

Wave Energy Systems for Recharging AUV Energy Supplies

George Hagerman, Research Associate
Center for Energy and the Global Environment
Virginia Tech Alexandria Research Institute
206 N. Washington St., Suite 400
Alexandria, VA 22314

Abstract—This paper describes ocean wave energy resources and characterizes their global distribution and temporal variability. It presents an overview of wave energy conversion devices that have progressed beyond the laboratory wave tank and have been proven at sea, and which lend themselves to miniaturization and packaging in a configuration suitable for recharging AUV power supplies from a docking station base. Finally, it describes a wave-powered docking station concept that takes advantage of ocean engineering developments in rapidly deployed mooring systems and artificial, submerging seafloors to provide a relocatable AUV dock that also can serve as a sustainable “gateway” platform for undersea observatories.

I. INTRODUCTION

Considering that over 70% of the Earth's surface is covered by waters that are seldom still, ocean waves have great potential as a renewable source of energy on this planet. Yet most people know little of the technology that has been developed to harness the energy of ocean waves, or the associated engineering challenges posed by their variability in time and space.

The next section of this paper reviews the temporal and spatial variability of ocean wave energy resources, and Section III presents a brief overview of conversion devices that have been developed in Europe, Japan, and the United States, focusing on those devices that have progressed beyond the laboratory wave tank and have actually been tested at sea.

To date, virtually all wave energy devices have been developed for generating utility-scale power on the order of hundreds of kilowatts per device. Deployment of these utility systems entails installation and electrical interconnection of individual moorings, requiring lengthy weather windows and risking system loss in a partially deployed state. Such deployment methods also are not suited to water depths beyond the edge of the continental shelf.

Enabling technologies are now available that can overcome the difficulties noted above, and these are described in Section IV of this paper. Finally, Section V shows how the best features of previously developed heaving-buoy wave energy devices can be miniaturized and packaged together with these enabling technologies in a platform configuration suitable for recharging AUV power supplies. In this concept, the docking station would be configured as a “movable ground” platform that carries an array of pre-tethered heaving buoys in transit to the deployment site. On site it would be submerged and anchored as a slack-moored “artificial seafloor” that can be installed in a large range of water depths, providing an inertial reaction point for the heaving buoys and a roll-pitch stable platform for reliable AUV docking and satellite communications.

Unitary regenerative fuel cell (URFC) technology is a promising candidate for storing intermittent wave energy and delivering it to AUV charging stations on demand. Section V of this paper presents a notional power budget for a dock-based URFC storage system charging AUVs designed for North Atlantic under-ice surveys.

II. RESOURCE CHARACTERIZATION

Ocean waves are a derived form of solar energy, with wind being the agent that transfers the sun's energy to the sea surface. Simply stated, unequal solar heating of the Earth generates wind, and wind blowing over water generates waves. Only 0.01% of the Earth's solar energy flux is ultimately expressed as wave power. While sunlight falls on the planet at a global rate of 10^{16} to 10^{17} watts, wave energy is dissipated against the world's coastlines (and renewed by the wind) at a global rate of 10^{12} to 10^{13} watts [1].

A unique property of ocean waves is their ability to travel vast oceanic distances with negligible loss of energy. Even the longest waves do not begin to “feel the bottom” until they enter water depths of 300 meters or less. Consequently, wave energy generated anywhere within an ocean basin ultimately arrives at some island or continental margin of that basin, virtually undiminished.

Thus, while solar radiation and winds are distributed over the planet's entire surface area, wave energy is gathered along its coastlines, which total 336,000 km in length. At a global renewal rate of 2.7×10^{12} watts [2], the average wave energy flux worldwide is 8 kilowatts per meter (kW/m) of shoreline. By comparison, the annual average flux of solar or wind energy is generally less than 300 watts per square meter of panel area or rotor swept area. Therefore, the energy density of ocean waves is an order of magnitude greater than the natural processes that generate them.

The geographic distribution and temporal variability of wave energy resources are governed by the major wind systems that generate ocean waves: extra-tropical cyclones and trade winds. In some areas, notably the Indian Ocean, local monsoons also can influence the regional wave climate. Likewise, tropical cyclones can generate large wave energy fluxes over periods of days in regions normally not having high wave energy levels, such as the Gulf of Mexico.

A. Geographic Distribution

Extra-tropical cyclones are born as prevailing westerly winds off continental landmasses pick up heat and moisture from western ocean boundary currents such as the Gulf Stream and the Kuroshio Current. These low-pressure systems can develop sustained wind speeds up to 25 m/sec, blowing over a 1,000 km ocean fetch for two to four days before the storm makes landfall.

In the northern hemisphere, extra-tropical cyclones follow northeasterly tracks, continually building the waves in the storm's southern sector, which are traveling in the same direction as the storm. Consequently, wave energy resources are quite good along the northeastern margins of ocean basins in the northern hemisphere.

As waves grow, their periods increase, as does their speed. Eventually they travel faster than the storm and leave the region of active wind generation, at which point they are referred to as swell. Such swell arrives ahead of the storm, and can give rise to high wave energy levels even when local winds are calm.

On the other hand, waves generated in the northern sector of a northern-hemisphere cyclone travel opposite the direction of storm advance and have much less exposure to the storm's wind energy. Consequently, swell traveling "backwards" from such a storm has much less power than swell leaving the storm's southern sector. As a result, wave resources along the southwestern side of northern hemisphere ocean basins are generally poorer than on the eastern side.

In the north Atlantic Ocean, for example, annual average wave power along the edge of North America's eastern continental shelf ranges from 10 to 20 kW/m. By comparison, shelf-edge wave power off the exposed western coasts of the British Isles averages 60 to 70 kW/m, decreasing farther south, to about 30 kW/m off central Portugal. A similar pattern occurs in the north Pacific Ocean. On the western side of the basin, off Taiwan and Japan, wave power averages 5 to 15 kW/m. On the opposite side, off the coast of northern California, it ranges from 25 to 35 kW/m.

In the southern hemisphere, extra-tropical low-pressure systems develop in the open ocean expanse that surrounds Antarctica. These storms travel from west to east, uninterrupted by land, and generate high-energy swell that makes landfall along the southwest coasts of South America, Africa, Australia, and New Zealand. This swell also contributes significantly to the wave energy resources of Indonesia and island nations throughout the south Pacific Ocean. As in the northern hemisphere, incident wave energy flux decreases with decreasing latitude, averaging more than 100 kW/m just south of New Zealand, dropping to 30-40 kW/m in deep water west of Auckland. Even farther north, in the south Pacific region framed by Vanuatu, Tongatapu, Rarotonga, and Tuvalu, wave power densities at exposed island locations are estimated to be 15-20 kW/m.

As waves leave deep water and travel shoreward across island and continental shelves, they experience refraction and bottom drag. Refraction is the process whereby waves crossing the shelf at an angle bend toward the coast as they enter shoaling water. This spreads adjacent wave rays, which decreases the power per unit width of wave crest. Bottom drag dissipates wave energy through turbulence created as sub-surface water motion encounters an unmoving seafloor.

Both processes can lead to a substantial reduction in the wave energy flux per unit width of any device deployed to absorb and convert this energy to useful work. Off northern California, for example, the incident wave energy flux in deep water beyond the edge of the continental shelf varies from 35 kW/m near the Oregon border to 25 kW/m off Point Conception, 1,000 km to the south. By the time waves reach the 10 m depth contour, their coast-wide average energy flux has dropped to 12 kW/m, and its local distribution over tens of kilometers is quite variable, ranging from 1 kW/m where the shoreline faces south or is sheltered by rocky headlands, to 18 kW/m along exposed open coasts [3].

B. Temporal Variability

Like the sun and wind, ocean waves are an intermittent energy resource. In order to engineer or evaluate the conversion technology that has been developed to harness this resource, it is important to understand wave energy's variability over several time scales:

- Wave to wave (seconds)
- Wave group to wave group (minutes)
- Sea state to sea state (hours to days)
- Season to season (months)
- Power plant service life (years)

Sea states can be described by two statistical parameters: significant wave height and some characteristic wave period, either the mean wave period or the peak wave period. Significant wave height is defined as the average height of the highest one-third waves. This approximates the height that a shipboard observer will report from visual inspection of the sea state, since such an observer tends to overlook the smaller, less conspicuous waves. Peak wave period is defined as the period corresponding to the peak in the variance density spectrum of sea surface elevation. It thus represents the harmonic frequency component having the greatest amount of energy in a given sea state. Some wave energy devices can be "tuned" to this frequency in a manner analogous to the tuning of a radio circuit in an electromagnetic wave field.

Although a statistically stationary sea state (*i.e.*, waves neither building nor decaying) can be described by its significant wave height and peak or mean wave period, individual wave height and period vary more or less randomly from one wave to the next. Such variability is more random in seas generated by strong local winds and less random in swell that arrives from far distant storms.

Waves often occur in successive groups of alternately high and low waves, a phenomenon familiar to any surfer. The output of a wave energy device will tend to follow the envelope profile of such wave groups. Incorporating minutes-long storage of mechanical or fluid power (*e.g.*, flywheels or hydraulic accumulators) smoothes these pulses, and enables the use of lower capacity electrical equipment. This saving can more than offset the cost of such storage components, thereby improving overall system economics.

Wave energy levels change over periods of hours to days, either in response to local wind conditions, or the arrival of swell from distant storms. Developing long-term statistics associated with the day-to-day variability of wave energy levels is important, since it is this variability that governs conversion equipment rating. The system designer must make a trade-off between under-utilization of installed capacity and excessive shedding of absorbed power. If the equipment is rated too high, it will be under-utilized and will operate at less-than-optimal conversion efficiency too much of the time. On the other hand, if the equipment is rated too low, it will not harness much of the available wave energy. Thus to achieve the most economical design requires proper characterization of site-specific hourly and daily variations.

Extra-tropical storms are most frequent and intense during the winter, when monthly average wave energy levels typically are three to five times greater than summer monthly averages. Seasonal variability is much less pronounced in the tropical open ocean, however, due to persistent trade winds and the presence of swell from high-latitude extra-tropical storms in both hemispheres.

Finally, year-to-year variability in wave energy levels must be considered, particularly in projecting long-term power plant performance. In many cases, only a few years of measured wave data may be available from a proposed plant site. To minimize project financing risk, one must determine how well these data represent the long-term wave climate.

III. WAVE ENERGY CONVERSION DEVICES

The high energy density of ocean waves has attracted the attention of inventors for more than two centuries. Electric power was first generated from waves in the early 1900s, but widespread exploration of wave energy did not occur until the 1973 oil embargo by the Organization of Petroleum Exporting Countries (OPEC) ushered in a decade of dramatic price increases for fossil fuels around the world. This in turn led to establishment of several national government-sponsored programs in wave energy research and development. The greatest efforts by far were in the United Kingdom, Norway, and Japan. Although not as large, national programs involving sea trials of ocean prototypes have been conducted in Sweden, Denmark, Ireland, Portugal, India, and China. The U.S. program focused its attention on ocean thermal gradients, and funded little wave energy work by comparison [4].

A short review summarizing the status of wave energy conversion devices *circa* 1996 was published in [5], and a comprehensive encyclopedia article was published a year earlier by the same author [6]. An overview describing more recent developments in Europe and Japan was published last year by Thorpe and is posted at [7].

The basic wave energy conversion process can be stated in very general terms as follows: the force (or torque) of an incident wave causes relative motion between an absorber and a reaction point, which drives a working fluid through a generator prime mover. The periodic nature of ocean waves dictates that this relative motion will be oscillatory and have a frequency range of 3 to 30 cycles per minute, much less than the hundreds of revolutions per minute required for electric power generation. A variety of working fluids and prime movers can be employed to convert these slow-acting, reversing wave forces into high-speed, unidirectional rotation of a generator shaft.

Twelve distinct wave energy conversion process variations can be identified, as shown in Fig. 1. Energy can be absorbed from heave (vertical motion), surge (horizontal motion in the direction of wave travel), pitch (angular motion about an axis parallel to the wave crests), or some combination of these modes. Absorbers can be fabricated of rigid or flexible material or can be the free surface of the water itself. Reaction points can be inertial masses (suspended plates, buoyant spines, or other absorbers), seafloor anchors (deadweight or piled), or fixed, surface-piercing masses (concrete caissons or land). Two wave energy conversion processes well suited to the AUV dock concept presented herein are heaving buoy devices (Processes 6 and 7 in Fig. 1), and these are described in the remainder of this section.

A. DELBUOY Wave-Powered Desalination Device

In the United States, at the University of Delaware, Doug Hicks and Michael Pleass developed the DELBUOY system for desalination of seawater by direct reverse osmosis (RO). Beginning in 1982, they installed an evolving series of prototypes off the southwest coast of Puerto Rico. License to this device is now held by CHPT, Inc., a Delaware company specializing in the design and fabrication of high-pressure seawater hydraulic components from composite materials.

DELBUOY employs a 2.1 m diameter buoy tethered to a seafloor anchor by a single-acting hydraulic cylinder with a bore diameter of 4 cm. Wave heave forces over the entire waterplane area of the buoy are applied to the effective inner sectional area of the hydraulic cylinder. This gives a pressure amplification ratio of nearly 2800:1, such that relatively small waves can generate a pump pressure of 5.5 MPa (800 psi), which is adequate to develop reverse osmotic flow. Six buoy/pump moorings supply one RO module that delivers 5,680 liters (1,500 gallons) of fresh water per day, in waves just 1 m high, having a period of 3-6 seconds, which are typical of trade wind wave climates.

B. Swedish Hose Pump Device with Inertial Reaction Point

Use of a seafloor anchor makes the performance of a heaving buoy device sensitive to tidal changes in sea level. By using an inertial reaction point, this sensitivity can be eliminated. A suspended damper plate concept developed in Sweden is the most advanced example of this process, and makes use of a unique seawater pump that does not have the shaft seals or end stops of a hydraulic cylinder.

Consider the buoys illustrated in Fig. 2. Each buoy is attached to a collecting line by a length of specially designed elastomeric hose. During the passage of a wave crest, the buoy heaves up, stretching the hose. The helically wound, steel reinforcing wires in the hose wall cause the hose to constrict as it is stretched, thereby reducing its internal volume. This forces seawater out of the hose, through a check valve, and into the collecting line. After the wave crest has passed and the buoy drops down into the succeeding wave trough, the pump returns to its original length, restoring the hose diameter to its un-stretched value. This increase in internal volume draws water into the hose through another check valve, which is open to the sea. The hose is thus primed to pump seawater into the collecting line during passage of the next wave crest.

In order to provide a reaction point for its pumping action, the bottom end of each hose is tethered to a horizontal damper plate. When the buoy heaves up, it attempts to move this plate vertically through the water. Due to its large surface area, the plate acts like a sea anchor and its motion lags behind that of the buoy. Thus, relative motion between each buoy and damper plate alternately constricts and dilates the hose that is tethered between these two components.

Developed by Gotaverken Energy and Technocean AB, a prototype system was tested near Vinga Island, off Sweden's west coast, in 1983-84. Three buoys were deployed about 600 m from the island and supplied an onshore 30 kW Pelton turbine/generator. Each buoy had a diameter of 5 m (about 1/3 that of a utility-scale power plant buoy). The measured output agreed well with numerical predictions.

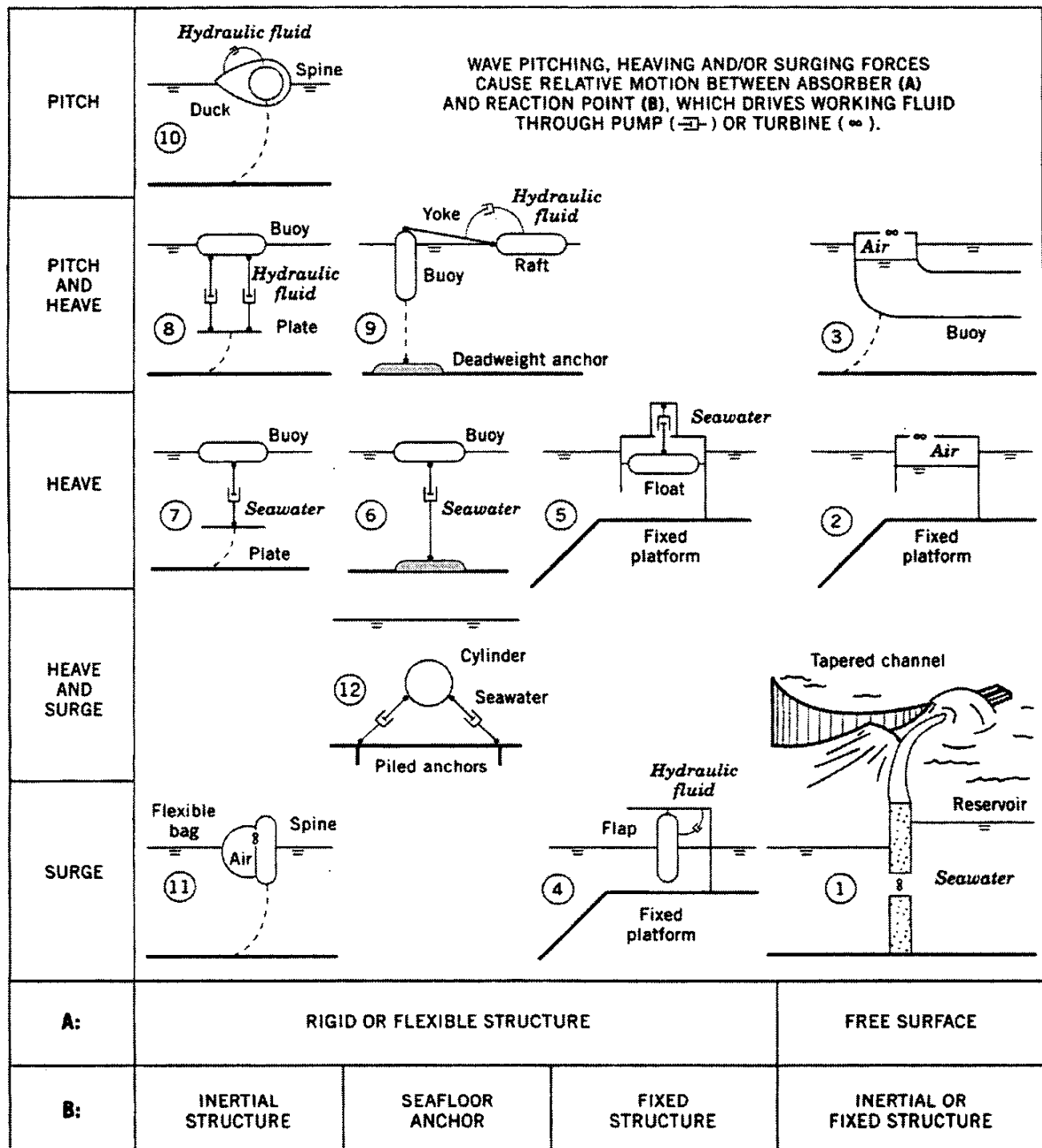


Fig.1 Twelve basic wave energy conversion processes. Device classification scheme is based on mode of energy absorption (pitch, heave, surge, or combined modes), type of absorber, and type of reaction point. The working fluid and type of prime mover strongly affect the hydrodynamic response and relative motions between absorber and reaction point in any given mode.

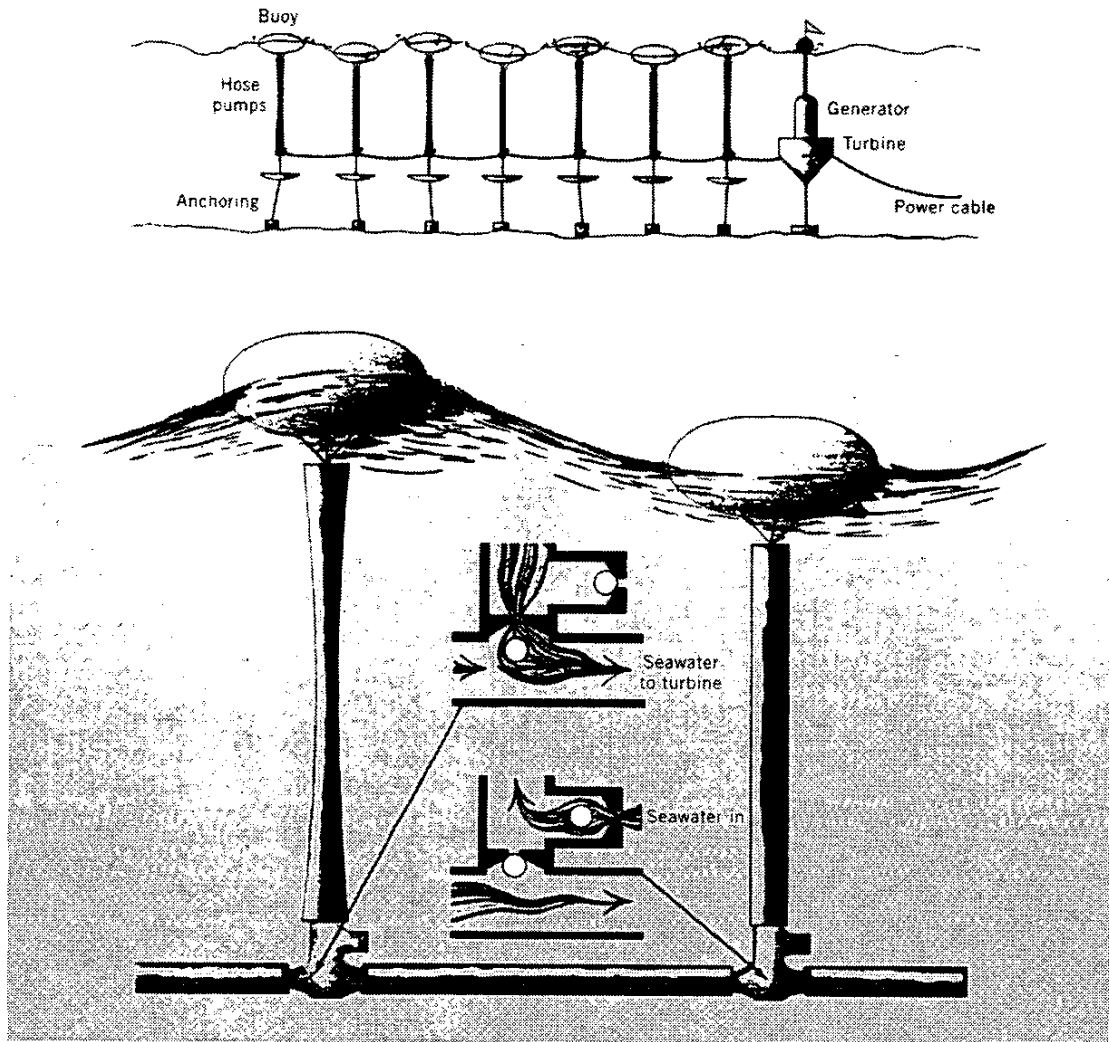


Fig. 2. Swedish heaving buoy concept, in which the reaction point is a suspended damper plate rather than a seafloor anchor. Relative motion between each buoy and damper plate alternately constricts and dilates the elastomeric hose between them. With two check valves as the only moving parts, arranged as shown above, this creates a single-acting pump. These "hose pumps" generate a one-way flow of seawater into a collecting line that leads to a submerged Pelton turbine/generator.

IV. ENABLING TECHNOLOGIES

As attractive as the simplicity of the hose pump is, the complexity of the multi-buoy interconnection and mooring arrangements shown at the top of Fig. 2 makes deployment of this system highly sensitive to sea state, with high probability of installation delays caused by deterioration of ocean or weather conditions. These in-turn would make the system vulnerable to damage should conditions further deteriorate to the point that they might overwhelm anchor-holding or hose coupling capacities, particularly in a partially-installed state that was not designed to withstand severe storm conditions. In 1995, this type of cascading deployment failure caused the multi-million dollar loss of Wavegen's *Osprey 1* prototype, a 2-megawatt caisson-based oscillating water column device. Those events are detailed in [5].

There are two enabling technologies developed for other ocean engineering applications that, when combined with an array of suitably miniaturized heaving buoy and hose pump wave energy devices, yield the basic components of a rapidly relocatable wave-powered AUV dock that can be deployed in a single, relatively brief offshore operation. Each of these enabling technologies is described separately, below.

A. USN Rapidly Deployed Single Anchor Leg Mooring

In 1984-85, the U.S. Navy contracted SOFEC, Inc., of Houston, Texas, to develop and build a Rapidly Deployed Single Anchor Leg Mooring (Ra-De-SALM) capable of mooring tankers of up to 70,000 deadweight tons in water depths up to 60 m, delivering 4,500 m³ of fuel per day to landing forces on shore.

A Ra-De-SALM can be made fully operational within 24 to 48 hours of arrival on site, including deployment of up to 6.4 km (4 miles) of 15 cm (6-inch) diameter flexible conduit between the mooring and beach, with delivery pressures of 4.1 MPa (600 psi). This rapid deployment is accomplished with three tugs or workboats, and two divers.

The Ra-De-SALM anchor base is configured as a towable barge to provide the necessary buoyancy, freeboard, and stability to ensure safe transport of the mooring buoy (which weighs 100 metric tons), and it can be towed at speeds up to 18.5 km/hr (10 knots) using a single towing vessel. The base is 46 m long, 17 m wide, and 3.7 m deep, having very similar dimensions to an ocean deck barge, and can be fabricated by small boat yards. The base has a dry weight of approximately 800 metric tons, which includes solid ballast material. Installation is accomplished by selective flooding of fore and aft flotation tanks. Anchor base retrieval is accomplished simply by de-ballasting these tanks, and the base is fitted with a jetting system to break any suction that might have developed between the base and underlying sediment.

A full ocean test of the system occurred in October 1985 at a depth of 30 m off Cape Charles, Virginia [8]. During this demonstration, the anchor base, mooring buoy, and dual-product delivery hoses were installed in four hours. Connection of the tanker was delayed by passage of Hurricane Gloria, during which time the base, buoy, and conduit remained in place without damage or movement. Following the storm, the tanker was connected and delivered 3,800 m³ of product to beach storage in 20 hours. The system was recovered using the same vessels - no crane barge or other costly heavy-lift equipment was required for retrieval. Ra-De-SALM units of this design were used successfully during Operations "Desert Shield" and "Desert Storm."

B. JAMSTEC Artificial Submerging Seafloor

During the 1990s, the Japan Marine Science and Technology Agency (JAMSTEC), in cooperation with the Iwate Prefecture government, built and deployed two prototype submerging artificial seafloors, to be used for offshore mariculture [9]. The objective of this program was to develop a means of culturing seafood species such as abalone, which normally live in shallow-bottom habitats, in offshore waters where the mariculture operation does not have to compete with other marine activities, which are more intensive near the coast. Offshore waters also are relatively free of pollution compared to coastal waters.

The first platform, *Marine Aya No. 1*, had an artificial seafloor 20 m wide by 20 m long, which could be submerged to a depth 4 m below the sea surface. The second platform, *Ohcyan Marine No. 1*, was deployed from 1996 to 1998 in Funakoshi Bay, where the water depth was 40 m (Fig. 3). This platform had an artificial seafloor 20 m wide by 36.4 m long, and was submerged 7 m below the sea surface. It took 25 minutes to lower the seafloor to its submerged depth and 60 minutes to raise it to the sea surface. A central ballast tank was used for submerging and raising operations, and four corner tanks were used for seafloor attitude adjustment.

Ohcyan Marine No. 1 was anchored to the seafloor with a two-point, all-chain catenary mooring and Danforth anchors. Since the prevailing wave direction was from the east, the two mooring lines were laid along a north-south axis.

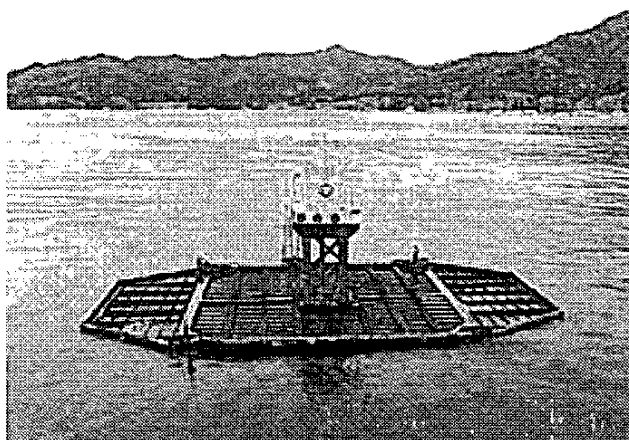


Fig. 3. *Ohcyan Marine No. 1* in raised position.

V. WAVE-POWERED AUV DOCKING PLATFORM CONCEPT

The two enabling technologies described above can be combined to create a wave-powered AUV dock that is rapidly relocatable, with all wave energy buoys pre-moored to an artificial seafloor, which is outfitted with hard piping to manifold the output of multiple hose pumps into a central turbine/generator plant, which can be located in a deckhouse mounted on a central column (Fig. 4).

This approach has many advantages over the existing state-of-the-art in utility-scale wave energy systems. It uses a single, centralized mechanical and electrical plant, which achieves cost economies of scale for the turbine/generator and simplifies plant maintenance. It also enables the absorbers to be fabricated from lightweight, low-cost materials, since they are simple structures without imbedded power equipment.

With absorbers pre-tethered to the artificial seafloor and connected to hard piping at the time of platform outfitting, costly underwater work systems and long weather windows to individually moor and interconnect the absorbers are not required. The system can be installed by setting anchors and flooding ballast tanks in the lower hull. Likewise, it can be retrieved by de-ballasting the lower hull with compressed air, which also provides a means of raising the artificial seafloor to inspect and service the buoys, mooring tethers, and hose pumps, again without needing underwater work systems or divers to inspect or replace these components.

Finally, use of an open-circuit seawater system rather than closed-circuit hydraulics conveys its own advantages:

- No heat build-up in high sea states, and therefore no need for heat exchangers to cool the hydraulic system, which simplifies the mechanical design
- No pollution risk in the event of a piping, check valve or hose pump failure
- Production of fresh water (for cooling electronic equipment) by direct reverse osmosis (see Section III.A)

It should be noted that experience during the months-long sea trials of the hose pump off Sweden indicate that its flexing even in mild seastates keeps fouling organisms from settling.

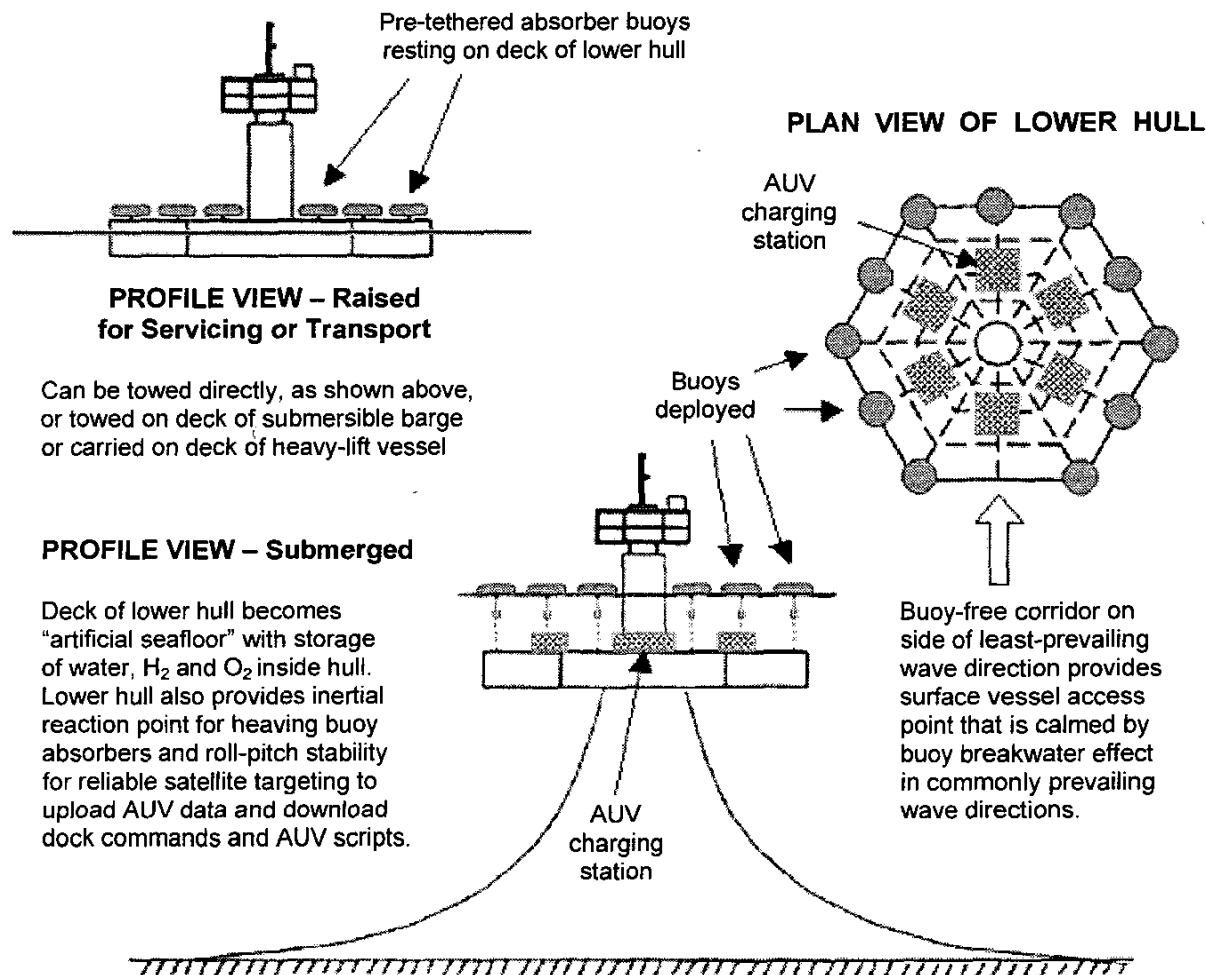


Fig. 4. Wave-powered AUV dock concept, combining heaving-buoy wave energy absorbers with pre-tethered buoy moorings and fluid interconnections (as in Ra-De-SALM), based on submerging lower hull (as in JAMSTEC artificial seafloors: of comparable scale to photo in Fig. 3). Unlike JAMSTEC artificial seafloors, dock lower hull has dry compartments for energy storage systems, consisting of unitized regenerative fuel cells, compressed H_2 and O_2 gas cylinders, and fresh water tanks. Concept drawing shows hexagonal arrangement of six AUV charging stations, each with its own energy storage system.

For the AUV dock concept illustrated above, the following paragraphs establish a notional power budget whereby the time-variable output of the dock's wave power plant is stored for on-demand charging of AUVs docked at the platform to upload data and download mission scripts. The estimated available charging power is then compared with demonstrated underwater AUV charging capabilities.

A. Wave-Powered AUV Dock Energy Budget

Unitary regenerative fuel cell (URFC) technology is a promising candidate for delivering continuous power on demand from the intermittent wave energy resource, particularly since DELBUOY sea trials have proved that heaving-buoy devices can efficiently produce any make-up fresh water that the URFCs might require.

Imagine that the AUV dock has plan dimensions in the range of 20 to 30 m across (similar to *Ohcyan Marine No. 1*), supporting eleven buoys, as shown in Fig. 4. Reported "wave-to-wire" conversion efficiencies for the Swedish hose pump are in the range of 10-30%. If each buoy is 2 m in diameter, and its efficiency is 20%, then the average electric power contribution associated with each buoy would be 2 kW for every 5 kW/m of incident wave energy flux. Assuming that only ten buoys are continually producing, with one always unavailable (due to forced or scheduled outage), then the wave power plant would have an average electric output of 20 kW. Assume that half of this is dedicated to other activities aboard the dock, such as monitoring the immediate vicinity with oceanographic sensors, and maintaining a satellite link for data uploading and command downloading.

The above power budget yields 10 kW of electric power available to the energy storage systems of the AUV charging stations for every 5 kW/m of incident wave energy flux. Assuming a URFC charge/discharge round-trip efficiency of 50%, this in turn yields 5 kW of electric charging power for AUV secondary batteries or rechargeable fuel cells.

A world map showing the global distribution of annual average wave energy flux is presented in Fig. 5, which has been modified after Barstow's original map posted at [10]. In the above wave-powered dock scenario, the incident wave energy flux in kilowatts per meter of wave crest width has a 1:1 correspondence with the charging power available to AUV on-board energy supplies. For example, in the north Atlantic Ocean region between Iceland and the northern British Isles, the annual average incident wave energy flux is 60 kW/m. In this wave climate, the conceptual dock design and power budget outlined above would yield an average of 60 kW of electric power for AUV charging, corresponding to 240 kWh per day at each of the dock's six charging stations.

By comparison, the energy storage module of the AUV for the Atlantic Layer Tracking Experiment (ALTEX) has a capacity of 66 kWh at neutral buoyancy, giving it a mission period of 264 hours at an average power drain that combines 150 watts for propulsion and 100 watts for hotel loads [11]. This gives the AUV a mission range of nearly 1,500 km, traveling at a speed of 5.56 kph (3 knots). It should be noted, however, that the aluminum/oxygen semi-fuel cell embarked on the ALTEX submersible is not electrically rechargeable. The fuel is solid aluminum, and the oxidant is hydrogen peroxide, both of which must be periodically replenished.

Lithium-ion secondary battery technology is a strong contender for embarking a power supply on board an AUV that would be electrically rechargeable [12]. With a specific energy of 135 Wh/kg and an energy density of 450 Wh/m³, a lithium-ion battery to replace the aluminum/oxygen semi-fuel cell in the ALTEX submersible could have a capacity of 45 kWh and still maintain neutral buoyancy of the energy storage module (which displaces 335 kg of seawater). Thus an AUV embarking a lithium-ion battery with the ALTEX propulsion system and payload would have an endurance of 180 hours and an effective range of 1,000 km.

In the notional power budget previously described, each dock charging station has a daily average of 240 kWh available for AUV charging. Assuming a 75% underwater transfer efficiency, then the dock as a whole could support a fleet of 24 ALTEX submersibles (4 x 45 kWh per charging station) while still having an additional 60 kW of sustainable power for dock sensors, computers, and communications equipment; and to supply any undersea cabled observatory to which the docking platform might be connected.

The above scenario illustrates the type of ocean monitoring and under-ice AUV survey capability possible in this region with a modestly sized AUV docking platform, using ocean hardware of comparable dimensions to that already tested at sea. With a fleet of 24 submersibles, one could design a monitoring strategy whereby twelve AUVs always are on mission while twelve AUVs are charged by URFC-delivered wave power. Each charging station would be coupled to two AUVs at once, transferring 60 kWh of energy to each AUV in 24 hours, a required transfer rate of 2.5 kW per vehicle.

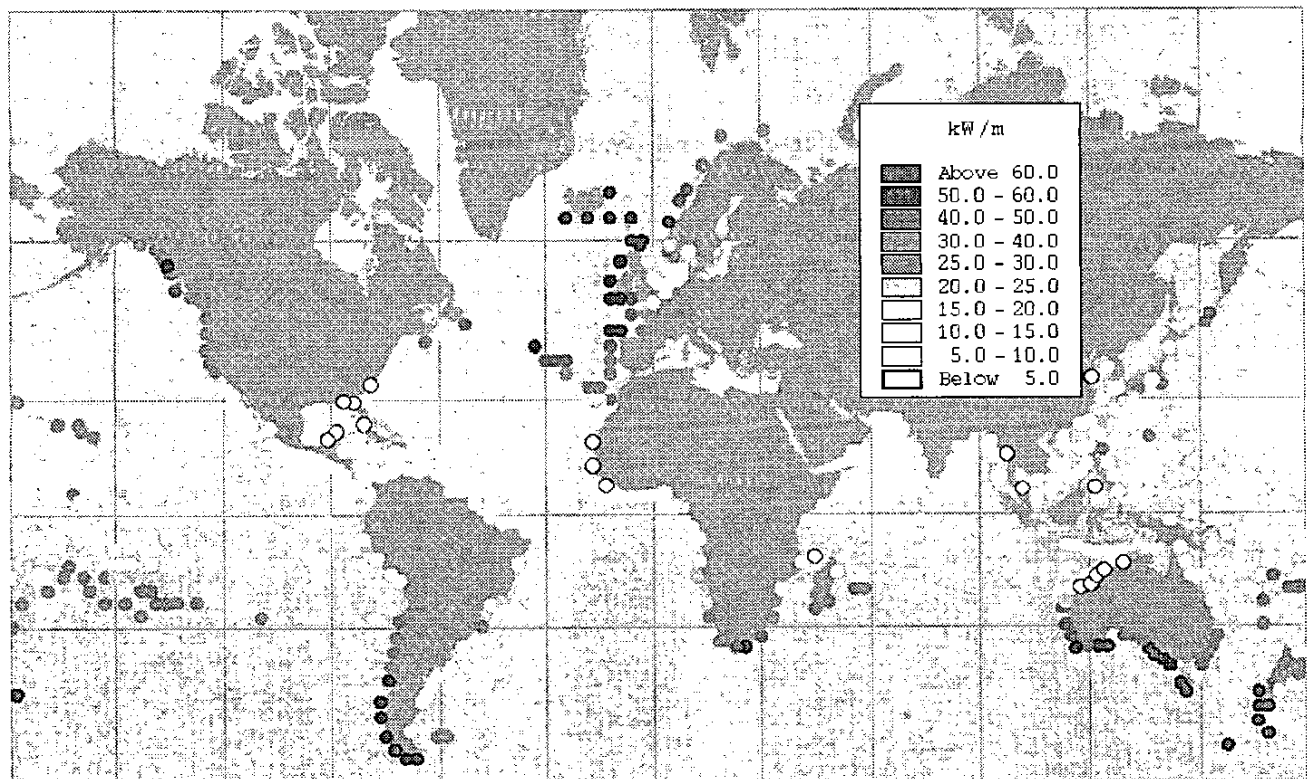


Fig. 5. Global distribution of annual average incident wave energy flux in kilowatts per meter of wave crest width.

B. Underwater Electrical Coupling and Energy Transfer

At least two ocean demonstrations have proved that AUVs can be electrically coupled to a submerged docking station. These are described briefly in the next two paragraphs.

The AUV Laboratory at Massachusetts Institute of Technology (MIT) has developed a docking system capable of supporting the development of Autonomous Ocean Sampling Networks. Using an *Odyssey*-type AUV, the dock can exchange power and data, as well as update mission scripting information and communicate with the surface. The MIT dock utilizes an ultra-short baseline acoustic navigation system to home the AUV into the dock. The dock is approachable from any direction, with its central member being a vertical pole. The vehicle captures the pole with a bow-mounted, forked latch. A horizontal hoop coaxial with the pole drives up the pole bringing the vehicle into contact with inductive cores used for data and energy transfer [13].

In May 1997, sea trials demonstrated that this system is robust with relatively high reliability achieved by scripting the AUV to retry each stage of the docking operation until the exit condition for that stage is achieved. The maximum demonstrated rate of inductive energy transfer was 200 watts, and the entire process was estimated to be 80% efficient [14].

In May 2001, Maridan A/S, together with its project partners, completed sea trials of the Eurodoker project in Kiel Harbor, Germany. The trials of the docking system were performed at various levels in the harbor, ranging from just below the surface to full-depth submergence. As a possible alternative to inductive coupling, this project demonstrated the technology necessary to accomplish the complex task of docking an AUV with wet-mateable connectors for data and energy transfer [15].

Although it was not possible to learn the charge rate demonstrated by Eurodoker in the time available for writing this paper, it appears that the bottleneck in wave-powered AUV charging may be the underwater energy transfer rate relative to the availability of URFC-dispatched wave energy.

VI. NEXT STEPS

In a recent overview paper, Griffiths *et al.* [16] suggest that "AUVs shuttling between moored docking stations is one possible scenario for their early introduction as parts of a sustainable observing system." They also suggest that private capital may finance development of "Platforms specifically designed for sustained observations, bypassing the proving ground of process studies; driven by companies recognizing the market potential of operational oceanography."

The wave-powered AUV dock concept presented herein is derived from hardware components that all have been ocean tested individually but which have never been combined in a value-engineered, integrated design. There is considerable scope for a multi-year research and development program to create and validate a numerical simulation model of this system and to then proceed with the optimization, design, fabrication, and deployment of an ocean prototype. This would open the door to commercial production of relocatable AUV docking and charging stations that can be moored in a wide range of water depths, to support operational oceanography and other ocean monitoring activities.

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