockheed project is testing continuously laminating the cold water pipe at sea and gradually extending it downwards as it is cast.

Installation represents an enormous cost. A 5 MW wind turbine nacelle is as much as 100 meters above the waterline and with the hub and blades weighs about 300 tons. The cost of a crane to lift this equipment is around $150,000 per day. Even if the turbine produces at full nameplate rating for 24 hours per day, the feed-in tariff revenue is only around $7,200 per day. This suggests that creativity in the installation process is valuable. Floating systems may have an advantage here in that they can be floated out. As an example, the offshore oil industry occasionally made use of special auxiliary buoyancy systems for oil platform installations, but infrequently, because platforms were generally one of a kind. This will not be the case for wind turbines, or hydrokinetic devices. Another useful oil patch technique was installation simulation, which allowed early design decisions to be made to minimize cost and risk. The authors would suggest that looking at past Offshore Technology Conference proceedings might be profitable.

Another point is that the current fleet of support craft for offshore construction is probably not well matched to some types of alternative energy systems. Wind turbine support, for example, probably requires higher lifts of lower weights than would be prevalent in the existing fleet, especially for maintenance. This latter need suggests some opportunities for small shipyards, especially those outside of the Gulf of Mexico.

PERMITTING

Permitting of ocean projects is especially problematic compared to shore side installations because no one actually owns even near shore ocean sites, much less sites beyond the three mile state limit or worse, on the high seas.

On the Outer Continental Shelf (OCS), in the region between (U.S.) state-controlled waters and the edge of the economic zone, the Minerals Management Service (MMS) has been given the lead responsibility for permitting, including granting lease, easements and rights of way. This is the same agency that handles offshore oil platforms, so there is some expertise in this area and some precedents for evaluating projects. The MMS has established a process for the permitting of production systems and a process for leases on test or site assessment facilities, under 30 CFR Part 250, 285 and 290, (MMS 2009) and Secretary Salazar has expressed his determination to move ahead quickly in this area as regards actual projects. The test leases may only produce limited commercial power, are not charged operational fees and run five years. Production leases are intended to run 30 years. One valuable provision allows applicants to pursue commercial leases while testing, without incurring an obligation to subsequently develop the site commercially. There are also provisions for revenue sharing with the shoreward state.

Other agencies are responsible under the aegis of MMS for specific aspects of permitting or are otherwise involved. The Federal Energy Regulatory Commission, (FERC) has the jurisdiction to issue licenses for generating electricity from hydrokinetic sources, but the issuance of a lease by MMS is a precondition of a license from FERC. FERC also has a test permitting process designed to facilitate early stage validation of concepts. The Coast Guard has signed a Memorandum of Agreement with MMS clarifying their responsibilities for such installations, primarily so they don’t become hazards to navigation and has promulgated Navigation and Inspection Circular 02-07. The Coast Guard has also worked with the IALA to extend international standards in this area (IALA 2008).

The MMS also explicitly does not have authority over OTEC plants. OTEC plants are regulated under the Ocean Thermal Energy Act of 1980, by NOAA and the Coast Guard, but it remains to be seen whether the extraction of a valuable resource from the high seas will engender efforts from other nations, especially those in latitudes where there is a substantial OTEC resource, to regulate or otherwise share revenues from OTEC plants.

However, in state waters, the situation is much more complex and varied, with numerous agencies involved and with various policies in each state and this may be an important reason why offshore wind in shallow water is not yet common in the U.S. In some cases, the states have been very proactive and supportive of the industry; New Jersey has provided grants for meteorological towers offshore to assess its wind resources, Rhode Island has begun an effort to zone its waters for renewable energy, and Delaware has granted permits to developers. In the long term, the situation as regards permitting will be stabilized, but represents a risk and a potential barrier to ocean energy. Those interested in ocean renewable energy should be proactive in contacting authorities to develop a reasonable and predictable permitting process.

ENVIRONMENTAL IMPACT

Like any other human activity, ocean alternative energy systems will have adverse environmental effects, some of which we probably don't yet know. One known effect is the possible disruption of sand transport along beaches. Sand transport is caused by waves beating on the shore, which cause a current along the beach (the undertow). Wave conversion devices could weaken this transport, resulting in sand building up into a tombolo, a sort of sand spit extending seawards. This could then starve other areas of beach and result in loss of shoreline or disruption of shore species. Strikes on fish and marine mammals from tidal current turbines may also be of concern. Ocean energy devices will also have to compete with other users of the ocean, most notably fishermen, who will probably be unable to trawl or possibly conduct other fisheries in wave, wind or current generation "farms".

CONCLUSIONS

Ocean energy represents a significant opportunity to address the growing need for energy and the problems associated with traditional fossil fuels. There is significant room for innovation and for more routine engineering development. Development is needed not only in energy harvesting and conversion devices themselves, but in associated systems such as mooring systems, power export cables, energy storage and conversion systems and in all of the infrastructure required to support the construction, installation, maintenance and decommissioning of these systems.

The authors would like to emphasize the importance of thinking quantitatively early in the concept development process. That is, we as the naval architecture/offshore engineering community should be quick to ask for, provide, or facilitate calculation of the cost per KWH. There will never be a shortage of whacky proposals from the fringe - and some of them might ultimately prove to be viable - but we will get to good solutions faster if we apply our real-world reality filters early and often.

Naval architects, marine engineers, shipbuilders and all of the rest of us associated with the traditional marine industry have unique experience, technology and skills to be the leaders of the ocean renewable marine industry, but we will have to make our abilities known.

We will also have to communicate with policy makers and the public so that they can understand the opportunities and limits of ocean energy. We can neither under- nor over-promise.

An important part of public outreach is communicating with young people, especially those that might find jobs in ocean alternative energy. SNAME supports a program of K-12 outreach, Seaperch, which has students building and using small underwater ROVs, but the excitement about alternative energy suggests that ocean energy oriented projects might be a similar opportunity, though perhaps on a smaller scale. One possibility would be to build small public demonstration devices at shore side parks or other public space with youth groups or museums like the Exploratorium (which has an ocean science component already).

Finally, as a lead technical society involved in the marine industry, SNAME has to reach out to all of the other stakeholders in ocean renewable energy to make sure our knowledge and expertise is available to them, so that they can profit by our experience. There isn't enough money or time available for ocean energy promoters to "re-invent the wheel".

The ad hoc panel on ocean renewable energy was founded in 2006 to address some of these concerns, and to a very limited extent, some progress has been made. Similar efforts have been made by the organizing committee of the Offshore Technical Conference and a number of excellent papers and special panel sessions on aspects of ocean energy have occurred since 2006 (including a special panel session on OTEC in 2009).

At least now many proponents of ocean renewable energy are aware of the existence of the offshore and marine industry and SNAME in particular, and have a vague idea of our potential contributions. We are now asking for more from you, especially your ideas and your time, to reach out, to attend the conferences of other organizations, to offer papers and to contact your legislators and the public. Please contact us. Thank you, in advance, for your time and interest.

The opinions expressed in this paper are those of the authors and do not necessarily reflect the opinions or official policy of the Coast Guard or the Department of Homeland Security.

ACKNOWLEDGEMENTS

There are many people who have been diligently working to promote, support and expand the field of ocean alternative energy, some since the early 70's. There is insufficient space here to acknowledge them individually, but we know who they are and we thank them for their long and often thankless efforts.

REFERENCES

Adeyeye, A., Barrett, J., Diamond, J., Goldman, L., Pendergrass, J., Schramm, D., *Estimating U.S. Government Subsidies to Energy Sources: 2002-2008*, Environmental Law Institute, Sept. 2009 http://www.elistore.org/Data/products/d19_07.pdf

Brady, J., "Could Energy Innovation Create a 'Green Bubble'?", May 1, 2009, National Public Radio, http://www.npr.org/templates/story/story.php?storyId=103631430

Baumann, P., Department of Geography, State University of New York, College at Oneonta, Oneonta, New York http://employees.oneonta.edu/baumanpr/geosat2/Shrinking_Bay/Shrinking_Bay.htm

Bedard, R., "Overview: EPRI Ocean Energy Program – The Possibilities in California", June, 2006, Electric Power Research Institute

Butterfield S., Musial W., Jonkman, J., Sclavounos P., "Engineering Challenges for Floating Offshore Wind Turbines", *2005 Copenhagen Offshore Wind Conference*, October, 2005

COMDTPUB P16700.4, "Guidance on the Coast Guard's Roles and Responsibilities for Offshore Renewable Energy Installations" U. S. Coast Guard, March 9 2007

DiPietro, J., Skolnik, E., "Analysis of the Sodium Hydride-based Hydrogen Storage System being developed by PowerBall Technologies, LLC", *Proceedings of the 200 DOE Hydrogen Program Review*, October, 2009, NREL/CP-570-28890

Dorner, R., Hardy, D., Williams, F., Willauer, H., "Catalytic CO_2 hydrogenation to feedstock chemicals for jet fuel synthesis", *ACS National Meeting*, Washington DC, August 2009

Dvorak, M, Mark Z. Jacobson, and Cristina L. Archer, "Development Potential for California's Offshore Wind Energy Resource", Stanford University, Atmosphere / Energy Program

Greene, E., "Composites for Renewable Energy", Obama-Biden Transition Website, December 2008, http://change.gov/open_government/entry/composites_for_renewable_energy/

Hogben, N., Lumb, F., *Ocean Wave Statistics*, Her Majesty's Stationary Office, London, 1967

IALA Recommendation O-139, "On the Marking of Man-Made Offshore Structures Edition 1", International Association of Marine Aids to Navigation and Lighthouse Authorities, December 2008

Janszen, E., "The Next Bubble: Priming the Market for Tomorrow's Big Crash", *Harper's Magazine*, February 2008: http://www.harpers.org/archive/2008/02/0081908

Jonkman, J. and Sclavounos, P. D. (2006) "Development of Fully Coupled Aeroelastic and Hydrodynamic Models for Offshore Wind Turbines", *AIAA Conference*, Reno, Nevada, January 2006.

Karl, D., Letelier, R., "Nitrogen fixation-enhanced carbon sequestration in low-nitrate, low-chlorophyll seascapes", *Marine Ecology Progress Series* 2008

Kopits, S., Westwood, A., "Offshore Wind, Time for a Market Takeoff?", *Renewable Energy World*, Sept. – Oct. 2009

LaBelle, R., "Alternative Energy on the Outer Continental Shelf", *Ocean Energy for New England Conference* Marine Renewable Energy Center, October 6, 2008

Lee, K., Sclavounos, P. D. and Wayman, E. N. (2005). Floating Wind Turbines. *20th Workshop on Water Waves and Floating Bodies* - Spitsbergen, Norway - May 29 to June 1, 2005

Lewis, T. "Technology Status & Development Wave Energy", *Global Marine Renewable Energy Conference*, April 2009

Lovelock, J., Rapley, C., "Ocean pipes could help the Earth to cure itself", *Nature*, September, 2007

Maugeri, L. "Squeezing More Oil from the Ground", *Scientific American*, October 2009

McCormick, M., *Ocean Wave Energy Conversion*, Dover, 2007 (originally Wiley, 1981) Dover Publications, Minola NY, ISBN-13:978-0-486-46245-5

Medical College of Wisconsin (2009, August 19). "Renewable Energies Will Benefit US Workers' Health, Expert Predicts." *ScienceDaily*

Mendonca, M., *Feed-in Tariffs - Accelerating the Deployment of Renewable Energy*, World Futures Council, April 2007, ISBN 9781844077885

Milne, J., *The Reality of Carbon Taxes in the 21st Century*, Jan. 2008, Vermont Journal of Environmental Law, Vermont Law School

MMS, *Guidelines for the Minerals Management Service*

Renewable Energy Framework, July 2009, Office of Offshore Alternative Energy Programs, Minerals Management Service, U.S. Department of the Interior

Morris, R., "Could Cap and Trade Cause Another Market Meltdown?", *Mother Jones*, June, 2009: http://www.motherjones.com/politics/2009/06/could-cap-and-trade-cause-another-market-meltdown

Musial, W., Butterfield, S., Ram, B. "Energy from Offshore Wind", *Offshore Technology Conference* Houston, Texas, May, 2006

Norhaus, W. A, *Question of Balance - Weighing the Options on Global Warming Policies*, Yale University Press, 2008, ISBN: 9780300137484

Naval Studies Board, *National Security Implications of Climate Change for U.S. Naval Forces: Letter Report*, National Research Council, 2010 http://www.nap.edu/catalog/12897.html

Raftery, M., Datla, R., "Key Engineering Issues for Economically Viable Ocean Wave Energy Conversion" *SNAME Annual Meeting*, 2009

Robinson, M., "Offshore Ocean Energy Technology Development", National Wind Technology Center, National Renewable Energy Laboratory NREL/PR-500-40461, October 2006

Robinson, M., Musial, W., "Offshore Wind Technology Overview", National Wind Technology Center, National Renewable Energy Laboratory NREL/PR-500-40462, October 2006

Roddier, D., Cermelli, C., Aubalt, A. / Weinstein, A. Windfloat: A Floating Foundation For Offshore Wind Turbines (Parts I-III, "Design Basis …", "Hydrodynamics…", "Structural …"), *OMAE2009*, June 2009

Sclavounos, P. D., "Floating Wind Turbines" http://www.ebcne.org/fileadmin/pres/Sclavounos.pdf

Sclavounos, P. D., Tracy, C. and Lee, S. "Floating Offshore Wind Turbines: Responses in a Seastate, Pareto Optimal Designs and Economic Assessment", Massachusetts Institute of Technology, 2007

Sclavounos, P. D. and Wayman, E. N. (MIT), Butterfield, S., Jonkman, J. and Musial, W. (NREL) (2006). Floating Wind Turbine Concepts, *European Wind Energy Association Conference (EWAC)*, Athens, Greece, 27 February - 2 March, 2006.

Simmons, M., *Twilight in the Desert*, Wiley, June 2005, ISBN-13: 978-0471738763

Sorensen, B., *Renewable Energy, 3rd Ed.*, Academic Press, July, 2004, ISBN-10: 0126561532

University of California, San Diego, Scripps Institution of Oceanography, "Biofuel Development Shifting From Soil To Sea, Specifically To Marine Algae" 2009, January 4, *ScienceDaily*

U.S., "Ocean Thermal Energy Conversion Research and Development" 42 USC Chapter 98

U.S. Department of Energy, *2008 Renewable Energy Data Book*, July 2009

U.S. Department of Energy, "Financial Assistance Funding Opportunity Announcement, Advanced Water Power", Announcement Number: DE-FOA-0000069, Golden Field Office, Golden CO, April 2009

U.S. Department of Energy, "Program Announcement To National Laboratories, Advanced Water Power" Announcement Number: DE-FOA-0000070, Golden Field Office, Golden CO, April 2009

U.S. Department of Energy, Office Of Energy Efficiency And Renewable Energy, *Proceedings of the Hydrokinetic and Wave Energy Technologies Technical and Environmental Issues Workshop*, October 26-28, 2005, Washington, D.C., http://hydropower.inl.gov/hydrokinetic&wave/

Withee, J. E. and Sclavounos, P. D. (2004). Fully Coupled Dynamic Analysis of a Floating Wind Turbine System. *8th World Renewable Energy Congress*, Denver Colorado

World Ocean Atlas, Ocean Climate Laboratory, National Oceanographic Data Center (U.S.), 2005

Wilson, H.A., "The Ocean Food and Energy Project", 2nd STAR Symposium, SNAME, 1977

Zambrano, T., MacCready, T., Kicenuk, T., Roddier, D., Cermelli, C., "Dynamic Modeling Of Deepwater Offshore Wind Turbine Structures In Gulf Of Mexico Storm Conditions", *OMAE2006*, ASME, June 2006

Zambrano, T., MacCready, T., Roddier, D., Cermelli, C., "Design And Installation Of A Tension Moored Wind Turbine", *OMAE2007*, ASME, June 2007

WEBLIOGRAPHY

2009 OTC Panel on OTEC Papers: http://www.otcnet.org/2009/pages/schedule/tech_thursPrint.html
Videos: http://www.otcnet.org/2009/pages/media.html

The Abell Foundation: www.abell.org

AWATEA (Hydrokinetic power in New Zealand): http://www.awatea.org.nz/

Atmocean (Ocean nutrification): http://www.atmocean.com/sequestration.htm

Blank, Rome LLC (Ocean energy regulatory law): http://www.blankrome.com/index.cfm?contentID=13&itemID=160

California offshore wind energy potential
http://www.stanford.edu/~dvorak/papers/dvorak-archer-jacobson-2009-california-offshore-wind-energy-potential.html

Carbon Dioxide and Climate: A Scientific Assessment Climate Research Board, NAS, 1979
http://www.nap.edu/catalog/12181.html

Environmental Entrepreneurship (E^2) Lab (at Stevens Institute of Technology):
http://www.stevens.edu/entrepreneurship/e2lab/

The Exploratorium: www.exploratorium.edu

FERC Test Permit Process:
http://www.ferc.gov/industries/hydropower/indus-act/hydrokinetics/energy-pilot.asp

FERC/MMS Production Permit Process:
http://www.ferc.gov/industries/hydropower/indus-act/hydrokinetics.asp

Global Marine Renewable Energy Conference:
http://globalmarinerenewable.com/

Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use
http://www.nap.edu/catalog.php?record_id=12794

Innocentive (a new approach to commercializing innovation): www.innocentive.com

International Energy Agency - Ocean Energy Systems:
http://www.iea-oceans.org/

MMS Permit Process:
http://www.mms.gov/offshore/RenewableEnergy/index.htm

Hydraulics and Maritime Research Centre, University College, Cork: http://hmrc.ucc.ie

The Limpet Device WaveCam:
http://www.wavegen.co.uk/what_we_offer_limpet_islay_wavecam.htm

Marine Innovation and Technology:
http://www.minifloat.com/

Marine Renewable Energy Center:
http://www.mrec.umassd.edu/

Marine Renewable Energy - State of the industry report – October 2009
http://www.bwea.com/pdf/marine/Marine_report_enteclogo.pdf

Matt Simmons (Oil Financier):
http://www.simmonsco-intl.com/research.aspx?Type=msspeeches
and his ocean energy institute in Maine:
http://www.oceanenergy.org/

MMS Ohmsett Test Facility:
http://www.ohmsett.com/

MMS Website for ocean energy:
www.mms.gov/offshore/alternativeenergy

National Shipbuilding Research Program:
http://www.nsrp.org

NREL Marine and Hydrokinetic Technology Database:
http://www1.eere.energy.gov/windandhydro/hydrokinetic/default.aspx

Ocean Energy Council:
http://www.oceanenergycouncil.com

Ocean Renewable Energy Coalition:
http://www.oceanrenewable.com/

Ocean Renewable Energy Group (Canada):
http://oreg.ca/index.html

Oregon Wave Energy Trust:
http://www.oregonwave.org/

Planet Mechanics,"Surf Power":
http://www1.natgeochannel.co.uk/explore/green/mechanics_prog.aspx?mediaType=video&ep=6

The Reality of Carbon Taxes in the 21st Century:
http://www.vermontlaw.edu/Documents/020309-carbonTaxPaper(0).pdf

Regional Greenhouse Gas Initiative:
http://www.rggi.org

Renewable Energy World (Website and print journals):
http://www.renewableenergyworld.com/rea/home

Salter's Duck:
http://www.mech.ed.ac.uk/research/wavepower/

Science Daily: http://www.sciencedaily.com/

Seaperch Program: http://www.seaperch.org/

SeaSolarPower (OTEC):
http://www.seasolarpower.com/

Sustainable Energy – Without the Hot Air
www.withouthotair.com

UNH Center for Ocean Renewable Energy:
http://www.unh.edu/core/

U.S. Department of Energy, Energy Efficiency and Renewable Energy: http://www.eere.energy.gov/

U.S. Coast Guard COMDTPUB P16700.4, - NVIC 02-07:
http://www.uscg.mil/hq/cg5/nvic/pdf/2007/NVIC02-07.pdf

Winning The Oil Endgame: www.oilendgame.com