September 15, 2005

IEEE POWER ENGINEERING SOCIETY
ENERGY DEVELOPMENT AND POWER GENERATION COMMITTEE

2005 PANEL SESSION HARNESSING THE UNTAPPED ENERGY POTENTIAL OF THE OCEANS: TIDAL, WAVE, CURRENTS AND OTEC

Peter Meisen and Tom Hammons

IEEE 2005 General Meeting, San Francisco Hilton Hotel, 12-16 June 2005
Wednesday June 15, Room 3:00 p.m.—6:00 p.m.

INTRODUCTION

Sponsored by: International Practices for Energy Development and Power Generation Subcommittee

Chairs: Peter Meisen, Global Energy Network Institute, San Diego, CA, USA.
E-mail: Peter@geni.org
Tom Hammons, University of Glasgow, Scotland, UK.
E-mail: T.Hammons@ieee.org

Track 2: Securing New Sources of Energy

On behalf of the Energy Development and Power Generation Committee, welcome to this Panel Session on Harnessing the Untapped Energy Potential of the Oceans: Tidal, Wave, Currents and OTEC.

Renewable energy sources from the oceans include offshore wind, wave energy, tidal energy, OTEC and underwater currents. Harvesting ocean energy is not a new concept, yet it has remained a marginal resource. Today there is serious interest in offshore technology in Europe, Asia and the United States.

Wind farm technology has moved offshore where the prevailing winds can be more consistent and out of sight. Offshore wind energy is the fastest growing sector in renewable energy. Capacity by 2010 is projected to grow to at least 2000 MW.

Areas of great tidal differences produce regular and predictable tidal currents of 5 knots or more, creating tremendous energy potentials. France has had a 240MW tidal power generating facility for 40 years. Projects harnessing tidal currents have shifted toward capturing tidal-driven coastal currents. A study of 106 possible locations in the EU countries for tidal turbines showed that such sites could generate power on the order of 50 TWh per year. Compared with the largest wind turbine operating or planned today (4.5MW), the power output as well as the size of a marine current turbine is extremely promising.

The first commercial-scale wave power facility turning wave energy into compressed air was established in Scotland. Some proposed schemes involve hinged pontoons with hydraulics, while others appear like floating pistons that rise and fall with the wave action. Several prototype demonstrations are planned in the next few years. Growth in this sector is anticipated to reach $100 million per annum by 2010.

The difference in temperature between the surface waters and the deeper ocean waters can produce significant thermal energy. The US DOE has been studying OTEC (Ocean Thermal Energy Conversion) in Hawaii for many years.

This session will focus on the potential for power production from the oceans, Tidal, Wave, Currents and OTEC.

The Panelists and Titles of their Presentations (and Invited Discussers) are**:**

1. Peter O'Donnell, Sr. Energy Specialist, Manager Generation Solar & Renewables Programs, SF Environment Organization, CA, USA. Ocean Wave and Tidal Power Generation Projects in San Francisco.
2. Omar Siddiqui, EPRIsolutions, CA, USA. and Roger Bedard, Manager, EPRI, CA, USA Feasibility Assesment of Offshore Wave and Tidal Current Power Production: A Collaborative Public/ Private Partnership
3. Andrew Mill, Managing Director European Marine Energy Centre, UK. Wave and Tidal Stream Energy Outlook from the UK (Invited Discussion)
4. Mirko Previsic, Electric Power Research Institute {EPRI}, Palo Alto, CA, USA. Wave Power Technologies
5. Anthony T Jones Senior Oceanographer, oceanUS consulting, San Francisco, CA, USA and Adam Westwood, Analyst, Douglas Westwood Associates, UK. Recent Progress in Offshore Renewable Energy Technology Development.

Each Panelist will speak for approximately 20 minutes. Each presentation will be discussed immediately following the respective presentation. There will be a further opportunity for discussion of the presentations following the final presentation.

The Panel Session has been organized by Peter Meisen (GENI, CA, USA) and Tom Hammons, (University of Glasgow, UK).

The Panel Session is moderated by Tom Hammons and Peter Meisen.

The first presentation is on Ocean Wave and Tidal Power Generation Projects in San Francisco. . It will be presented by Peter O'Donnell, Sr. Energy Specialist, Manager Generation Solar & Renewables Programs, SF Environment Organization, CA, USA.

San Francisco sits on a hilly peninsula with the Pacific Ocean and six miles of sandy beach along its western shore. The narrow Golden Gate passage stretches for almost three miles along its northern coast, leading into the deep water San Francisco Bay along its northern and eastern shore. These ocean waves and the Bay tides, combine to create two first-class renewable energy resources – tidal currents and offshore ocean waves. These are two distinctly different resources – tidal currents are driven primarily by the gravitational pull of the moon and are independent of sun, rain and other local weather conditions. Long rolling ocean waves are a condensed form of wind energy, blowing out of the northwest across the Pacific Ocean. How San Francisco is harvesting this Energy will be discussed.

Peter O'Donnell is Manager Generation Solar & Renewables Programs, SF Environment Organization, USA,

He graduated from the University of Florida in 1972 with a B.S. Journalism degree. He worked overseas in international advertising in South Africa and Japan for ten years. In California he founded and developed Software and Internet companies with venture capital support. At San Francisco's Department of the Environment, he manages aver, tidal, and urban wind renewable energy programs as well as marketing and outreach for a residential solar program. The Electric Power Research Institute (EPRI) first published his work on tidal power technologies in 2001. He has published more than 100 Magazine Articles in his career.

The second presentation is entitled: Feasibility Assessment of Offshore Wave and Tidal Current Power Production: A Collaborative Public/ Private Partnership . It has been prepared by Omar Siddiqui, EPRIsolutions, CA, USA. and Roger Bedard, Manager, EPRI, CA, USA. Omar Siddiqui will present it.

The Electric Power Research Institute (EPRI) and EPRIsolutions are conducting collaborative power production feasibility definition studies on offshore wave energy and tidal current energy on behalf of a number of public and private entities. The outcome of the offshore wave study, which began in 2004, is a compelling techno-economic case for investing in the research, development and demonstration (RD&D) of technology to convert the kinetic energy of ocean waves into electricity. The tidal current studies began in early 2005 and are currently at the site identification and device assessment stage). Techno-economic results for tidal plant designs at various sites are expected in late 2005. In the presentation, this will be introduced, described and discussed.

Omar Siddiqui is a Senior Associate at EPRIsolutions, a subsidiary of EPRI that provides application services based on EPRI R&D products and management consulting services to the energy industry. He has over 10 years of experience in the energy sector and provides expertise in electro technologies, financial analysis, energy efficiency, program design, and planning. Mr. Siddiqui is currently the project manager for both the EPRI-Global Offshore Wave- and Tidal Flow- Power Feasibility Assessments He also manages a variety of other projects for Global Energy Partners, with a focus on assessments of end-use electro technologies for electric utilities to advance beneficial electrification.

Omar Siddiqui holds a B.S. in Chemical Engineering from Stanford University and an M.B.A. from the Anderson School at U.C.L.A.

Roger Bedard has over thirty-five years of experience in developing and managing medium size ($500K - $10M) engineering development projects. He has successfully managed many renewable energy demonstration projects including solar thermal heating, solar thermal electric (both line and point focus) and solar photovoltaic combined electricity and process heat (line tracking PV system where PV cell coolant was used for process heat) projects. His renewable energy experience was gained in three different career positions over the past twenty-five years.

Roger Bedard holds a B.S. in Mechanical Engineering from the University of Rhode Island and a M.S. in Mechanical Engineering from the University of Southern California.

The third presentation is an invited discussion on Wave and Tidal Stream Energy Outlook from the UK and will be given by on Andrew Mill, Managing Director European Marine Energy Centre, UK.

The UK's heritage in marine energy conversion research began in the 1970s. Edinburgh developers Ocean Power Delivery have recently begun generating electricity at sea off the Orkney islands from their prototype 750kW Pelamis. It was the world's first far-shore wave device delivering network electricity. The UK's research and manufacturing base are at the forefront of the resurgence of interest in marine energy with a number of projects under way.

This presentation reviews the progress to date in the UK on development of devices, standards and test facilities. It describes the world-leading European Marine Energy Centre (EMEC) on Orkney. It is a purpose built, multi-berth, network-connected and instrumented wave energy test facility that can accommodate up to four separate full-scale devices each rated up to 2.4MW. It is currently embarking on a project to build a complimentary tidal test facility for full-scale devices.

This presentation will review the need for standards, what standards and codes are required, and how they may be developed. The UK has already started work in this area and is looking to develop a scheme for certification in the longer term. Andrew Mill will consider where the industry is to day and put forward a model for certification that will ensure that the industry sets the level of regulation while ensuring that the other stakeholders buy in. It will also look at the wind industry model for regulation and draw upon this to identify the needs of the marine industry. Finally, it will look to identify what stakeholders require from regulation and how the device developers can best meet that, test houses and other stakeholders working together.

Andrew Mill is the Managing Director of EMEC. He attended The University of Strathclyde where he was awarded a degree in Electrical Engineering and Electronic Science. He has held a number of posts in the energy industry including; Director and General Manger of NEI Peebles projects division, Chief Executive of Scotia Energy, and Business Development Director Southern Europe with British Energy. Before joining EMEC he was Operations Director at Vianet responsible for the implementation of a remote data collection system.

The fourth presentation is on Wave Power Technologies. . It will be made Mirko Previsic, Electric Power Research Institute {EPRI}, Palo Alto, CA, USA

The oceans contain a vast amount of mechanical energy in form of ocean waves and tides. The high density of oscillating water results in high energy densities, making it a favorable form of hydropower. The total U.S. available incident wave energy flux is about 2,300 TWh/yr. The DOE Energy Information Energy (EIA) estimates 2003 hydroelectric generation to be about 270 TWh, which is a little more than a tenth of the offshore wave energy flux into the U.S. The fact that good wave and tidal energy resources can be found in close proximity to population centers and technologies being developed to harness the resource have a low visual profile, makes this an attractive source of energy. Recent advances in offshore oil exploration technology and remote management of power generation systems have enabled significant progress in advancing technology development by simple technology transfer. A few systems have made it to full-scale prototype stage allowing experience to be gained from operational aspects, which is a critical aspect to develop economic models. However, despite enormous progress over the past 5 years, current and wave power conversion technologies are at an immature stage of development. A lack of accepted standards, a wide range of technical approaches and large uncertainties on performance and cost of these systems show this. Further RD&D and the creation of early adopter markets through government subsidies is required to move these technologies into a competitive market place.

Mirko Previsic has 10 years experience with the design, evaluation and optimization of offshore renewable power generation systems, resource assessments, feasibility studies and economic assessments. In recent years he has served as expert advisor to the Electric Power Research Institute, the California Energy Commission and other organizations on these emerging technologies. Mr. Previsic has written numerous studies on offshore renewable technologies and has a background in electrical engineering.

The penultimate presentation is on. Recent Progress in Offshore Renewable Energy Technology Development. It has been prepared by Anthony T Jones Senior Oceanographer, oceanUS consulting, San Francisco, CA, USA and Adam Westwood, Analyst, Douglas Westwood Associates, UK. Anthony T Jones Senior Oceanographer, oceanUS will present it.

International treaties related to climate control have triggered resurgence in development of renewable ocean energy technologies. Several demonstration projects in tidal power are scheduled to capture the tidal-generated coastal currents. Commercial-scale wave power stations exist and are delivering power to national grids. Offshore wind farms are delivering energy to shore. As government policies shift towards inclusion of renewable sources, the near shore ocean resources have tremendous potential. Worldwide investments in renewable energy technologies reveals that offshore wind energy is the fastest growing sectors. Strong growth in offshore wind power installations is anticipated over the next decade. In 2000, development of systems to capture wave energy reached a milestone with the commissioning of the first commercial-scale power facility in Scotland. Technical capabilities, both engineering and management, exist in the offshore sector to undertake the size of projects envisioned. Harnessing the untapped potential of ocean energy has commenced. In this presentation the progress to date and future plans and prospects will be evaluated and discussed.

Anthony Jones was born in California, USA and holds a doctorate in oceanography from the University of Hawaii.

His employment experience includes the U.S. Department of Energy Lawrence Berkeley Laboratory, the International Seabed Authority, and Oases International. His research interest is in coupling of marine renewable energy to seawater desalination to provide sustainable source of potable water.

Dr. Tony Jones is a senior oceanography with oceanUS consulting in San Francisco. He has been a consultant to various marine renewable energy developers including SeaVolt Technologies, a winner of the UK Carbon Trust's Marine Energy Challenge. Dr. Jones holds patents in salinity gradient power technology and is widely published in the field including a seminal paper on economic forecast for ocean energy over the next decade.

Adam Westwood manages DWL's World Offshore Wind, World Onshore Wind, and World Offshore Wave & Tidal project databases. He is author of The World Offshore Renewable Energy Report commissioned by the UK Department of Trade & Industry, and for Scottish Enterprise Renewable Energy Spends & Trends. Past research activity also includes offshore renewable energy studies for major international companies and work on renewable energy industry business prospects worldwide. Projects also include work for the DTI and investment trust 3i relating to financing of a wind turbine installation vessel. Published work also includes a number of papers and articles on renewables and he is a regular contributor to renewable energy trade journals.

PANEL SESSION SUMMARIES

1 OCEAN WAVE AND TIDAL POWER GENERATION PROJECTS IN SAN FRANCISCO (PAPER 05GM1060)

Peter O'Donnell, Sr. Energy Specialist, Manager Generation Solar & Renewables Programs, SF Environment Organization, CA, USA

1.0 Summary

San Francisco sits on a hilly peninsula with the Pacific Ocean and six miles of sandy beach along its western shore. The narrow Golden Gate passage stretches for almost three miles along its northern coast, leading into the deep water San Francisco Bay along its northern and eastern shore. These ocean waves and the Bay tides, pushed by the Sacramento River flowing down from the Sierra Nevada Mountains, combine to create two world-class renewable energy resources – tidal currents and offshore ocean waves. These are two distinctly different resources – tidal currents are driven primarily by the gravitational pull of the moon and are independent of sun, rain and other local weather conditions. Long rolling ocean waves are a condensed form of wind energy, blowing out of the northwest across the Pacific Ocean.

Location, location, location – it's the first rule of real estate. It's also the first rule for renewable energy projects – you have to go where the resource is accessible, with supporting infrastructure and grid access, and where a supportive community welcomes your project. Otherwise, shortsighted parochial interests reign and nothing gets done.

The citizens of San Francisco support renewable energy, having voted for the City to spend up to $100 million in bond financing for renewable projects. While no public money has yet been invested, San Francisco is preparing to launch two types of renewable energy projects in 2005 – a pilot demonstration for tidal power in May '05 and a first U.S. commercial installation for wave energy that is expected to be producing up to 750kW by 2007. Combined, both projects could then be expanded in prudent phases to provide a significant portion of San Francisco's current 840MW peak demand. More importantly, San Francisco would be modeling these technologies for environmentally safe implementation in coastal and riverine communities round the world.

Both ocean wave and tidal current renewable energy generation technologies are due to be revolutionized in the next ten years. These technologies should be ready for large-scale commercial implementation about the time that the North Sea natural gas reserves are depleted in the next ten years.

<u>Tidal Power</u>: The tidal current technology that San Francisco is considering has emerged from the physics lab at Imperial College in London, England, evolved over eight years by Dr. Geoff Rochester and Dr. John Hassard. The company, HydroVenturi, London, England, (www.HydroVenturi.com) has piloted its approach in a 150kW configuration in the Humber River, three hours north of London. The HydroVenturi value proposition -- no moving parts underwater – promises marginal if any impacts on plankton, fish, and marine creatures.

The HydroVenturi tidal power device comprised a cube of venture tubes or wings attached to the marine bottom on a rack safely sited 18m below the water surface and outside the navigation channel in the Golden Gate Passage. The tidal current flowing through the device is accelerated through the Venturi tubes to create a 2.5kg pressure drop, thus creating suction enough to pull air down to a storage tank integrated into the cube below the Venturi tubes. The compressed air is then pushed through a pipe to an on-shore air turbine to produce electricity.

The first phase of the San Francisco tidal project with HydroVenturi is planned for May '05, and will utilize a barge moored in the tidal flow from which several HydroVenturi tubes will be suspended to harvest tidal current energy. An air turbine on the barge will produce electricity as a proof of concept for skeptical environmentalists, state and federal agencies. With the technology demonstrated and made familiar, the permitting and environmental impact study process will be the next required steps, and which are anticipated to require two years to complete.

A one Megawatt HydroVenturi installation could be completed and grid connected by 2008, with expansion to be phased in 5-20 Megawatt increments. A single Megawatt HydroVenturi cube of Venturi wings (see illustration one) measures 23-meters across the bi-directional tidal glow, by 10-meters by 13-meters. The on-shore air turbines in this commercial phase may be housed in a secure facility near the Golden Gate Bridge. Several other tidal generation sites have been selected to serve the nearby communities of Marin County and Oakland.

Wave Power: Ocean Power Delivery, Edinburgh, Scotland, (www.OceanPD.com) manufactures the Pelamis wave power generation device, rated at 750kW. Its first commercial installation on the Orkney Islands grid above Scotland was completed September '03. This technical approach has evolved after almost ten years of scale model tank tests, pilots, and field trials. The original design was tailored for the North Sea wave regime. Suitability for the San Francisco wave resource requires that the device be expanded by 10m in length.

Wave power can be harvested by a variety of methods and devices, with several unique approaches nearing commercialization. San Francisco, however, can only explore technology already developed to a commercial stage, as public funds cannot be applied to RR&D projects. This said, almost all wave energy conversion devices take advantage of hydraulic pumps and turbines to generate power. The Pelamis approach was selected after an Offshore Wave Power Feasibility Study performed by EPRI and completed in December '04. As the EPRI report will be presented at the June '05 IEEE proceedings, this paper will emphasize tidal current issues, a topic which EPRI will begin assessment of in March '05.

The Pelamis device consists of a total of four cylindrical sections, which are connected together by three hydraulic power conversion modules, for seven sections in all. The total length of the device is 120m and device diameter is 4.6m. Each power conversion module comprises hour hydraulic rams (two heave, two sway); high-pressure accumulators for power smoothing storage; two variable displacement motors for power conversion; two 125kW generators revolving at speeds of 1500rpm; and an integrated transformer to send AC power to shore by a shielded cable. The power conversion modules are constructed and shipped from Scotland, while the interconnecting tubes are constructed locally of steel, and eventually can be made from marine-grade cement.

The Pelamis device, named after a sea goddess, is secured by a compliant slack moored anchoring system. The device is bright red in color, observable from one nautical mile away, and well marked for radar detection by passing ships. It is ballasted by sand to ride semi-submerged in the waves. See streaming video at www.OceanPD.com. The device will be sited in an area outside the shipping channel, and about six miles offshore from the San Francisco coastline. At a later date, a series of these devices can be installed to comprise a wave farm. By employing the Pelamis device, a generation capacity of 35 Megawatts per mile is anticipated, and additional device optimization is anticipated.

While renewable energy and power production is one goal of these projects, the City and County of San Francisco is equally interested in becoming a center of excellence for the implementation of these technologies to a world market. Local job creation and the establishment of a Green Business Park focusing on renewable energy technologies is another goal of the City.

In summary, San Francisco's interest in the HydroVenturi approach is due to the vaklue proposition of no moving parts underwater, compared to the underwater turbines of a LaRance River-type saltwater entranement, or a Blue Energy or Verdant Power (see www.VerdantPower.com) vertical or horizontal axis-type propeller installation. A technology with no moving parts underwater makes tidal power attractive to San Francisco's well-established environmental community. This approach is viewed as the most environmentally benign for the Bay Area's endangered salmon runs, delta smelt, anchovies, dolphins, whales, seals, sea lions, and benthic creatures, other fish species and marine mammals. For these reasons, San Francisco believes the time has come to harvest the City's tidal and ocean wave resources. Renewable energy development also creates jobs for the local community, at an anticipated rate of 10 jobs per Megawatt.

2.0 Harvesting San Francisco's Renewable Tidal Current Resource

The HydroVenturi approach has value in run of river applications in the Mississippi, Missouri, Ohio and other riverine communities. In the next decade, many new bridge constructions at significant current flow locations may well integrate renewable energy generation schemes. This technical advancement has the potential to make tidal current power production environmentally benign for endangered salmon runs, other fish and marine mammals as well.

Tidal current is in abundance in San Francisco's Golden Gate passage and at other Bay locations. Tidal current is generated by the gravitational pull of the moon, and to some extent the sun, on the Bay's surface, pushing some eight billion gallons of water up the Bay and pulling it back out to the Pacific Ocean in six-hour cycles.

More than 40% of California's fresh water eventually flows through the Golden Gate passage. This tidal current resource has been equated to a 240-mph-hurricane-force wind, yet it remains often overlooked. Experts consider San Francisco one of the top 10 locations for developing tidal power. For such reasons as municipal commitment to renewable energy production combined with strict environmental oversight, San Francisco may well be the best site in North America for a first commercial installation of "no-moving-parts" technology.

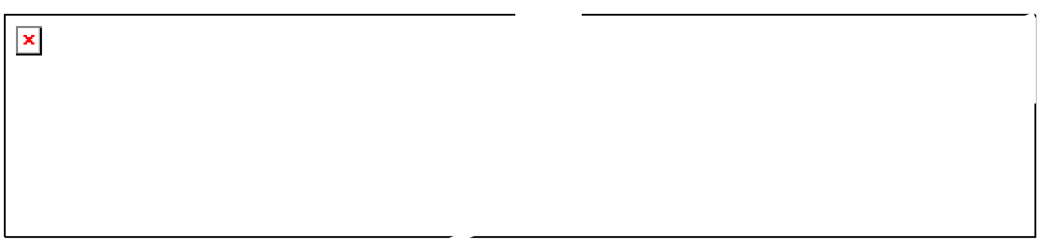


Illustration: copyright 2002, HydroVenturi, Inc. All rights reserved

a) Water enters the module
b) The flow is passed through the Venturi. This causes the water to accelerate and the pressure to drop.

c) Where the maximum pressure drop occurs, air or water is sucked from the surface through a system of pipes. The suction created in this circuit is sufficient to drive on-shore air turbines.

Regardless of the specific underwater construction, an on-shore tidal power facility would comprise a continuous control and monitoring station, office, maintenance area, interpretive center, shrouded air turbines, sub-station and a few miles of underground cable to deliver this power to the grid. The following is useful when comparing tidal power to other renewable energy resources:

Benefits:

- Tidal current is predictable and regular
- Tidal power is independent of weather conditions and fuel purchases
- Tidal power generation is not affected by climate change, lack of rain or snowmelt
- The San Francisco Bay tidal resource could exceed 2,500MW
- Environmental and physical impacts, and visual pollution, are expected to be small
- Tidal power is ideally placed to support hydrogen production and desalination

Concerns:

- Tidal power generation is in its infancy
- Tidal power generation per day has four slack tide periods of no power production for up to 90-minutes every 24-hours

Why San Francisco? Located at the tip of a peninsula, San Francisco has already experienced a series of electrical power outages in the winter of 2000. San Francisco is committed to shutting down its old, fossil-fuel burning power plants and to improve local and regional air quality. San Francisco has demonstrated the political will to support renewable energy with bond financing. San Francisco has the infrastructure to showcase tidal power beside the landmark Golden Gate Bridge to the many international visitors who will want to attend annual ocean energy symposiums, and perhaps purchase ocean energy systems. The global opportunity for ocean energy is huge and San Francisco can grow to become a center of technical expertise.

2.1 Tidal Power History

Tidal and river power are not new. River current has been used to drive mill wheels that grind grain in Britain and France from the 11th century. In the 1960s at LaRance, France commissioned the first commercial tidal barrage system using ten 240kW bulb turbines. The U.S. Congressional record notes that President John F. Kennedy, one month before his death, suggested an estuary in New England be evaluated for a barrage system.

In the early 1980s, the Canadian government's National Resource Council spent about six million dollars for tank tests and in-river trials of the Davis vertical-axis turbine system. See www.blueenergy.com. The European Commission has also sponsored research projects. In Canada, the design work and pilot trials emphasized vertical axis turbine designs rather than horizontal propeller designs. However, vertical axis turbines, while stronger, expend half the energy of their rotor arc working against the resource. This is not efficient. Equally, propeller designs have moving parts underwater, must be geared to adjust to address the oncoming current flow, and in a "farm" configuration could create a navigational hazard. Pilots and evaluations are continuing in the UK, Canada, and

Alaska's Yukon River. The trend is toward new designs that emphasize minimal civil works and a small ecological footprint.

2.2 Resource Potential

Conservatively, an average 3-knot tidal current flows through the Golden Gate passage and at other points in the Bay. While sailors speak of five and six knot currents at spring tides, it is better to under-promise and over-deliver in resource projections. Properly harnessed, the Bay's tidal power potential could exceed 2,500MW, about three times San Francisco's daily peak of 840MW. Worldwide, San Francisco's resource is a drop in the bucket.

The global ocean energy resource is estimated at about four million Megawatts. Properly harnessed, annual production could exceed about 15% of world electricity consumption anticipated in 2020. Many opportunistic sites have yet to be examined or surveyed. The World Bank has projected developing countries will need five million megawatts of new electrical capacity by 2040, and tidal current generation may be a well-suited opportunity.

2.3 The Advantages of Tidal Power

Predictability: As a renewable resource, tidal current flow is very predictable, to within 98% accuracy for decades. Tidal charts are accurate to within minutes, for years ahead. Tidal current is independent of prevailing weather conditions such as wind, fog, rain, and clouds that can impact other renewable generation forecasts. Solar generation is impacted by rain, clouds and fog. Wind turbines are impacted by calm weather, yet tidal cycles are as reliable as the rising of the moon. While solar and wind are valuable renewable resources, neither can be plotted with the predictability of tidal energy, especially n a five-year forward contracts market. Thus, reliable amounts of tidal power can be forecast with confidence. This predictability is critical to successful integration of renewable resources into the electrical grid. As an official from the California Dept. of Water Resources, familiar with power purchase contracts, said after reviewing a tidal power proposal: This expands our portfolio of renewable resources; we can always tell the 'peaker' plants when to turn on and turn off.

2.4 Generation cycle:

In San Francisco, high tide follows low tide approximately every six hours. Thus, a tidal power system will generate at "peak" for four periods of about 120 minutes per 24 hours, or up to eight hours per day. It will also generate some power at ramp up and ramp down to high and low tide, in all generating some power for 16-17 hours per day. There is also a midnight-to-six am cycle that might be better used for renewable hydrogen power generation, if combined with electrolysis and desalinization technologies, or simply with de-salinization for drinking water production.

Most solar and wind systems generate some power for about five to eight hours per day.

2.5 Benefits:

Tidal current power production has many of the traditional advantages of hydro projects: economies of scale; significant power production; accurate financial modeling; reasonable grid access; ability to leverage existing on-shore infrastructure and civil works. However, high-head hydroelectric dam schemes are no longer in favor due to urban and agricultural demand for freshwater resources; the environmental impacts when narrow gorges and their uplands are flooded; the availability of few remaining desirable sites in the continental US.

Except for barrage systems, all tidal power systems – Venturi pipes, fences, propeller towers, collared floating turbines -- have the following distinct advantages:

1) **Sustainability**: On average, a tidal resource generates some power for up to 17 hours/day, contributing to "peak" demand some 78% of the time on an annual average.
2) **Low-cost**: Tidal power may cost about U.S. two million dollars per Megawatt or about 5-cents/kWh, which makes it very competitive with renewable wind at 3-cents/kWh. While initial capital costs are higher than traditional power plants, there is no follow-on fuel purchase, no air pollution, and projects are engineered for a 50-year life.
3) **High density**: Water has a power density approximately 180 times greater than wind or air, thus allowing a 1MW tidal system to require approximately one-third the space of a comparable wind generation system.
4) **Environmentally benign:** Tidal power systems produce no pollution or greenhouse gas emissions. The potential for fish kill may be greater during construction than during operation. Canadian river tests showed no fish kill and no silt flow impediment. Large marine animals - harbor seals, dolphins, whales - instinctively shy away from the pull of underwater intakes and vibration. Salmon runs are projected to pass through the center of the Golden Gate channel. However, long-term monitoring of pilot sites is required.
5) **Predictability**: Cyclical tidal patterns allow power outputs to be predicted to within 2% far in advance, providing reliable base power for integration with electrical grids.
6) **Modular design:** Engineered underwater components of a tidal power project can be constructed off-site and brought to the site for installation. Projects can be expanded in a building block approach. Power production begins with the first unit installed; output increases incrementally as units are added.
7) **Low maintenance**: With no moving parts underwater, maintenance is minimized. However, the pilot project and extensions will be staffed at all times to monitor systems and watch for seaweed fowling, etc. Visual inspection and maintenance, if required, can be performed during four slack tide periods per day, and by remote underwater cameras.
8) **Local control:** Perhaps the next few decades will be a time in which we are able to build renewable electrical power options that make us no longer dependant on a centralized, fossil-fuel based grid. Sunny climates can harvest solar power; central plains states can harvest wind power; ocean, riverine and bay communities can harvest ocean wave and tidal current power. This will give our communities healthier choices, and long-term price stability and less dependency on oil imports, thus allowing communities to recycle their energy costs and boost their eco0nomies. Job creation, of course, is a factor with one metric suggesting tat each Megawatt of renewable energy can generate 10 jobs.

3.0 Permit Process and Site Selection

The proposed 1MW pilot project for tidal current power generation would be sited along the south side of San Francisco's Golden Gate passage, well out of the required 133-meter navigation channel. However, further site selection research is required. The Federal Energy Regulatory Commission (FERC) is the designated permitting agency, as they permit all hydro projects. Tidal power, however, is so new that some 14 other federal, state, regional and municipal agencies will take a keen interest with right to comment and review plans.

A partial list of commenting agencies, plus community-based environmental and land use groups, includes: National Ocean and Atmospheric Agency; Department of the Interior; Department of Energy; US Navy; US Coast Guard; Bar Pilots; California Bureau of Land Management for bay bottom submerged lands jurisdictional assessment and potential lease negotiation; various agencies on mitigation or remediation, if required; and other agencies commenting on their areas of expertise. Additionally, other identified commenting agencies are the California Energy Commission; California Public Utilities Commission; State Lands Bureau; State and Federal fish and game bureaus; California Department of Water Resources; California Water Quality Board. Permits will include: a County land use permit; a waterways encroachment permit; a tidal facility marine lighting permit from the US Coast Guard. A series of community outreach and education events will be required. As one project advisor has stated, even if no one objects the permit and environmental review process will take about two years. In other words, do not hold your breath. However, in San Francisco, early and repeated education, TV new stories, printed articles and outreach events have paved the way to community support. Even key environmental groups support these projects in principle, though they reserve the right to comment based on a final review of environmental impact studies.

3.1 Other Issues

Marine creature impacts: Protection of winter-run and spring-run Chinook salmon, an endangered species, is mandatory in California. Salmon may select to remain in the wider navigation channel and avoid a tidal power project. Intakes would be screened to protect larger species and avoid floating debris.

Air quality impacts: Since no combustion occurs in tidal power projects, there are no emissions. Every MWh of electricity generated by a tidal power project offsets the equivalent of 500 -1,000kg. carbon dioxide, up to seven kilograms of sulfur and nitrogen oxides and particulates, 0.1 kilogram of trace metals (e.g., mercury), and more than 200kg. of solid waste pollution.

Navigation channel impacts: A tidal generation project must be sited well clear of the charted navigation channel and pose no threat to shipping or recreation craft. It must be marked and lighted in accordance with US Coast Guard standards. It must be secured to the marine bottom, probably with screw-pilings and secured to a racking system, in a method that assures no threat to nearby bridges and civil works.

3.2 Site Selection

Survey requirements: Data requirements for site selection can require all of the following:
a) Class 1 pre-dredge hydrographic survey, though dredging may not be required in construction;

- b) side-scan and multi-beam sonar surveys
- dredge volume computations (if required)
- sub-bottom profiling and seismic surveys
- vibracoring and gravity coring
- dye and drogue studies
- monitoring of currents, waves and tides
- cross-sectional profiles
- 3-D charting
- bathymetric contour chart
- isopach (sediment thickness) maps
- site characterization and clearance
- geological mapping
- sand resource mapping
- other topographic surveys, geological surveys, hydrographic surveys and site strata analysis
- hydrographic survey for volumetric flow rates
- computer modeling & analysis

4.0 Pilot Installation

HydroVenturi is a spinout from Imperial College, University of London. Its patented system uses a series of open pipes that narrow to create a venturi effect and accelerate current flow. By accelerating flow through the choke (venturi), water pressure within the venturi becomes lower than ambient (a pressure drop creates a siphon effect). The resulting pressure gradient is then harnessed to drive a conventional pipeline turbine.

The technique concentrates the tidal energy in the current flow and accelerates a smaller quantity of water into another water pipe or secondary circuit. This circuit then drives a third circuit of air to drive on-shore air turbines and produce electrical power. The advantages of the approach are a lack of moving parts underwater, a step-up of the kinetic energy in the primary tidal flow, and the use of air turbines located on-shore for ease of maintenance.

HydroVenturi has built, tested and modeled a 0.6m aperture tidal power system in Grimsby, England.

Illustration 2: The HydroVenturi alpha test unit being sited in Grimsby, England, comprises a traditional Venturi tube with air storage tank integrated on the left.

The Grimsby site is operated as an R&D facility for improvements on system efficiencies. As third generation technology, HydroVenturi is not a barrage system that floods environmentally sensitive estuaries. It is not a submerged turbine or propeller system with moving parts or underwater generators. Many of the environmental and marine creature concerns are thus eliminated.

5.0 Managing Community Outreach

San Francisco's Department of the Environment has taken a proactive approach to educating community and environmental groups on tidal power technology. Several such groups were asked to submit written questions about the planned technical approach. Written replies were then drafted by HydroVenturi and presented in community outreach meetings for discussion by SF Environment. The questions and answers follow:

1. What are the dimensions of the Hydro Venturi system (modules) required for a 1 MW pilot project? What volume will they displace?

The answer depends on the site, particularly the currents and the tides. Let's assume a about 1 MW installed capacity, not 1 MW average output. For sites HydroVenturi has studied in the San Francisco Bay area, an "open-ocean" device is proposed, to differentiate it from the causeway insertions planned for sites in Iceland. The engineering assumption is that the current is high enough for a one-meter head to be generated across the Venturis by their resistance to the flow -- not a difficulty in the fast waters in San Francisco Bay. This head would be over a 50-foot distance in the direction of the water flow and would not be easily visible except with sensitive measuring devices.

In a nominal system, HydroVenturi need 25x16x25 cubic meters per installed MW in the open ocean. The 16-meter face is in the direction of flow, so this system presents 25x25-meters to the tidal stream. HydroVernturi continues to refine the components of its technology. The company is confident there are ways to reduce this size by as much as 20% in both 'transverse' dimensions, but this is not yet proven.

To first order, where the water has a good velocity profile in depth, the area is what counts. This water roughly corresponds to 1.5-m/per second velocity. If velocity accelerates to 2.5-m/per second, generation increases from one Megawatt to to 4.6 Megawatts. An increase to 3.5-m/per second (maximum velocity in the Bay), then the system could generate 12 Megawatts. Power output is approximately at the cube of the water speed. If the very fastest waters are chosen for siting, then the unit can be scaled down considerably in all dimensions; however this may not be the best approach strategically. For example, if the water averaged 3.5-m/per second, then the nominal one Megawatt 'cube' would be less than 10x10-meters in face area.

On-shore air turbines, air pipe connections, and a seated 'cube' of Venturi wings with underwater air storage comprise the components. The 'cube' will be sited on a rack secured by pilings into the marine bottom down to near bedrock. In the nominal case: Displacement is 341,000 cu. ft.

2. What material are the modules made of?

Concrete is much more expensive than steel. Steel is less durable than concrete. It is difficult to estimate the lifetime of deep-sea modules made of steel since this will depend on site-specific issues, most importantly pebble and gravel scouring. The Grimsby Venturi system, which has been running intermittently since last June 2002, gives a clue about the durability of steel in these conditions. For the pilot project, an all steel cube will be used to offer ease of construction and modification. It will sit on a steel plinth. The second system will almost certainly sit on a concrete plinth, and gravel will be diverted away from the system. Steel in German Battleships sunk in Scottish water has survived relatively intact over the last 90 years. Pilings will be made of steel and concrete, but do not have significant survivability issues.

3. *How deep must the system (the modules) be submerged under water?*

The effectiveness of the HydroVenturi system increases with depth for a given water speed. This is because when the Venturis entrain air, the air/water flow volume ratio is what limits the entrainment capacity. As air is a compressible fluid, it follows that the air mass flow rate, which is what counts when considering the drive to the turbine, increases with depth. However, generally the water is faster near the surface, and this compensates somewhat. In general, the cubes will work at any depth, but for safety, they will be submerged to a depth of at least 16-meters as dictated by the U.S. Coast Guard, in order to provide unhampered use of the water above by commercial vessels, recreational craft, and wind surfers. Siting may approach a navigation channel but will not impinge upon it, per U.S. Navy, Coast Guard, etc. requirements.

4. How will the modules be anchored to the Bay floor? How and where will power be transferred to the land and existing power grid?

Dr. John Hassard replies: If you work out the weight and the force exerted by a typical current, you will find that the weight wins every time. However, to avoid any chance of tidal surges making any movements, a plinth will be secured to the marine bottom, by placing concrete pilings through the mud layers to approach the bedrock. On these pilings will be placed a series of rails upon which to site the cubes. The cubes will have safety grills front and back, and be covered so that nothing may get into the Venturis. The interior gap between Venturi wings is anticipated to be 24-inches. Fingerlings, should they enter the system will pass through safely. Larger salmon up to 24-inches in diameter are assumed to pass through safely. Larger fishes, aquatic mammals and scuba divers will not be able to get into the system, and the perimeter guard grilles will be far enough away that the water speed will be low enough not to cause any scuba diver a difficulty. Detailed marine bottom profiling studies will be required. Best technologies developed in the North Sea are being reviewed.

Power, in the form of compressed air in a pipe, will be transferred to shore to sited air turbines within one mile of the cubes. The air, on intake and outflow, will drive air turbines to generate electricity. The site will require power processing and a sub-station, and cabling to a grid inter-tie.

.

5. What are the known and suspected impacts on tidal flows and sedimentation rates in the immediate vicinity and in other areas of the Bay?

HydroVenturi points out there will be no compression of water, simply an acceleration of water through the cube. Water speed before and after will be almost the same, though it must be noted that it is impossible to extract energy without taking something from the water speed. There may be minor sediment fall out on either sides of the cube in a bi-directional system, which is the planned design. There will be some sediment displacement with the siting of the piers. However, as water can flow through the artificial reef of the cubes, there will also be benefit to marine creatures. There may be some minor scouring of sediment, depending on height from cubes to marine bottom, or none.

Note, Dr. Ralph Cheng of the U.S. Geological Survey believes that there will be some site-specific impact on the tidal flow but no impact overall to Bay flow velocities. Certainly with several installations sited, the Bay will be monitored for sedimentation impacts. The system modularity makes environmental impact one of HydroVenturi's strongest suites. Given the cube-law of power from water moving at a given velocity, one can extract a great deal of power with a very small effect on water speed. .

6. *What is the anticipated amount of dredging necessary for the construction of the pilot project?*

The required dredging is simply to site the pilings for the racks. This is very site specific and will be negligible, since the sites where lots of dredging is required are less attractive. For example, in the case of the mud depths between Tiburon and Angle Island, we envisage a subsurface 'bridge' configuration spanning the deeper parts and the deepest mud, with pilings only inserted where there is rock near the surface. State law requires that these be over-engineered to protect in case of earthquake. Should there be a quake, the anticipated land shift is from south to north, along the line of the sited cubes.

7. What impact will the tidal power system will have on salmon runs? On plankton? Other species and their habitat?

According to Dr. Hassard, these impacts are expected to be negligible. In discussions with several marine monitoring agencies, it is assumed that most salmon will pass above the artificial reef of the cubes. Going upstream, they are driven to do their business; going downstream they are hungry and seeking open water and bait. Smaller salmon can go through the system with, we believe, not noticing the system (they momentarily speed up, but are forced away from the steel sides by the secondary circuit water entering the primary circuit where they are swimming.) Larger salmon cannot enter.

Zooplankton and phytoplankton are assumed to be able to pass through the cubes safety. In the water column, these creatures tend to be near surface in the undisturbed top 16-meters above the Venturi cube.

Porpoise and seals will be curious and certainly inspect the artificial reef. Whales, should they enter the Bay, can pass by and will be screened from passing through the system, as will anything larger than about 4-6 inches. Some creatures may enter the system and be accelerated out when the tide starts to run strong. Crabs, etc, may choose to live under the cubes. Construction will include underwater cameras in order to observe these phenomena. Scuba diver inspection is planned at slack tide, which happens four times per 24-hour cycle. HydroVenturi will ensure a failsafe system to avoid any chance of human injury.

HydroVenturi is committed to Bay area job creation and project construction in San Francisco, possibly at the City's new proposed Green Business Park in the Bayview

Hunter's Pont area. To meet City mandates, a public bid process is anticipated in order to construct the project, and HydroVenturi is expected to partner with a U.S.-based marine construction company in order to better manage this process and associated requirements, should they be the selected technology vendor. As an open and public process, however, San Francisco remains willing to discuss and review technical approaches that are supported by independent third party engineering assessments and which pass the "no moving parts underwater" environmental criteria. In summary, the project must make reliable, renewable electricity at something below 12-cents per kWh; the project may not make *sushi*.

REFERENCES

[1] "A Major Source of Energy from the World's Oceans," IECEC-97 Intersociety Energy Conversion Engineering Conference, 1997, Barry V. Davis

[2] Evaluation of Nova Energy Ltd.'s Hydro Turbine for (Canadian) Ministry of Employment and Investment by N.H. Halvorson Consultants Ltd.

[3] Renewable Energy: Power for a sustainable Future; Technology Update: (2001) Tidal Current Power Update & Wave Power Update, Oxford University Press

[4] Interview, Martin Burger, CEO, Blue Energy Canada, Inc.

[5] Interview, Dr. Steven Allison, CEO, Clean Current Canada Inc.

[6] Interview, Rich Ferguson, PhD, Director of Research, Center for Energy Efficiency & Renewable Technologies, Sacramento, CA.

[7] Interview, Bob Lynette, renewable wind generation consultant; former COO FloWind

[8] Interview, Robert Harmon, VP Renewable Energy Programs, Bonneville Environmental Foundation.

[9] Interview, Richard M. Rhoads, P.E., Moffatt & Nichol Engineers, Walnut Creek, CA.

[10] Interview, John P. Christensen, P.E., Christensen Associates Inc., Water Resources & Hydropower Consulting Services, San Rafael, CA.

[11] Renewables; Is the Tide Turning for Marine Current Turbines?, (June 30, 2001, Modern Power System, Peter Fraenkel, Marine Current Turbines Ltd, London, UK.

[12] Hydroelectric Power Without a Dam on the Yukon River, (March 2000) Alaska Power & Telegraph newsletter.

[13] San Francisco LAFCO Hearings on Renewables, Wave & Tidal Power (2003-2004) Chaired by Supervisor Matt Gonzalez

[14] Final Summary Report: Offshore Wave Power Feasibility Demonstration Project, (2005) Roger Bedard, (E2I EPRI Global WP009 – US).

[15] System Level Design, Performance and Costs for San Francisco Pelamis Offshore Wave Power Plant, (2004) Mirko Previsic (E2I EPRI Global – 006A – SF)

[16] Offshore Wave Power in the US: Environmental Issues, (2004) George Hagerman (E2I Global EPRI – 007 – US)

[17] Wave Power in the US: Permitting and Jurisdictional Issues, (2004) Bonnie Ram (E2I Global EPRI DOE NREL – 008 – US)

Peter O'Donnell, Sr. Energy Specialist, Manager Generation Solar & Renewables Programs, SF Environment Organization, USA, peter.o'donnell@sfgov.org , (415) 355-3715

O'Donnell grew up in a beach community across the street from the Gulf of exico on the west coast of Florida. He is a world-class scuba diver and underwater photographer. He graduated from the University of Florida in 1972 with a B.S. Journalism degree. He worked overseas in international advertising in South Africa and Japan for ten years. In California he has founded and developed Software and Internet companies with venture capital support. At San Francisco's Department of the Environment, he manages aver, tidal, and urban wind renewable energy programs as well as marketing and outreach for a residential solar program.

The Electric Power Research Institute (EPRI) first published his work on tidal power technologies in 2001. He has published more than 100 Magazine Articles in his career. O'Donnell managed an eight million dollar lighting electro fit program that served more than 4,000 disadvantaged small businesses in San Francisco, saving each about $600 per year, reducing consumption by MWs, and his municipal program was the first to win an Energy Star award from the U.S. Environmental Protection Agency.

2. FEASIBILITY ASSESSMENT OF OFFSHORE WAVE AND TIDAL CURRENT POWER PRODUCTION: A COLLABORATIVE PUBLIC/ PRIVATE PARTNERSHIP (PAPER 05GM0538)

Omar Siddiqui, EPRIsolutions, CA, USA
Roger Bedard, Manager, EPRI, CA, UCA–

Abstract**—**The Electric Power Research Institute (EPRI) and EPRIsolutions are conducting collaborative power production feasibility definition studies on offshore wave energy and tidal current energy on behalf of a number of public and private entities. The outcome of the offshore wave study, which began in 2004, is a compelling techno-economic case for investing in the research, development and demonstration (RD&D) of technology to convert the kinetic energy of ocean waves into electricity. The tidal current studies began in early 2005 and are currently at the site identification and device assessment stage (steps a and b below). Techno-economic results for tidal plant designs at various sites are expected in late 2005.

Index Terms—Marine technology, Waves, Tidal power generation, Power generation economics.

Introduction

The elements of the EPRI wave and tidal current energy feasibility study are: a) Identify and characterize potential sites for assembling and deploying a power plant and for connecting the plant to the electric grid; b) Identify and assess wave energy conversion (WEC) devices; c) Conduct a conceptual design of a demonstration- and commercial-scale offshore wave power plant and, based on performance and cost estimates, assess the techno-economic viability of the wave energy source and the energy conversion technology; and d) Identify and assess the environmental and regulatory issues associated with implementing the technology.

The natural power of the ocean has inspired awe since the dawn of mankind. Mariners and others who deal with the forces of the sea have learned to understand the potentially destructive powers of ocean waves as well as the regularity and predictability of the tides. Ocean waves and tides convey vast amounts of kinetic energy, derived from the winds and gravitational pull of the sun-earth-moon system. Even though early civilizations developed devices to convert waves and tides into mechanical energy, the technology to efficiently, reliably, and cost-effectively convert ocean waves and tidal flow into electrical energy is still in its early stages.

Two characteristics of waves and tides important to the generation and dispatch of electricity from wave energy conversion devices are its variability and predictability. While the ocean is never totally calm, wave power is more continuous than the winds that generate it. The average power during the winter may be six times that obtained during the summer, however, power values may vary by a factor of a hundred with the random occurrences of storms. Therefore, the power of waves is highly variable. The predictability of wave energy is on the order of a few days. The waves resulting, for example, from storms that occur off the coast of Japan, will take that long to reach the northwest cost of the United States. The power from tidal currents, on the other hand, typically varies according to a diurnal cycle. The major benefit of tidal power is its high predictability for a given site years in advance, provided there is a thorough knowledge of the site. A drawback of tidal power is its low capacity factor, and that its peak availability misses peak demand times because of the 12.5-hour cycle of the tides.

Ocean waves are generated by the winds that result from uneven heating around the globe. Waves are formed by winds blowing over the water surface, which make the water particles adopt circular motions as depicted in Figure 1. This motion carries kinetic energy, the amount of which is determined by the speed and duration of the wind, the length of sea it blows over, the water depth, sea bed conditions and also interactions with the tides. Waves occur only in the volume of water closest to the water surface, whereas in tides, the entire water body moves, from the surface to the seabed.

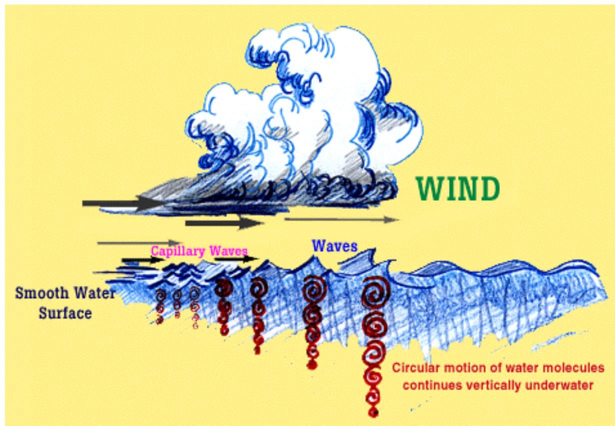


Figure 1. Wave Generating Forces based on Wind-Water Interaction

The tides are generated by the rotation of the earth within the gravitational fields of the moon and sun. The relative motion of these bodies causes the surface on the oceans to be raised and lowered periodically, as illustrated in Figure 2.

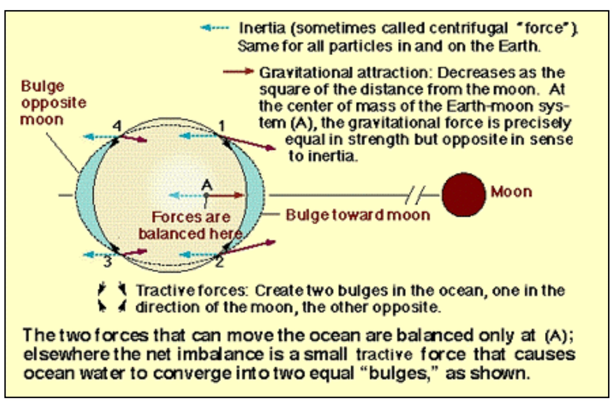


Figure 2. Tide-Generating Forces Based on Earth-Moon Interactions.

In deep water, the wave power spatial flux (in kW/m of wave front crest) is given by significant wave height (H_s in m) and the peak wave period (T_p in sec). Based on these two parameters, the incident wave power (J in kilowatts per meter of wave crest length, or kW/m) associated with each sea state record is estimated by the following equation:

$$J = 0.42 \times (H_s)^2 \times T_p$$

It is significant to note that wave power varies with the square of wave height – that is, a wave whose height is doubled generates four times as much power.

The power of a tidal current is given by the following equation:

$$P_{water} = \frac{1}{2} \,\Box\, A\, V^3 \quad \text{(Watts)}$$

Where A is the cross- sectional area of flow intercepted by the turbine device (in square meters), □ is the water density (in kilograms per cubic meter) and V is current velocity speed (meters per second). The current velocity V varies in a precisely predictable manner as an additive function of period of the different sinusoidal tidal components.

Since the tidal flow energy study is still in process at the time of this paper, the techno-economic results are not available. Therefore, the focus of this paper will be on the results of the wave energy feasibility definition study of 2004 and the presentation in June 2005 will include recently available tidal current site identification and device assessment results.

Wave Project RESULTS

A U.S. Wave Energy Resources

An ideal site to deploy, operate and maintain an offshore wave energy power plant must have many attributes. First and foremost is a sufficient native energy and energy spectra potential.[1] The U.S. regional wave regimes and the total annual incident wave energy for each of these regimes are shown in Figure 3. The total U.S. available incident wave energy flux is about 2,300 TWh/yr. The DOE Energy Information Energy (EIA) estimates 2003 hydroelectric generation to be about 270 TWh which is a little more than a tenth of the yearly offshore wave energy flux into the U.S. Therefore, wave energy is a significant resource.

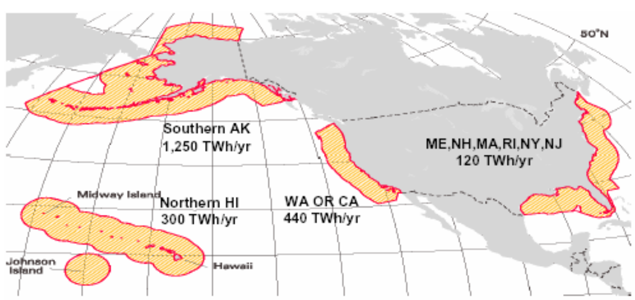


Figure 3. U.S. Energy Resources.

B. Feasibility Definition Study Sites

Site attributes characterized by the Project Team included offshore bathymetry[2] and seafloor surface geology, robustness of the coastal utility grid, regional maritime infrastructure for both fabrication and maintenance, conflicts with competing uses of sea space and existence of other unique characteristics that might minimize project

[1] Energy as function of wave height and wave period or frequency

development costs (e.g., existing ocean outfall easements for routing power cable and shore crossing).

Table 1 identifies the site selected in each of the five states that participated in the study, and also provides a few key characteristics of each selected site.

TABLE I

ESTIMATED PERFORMANCE OF PILOT DEMONSTRATION PLANTS

	HI	OR	CA	Mass	Maine
County	Oahu	Douglas	SF	Cape Cod	Cumber -land
Grid I/C	Wai-manal o Beach	Gardner	Wastew ater Plant	Well Fleet	Old Orchard Beach S/S
Average Annual J (kW/m)	15.2	21.2	11.2$^{(1)}$	13.8	4.9
Depth (m)	60	60	30	60	60
Distance from Shore	2	3.5	13	9	9
Cable Landing	Makai Pier	IPP out flow pipe	Water out flow	Dir Drill	Dir Drill

(1) Sited within the marine sanctuary exclusionary zone

C. Feasibility Study - WEC Devices

Twelve companies responded to our request for information. An initial screening considered two key issues 1) technology readiness (i.e. readiness of device for demonstration in the 2006 time period) and 2) survivability in adverse conditions (i.e. sufficiency of technical information provided by the device manufacturer to prove the survivability in storm conditions). The eight devices that passed the initial screening criteria are shown in Table 2.

TABLE 2

ESTIMATED PERFORMANCE OF PILOT DEMONSTRATION PLANTS

	Len	Wi	Power	Type	Ratin

[2] Bathymetry is the depth of the seafloor below mean water height (i.e., the inverse of a topographic map)

	(m)	d (m)	(kW)(1)		g
Ocean Power Delivery	120	4.6	153	Floating Attentuator	1
Energetech	25	35	259	OWC - Bottom Terminator	2
Wave Dragon	150	260	1369	Floating Overtopping	2
Wave Swing	9.5	9.5	351	Bottom Point Absorber	2
WaveBob	16	15	131	Floating Point Absorber	3
AquaEnergy	6	6	17	Floating Point Absorber	3
OreCON	32	32	532	Floating OWC	3
Ind Natural Resources Inc	5.4	5.4	112	Bottom Point Absorber	3

(1) Based on Oregon average annual wave energy resource

These eight devices were then assessed with the objective of determining any critical issues and recommending RD&D needed to achieve technological readiness for an at sea demonstration. As a result of this assessment, the eight devices were grouped into one of three levels of development categories:

- Level 1 – Development complete and full-scale testing in the ocean underway
- Level 2 – Development near complete. Only deployment, recovery and mooring issues are yet to be validated. There are funded plans for full-scale at sea testing.
- Level 3 – Most critical R&D issues are resolved. Additional laboratory and sub-scale testing, simulations and systems integration work is needed prior to finalization of the full-scale design. There are no funded plans for full-scale at sea testing.

At the time of our analysis (March 2004), only one WEC device manufacturer had attained a Level 1 technology readiness status – Ocean Power Delivery with its Pelamis device. At the time of this paper (January 2005) there are an additional four WEC device manufacturers that are close to reaching that status: TeamWorks of the Netherlands with its Wave Swing, Energetechs of Australia with its oscillating water column (OWC), Wave Dragon of Denmark with its overtopping device, and Ocean Power Technology of the U.S. with a floating buoy.

D. Demonstration-Scale Plant Design – Oregon Example

Demonstration-scale (as well as commercial-scale) designs were based on the Ocean Power Delivery (OPD) Pemamis WEC device for the five sites listed in Table 1. The Pelamis WEC device consists of four cylindrical steel sections, which are connected by three hydraulic power conversion modules (PCM). Total length of the device is 120m and device diameter is 4.6m. Figure 4 shows the device being tested off the Scottish coast.

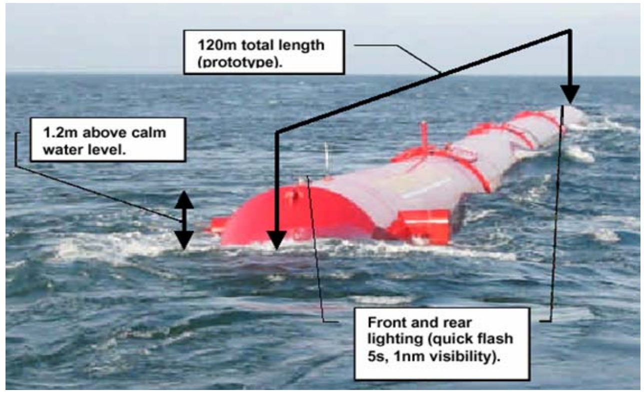


Figure 4. OPD Pelamis WEC Device.

A second San Francisco, CA design based on the Energetech OWC WEC device depicted in Figure 5 was also conducted.

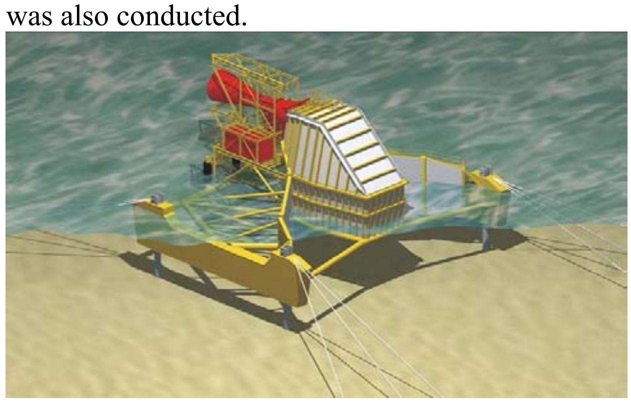


Figure 5. Energetech WEC Device.

Figure 6 shows the electrical interconnection of the demonstration plant for the Oregon site. A single floating Pelamis device is moored at a water depth of 50m – 60m. An umbilical riser cable connects the Pelamis to a junction box on the ocean floor. From this junction box, a double-armored 3-phase cable is buried into soft sediments along a 3-km route leading to the outfall of the effluent pipe, which is 1 km offshore. The cable is then routed through the 5 km effluent pipe to the International Paper Facility, which is about 4 km inland. An additional cable section connects to the Gardiner substation located next to the property of the International Paper facility.

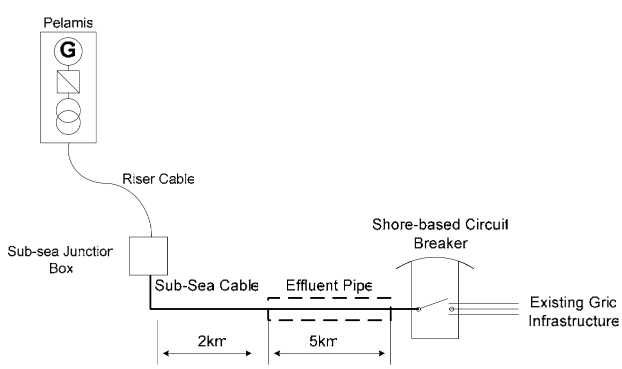


Figure 6. Electrical Interconnection of Demo-Plant – Oregon Example.

The estimated performance of the single unit demonstration plant at each of the five sites is shown in the following table.

TABLE 3
ESTIMATED PERFORMANCE OF PELAMIS PILOT DEMONSTRATION PLANTS

	HI	OR	CA [1]	Mass	Maine
Device Rated Capacity (kW)	750	750	750	750	750
Annual Energy Absorbed (MWh/yr)	1,989	1,472	1,229	1,268	426
Annual Energy Produced (MWh/yr)	1,663	1,001	835	964	290
Average Electrical Power (kW)	180	114	95	98	33
Number of Homes Powered by Plant	180	114	95	98	33

(1) Energetech site numbers: 1000 kW, 1643 MWh/yr, 1264 MWh/yr, and 144 kW respectively

E. Commercial-Scale Plant Design – Oregon Example

As shown in Figure 7, the commercial system uses a total of 4 clusters, each one containing 45 Pelamis units (i.e., 180 total Pelamis WEC devices), connected to sub-sea cables. Each cluster consists of 3 rows with 15 devices per row. The other state designs are organized in a similar manner with 4 clusters. The number of devices per cluster varies such that each plant produces an annual energy output of 300,000 MWh/yr. The 4 sub-sea cables connect the 4 clusters to shore as shown in Figure 6. The electrical interconnection of the devices is accomplished with flexible jumper cables, connecting the units in mid-water. The introduction of 4 independent sub-sea cables and the interconnection on the surface will provide some redundancy in the wave farm arrangement.

The 4 clusters are each 2.25 km long and 1.8 km wide, covering an ocean stretch of roughly 9 km. The 4 arrays and their safety area occupy roughly 16 square kilometers. Further device stacking of up to 4 rows might be possible reducing the array length, but is not considered in this design since subsequent rows of devices will likely see a diminished wave energy resource and therefore yield a lower output.

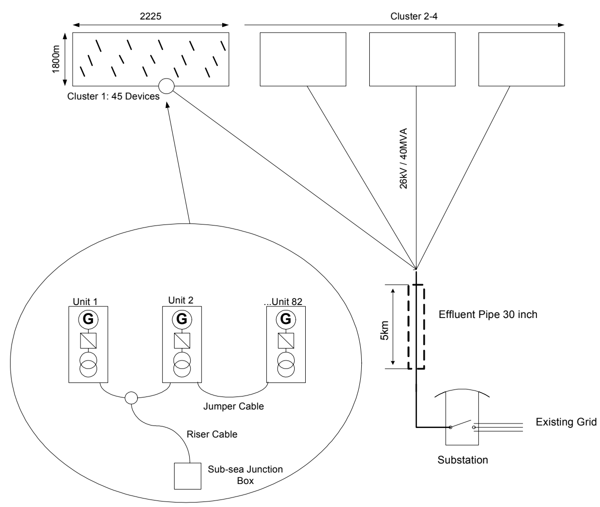


Figure 7. Electrical Interconnection of Demo-Plant – Oregon Example.

The estimated performance of the commercial-scale plant at each of the five sites is shown in the following table.

TABLE 4
ESTIMATED PERFORMANCE OF PELAMIS COMMERCIAL PLANTS

	HI	OR	CA	Mass	Maine
Device Rated Capacity (kW)	500	500	500	500	500
Annual Energy Absorbed (MWh/yr)	1,989	1,997	1,683	1,738	584
Annual Energy Produced (MWh/yr)	1,663	1,669	1,407	1,453	488
Average Electrical Power at Busbar (kW)	191	191	161	166	56
Number of OPD Pelamis Units Needed for 300,000 MWh/yr	180	180	213	206	615
Number of Homes Powered by Plant	34,000	34,000	34,000	34,000	34,000

(1) Energetech SF site numbers are 1000, 2714, 1973, 225, 152 and 225

The device rated capacity has been derated from 750 kW in the demonstration plant to 500 kW for the commercial plant. The performance assessment of the demonstration plants shows that the PCMs are overrated and reducing the rated power to 500kW per device would yield a significant cost reduction and only a relatively small decrease in annual output (attributed to the fact that the U.S. sites have a lower energy level then UK sites for which the device was originally developed).

F. Learning Curves and Economics

The costs and cost of electricity shown in the previous section are for the *first* commercial scale wave plant. It is an established fact that learning through production experience reduces costs – a phenomenon that follows a logarithmic relationship such that for every doubling of the cumulative production volume, there is a specific percentage drop in production costs. The specific percentage used in this study was 82%, which is consistent with documented experience in the wind energy, photovoltaic, shipbuilding, and offshore oil and gas industries.

The industry-documented historical wind energy learning curve is shown as the top line in Figure 8 (Reference 16). The cost of electricity is about 4 cents/kWh in 2004 U.S. dollars based on 40,000 MW of worldwide installed capacity and a good wind site. The lower and higher bound cost estimates of wave energy are also shown in Figure 8. The 82% learning curve is applied to the wave power plant installed cost but not to the operation and maintenance part of the cost of electricity (hence the reason that the three lines are not parallel).

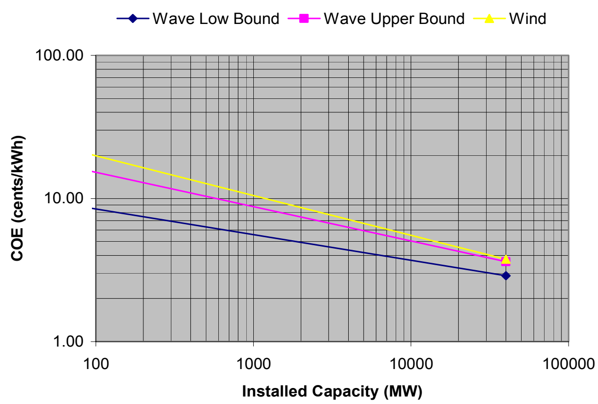


Figure.8. Electrical Interconnection of Demo-Plant – Oregon Example.

Figure 8 shows that the cost of wave-generated electricity is less than wind-generated electricity at any equal cumulative production volume under all cost estimating assumptions for the wave plant. The lower capital cost of a wave machine (compared to a wind machine) more than compensates for the higher O&M cost for the remotely located offshore wave machine. A challenge to the wave energy industry is to drive down O&M costs to offer even more economic favorability and to delay the crossover point shown at greater than 40,000 MW.

G. Conclusions

The techno-economic forecast made by the Project Team is that wave energy will first become commercially competitive with the current 40,000 MW installed land-based wind technology at a cumulative production volume of 15,000 or less MW in Hawaii and northern California, about 20,000 MW in Oregon and about 40, 000 MW in Massachusetts. This forecast was made on the basis of a 300,000 MWh/yr (nominal 90 MW at 38% capacity factor) Pelamis WEC commercial plant design and application of technology learning curves. Maine was the only state in our study whose wave climate was such that wave energy may never be able to economically compete with a good wind energy site.

In addition to economics, there are other compelling arguments for investing in offshore wave energy technology. First, with proper siting, converting ocean wave energy to electricity is believed to be one of the most environmentally benign ways to generate electricity. Second, offshore wave energy offers a way to minimize the ‘Not In My Backyard’ (NIMBY) issues that plague many energy infrastructure projects, from nuclear to coal and to wind generation. Because these devices have a very low profile and are located at a distance from the shore, they are generally not visible. Third, because wave energy is more predictable than solar and wind energy, it offers a better possibility than either solar or wind of being dispatch able and earning a capacity payment.

A characteristic of wave energy that suggests that it may be one of the lowest cost renewable energy sources is its high power density. Processes in the ocean concentrate solar and wind energy into ocean waves making it easier and cheaper to harvest. Solar and wind energy sources are much more diffuse, by comparison.

Lastly, since a diversity of energy sources is the bedrock of a robust electricity system, to overlook wave energy is inconsistent with our national needs and goals. Wave energy is an energy source that is too important to overlook.

H. Recommendations

In order to accelerate the growth and development of an ocean energy industry in the United States and to address and answer the inherent techno-economic challenges, a technology roadmap developed through leadership at the national level is needed.

The development of ocean energy technology and the deployment of this clean renewable energy technology would be greatly accelerated by adequate support from the federal government. Appropriate roles for the federal government in ocean energy development could include:

- Providing leadership for the development of an ocean energy RD&D program to fill known R&D gaps identified in this report, and to accelerate technology development and prototype system deployment
- Operating a national offshore wave test center to test the performance and reliability of prototype ocean energy systems under real conditions
- Development of design and testing standards for ocean energy devices
- Joining the International Energy Agency Ocean Energy Systems Implementing Agreement to collaborate RD&D activities, and appropriate ocean energy policies with other governments and organizations
- Leading activities to streamline the process for licensing, leasing, and permitting renewable energy facilities in U.S. waters
- Studying provision of production tax credits, renewable energy credits, and other incentives to spur private investment in ocean energy technologies and projects, and implementing appropriate incentives to accelerate ocean energy deployment
- Ensuring that the public receives a fair return from the use of ocean energy resources
- Ensuring that development rights are allocated through a transparent process that takes into account state, local, and public concerns.

I Acknowledgment

The authors gratefully acknowledge the contributions of M. Previsic and G. Hagerman for their work on the original version of this document.

References

EPRI Wave Power (WP) Reports are available on our website www.epri.com

1) WP-001-US – Guidelines of Preliminary Estimation of Power Production by Offshore Wave Energy Conversion Devices
2) WP-002-US Rev 4 – Cost of Electricity (COE) Assessment Methodology for Offshore Wave Energy Devices
3) WP-003-HI – Results of Survey and Assessment of Potential Offshore Wave Energy Site Locations in Hawaii
4) WP-003-WA – Results of Survey and Assessment of Potential Offshore Wave Energy Site Locations in Washington
5) WP-003-OR – Results of Survey and Assessment of Potential Offshore Wave Energy Site Locations in Oregon
6) WP-003-ME – Results of Survey and Assessment of Potential Offshore Wave Energy Site Locations in Maine
7) WP-004-US Rev 1 – Assessment of Offshore Wave Energy Conversion Devices
8) WP-005-US – Methodology, Guidelines and Assumptions for the Conceptual Design of Offshore Wave Energy Power Plants (Farms)
9) WP-006-HI – System Level Design, Preliminary Performance and Cost Estimate – Hawaii
10) WP-006-OR – System Level Design, Preliminary Performance and Cost Estimate – Oregon
11) WP-006-ME – System Level Design, Preliminary Performance and Cost Estimate – Maine
12) WP-006-MA – System Level Design, Preliminary Performance and Cost Estimate – Massachusetts
13) WP-006-SFa – System Level Design, Preliminary Performance and Cost Estimate – San Francisco, California Pelamis Offshore Wave Power Plant
14) WP-006-SFb – System Level Design, Preliminary Performance and Cost Estimate – San Francisco Energetech Offshore Wave Power Plant
15) WP-007-US – Identification of Environmental Issues
16) WP-008-US – Identification of Permitting Issues
17) WP-009-US – Final Summary Report
18) "Wind Energy Costs." NWCC Wind Energy Series, Jan 1997, No 11

Biographies

Omar Siddiqui is a Senior Associate at EPRIsolutions, a subsidiary of EPRI that provides application services based on EPRI R&D products and management consulting services to the energy industry. Mr. Siddiqui has over 10 years of experience in the energy sector and provides expertise in electro technologies, financial analysis, energy efficiency, program design, and planning. Mr. Siddiqui is currently the project manager for both the EPRI-Global Offshore Wave- and Tidal Flow- Power Feasibility Assessments. Each project is a public-private partnership between federal and state government agencies, utilities, and research organizations from several states to define the system design, performance, and economics of pilot and commercial scale wave and tidal flow power plants. Mr. Siddiqui also manages a variety of other projects for Global Energy Partners, with a focus on assessments of end-use electro technologies for electric utilities to advance beneficial electrification.

Previously, Mr. Siddiqui worked as an investment banker at J.P. Morgan, where he conducted due diligence on, and executed financial transactions for, high technology companies. He has also worked as a management consultant for A.T. Kearney, where he managed supply chain initiatives for Fortune 500 clients, as well as for Barakat & Chamberlin, where he provided analytical support on DSM planning, program design and electro technology assessment services for electric utility clients.

Mr. Siddiqui holds a B.S. in Chemical Engineering from Stanford University and an M.B.A. from the Anderson School at U.C.L.A.

Roger Bedard has over thirty-five years of experience in developing and managing medium size ($500K - $10M) engineering development projects in many diverse technical disciplines with a focus on energy systems. He has successfully managed many renewable energy demonstration projects including solar thermal heating, solar thermal electric (both line and point focus) and solar photovoltaic combined electricity and process heat (line tracking PV system where PV cell coolant was used for process heat) projects. His renewable energy experience was gained in three different career positions over the past twenty-five years.

Mr. Bedard developed and project managed the 2004 E2I EPRI Offshore Wave Energy Project Phase I Project Definition Study.

Mr. Bedard holds a B.S. in Mechanical Engineering from the University of Rhode Island and a M.S. in Mechanical Engineering from the University of Southern California.

3. WAVE AND TIDAL STREAM ENERGY OUTLOOK FROM THE UK' (INVITED DISCUSSION)

Andrew Mill, Managing Director European Marine Energy Centre, UK

Synopsis:

The UK's heritage in marine energy conversion research began in the 1970s. Edinburgh developers Ocean Power Delivery have recently begun generating electricity at sea off the Orkney islands from their prototype 750kW Pelamis. It was the world's first far-shore wave device delivering network electricity. The UK's research and manufacturing base are at the forefront of the resurgence of interest in marine energy with a number of projects under way.

As the marine energy industry progresses from its current fledgling state to a mature commercial industry there is a need for appropriate regulation to be developed. The current designs and models built draw on standards and codes from other industries not always the most appropriate or indeed cost effective. If the industry does not address the needs then the other stakeholders such as investors, financiers and government will impose their regulation. Potentially this will result in over regulation stifling the growth of the industry. Other industries have introduced regulation part way through their development resulting in conflict between stakeholders and different country's approaches.

It is an essential part of the industry's development to build confidence and to reduce the risk to the investors and insurers. Only then will the industry secure the funding for commercial project development. The industry has already suffered a number of failures more are inevitable as the industry matures. Through the controls of verification and certification the industry can build the mechanism to ensure that these experiences are minimized and that confidence is gained.

This paper reviews the progress made to date in the UK on development of devices, standards and test facilities. It describes the world-leading European Marine Energy Centre (EMEC) on Orkney. It is a purpose built, multi-berth, network-connected and instrumented wave energy test facility that can accommodate up to four separate full-scale devices each rated up to 2.4MW. It is currently embarking on a project to build a complimentary tidal test facility for full-scale devices.

This paper will review the need for standards, what standards and codes are required, and how they may be developed. The UK has already started work in this area and is looking to develop a scheme for certification in the longer term. The paper will consider where the industry is to day and put forward a model for certification that will ensure that the industry sets the level of regulation while ensuring that the other stakeholders buy in.

It will also look at the wind industry model for regulation and draw upon this to identify the needs of the marine industry. It will look to identify what stakeholders require from regulation and how the device developers can best meet that, test houses and other stakeholders working together.

Author's Biography

Andrew is the Managing Director of EMEC. He attended The University of Strathclyde where he was awarded a degree in electrical engineering and electronic science. He has held a number of posts in the energy industry including; Director and General Manger of NEI Peebles projects division, Chief Executive of Scotia Energy, and Business Development

Director Southern Europe with British Energy. Before joining EMEC he was Operations Director at Vianet responsible for the implementation of a remote data collection system.

4. WAVE POWER TECHNOLOGIES (PAPER 05 GM 0542)

Mirko Previsic, Electric Power Research Institute, Palo Alto, CA

Abstract

The oceans contain a vast amount of mechanical energy in form of ocean waves and tides. The high density of oscillating water results in high energy densities, making it a favorable form of hydropower. The total U.S. available incident wave energy flux is about 2,300 TWh/yr. The DOE Energy Information Energy (EIA) estimates 2003 hydroelectric generation to be about 270 TWh, which is a little more than a tenth of the offshore wave energy flux into the U.S. The fact that good wave and tidal energy resources can be found in close proximity to population centers and technologies being developed to harness the resource have a low visual profile, makes this an attractive source of energy. Recent advances in offshore oil exploration technology and remote management of power generation systems have enabled significant progress in advancing technology development by simple technology transfer. A few systems have made it to full-scale prototype stage allowing experience to be gained from operational aspects, which is a critical aspect to develop economic models. However, despite enormous progress over the past 5 years, current and wave power conversion technologies are at an immature stage of development. A lack of accepted standards, a wide range of technical approaches and large uncertainties on performance and cost of these systems show this. Further RD&D and the creation of early adopter markets through government subsidies is required to move these technologies into a competitive market place.

Wave Power Technologies

Wave power conversion devices are installed either **on-shore** and embedded in a cliff or an existing harbor wall, **near-shore** in close proximity to shore standing on the seabed or **off-shore** in deep waters. Similar to offshore wind, a wider applicability and more consistent and concentrated resource of energy can be found offshore and is more suitable for large-scale deployments. Installing such devices away from the coastline solves many issues such as visual impact, permitting and environmental impact.

Most designs have two major difficulties to overcome. First, even in areas where waves are consistent throughout the day and throughout the seasons, the device must be able to handle a wide range of incident wave power levels, from near-flat seas to the most extreme storm conditions (which produce waves power levels more than an order of magnitude above the average). Second, waves typically have a low frequency on the order of 0.1 Hz, while power generation equipment runs at hundreds of rpm. The device must change the slow-acting, multi-directional wave force into a high-speed, unidirectional force capable of powering a generator. Short-term storage becomes and important consideration to maintain consistent power output.

Technologies to convert ocean wave power into electricity are many. It remains unclear what the winning technical approach is. This is reflected by a myriad of different technical approaches. The main ones are:

Oscillating Water Column - (OWC) systems consist of a partially submerged structure, which forms an air chamber, with an underwater opening that allows the seawater to flow into the chamber. The volume of air inside the chamber is compressed as the water rise inside the chamber, driving air through a turbine. As the water level in the chamber subsides, the air is drawn back through the turbine. Both directional and self-rectifying air turbines have been developed. The axial-flow Wells turbine is the best-known turbine for this kind of application and has the advantage of not requiring rectifying air valves.

Overtopping Devices - guides incoming waves up a ramp and up into a reservoir raised slightly above sea level. The water trapped in the reservoir flows back to the sea through a conventional low-head hydroelectric generator.

Float Systems - Their common feature is a buoy that sits on the ocean's surface. The motion of this buoy is converted into electricity typically by a hydraulic power take off such as a hydraulic ram. These float systems come in different shapes and forms.

Hinged Contour Devices - contains different floating sections, which are hinged together. As the wave passes, the sections move relative to each other and the hinges produce power. The power conversion uses hydraulic elements.

As part of a nationwide collaborative program to demonstrate offshore wave power technologies, EPRI reviewed available technology options in 2004. Some of the results are outlined below. The wide range of different specifications is a clear indicator of the immaturity of this emerging market and the fact that no technology lock-in has occurred yet as this is the case with wind power or any other mature technology. Average Power Output was assessed for a typical Oregon wave climate with an incident wave power level of 21kW/m. This is a typical US west coast wave power level.

Table 1.**Technology Comparison**

Maturity Rating	Company	Device Width (m)	Device Weight (tons)	Average Power (kW)	Power Train
1	Ocean Power Delivery	4.6	380	153	Hydraulic
2	Energetech	35	450	259	Air Turbine
2	Wave Dragon	260	22,000	1369	Low Head Hydro
2	Wave Swing	9.5	NA	351	Linear Generator
3	WaveBob	15	440	131	Hydraulic
3	Aqua Energy	6	22	17	Water Pump
3	OreCON	32	1250	532	Air/Hydraulic
3	INRI	5.4	112	16	Water Pump

The most important criteria assessing these devices was the maturity of the development stage shown in the above table as maturity rating. Definitions are included below.

Level 1 – Development complete and full-scale testing in the ocean underway

Level 2 – Development near complete. Only deployment, recovery and mooring issues are yet to be validated. There are funded plans for full-scale at sea testing

Level 3 – Most critical R&D issues are resolved. Additional laboratory and sub-scale testing, simulations and systems integration work is needed prior to finalization of the full-scale design. There are no funded plans for full-scale at sea testing.

Electrical Interconnection

Most wave power conversion devices under development incorporate frequency converters and step-up transformers to synchronize with the grid. As a result, power quality tends to be good and power factors high. Short-term storage is incorporated to account for wave-to-wave variations. Storage options depend on the power take off train, and can incorporate hydraulic accumulators, storage through flywheel effects and capacitor banks. It remains to be seen how well these short-term storage options deal with the large variability of power levels in ocean waves.

Wave farm interconnection voltage levels depend on many variables, but are typically in the range of 12kV to 33kV. Recent offshore wind projects in Europe, showed that the environmental risks prohibit the use of oil insulated cables in the sensitive coastal environment. XLPE insulations have proven to be an excellent alternative, having no such potential hazards associated with its operation.

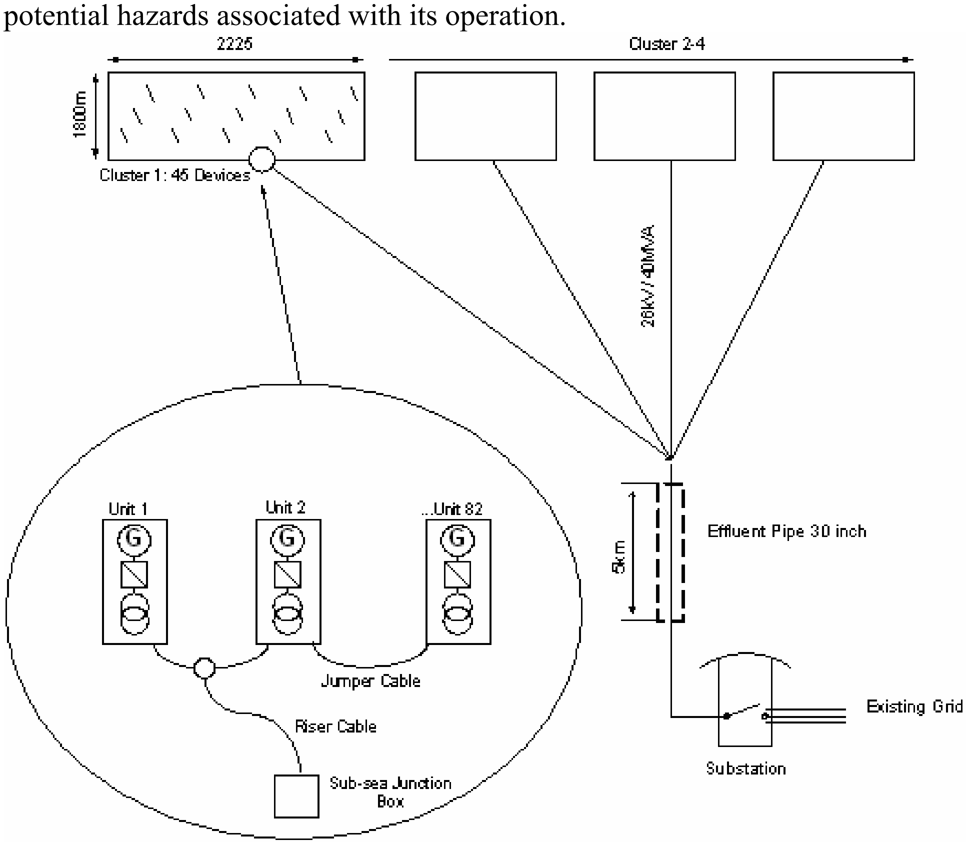


Figure 1. Example of a Wave Farm Layout and Associated Electrical Interconnection

Cost

Ocean Power Deliveries Pelamis wave energy conversion device was used to establish costing models for a commercial scale (300,000 MWh/year) wave farm. Levelized cost components are shown in the illustration below. The cost breakdown shows that the impact on the cost of electricity of O&M is significant and the one component that has most uncertainty associated to it. The only way such O&M costs can be driven down and confidence established is by building demonstration projects.

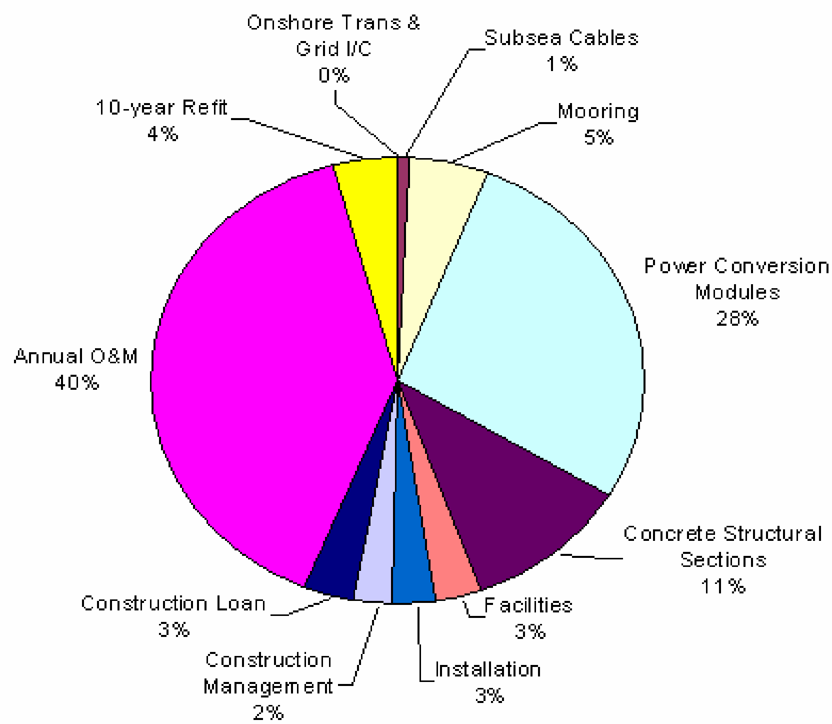


Figure 2.

REFERENCES

Recent Publications: Most of the studies below can be found at www.e2i.org.

1) E2i/EPRI WP-004-US Rev 1 Assessment of Offshore Wave Energy Conversion Devices
2) E2i/EPRI WP-005-US Methodology, Guidelines and Assumptions for the Conceptual Design of Offshore Wave Energy Power Plants (Farms)
3) E2I/EPRI WP-006-HI System Level Design, Preliminary Performance and Cost Estimate – Hawaii -
4) E2I EPRI WP-006-OR System Level Design, Preliminary Performance and Cost Estimate – Oregon

5) E2I/EPRI WP-006-ME System Level Design, Preliminary Performance and Cost Estimate – Maine
6) E2i/EPRI WP-006-MA System Level Design, Preliminary Performance and Cost Estimate – Massachusetts
7) E2i/EPRI WP-006-SFa System Level Design, Preliminary Performance and Cost Estimate – San Francisco, California Pelamis Offshore Wave Power Plant
8) E2i/EPRI WP-006-SFb System Level Design, Preliminary Performance and Cost Estimate – San Francisco Energetech Offshore Wave Power Plant
9) E2i/EPRI WP-002-US Rev 4 Cost of Electricity (COE) Assessment Methodology for Offshore Wave Energy Devices
10) Sea Technology Magazine August 2003, Wave Energy Conversion – The State of the Art
11) EPRI – RE Technical Assessment Guide Ocean Wave Power Section for the years 2001, 2002 and 2003
12) California Energy Commission – Wave Energy Resource Assessment for the State of California

Mirko Previsic has 10 years experience with the design, evaluation and optimization of offshore renewable power generation systems, resource assessments, feasibility studies and economic assessments. In recent years he has served as expert advisor to the Electric Power Research Institute, the California Energy Commission and other organizations on these emerging technologies. Mr. Previsic has written numerous studies on offshore renewable technologies and has a background in electrical engineering.

5. RECENT PROGRESS IN OFFSHORE RENEWABLE ENERGY TECHNOLOGY DEVELOPMENT (PAPER 05GM0543)

Anthony T Jones, Senior Oceanographer, oceanUS consulting, San Francisco, CA, USA.
Adam Westwood, Analyst, Douglas Westwood Associates, UK

Abstract--International treaties related to climate control have triggered resurgence in development of renewable ocean energy technologies. Several demonstration projects in tidal power are scheduled to capture the tidal-generated coastal currents. Commercial-scale wave power stations exist and are delivering power to national grids. Offshore wind farms are delivering energy to shore. As government policies shift towards inclusion of renewable sources, the near shore ocean resources have tremendous potential. Worldwide investments in renewable energy technologies reveals that offshore wind energy is the fastest growing sectors. Strong growth in offshore wind power installations is anticipated over the next decade. In 2000, development of systems to capture wave energy reached a milestone with the commissioning of the first commercial-scale power facility in Scotland. Technical capabilities, both engineering and management, exist in the offshore sector to undertake the size of projects envisioned. Harnessing the untapped potential of ocean energy has commenced.

Index Terms-- Energy resources, marine technology, ocean thermal energy conversion, power system economics, tidal power generation, wind energy.

Introduction

INTEREST in marine renewable energy is at an all-time high, and prospects for ocean-based renewable energy development look brighter all the time. This paper examines the recent progress in offshore renewable energy technology development and considers potential markets for tidal power, wave energy conversion, and offshore wind, all of which are expected to show considerable growth over the next few years. The analysis of market potentials for offshore renewable technology is based solely on identified projects. Therefore, the forecasts are relatively conservative, as the prospective markets could expand as technological advances are achieved and as regulatory environments improve.

Tidal Energy

Historically, tidal projects have been large-scale barrage systems that block estuaries. Within the last few decades, developers have shifted toward technologies that capture the tidally driven coastal currents or tidal stream. Very large amounts of energy are available in coastal waters. The challenge is, “to develop technology and innovate in a way that will allow this form of low density renewable energy to become practical and economic” [1].

At present, smaller units that can be deployed individually or in multiple units characterize tidal current stream technologies. Two groups of technologies are in operation or planning; these are tidal current turbines and tidal stream generators.

Tidal current turbines are basically underwater windmills. The tidal currents are used to rotate an underwater turbine. First proposed during the 1970’s oil crisis, the technology has only recently become a reality. One company, Marine Current Turbine (U.K.) installed the first full-scale prototype turbine (300 kW) off Lyn mouth in Devon, U.K. in 2003. Shortly thereafter, the Norwegian company Hammer fest Støm installed their first prototype device.

There are a great number of sites suitable for tidal current turbines. As tidal currents are predictable and reliable, tidal turbines have advantages over offshore wind counterparts. The ideal sites are generally within 1 km of the shore in water depths of 20-30 m.

Tidal stream generators use the tidal stream to generate power from, for example, the raising and lowering of a hydraulic arm. Several very promising devices are at the advanced stage of development. For example, the UK firm, The Engineering Business Ltd. has developed and tested a simple concept of placing hydrofoils in tidal stream to produce an oscillatory motion in the vertical or horizontal plane. The device, know as the Stingray™ Tidal Current Generator, "transforms the kinetic energy of the moving water into hydraulic power, which turns a generator by means of a hydraulic motor" [1].

Tidal Forecasts

At this time, announced projects over the next five years are few, but it is anticipated that multi-megawatt installations will emerge by the end of the decade (Figure 1). By 2008, a t forecast of 14.8 MW installed capacity is expected with 65% of the capacity in the United Kingdom. Norway, which already has installed capacity, will be the second dominant player, but lacks defined projects over the next 5 years. Other countries (Canada, France and United States) have a minor role, but could expand prototype devices as the devices progress. Canada and the United States have potential locations, some of which are under negotiation for U.K. tidal generation technology [2].

Almost 70% of forecast capacity by 2008 is anticipated from tidal current turbines with approximately 30% from tidal stream generators.

Tidal current turbines represent an extremely important sector for offshore renewables as there are several well-developed devices and such technology, once proven, could be installed in large numbers in the near future. However, a lack of identified projects distorts the forecast near the end of the 5- year period, precisely when significant projects could materialize.

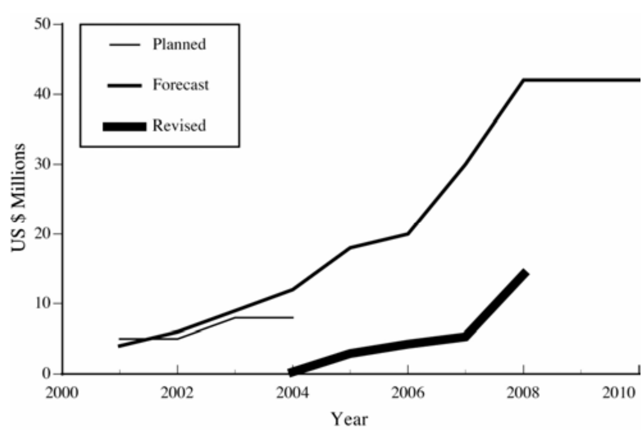


Figure 1. Revised Global Estimates of Capital Expenditure in Tidal Power Technology (Modified from [3]).

It is conceivable that tidal current turbines such as those of Marine Current Turbines or Hammer fest Støm could eventually be installed in large projects comparable in size to offshore wind farms.

With fewer announced projects, tidal stream generators have a lower forecast. Many of the devices are at earlier stage of design. One system that is generating much interest and has potential is the 'Stingray' device, designed and built by experienced offshore engineers [4].

Capital expenditures for tidal energy are forecast at $ 35 million over the next five-year period. The U.K. is the biggest market with $23 million of expenditures forecast to 2008. Forecasts for Norway at a level of $10 million of expenditures over the same period are anticipated. Successful projects could lead to further development later in the period and beyond [2]. Several projects await financial support and could significantly impact the installed capacity as the projects are in excess of 100 MW.

Projects

Shihwa Lake Tidal Power Plant, Korea

Korea has a plentiful tidal and tidal current energy resource. Under construction is a single stream style generator at Ansan City's Shiswa Lake, which will have a capacity of 252 MW, comprised of 12 units of 21,000 kW generators. Annual power generation, when completed in 2008, is projected at 552 million kWhr. Designed by the Korea Ocean Research & Development Institute, the project is funded by the Korea Water Resource Corporation. Construction. Costs are estimated at US $ 320 million with a price per kWhr of US $0.09. The system relies on a tidal differential of 5.6 m. If successful, this project will surpass La Rance (France) as the largest tidal power plant in the world. Korea is also planning a tidal current power plant in Uldol-muk Strait, a restriction in the strait where maximum water speed exceeds 6.5 m/s. The experimental plant will utilize helical or "Gorlov" turbines developed by GCK Technology [5]. The 1000 Whr system is anticipated to be operating in 2007.

Yalu River, China

By creating a tidal lagoon offshore, Tidal Electric has taken a novel approach to resolve environmental and economic concerns of tidal barrage technology [6]. Due the highly predictive nature of the ocean tides, the company has developed simulation models with performance data from available generators to optimize design for particular locations. Recent announcement of a cooperative agreement with the Chinese government for ambitious 300 MW offshore tidal power generation facilities off Yalu River, Liaoning Province allows for an engineering feasibility study to be undertaken.

Tidal Electric also has plan under consideration for United Kingdom-based projects in Swansea Bay (30 MW), Fifoots Point 930 MW), and North Wales (432 MW).

Wave Energy

Wave energy is moving offshore. Although a number of successful devices have been installed at shoreline locations, the true potential of wave energy will only be realized in the offshore environment where large developments are conceivable. At present, nearly 300 concepts for wave energy devices have been proposed. This tremendous number of devices demonstrates the difficulty of developing an efficient, reliable, and cost-effective wave energy converter. Of all the concepts, less than ten are likely to have progressed to a sufficient state to meet commercial demands by the end of the decade.

Modular offshore wave energy devices that can be deployed quickly and cost effectively in a wide range of conditions will accelerate commercial wave energy. In the coming decade, wave energy will become commercially successful through multiple-unit projects

Opportunities for expansion of the offshore market is expected to increase, in part because the growth of shoreline wave energy devices will be increasingly limited by the low number of available sites and by high installation costs, both of which contribute to a high price in terms of kWh. Deployment costs for shoreline wave energy devices are very high because they are individual projects and economies of scale are therefore not applicable. The site-specific demands of shoreline wave energy devices mean a further restriction of growth in this sub-sector. Whereas an offshore 50-MW wave farm is conceivable, and will in time be developed, no shoreline wave energy converter can offer such potential for deployment in this way. As such, individual coastal installations are expected to be few and far between [2].

Shoreline wave energy will, however, continue to be relevant, with approximately 25 percent of the forecast capacity over the next five years. The average unit capacity is generally higher than existing offshore technology. Individual devices can be very effective, especially for remote or island communities where, for example, an individual unit of 4 MW could have a big impact [2].

Offshore locations offer greater power potential than shoreline locations; however, devices in offshore locations have more difficult conditions to contend with. Shoreline technologies have the benefit of easy access for maintenance purposes, whereas offshore devices are in most cases more difficult to access. Improvements in reliability and accessibility will be critical to the commercial success of the many devices currently under development [2].

Most wave energy projects to date have been small, and few are connected to a power grid. However, grid connection will be crucial in the future. Shoreline devices offer the advantage of easier access to a grid. For offshore devices, meeting this need will be challenging and costly, although not prohibitively so.

Wave Energy Forecast

The most promising sector over the 2004-2008 period and indeed into the long-term future is wave energy (Figure 2). Shoreline devices are expected to grow in size, but the greater cost, lengthier set-up period, and shortage of viable sites (due more to market conditions than any shortage of natural locations) indicate that offshore wave energy will become more important, commercially and in terms of installed capacity, in the future [2].

The development process for wave energy can be looked at in three phases. First, small-scale prototype devices, typically with low capacity, will be deployed. Successful prototype devices will lead to larger-capacity prototypes. During the second stage, outside funding from government or private investors is possible for the most promising devices. The final stage, representing the culmination of development, is the production of full-scale, grid-connected devices that will in some cases deployable in farm style configurations. To date, hundreds of wave energy prototype devices have been designed, but only about 20 have progressed to the second stage. Of these, only a handful is close to entering the final stage and commercial deployment [2].

Although several wave energy devices are getting closer to full-scale deployments, the fact remains that real-world operational experience is limited. Large-scale demonstrations are required in order to test survivability and efficiency issues that have not yet been resolved. It is difficult to assess potential of a system until it is tested in its final state. However, some leaders in the wave (and tidal) industries have implemented programs that slowly--but publicly--will build up to commercial-scale deployments (Pelamis, Stingray, etc.). Realistically only a tiny proportion of wave energy concepts will move on to a commercial level. Limited resources, in many cases, hamper launch of technology as the sector is dominated by small and medium enterprises. These small companies are, in most cases, unwilling to collaborate because they wish to protect their investments. Needed collaboration and cohesion could be aided if regional and national organizations, such as the British Wind Energy Association, were to take a more active role [2].

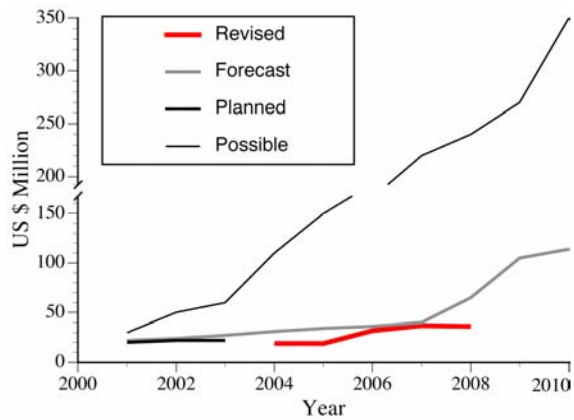


Figure 2. Revised Estimates on Capital Expenditure in Wave Energy Conversion Technology. (Modified from [3]).

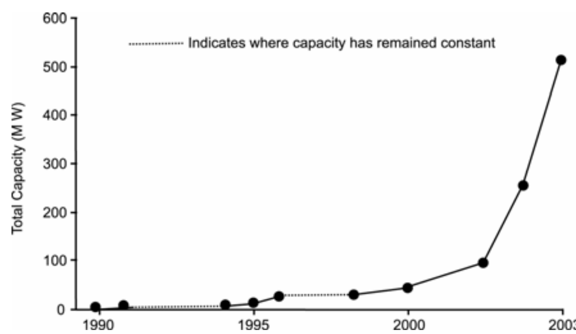
The United Kingdom is expected to be the dominant player over the next five years, with a forecast capacity of 10.6 MW--about half the market share. In comparison with other countries, the UK has forecast capacity every year to 2008, whereas installations elsewhere are more intermittent. Australia, Portugal, and Denmark are the next most significant markets and have several projected installations, but they lag far behind the UK. The United Kingdom government has shown reasonable levels of support, which have injected many technologies with valuable grants. The result is a number of advanced wave technologies with good prospects for deployment of prototype devices. Coupled with a world-class natural resource, the United Kingdom could be the undisputed world leader in wave energy by 2008. Prospects after 2008 are even brighter [2].

The United States market shows encouraging levels of interest in wave technology; however, the market will be affected by the lack of positive government involvement [2].

Overall, wave energy will see a total expenditure of $111 million over the five-year period to 2008. The United Kingdom's total expenditure is expected to be $72 million over the five-year period, more than all other countries combined. Spending is projected to peak in 2007 at a level of $37 million before slumping dramatically. This decline is attributable to a small number of currently identified projects. Although projected spending in 2008 is low, this represents a lack of announced projects rather than a collapse in the industry. Developers are hesitant to indicate future plans beyond the proving of existing devices. Toward the end of the decade, developers will negotiate and plan larger-scale projects based on proven technology, which are unlikely to see installation until 2008 or later. At that time, wave energy farms could begin to emerge. When devices reach this advanced stage, the prospect capacity will begin to rocket. Over time, the initial high costs of development and research will level out, and individual technologies will become more cost effective. Once a device is established, serial production will result in much lower costs. At this stage, there are several devices that have very promising electricity generation costs forecast that would further benefit their commercial success [2].

Offshore Wind

Offshore wind capacity has taken off in the European market since 2002. Currently, Europe is the only region in the world with any operational capacity and is expected to have 88 percent of the new capacity over the coming five years. Installed capacity has increased more than five-fold within the last year alone (Fig. 3). Over the next five years, installation of 5,820 MW is projected (Fig. 4), predominantly in European waters. Within Europe, Germany and the United Kingdom are the two most important countries in terms of capital expenditures. The five-year market (to 2008) is projected to be $9.5 billion, growing from $257 million in 2004 to $2.9 billion in 2008. Germany is poised to lead the market, and is expected to overtake Denmark and the United Kingdom in terms of total installed capacity by 2007



Figore 3. Recent Worldwide Growth in Offshore Wind Capacity [7].

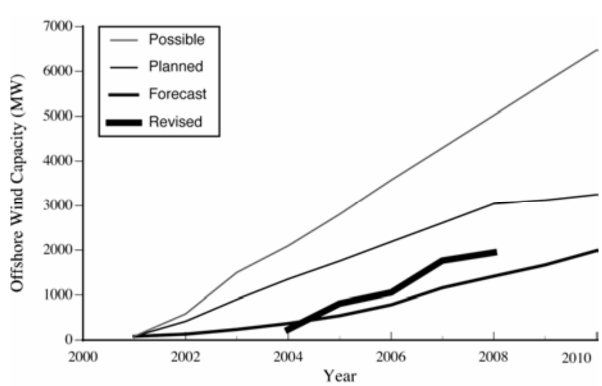


Figure 4. Revised Estimates for Global Offshore Wind Capacity. (Modified from [3]).

The United Kingdom, the second largest market, is expected to install approximately 25 percent of the total capacity by 2008. The value of the UK's market is projected to be $2.25 billion between now and 2008. The North American market lags approximately five years behind the European market, but it is expected to increase capacity and become prominent in the market after 2007. The Netherlands, Sweden, and Ireland also are expected to become significant players over the coming years [2].

Germany and the UK account for 66 percent of the projected capital expenditures between 2004 and 2008. In 2004, the Netherlands has the greatest expenditure, from one 120-MW project. By the end of 2008, however, Germany is expected to be the dominant force. Buoyed by many large and expensive deepwater projects, its market share is substantial [2].

Technological progress is extremely important for the industry, and will drive developments. As better technology is implemented, large strides in capacity will be achieved using proportionally fewer turbines. For example, up to 1,776 turbines will be installed by 2008. Although relatively few installations are planned in 2004, a significant increase is expected in 2005, with more nations installing higher-capacity wind farms. In 2004, the average size of turbine is 2 to 3 MW, whereas in 2008, turbines of 4 MW and above will be the norm [2].

Long-term signals are good for the UK market, whereas an air of uncertainty hangs over Germany despite its very promising future forecast. The United Kingdom’s development is gradual, whereas Germany's depends on large, technologically challenging projects. Denmark’s five-year forecast is disappointing, with only one project scheduled to be installed in 2008. Although the country showed initial promise for offshore development, a lack of government commitment is deterring potential developers and investors

Offshore wind has a potentially large market in North America, but it could easily fail before it gets a chance to take off. Success of early projects, particularly in the United States, is critically important in the face of uncertain planning regulations for offshore wind. Offshore developers should heed the lessons from the traditional boom and bust cycle of onshore wind sector in North America. In Canada, there are fewer immediate projects, but the long-term view is more positive. The present government is increasingly warming to marine renewables. If the flagship Nai Kun project off Prince Rupert in British Columbia is successful, then it could be the first of many such wind farms.

Although the United States has considerable offshore wind potential, regulatory uncertainty is a source of concern; a critical test of the market potential is under way in the form of the Cape Wind project. Cape Wind Associates' controversial 468-MW, 170-turbine project is considered critical to the future of offshore wind in the United States. Its success or failure is likely to set a precedent for future developments in the country. If the wind farm is approved, new and existing players are likely to take advantage of the potential and generate many proposals for new projects. On the other hand, if the project is rejected, and therefore effectively cancelled, it could have dire consequences for the future development of the United States industry.

Other than the Cape Wind project, the United States has a significant number of projects in the planning stages. These projects, many of which are very speculative, are not expected to arise until the end of the decade. For example, Winergy LLC has twenty sites on its books, some of which it has already submitted applications for. Although this ambition is encouraging, it is unlikely that all of these projects will be awarded permits. Three additional sites the company proposed were dropped because of concerns raised by the military.

One development worth watching is located off Long Island, New York. The Long Islands Power Authority (LIPA) issued a call for proposals for the development of a 100- to 140-MW project in January 2003. The winning bidder would pay for all the costs and be responsible for delivering the completed project to LIPA, which would offer a 15- to 20-year power purchase agreement. This $250-300 million project has much potential, and the successful bidder likely will have an easier route to success than Cape Wind Associates. The winning bidder was Florida Power & Light [8].

Ultimately, the United States government will determine the rate of progress for offshore wind. Mixed signals concerning subsidies and tax incentives have created an uncertain atmosphere for developers. With structured and targeted development plans based around real renewables targets, offshore wind in the US could receive the boost it needs. Currently, the planning system in the United States is too fragmented to support a large-scale expansion in offshore wind. The much-delayed Energy Policy Bill is causing friction. Despite 2003 being a record year for onshore wind in the United States, the failure to secure production tax credits for next year will crash the market. Although offshore should be viewed as a separate entity, cross-market issues, such as financing, are at play.

For the offshore wind industry to grow, the US needs to establish a comprehensive offshore management system with clear procedures, because at present there is no set precedent for applications. As previously mentioned, the success or failure of the early projects, especially Cape Wind, will dictate the terms by which future projects will be judged. Interestingly, several small coastal communities are initiating small-scale offshore wind projects using a single turbine. GE Wind is one company pursuing such schemes.

Discussion

Whilst success in the last twelve months has been high, much of the previously promised capacity has failed to materialize because of problems across the board from a project level to governmental level. However, a number of countries have made significant progress in the sector, most visibly the United Kingdom which now has more approved offshore wind capacity than any other country and leads the world in planned wave and tidal current stream capacity.

The more well established offshore wind sector will lead the offshore renewables industry, and will experience strong growth throughout the period led by countries such as Germany and the UK. Technological developments will drive the market forward. Increased interest from both the financial and commercial sectors are making projects a reality.

Countries with ambitious offshore wind plans such as Germany and the United Kingdom will be the major markets over the next few years. Countries that failed to adopt long-term goal driven policies, such as Denmark, have lost market share.

Germany is forecast to become world leader in offshore wind in the next three years. The United Kingdom is the second largest market. The United Kingdom, in comparison to Germany, is also a leader in the wave and tidal current stream industries. These comparatively small-scale industries will be of greater significance when they enter the next phase of development towards the end of the decade. For the entire marine renewables industry, Europe is the dominant region, leading in all three sectors: offshore wind, wave and tidal power. While North America will have offshore wind capacity by the end of the decade, it lags far behind the established European market. Wave and tidal projects are underway in both North America and Asia, although the focal point for those industries remains Europe.

Wave and tidal energy are of much importance over the next five-years, but they are overshadowed by the massive offshore wind sector. Progress in wave and tidal has been extremely encouraging over the last year, and in the near future a number of further key developments are set to take place. Within the five-year period ahead we will see a number of technologies reach commercial application, and be installed in multiple-unit configurations. In this respect these developing industries can be seen as being at a similar stage to offshore wind a little more than a decade ago. With time and sufficient encouragement, sizeable wave and tidal farms could be in place by the next decade.

It is becoming clear which countries are paving the way for an increased offshore renewables energy share, by creating the necessary market conditions and supporting projects from their outset through to realization. Commitment to renewables, especially offshore, must be sustained over the long-term and give clear signals of commitment – without this the market will flounder. Although the level of installed capacity is growing quickly, and the proposed number of projects is ever growing, the fragility of the entire industry is evident through project failings and about-turns by countries that have lost the will to foster the industry. The challenges of building offshore renewables sector have been made very clear. Early overly optimistic hype that inflated market predictions from some quarters is now viewed critically.

The UK is a particularly important market for the three offshore renewables sectors. Driven by a world-class natural resource, the past year has seen notable successes in wind, wave and tidal energies. Offshore wind, in particular, has generated much attention as the UK's first major offshore wind farm has been installed, with the second nearing completion. With more approved offshore wind capacity in the planning stage than any other country, prospects for the United Kingdom look bright. The system of offshore leases has shown a structuring that is lacking in other countries. Recent decisions to extend renewables energy portfolio targets to 15.4% by 2015 have provided a signal of long-term commitment. This sustained outlook is crucial to offshore renewables, not just offshore wind but the growing wave and tidal sectors. The importance of wave and tidal lies in the progression of the industry towards commerciality rather than the actual installed capacity.

In the United Kingdom, domestic offshore renewables industry is set to develop on the back of the high level of prospects, but challenges from other European countries where renewables, particularly wind, are more established should not be discounted. The UK has a large and highly skilled manufacturing sector and workforce remaining from oil and gas that is able to diversify into offshore renewables as the industry grows, but must heed the fragility of the market.

Conclusions

For the entire marine renewables sector, 5,800 MW of installed capacity is projected between 2004 and 2008. Some 99% of that capacity is in the form of offshore wind farms. Wind farms installed capacity of 237 MW is expected in 2004. By 2008, this will grow to 1953 MW – an eight-fold growth within five-years.

The value of the market over the next five-years is projected at $9.6 billion, growing from $276 million a year in 2004 to nearly $3 billion a year by the end of the period. Growth between 2004 and 2008 is forecast at more than ten-fold. By the end of the period, costs per MW will have fallen noticeably, making offshore renewables increasingly viable.

Wave and tidal power will only be a small percentage of the total expenditure in offshore renewables, on the order of $150 million in total expenditure between them. However, wave and tidal power currently attract higher expenditures per megawatt. This indicates higher costs of the immature developing industries. These costs will fall as time goes by and the industries progresses. The leading devices should be comparable with, and in some cases more competitive than offshore wind, by the end of the decade.

The dominance of offshore wind does not mean wave and tidal energy are not important, they are just less well developed, and the industry is much younger. If wave and tidal were compared to offshore wind market data from ten years ago, their market share would be much higher. Offshore wind is booming at present. From around 2010, wave and tidal could begin see this rapid growth.

Acknowledgment

Much of the research for this paper was presented with Adam Westwood at the EnergyOcean 2004 conference [2]. I thank Dan White, the conference organizer, for allowing the material to be included in the IEEE panel.

References

[1] A.D. Trapp and M. Watchorn, "EB development of tidal stream energy," in *Proceedings MAREC 2001*, p. 169-173, 2001.

[2] A.T. Jones and A. Westwood, "Economic Forecast for Renewable Ocean Energy Technologies," presented at EnergyOcean 2004, Palm Beach, Florida, 2004.

[3] A.T. Jones and W. Rowley, "Global Perspective: Economic Forecast for Renewable Ocean Energy technologies," MTS Journal, vol. 36. no. 4, pp. 85-90, Winter 2002.

[4] N.J. Baker, M.A. Mueller, M. Watchorn, D. Slee, L. Haydock and N. Brown, "Direct drive power take off for the Stingray tidal current generator," in *Proceedings MAREC 2002*, p. 1-10, 2002.

[5] A. M. Gorlov, "The Helical Turbine and its Applications for Tidal and Wave Power," in *Proc. OCEANS 2003*, p. 1996, 2003.

[6] P.W. Ullman, "Offshore Tidal Power Generation – A new approach to power conversion of the oceans' tides," *MTS Journal*, vol. 36. no. 4, pp. 16-24, Winter 2002.

[7] P. Breeze, "The Future of Global Offshore Wind Power," *Reuter Business Insight* 2004.

[8] L. Coakley, "Long Island Offshore Wind Park – 140 Megawatts of Offshore Wind Energy," presented at EnergyOcean 2004, Palm Beach, Florida, 2004.

Biographies

Anthony Jones, Ph.D. was born in California, USA and holds a doctorate in oceanography from the University of Hawaii.

His employment experience includes the U.S. Department of Energy Lawrence Berkeley Laboratory, the International Seabed Authority, and Oases International. His research interest is in coupling of marine renewable energy to seawater desalination to provide sustainable source of potable water.

Dr. Tony Jones is a senior oceanography with oceanUS consulting in San Francisco. He has been a consultant to various marine renewable energy developers including SeaVolt Technologies, a winner of the UK Carbon Trust's Marine Energy Challenge. Dr. Jones holds patents in salinity gradient power technology and is widely published in the field including a seminal paper on economic forecast for ocean energy over the next decade.

Adam Westwood manages DWL's World Offshore Wind, World Onshore Wind, and World Offshore Wave & Tidal project databases. He is author of The World Offshore Renewable Energy Report commissioned by the UK Department of Trade & Industry, and for Scottish Enterprise Renewable Energy Spends & Trends. Past research activity also includes offshore renewable energy studies for major international companies and work on renewable energy industry business prospects worldwide. Projects also include work for the DTI and investment trust 3i relating to financing of a wind turbine installation vessel. Published work also includes a number of papers and articles on renewables and he is a regular contributor to renewable energy trade journals.

PANELISTS AND DISCUSSERS

1. Peter O'Donnel
   Sr. Energy Specialist
   Generation Solar & Renewables Programs Manager
   SF Environment.Org
   USA
   E-mail: peter.o'donnell@sfgov.org
   Tel: +1 415 355-3715
   www.SolarSF.org

2. Omar Siddiqui
   Senior Associate
   Global Energy Partners, LLC
   3569 Mt. Diablo Blvd., Suite 200
   Lafayette, CA 94549
   USA
   E-mail: osiddiqui@gepllc.com
   Tel: +1 925 284-3780
   www.gepllc.com

3. Michael Hay
   Marine Renewables Development Manager
   British Wind Energy Association (BWEA)
   Renewable Energy House
   1 Aztec Row
   Berners Road
   London
   N1 0PW
   UK
   E-mail: michael@bwea.com
   Tel: +44 207 689 1960
   http://www.bwea.com

4. Mirko Previsic
   Consultant – Offshore Renewables
   274 Howe Ave #F
   Sacramento, CA 95825
   USA
   E-mail: mprevisi@epri.com
   Tel: ++1 916 977 3970
   Cell: ++1 916 217 1947
   Web: www.e2i.org

5 Anthony T Jones
   Senior Oceanographer
   oceanUS consulting
   380 W. Yorba Rd.
   Palm Springs, CA. 92262-1964

USA
E-mail: tjones@alum.calberkeley.org
Email: jxocean@yahoo.com
Tel: +1 760 778 6776

Adam Westwood
Analyst
Douglas Westwood Associates
St Andrew's House
Station Road East
Canterbury
CT1 2WD
UK
E-mail: adam@dw-1.com
Tel: +44 (0) 1227 780999
Fax: +44 (0) 1227 780880

PANEL SESSION CHAIRS:

Peter Meisen
President
Global Energy Network Institute
PO Box 1565
SanDiogo
CA 92101
USA
E-mail: Peter@geni.org
Tel: +1 619 595 0139
Fax: +1 619 595 0403
WEB: www.geni.org

Tom Hammons
Chair International Practices for Energy Development and Power Generation
Glasgow University
11C Winton Drive
Glasgow G12 0PZ
UK
E-mail: T.Hammons@ieee.org
Tel: +44 141 339 7770

E N D