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Subsurface Hybrid Power Options for Oil & Gas Production at Deep Ocean Sites

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Abstract

An investment in deep-sea (deep-ocean) hybrid power systems may enable certain off-shore oil and gas exploration and production. Advanced deep-ocean drilling and production operations, locally powered, may provide commercial access to oil and gas reserves otherwise inaccessible. Further, subsea generation of electrical power has the potential of featuring a low carbon output resulting in improved environmental conditions. Such technology therefore, enhances the energy security of the United States in a green and environmentally friendly manner. The objective of this study is to evaluate alternatives and recommend equipment to develop into hybrid energy conversion and storage systems for deep ocean operations. Such power systems will be located on the ocean floor and will be used to power offshore oil and gas exploration and production operations. Such power systems will be located on the oceans floor, and will be used to supply oil and gas exploration activities, as well as drilling operations required to harvest petroleum reserves. The following conceptual hybrid systems have been identified as candidates for powering sub-surface oil and gas production operations:

1. PWR = Pressurized-Water Nuclear Reactor + Lead-Acid Battery
2. FC1 = Line for Surface O_2 + Well Head Gas + Reformer + PEMFC + Lead-Acid & Li-Ion Batteries
3. FC2 = Stored O2 + Well Head Gas + Reformer + Fuel Cell + Lead-Acid & Li-Ion Batteries
4. SV1 = Submersible Vehicle + Stored O_2 + Fuel Cell + Lead-Acid & Li-Ion Batteries
5. SV2 = Submersible Vehicle + Stored O_2 + Engine or Turbine + Lead-Acid & Li-Ion Batteries
6. SV3 = Submersible Vehicle + Charge at Docking Station + ZEBRA & Li-Ion Batteries
7. PWR TEG = PWR + Thermoelectric Generator + Lead-Acid Battery
8. WELL TEG = Thermoelectric Generator + Well Head Waste Heat + Lead-Acid Battery
9. GRID = Ocean Floor Electrical Grid + Lead-Acid Battery
10. DOC = Deep Ocean Current + Lead-Acid Battery

Background

Importance of Investigation

As oil and gas reserves on shore or in close proximity to shore are exhausted, it will be necessary to develop fields further from shore and at greater depths. At some point, it may prove to be beneficial to locate both the production equipment, as well as the associated power generation equipment on the ocean floor. This study has explored a variety of conceptual hybrid power generation options for such applications, each evaluated at eight representative deep-ocean concept-of-operations (con-ops) sites.

An investment in sub-sea (deep-ocean) hybrid power systems is required to enable off-shore oil and gas exploration and harvesting. Advanced deep-ocean drilling operations, locally powered, will provide access to oil and gas reserves otherwise inaccessible. Such technology will therefore enhance the energy security of the United States. The oil and gas industry is being pushed beneath the surface by economic concerns. According to The Economist (September 8th – 14th 2007), there is a "sea change" in off-shore drilling technology. In regard to off-shore technology, they state that "rising costs and clever kits are transforming the oil-platform, and could even do away with it all together." The article discusses the cost and manpower required to operate a typical oil and gas platform in the middle of the North Sea. There are 435 such platforms in the British waters of the North Sea alone. In regard to costs, the Alwyn North Oil and Gas Platform was built for a cost of £1.5 billion ($2.4 billion) in the mid 1980's and has spent nearly half that amount upgrading the platform since its construction. Operation of this platform requires that approximately 300 personnel live aboard, with each receiving 3-weeks leave for every 2 weeks on the platform, and an associated cost for flying each to and from the platform being £1,000. According to Oil and Gas United Kingdom, an industry group, oil firms spent over £11 billion last year building and running offshore facilities in British waters alone. Such operating costs places production costs for one barrel of oil at $22 per barrel, which is nearly the highest in the world. These costs are rising rapidly. The Deutsche Bank estimates that inflation in the oil business has run at 30% a year over the past two years, and will continue to rise by at least 15% per year through 2008. The article goes on to state:

> *"No wonder, then, that firms are determined to reduce the expense of producing oil at sea, in the North Sean and elsewhere."*
>
> *"Even more distant fields can be tied back to a platform using pipelines along the sea floor. In a tie-back, the valves that open and close the well are located not on the rig, but on the sea floor; engineers operate them by rmote control. Several deposits of oil and gas, including Nuggets, a cluster of gas fields over 40 km away, are linked to Alwyn North in this way. Next, Total plans to connect a new discovery called Jura to the platform. As a result, the lifespan of Alwyn North, estimated at 10 years when it first started production in 1987, has been extended to over 40 years, while its projected output has almost quadrupled."*
>
> *"The next logical step is to put more equipment underwater, in the hope of dispensing with platforms altogether. Statoil, for example, is tapping a gas filed called Snohvit, which lies 143 km off-shore, without using a platform. But this is possible only because the pressure of the field is strong enough*

> *to keep the gas flowing through the long pipeline back to offshore. Norsk Hydro, another Norweigian energy firm on the verge of merging with Statoil, has developed another gas field, Ormen Lange, in the same way. But in a few years a compressor that can work underwater will be needed to supplement the falling pressure in the field. Last year, Norsk Hydro hired General Electric (GE), an American industrial giant, to build a prototype.*
>
> *"Fifteen years from now, "says Claudi Santiago of GE, "The vision is that offshore platforms will disappear."*
>
> *"Or maybe not … If some way can be found to liquiefy gas offshore, Mr. Santiago points out, then deposits that are currently too remote for the construction of pipelines could be developed, and the gas transported in liquid form by ship instead. That would give offshore platforms a whole new life."*

Clearly, there is a strong driving force for the development of sub-sea capabilities on the ocean floor. Such facilities will require ample supplies of local power to operate machinery on the floor, ranging from drills to pumps and compressors. Once can even envision safe, efficient and economical submarine tanker fleets to transport fuel, thereby eliminating the need for pipline construction and transport altogether. Such tankers could rely on natural-gas powered fuel cells, with power system construction analogous to that of the publicized HDW sub-sea vessels.

<u>Concept-of-Operation Sites Serving as Basis for Study</u>

Eight representative deep-ocean concept-of-operations (con-ops) sites with a wide range of locations, depths, tie-back distances, and power requirements, were selected for this study and are summarized in Table 1. Shtokman (Barents Sea) and Ormen Lange (Norway) have the greatest requirement for electrical power, at approximately 240 and 60 megawatts-electrical, respectively, and also have the greatest tie-back distances, 209 and 193 miles, respectively. The sites at the greatest depths are Chinook and Perdido (Gulf of Mexico), located at approximately 8,800 and 7,999 feet respectively, but have relatively short tie-back distances of approximately 12 miles, and modest power requirements, 7.2 and 5 megawatts-electrical, respectively. The Marimba Field (Campros Basin) has the least power requirement, at only 80 kilowatts-electrical, is located at a depth of only 1,296 feet, and has a tie-back distance of only 1 mile. While the power requirements, tie-back distance, and location for Shtokman and Ormen Lange appear to be sufficiently challenging to warrant extraordinary measures for power, it would be surprising if such measures could be justified at the Marimba Field. All have been included in this study to provide a wide range of scenarios.

<u>Hybrid Energy Conversion and Storage Systems Considered</u>

Based upon a preliminary screening of power generation and energy storage technologies, ten conceptual, energy conversion and storage, hybrid systems were developed for evaluation at each of the eight con-ops sites. These conceptual hybrid systems are summarized in Table 2 and repeated below:

1. PWR = Pressurized-Water Nuclear Reactor + Lead-Acid Battery
2. FC1 = Line for Surface O_2 + Well Head Gas + Reformer + PEMFC + Lead-Acid & Li-Ion Batteries
3. FC2 = Stored O2 + Well Head Gas + Reformer + Fuel Cell + Lead-Acid & Li-Ion Batteries
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Energy Conversion Technologies

Several energy conversion technologies have been considered: (1) proton-exchange membrane fuel cells powered with hydrogen and oxygen, similar to that used on proven subsurface vessels; (2) fuel-cells capable of using natural gas from deep-ocean wells; (3) internal combustion engines powered with natural gas from deep-ocean wells; (4) turbines powered with natural gas from deep-ocean wells; (5) solid-state thermoelectric and thermionic generators powered with natural gas from deep-ocean wells, geothermal sources, and radioisotopes; (7) renewable energy sources at the surface, including solar, wind and wave powered generators; (9) renewable energy sources on the sea floor, including turbines powered with ocean current; and (8) small pressurized-water reactors with low-enrichment fuel, similar to those used on the NS Savannah and NS Otto Hahn commercial ships (Appendix A, Figure A1). The performance characteristics of the leading candidates are summarized in Table 3.

<u>Nuclear Energy</u>

At the present time, there are more than 441 light water reactors (LWRs) worldwide, withy a total generating capacity of 358.7 GWe (Appendix A, Table A1). These reactors have generated more than 171,000 metric tons of spent nuclear fuel that must be stored at reactor sites, reprocessed, or ultimately disposed of in geologic repositories (Appendix A, Table A2).

Small modular nuclear reactors are currently being investigated for deployment at remote locations (Appendix A, Table A3). The m-Power reactor being developed by Babcock and Wilcox (B$W) of Lynchburg, Virginia is discussed in a front-page article of the Wall Street Journal [Smith 2010], and leverages a long history of success with earlier designs (Appendix A, Figures A2 through A4). This small PWR has a power of 125 megawatts, a coolant temperature and pressure of 620°F (600K) and 2000 psi (14 MPa), and a steam pressure of 1000 psi (7 MPa). The m-Power reactor has a volume of 158 cubic meters and a weight of 500 metric tons. It is fueled with uranium enriched to 7.0 percent U-235. This modular reactor has been designed to have an endurance of 1,825 days (time between refueling operations). The m-Power reactor has extremely high specific power, power density, specific energy and energy density: 250 W/kg, 792 W/L, 10,950,000 Wh/kg, and 34,672,967 Wh/L, respectively.

Small modular nuclear reactors are capable of producing immense electrical power, and require relatively little mass or volume. This has led to their application in military ships and boats, including aircraft carriers and submarines. Nuclear powered submarines of several countries have now operated in the oceans of the world for nearly fifty years. While such military systems are both unavailable and inappropriate for the oil and gas industry to consider, other types of nuclear power plants have been successfully deployed onboard commercial ships. For example, compare the Babcock and Wilcox (B&W) pressurized water reactor (PWR) used to power the NS Otto Hahn with the power available from high-performance automotive and aircraft engines:

- Auto and Aircraft Engines: 100-1000 kW / 0.9 to 1.1 kW/kg
- NS Otto Hahn PWR: 38 MW / 22.4 kW/kg / 4.8 to 105 kWh/kg

The NS Otto Hahn and NS Savannah Nuclear had displacements of 16,871 and 22,000 metric tons, and had pressurized water reactors capable of producing 38 and 74 megawatts, respectively. The NS Otto Hahn had a core volume of 35 cubic meters, and was fueled with 1.7 metric tons of uranium enriched to 3.5 to 6.6 percent U-235. This nuclear powered ship had an endurance of 900 days (time between refueling operations).

NS Otto Hahn Nuclear Powered Ship (1964-79)

- Builder Howaldtswerke Deutsche Werft AG of Kiel
- Displacement: 25,790 tons (Full); 16,871 tons (Standard)
- Length: 164.3 m (Waterline); 172.0 m (Overall)
- Beam: 23.4 m

Nuclear Reactor on NS Otto Hahn

- Deutsche Babcock & Wilcox-Dampfkesselwerke AG und Internationale Atomreaktorbau GmbH
- Reactor Power: 38 MW
- Volume: 35 m^3
- Pressure: 85 kp/cm^2 (8.3 MPa)
- Temperature: 300°C
- Fuel: 1.7 metric tons of 3.5-6.6% enriched uranium
- Endurance under full load: 900 days
- Average fuel burn-up: 23,000 MW day ton^{-1}
- Average thermal neutron flux: 1.1×1013 cm^{-2} s^{-1}
- Number of elements/fuel rods: 12/2810
- Equivalent minor diameter: 1050 mm
- Active core height: 830 mm
- Fuel rod diameter: 11.4 mm
- Fuel cladding: 0.8 mm of Zircaloy-4

NS Savannah Nuclear Powered Ship (1970-79)

- New York Shipbuilding, Camden, NJ
- Displacement: 22,000 tons
- Overall length: 596 ft (180 m)
- Beam: 78 ft (23.8 m)
- Load carrying capacity: 14,040 tons
- Watertight compartments: 14
- Loading spaces: 6
- Complement: 124 crew, 60 passengers
- Single propeller: 20,300 hp
- Cruising speed: 21 knots (40 km/h)
- Top speed: 24 knots (47 km/h)

Nuclear Reactor on NS Savannah

- Manufacturer: Babcock & Wilcox
- Power: 74 MW

Other reactor-driven technologies also exist, such at the SNAP 8 reactor-powered Rankin Cycle, which used mercury as the working fluid. Such systems could provide vast amounts of energy for oil and gas facilities on the sea floor. These systems will be explored as part of the proposed study, and will be compared to competing technologies.

PEMFC Powered with Hydrogen from Well Head Gas Reformer

The high reliability of fuel cells, coupled with high energy density, have led to their use in a variety of demanding applications, ranging from space exploration to sub-sea vessels with long endurance. Proton-exchange membrane fuel cells, with solid-state hydrogen storage and liquid oxygen have been developed and used by HDW in Kiel Germany for powering small sub-sea vessels (Figures 5 through 8). A variant of this air-independent-propulsion system has also been developed which substitutes hydrogen-powered Sterling engines for the PEM fuel cell. These small and efficient submarines have now been produced in relatively large numbers. Thus, the viability of sub-sea fuel-cell systems for demanding large-scale applications has been unambiguously demonstrated.

The components of the fuel cell system used by HDW shipyard in Kiel, Germany aboard sub-sea vessels such as the Class 212A Submarine (Appendix B, Figures B1 through B4). This subsea vehicle is powered by a proton-exchange membrane fuel cell (PEMFC), and has solid-state hydrogen storage canisters that are filled with iron-titanium hydride. The oxygen for this oxygen-breathing electrochemical energy conversion system is stored in a cryogenic tank.

The most obvious extension of HDW-type technology to sea floor operations for the oil and gas industry could involve the use of subsea vehicles to bring air to the ocean floor so that well head methane could be burned by on-board fuel cells, internal combustion engines, or gas turbines to generate local power for well-head equipment, such as drilling and pumping stations. Alternatively, such vehicles could carry large battery packs to the ocean floor, after charging at the surface with renewable sources of energy. Such mobile systems could also be used as subsea tankers, helping mitigate the need for pipelines for transporting oil and natural gas.

Natural gas from deep-ocean wells would be a logical energy source for supplying sub-surface fuel cells at deep-ocean production sites. The composition and properties of oil and gas for typical subsea wells have been published in the literature (Appendix C, Tables C1 through C5 and Figures C1 through C3) [Gonzalez SPE 110833]. Natural gas from the well could be converted to hydrogen via a reformer, and fed to an environmentally benign, ambient temperature PEMFC via gas purification membranes, required to filter out electro-catalytic poisons, including carbon monoxide and sulfur-bearing chemical species. This option could potentially eliminate the need for pipelines to transport natural gas away from subsea well heads. Alternatively, the natural gas could be used directly to fuel a high temperature solid oxide fuel cell (SOFC), though the operation of such a high temperature system on the sea floor poses additional complications.

The steam reforming of natural gas (NG) or methane (CH_4) from the well head to hydrogen that can be burned in a proton exchange membrane fuel cell (PEMFC) occurs via two sequential reactions. The first reaction is:

$$CH_4 + H_2O \longrightarrow CO + 3H_2$$

This reaction is endothermic with an estimated heat-of-reaction of approximately 206.16 kJ per mol-NG (57.27 Wh/mol-NG or 3,579 Wh/kg-NG).

$$CO + H_2O \longrightarrow CO_2 + H_2$$

This reaction is moderately exothermic with an estimated heat-of-reaction of approximately -41.16 kJ per mol-NG (-11.43 Wh/mol-NG or -715 Wh/kg-NG). The overall chemical reaction involved for the conversion of methane to hydrogen in the reformer is:

$$CH_4 + H_2O \longrightarrow CO_2 + 4H_2$$

This reaction is moderately endothermic, with an estimated heat-of-reaction of approximately 165.00 kJ per mol-NG (45.83 Wh/mol-NG or 2,865 Wh/kg-NG). As an approximation, it is assumed that both products and reactants are gases at ambient temperature and pressure. The overall efficiency of the reformer is assumed to be approximately 70-85%, which is representative. Hydrogen from the reformer is then burned in the PEMFC via the following reaction:

$$4H_2 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

The difference in enthalpy between the products and reactants is approximately -241.83 kJ per mol-NG (-67.18 Wh/mol-NG or -4,198 Wh/kg-NG). The corresponding change in Gibbs free energy is reflected in the electrochemical potential for this reaction, which under standard conditions is approximately 1.23 volts. The efficiency of the PEMFC is assumed to be approximately 65-75%, which is representative. The overall reaction for the conversion of methane to CO_2 and H_2O in the combined reformer and fuel cell system is:

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

The difference in enthalpy between the products and reactants is approximately -802.32 kJ per mol-NG (-222.87 Wh/mol-NG or -13,929 Wh/kg-NG).

Turbine or Internal Combustion Engine Power with Natural Gas from Well Head Gas Reformer

The reaction for burning methane in an internal combustion engine or turbine is:

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

The difference in enthalpy between the products and reactants in this case is also approximately -802.32 kJ per mol-NG (-222.87 Wh/mol-NG or -13,929 Wh/kg-NG).

Gas Turbine or Internal Combustion Engine Powered with Natural Gas from Well Head

The reaction for burning methane in an internal combustion engine or turbine is:

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

The difference in enthalpy between the products and reactants in this case is also approximately -802.32 kJ per mol-NG (-222.87 Wh/mol-NG or -13,929 Wh/kg-NG).

Thermoelectric Generator Powered by Heat from Well-Head or Nuclear Reactor

Solid-state thermoelectric generators have no moving parts, and can be used for the reliable direct conversion of heat to electrical energy, with exceptional reliability in remote and inaccessible locations, including deep space. Such energy converters could be powered on the sea floor in a variety of ways, including geothermal heat sources, heat from the combustion of natural gas from deep ocean wells, decay heat from radioisotopes, and small deployable nuclear reactors. Examples of thermoelectric generators that have been powered by small nuclear reactors and radioisotope sources include:

- SNAP 10: Reactor-Powered Thermoelectric Generator
- SNAP 19: Radioisotope Thermoelectric Generator
- SNAP 27: Radioisotope Thermoelectric Generator

Radioisotope sources with the necessary power density for the applications of interest to the oil and gas industry are believed to be too limited for serious consideration, but are included for completeness. Small deployable proliferation-resistant reactors may become a viable option in the coming years, and are now being considered for other applications.

Thermoelectric power generators are p-n junctions in which charge carriers and heat flow in parallel. Electrons and holes must acquire energy at the p-n junction to flow in a direction opposite to the temperature gradient (from cold to hot). Both ohmic heating and heat conduction must be minimized for the efficient operation of such devices. The thermodynamic efficiency of a thermoelectric power generator (η) is calculated from the dimensionless figure-of-merit (ZT). The dimensionless figure of merit, ZT, is determined by Seebeck coefficient (α), electrical conductivity (σ), electronic thermal conductivity (κ_{el}), and lattice thermal conductivity (κ_{ph}).

$$ZT = \frac{\sigma \alpha^2}{\kappa_{ph} + \kappa_{el}} T$$

The expressions for η at the optimum current level is

$$\eta = \frac{T_h - T_c}{T_h} \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + T_c / T_h}$$

T is the average temperature of the device, T_h is the hot temperature and T_c is the cold temperature. To achieve high values of η with a thermoelectric device, a material with a large ZT value must be found. Commonly used materials and the dependence of η on ZT, T_c and T_h can be found in the appendices (Appendix D, Table D1 and Figure D1)

The efficiencies of thermoelectric generators are limited by the properties of the solid state materials used in their construction, and the available temperature gradient. Promising thermoelectric materials should have high power factors ($\sigma\alpha^2$) and low thermal conductivities ($\kappa_{ph}+\kappa_{el}$). Furthermore, such materials should be plentiful enough (and sufficiently inexpensive) to enable the possible construction of large-scale devices. Degenerate semiconductors have the best combinations of these intrinsic properties.

Deep Ocean Currents

The use of deep ocean currents as an environmentally benign method of supplying power will also be investigated. Swiftly flowing ocean currents represent a significant untapped renewable energy resource. State-of-the art turbine designs will technology will be investigated collaboratively with these potential vendors and industrial partners from the oil and gas industry. The successful deployment of this energy conversion technology requires detailed knowledge of oceanographic parameters, including seasonal currents, surface wind and wave fields. Secondary ocean characteristics that must also be taken into consideration include: biological fouling potentials, the stability of the local sediments, their ability to accept moorings, and the potential for catastrophic storms.

While the conversion of deep ocean currents to electrical power is analogous to the conversion of terrestrial winds to electrical power, obvious differences in operating environment lead to very different mechanical and electrical designs. The turbines used for deep ocean applications are heavier and less agile than those used for wind generation since the density of seawater is three orders-of-magnitude greater than the density of air, and since ocean current velocities are less and more predictable than those of wind.

GCK is developing the Gorlov Helical Turbine (GHT). This technology provides a source of electricity by extracting the kinetic energy from flowing water (Appendix E, Figure E1). It is designed for hydroelectric applications in free flowing watercourses. The GHT is a cross-flow turbine with airfoil-shaped blades that provide a reaction thrust that can rotate the GHT at twice the speed of the water flow. It is self-starting and can produce power from a water current flow as low as about 3 knots (1.5 m/s) with power increasing in proportion to the water velocity cubed. A thorough review of turbine technologies, such as those developed by GCK, OpenHydro and others will be done. The readiness of this technology for deployment will be determined, using results from testing.

System design must consider under-water maintenance issues. The unavoidable corrosion and bio-fouling of turbine materials complicates the deployment of such deep ocean systems. However, recent advances in material technology, such as the use of thermal-spray coatings of high-performance corrosion-resistant amorphous-metal alloys, anti-fouling coatings, and carefully designed cathodic protection systems promise to mitigate such problems. Given the scale of the energy systems that are required, these materials will also need to be economical, minimizing the use of expensive alloying elements such as those used in conventional high-performance Ni-Cr-Mo alloys.

Energy Storage Technologies

Energy storage must be integrated with the selected energy conversion technology, thereby creating a hybrid system capable of providing a constant source of electrical power for pumps, drill motors, and other equipment. For example, turbines driven by fluctuating currents of wind and ocean will produce unsteady current, which will have to be rectified and used to charge batteries, which in turn can be used as a steady source of electrical power for pumps and motors.

The energy storage technologies that will be explored include: compressed-gas storage; liquid red-ox batteries; secondary batteries in sealed pressure vessels; pressure-tolerant secondary batteries; and other systems. Various energy storage technologies will be considered, and will include a wide range of conventional & unconventional batteries will be considered.

- Mechanical flywheels
- Compressed-gas storage
- Regenerative liquid red-ox batteries
- Lead-acid batteries
- Silver-zinc batteries
- Sodium-beta batteries
- Lithium-ion batteries
- Regenerative fuel cells

From this list of options, only the rechargeable batteries and the regenerative fuel cell were evaluated in detail. A summary of key attributes of energy storage options used to assess hybrid system options is presented in Table 4 with additional information is given in the appendices (Appendix F, Table F1 and Figures F1 through F6).

Lead-Acid Batteries

The lead-acid battery has a metallic anode made of a lead alloy, a lead-oxide cathode, a porous polyethylene separator, and an electrolyte of concentrated sulfuric acid. This battery can operate from -20 to +60°C. The open-circuit voltage is 2.1 V, with operation between 2.0 and 1.75 V. The specific power, power density, specific energy and energy density are 20 W/kg, 51 W/L, 20-35 Wh/kg, and 50-90 Wh/L, respectively. The cycle life of a typical lead acid battery can be as long as 1100 cycles (to 80% of the original capacity). The cost of energy storage is approximately $150 per kilowatt-hour. In summary, lead-acid batteries are proven technology, with a long history of sub-surface application in submarines. The lead-acid battery is relatively heavy, but is expensive and should be considered for the RPSEA application.

Silver Zinc Batteries

The silver-zinc battery has a metallic anode made of a zinc alloy, a silver-oxide cathode, a cellophane separator, and an electrolyte of 40% potassium hydroxide. This battery can operate from -20 to +60°C. The open-circuit voltage is 1.86 V, with operation between 1.7 and 1.3 V. The specific power, power density, specific energy and energy density are 5560-1470 W/kg, 9530-2520 W/L, 105-110 Wh/kg, and 180-300 Wh/L, respectively. The cycle life of a typical silver-zinc battery is limited, with a maximum live of approximately 250 cycles (to 80% of the original capacity). The cost of energy storage is approximately $600 per kilowatt-hour, which reflects the high cost of the silver used in the cathode. In summary, lead-acid batteries are proven technology, with a long history of sub-surface application in torpedoes and other sub-surface vehicles. The silver-zinc battery is relatively expensive, suffers from short cycle life, but has exceptional specific power and power density, and specific energy and energy density rivaling that possible with state-of-the-art (SOA) lithium-ion batteries. The limited cycle life prevents it from be a good candidate for RPSEA applications.

Sodium-Sulfur Batteries

The sodium-sulfur battery is categorized as a sodium-beta battery. It has a molten sodium anode, a β''-Al_2O_3 ceramic separator, which also serves as the solid-state, Na^+-conductive electrolyte, and a molten sulfur cathode. This battery is challenged by the need for a relatively high operating temperature of 290 to 390°C. The open-circuit voltage is 2.08 V, with operation between 1.95 and 1.78 V. The specific power, power density, specific energy and energy density are 390-250 W/kg, 604-386 W/L, 117-226 Wh/kg, and 147-370 Wh/L, respectively. The sodium-sulfur battery has exceptional cycle life, with a maximum life of approximately 2,250 cycles (to 80% of the original capacity), making it a reasonable choice for remote deployment where maintenance would be difficult. Despite the use of molten alkali electrodes, which can react with air and water, this battery has a very good safety record. No gaseous reaction products are formed during overcharge, and the separator tends to be self-healing. The cost of energy storage is approximately $300 per kilowatt-hour, which is modest. In summary, sodium-sulfur batteries are proven technology, with a solid history of applications in grid-storage (NGK Corporation of Japan). The sodium-sulfur battery is a reasonable contender for RPSEA sub-surface applications, but will require insulated battery bottles, and auxiliary heating equivalent to approximately 10% of the batteries stored energy [Reference: Joseph C. Farmer, Lawrence Livermore National Laboratory, 2009].

ZEBRA Batteries

The ZEBRA battery is also categorized as a sodium-beta battery, like the sodium-sulfur battery. The ZEBRA also has a molten sodium anode and a β''-Al_2O_3 ceramic separator, which also serves as the solid-state, Na^+-conductive electrolyte, but has a $Ni/NiCl_2$ cathode with a secondary $NaAlCl_4$ electrolyte, instead of the sulfur-based cathode used in the sodium-sulfur battery. This battery is also challenged by the need for a relatively high operating temperature of 220 to 450°C. The open-circuit voltage is approximately 2.58 V, with operation believed to occur between 2.25 and 1.72 V, slightly higher than the terminal voltage of the sodium-sulfur battery. The specific power, power density, specific energy and energy density are 171-169 W/kg, 265-261 W/L, 94-119 Wh/kg, and 148-183 Wh/L, respectively, lower than that possible with sodium-sulfur technology. The ZEBRA battery has exceptional cycle life, even better than that achieved with the sodium-sulfur battery, with a maximum life of approximately 3,500 cycles (to 80% of the original capacity), making it a reasonable choice for remote deployment where maintenance would be difficult. The cost of energy storage is only $220 per kilowatt-hour, which is less than that for the sodium-sulfur battery. In summary, sodium-sulfur batteries are proven technology, with a solid history of applications in transportation (electrical school buses for the Sacramento Utility District, and delivery vans in Europe), grid-storage (Canada), and deep-ocean applications (NATO DSRV, or deep-sea rescue vehicle). The ZEBRA battery is a reasonable contender for RPSEA sub-surface applications, but will require insulated battery bottles, and auxiliary heating equivalent to approximately 10% of the batteries stored energy [Reference: Joseph C. Farmer, Lawrence Livermore National Laboratory, 2009].

Lithium Ion Batteries

The modern lithium-ion battery has: an anode that consists of a graphite-based active material (Li-C6) with carbon filler and PVDF binder coated onto a copper foil current collector; a cathode that consists of a transition metal oxide or iron phosphate (Li-NiO_2, Li-CoO_2, Li-MnO_2, or Li-$FePO_4$) active material with a PVDF binder coated onto an aluminum foil current collector; a microporous porous polyethylene separator, and an electrolyte consisting of a mixed organic carbonate solvent (EC:DMC:DEC) and $LiPF_6$ salt. Of course, more advanced materials are evolving, such as the lithium titanate anode (Li-Ti_2O_4) and solid state electrolytes such as LiPON™. The liquid cylindrical or prismatic cells are contained in a hermetically sealed metal can, while polymer-gel cells are contained in a soft aluminum-polyethylene laminate package, with thermally laminated seams. In the case of the polymer-gel cell, the polyethylene separator is usually coated on both sides with porous PVDF layers. This battery can operate from -40 to +60°C. The open-circuit voltage is 4.1 V, with operation between 4.0 and 3.0 V (possibly as low as 2.8 V). The specific power, power density, specific energy and energy density are 1100-74 W/kg, 2270-147 W/L, 75-182 Wh/kg, and 139-359 Wh/L, respectively. The cycle life of the best state-of-the-art lithium-ion batteries can be as great as 1500 cycles (to 80% of the original capacity). However, poorly constructed cells can have much shorter lives (300 cycles representing poorer cells). Based upon published data, the cost of energy storage is believed to be approximately $300 per kilowatt-hour (though some quote $1000 per kilowatt-hour). In summary, lithium-ion batteries are proven technology, and are leading candidates for terrestrial electric vehicles. This technology has also enjoyed limited but successful use in autonomous underwater vehicles used for oceanographic research. Unfortunately, lithium ion batteries have been plagued by a history of significant safety incidents, with some causing serious human injury and property damage (loss of commercial cargo plane, for example). The lithium-acid battery may prove to be relatively expensive, has safety issues that must be dealt with, but has exceptional performance characteristics, that make it a leading candidate for consideration. Designs would have to emphasize safety, thermal management during charge and discharge, and enhanced battery management systems.

Regenerative Fuel Cells

During discharge, regenerative fuel cells burn stored hydrogen and oxygen, with the production of electricity and water. Due to the energy penalty associated with separating pure water from seawater (theoretical minimum of 2.5 Wh/gal, with actual values of 24-36 Wh/gal required for separation with reverse osmosis), the pure water produced by the oxidation of hydrogen in the fuel cell is stored during discharge. During recharging, this stored water is electrolyzed, with the formation of both hydrogen and oxygen, which is stored. In this case, we assume that the gases would be stored in bottles at a pressure of approximately 10,000 pounds per square inch absolute (psia). Assuming that a proton exchange membrane fuel cell (PEMFC) is used as the basis for this system, the air cathode would consist of a dispersed platinum catalyst on a porous carbon substrate, the hydrogen anode would consist of a dispersed platinum or platinum-ruthenium catalyst on a porous substrate, and the electrolyte is a polymeric cation-exchange membrane made of a material such as Nafion™. The operating temperature of a PEMFC ranges from 30 to 120C°. The open circuit voltage of such a regenerative fuel cell would be approximately 1.2 V, while the expected operating voltage under load would be 0.5-0.7 V. The specific power and power density of such a system would be approximately 27 W/kg and 17 W/L, while the specific energy and energy density would be approximately 326 Wh/kg and 209 Wh/L, respectively. Such systems provide greater specific energy and energy density than SOA secondary batteries, but have limited power density. The power density dictates the size of such systems in high power applications. Therefore, regenerative fuel cells are not considered good choices for the RPSEA application.

Hybrid Energy Conversion and Storage Systems

Hybrid systems use energy conversion devices with high specific power to efficiently achieve high levels of current, and energy storage devices with high specific energy to enable sustained operation in the event that the primary power generation systems fails. Typical ranges of power and energy densities are given in the appendices (Appendix G, Figure G1). The following combinations of energy conversion and storage devices have been evaluated in this study as candidate hybrid systems for powering subsea oil and gas production operations:

1. PWR = Pressurized-Water Nuclear Reactor + Lead-Acid Battery
2. FC1 = Line for Surface O_2 + Well Head Gas + Reformer + PEMFC + Lead-Acid & Li-Ion Batteries
3. FC2 = Stored O2 + Well Head Gas + Reformer + Fuel Cell + Lead-Acid & Li-Ion Batteries
4. SV1 = Submersible Vehicle + Stored O_2 + Fuel Cell + Lead-Acid & Li-Ion Batteries
5. SV2 = Submersible Vehicle + Stored O_2 + Engine or Turbine + Lead-Acid & Li-Ion Batteries
6. SV3 = Submersible Vehicle + Charge at Docking Station + ZEBRA & Li-Ion Batteries
7. PWR TEG = PWR + Thermoelectric Generator + Lead-Acid Battery
8. WELL TEG = Thermoelectric Generator + Well Head Waste Heat + Lead-Acid Battery
9. GRID = Floor Electrical Grid + Lead-Acid Battery
10. DOC = Deep Ocean Current + Lead-Acid Battery

The intrinsic advantages of fuel cell systems include: high energy density, which scales linearly with the quantity of fuel stored within the system or available at the site where the fuel cell is operated; exceptional reliability; and the possibility of environmentally benign low-noise and low-temperature operation. Unfortunately, while such systems generally have high energy density, their power density is relatively low, as shown in Figure 16. However, a hybrid system combining a fuel cell and storage battery can be designed that has both the high energy density of a fuel cell, as well as the high power density and steady current flow of a storage battery. Such stored energy is also required for control systems, startup, and to enable the system to tolerate fluctuations in fuel, oxidant and load.

Technical Approach

Concept-of-Operation Sites

Sizing of the hybrid energy conversion and storage system for each site requires knowledge of the power required to operate the oil and gas production equipment at the site (P_{site}), the tie-back distance at the site (T_{site}), which determines the length of cable that must be laid for the electrical grid option, and the depth of the site (D_{site}), which determines the pressure that the equipment must operate at, as well as the length of air supply line that must be extended to the site from the surface.

Sizing Energy Conversion Device for Each Site

The weight and volume of an energy conversion system (W_{EC} and V_{EC}) for a particular site is based upon the total power required by the site ($Power_{site}$), the specific power of the energy conversion device (SP_{EC}), the power density of the device (PD_{EC}), and the efficiency of the device (η_{EC}).

$$W_{EC} = \frac{Power_{site}}{\eta_{EC} \times SP_{EC}}$$

$$V_{EC} = \frac{Power_{site}}{\eta_{EC} \times PD_{EC}}$$

In some cases, such as the nuclear reactor option, the specific power and power density have been calculated with the device efficiency already accounted for.

$$W_{EC} = \frac{Power_{site}}{SP_{EC-net}}$$

$$V_{EC} = \frac{Power_{site}}{PD_{EC-net}}$$

The same is true for the options involving the use of thermoelectric generators. The efficiency of the natural gas burning options is accounted for in the adjusted power requirement for the site, as described below.

Adjusted Power Requirements for Site Accounting for Compression of Air from Surface

Energy conversion systems involving the burning of well head gas must account for: the supply of oxygen, from either high-pressure or cryogenic storage, or from the surface; fueling prior to the availability of well-head gas; possible reforming; gas separation and cleaning technologies up-stream of the fuel cell; pressure envelope design; and interfaces with energy storage, power conditioning, and control systems.

The total power required at the site, including both the equipment required to produce oil from the wells, as well as the compressors required to provide compressed air is:

$$Power_{total} = Power_{site} + Power_{comp}$$

The power for compression is proportional to the sum of all gases requiring compression (air, nitrogen, and carbon dioxide) is then:

$$Power_{comp} = \frac{1}{\Delta t} \times f(\Delta P) \times \sum_i n_i$$

The function $f(\Delta P) \approx W_s$ reflects the energy required for compression of a mole of ideal gas, and the duration (Δt) is the period where compression is required. The work involved in the compression of an ideal gas is:

$$W_s = -\Delta H = -c_p (T_2 - T_1) = -R\left(\frac{\kappa}{\kappa-1}\right)T_1\left[\left(\frac{P_2}{P_1}\right)^{(\kappa-1)/\kappa} - 1\right]$$

For standard air, the value of κ = 1.395 is recommended for calculations involving moderate temperatures and pressures. In cases involving the reformer-PEMFC combination, the internal combustion engine, or the gas turbine, the total power for the site will be obtained by burning NG from the well head:

$$Power_{total} = \eta_{total} \times n_{fuel} \times \Delta H_{fuel} \times \frac{1}{\Delta t}$$

In this case, ΔH_{fuel} represents the release of chemical energy from the oxidation of the fuel. The total power for the site, accounting for oil and gas production equipment, as well as the compressors required for the air and exhaust compressors:

$$Power_{total} = Power_{site} \left[1 - \frac{f(\Delta P) \times \sum_i n_i}{\eta_{total} \times n_{fuel} \times \Delta H_{fuel}} \right]^{-1}$$

In the case of the turbine or internal combustion engine (TIC), the moles of gas requiring compression include the air and exhaust. The exhaust includes both nitrogen, as well as carbon dioxide produced by the combustion.

$$\sum_i n_i = n_{air} + n_{N2} + n_{CO_2} \approx n_{fuel} \left(\frac{1}{0.21} + \frac{0.79}{0.21} + \frac{0.21}{0.21} \right) \approx n_{fuel} \left(\frac{2}{0.21} \right) \approx 9.524 \times n_{fuel}$$

The moles of fuel (n_{fuel}) are equivalent to the moles of methane (n_{CH4}), and ΔH_{fuel} represents the release of chemical energy from the burning of a mole of methane in the internal combustion engine or turbine.

In the case of the reformer-PEMFC system, the moles of gas that require compression are calculated with the following equation:

$$\sum_i n_i = n_{air} + n_{N2} + n_{CO_2} \approx n_{fuel} \left(\frac{1}{2 \times 0.21} + \frac{0.79}{2 \times 0.21} + \frac{1}{4} \right) \approx n_{fuel} \left(\frac{1.79}{0.42} + 0.25 \right) \approx 4.512 \times n_{fuel}$$

The moles of fuel (n_{fuel}) are equivalent to the moles of hydrogen (n_{H2}), and ΔH_{fuel} represents the release of chemical energy from the burning of a mole of hydrogen in the PEMFC.

Sizing Energy Storage Device for Each Site

The weight and volume of an energy storage system (W_{ES} and V_{ES}) for a particular site is based upon the total power required by the site ($Power_{site}$), the specific energy of the energy storagte device (SE_{ES}), the energy density of the device (ED_{ES}), and the efficiency of the device (η_{ES}).

$$W_{ES} = \frac{Power_{site}}{\eta_{ES} \times SE_{ES}}$$

$$V_{ES} = \frac{Power_{site}}{\eta_{ES} \times ED_{ES}}$$

Pressure Vessel Design

The following semi-empirical relationships have been developed to predict the critical pressure for ring-stiffened cylindrical vessels, designed to enclose the hybrid energy conversion and storage system, and capable of withstanding external pressurization at a particular sites depth. The equation for the buckling pressure is:

$$P_{CR} = S_y Z_1 (Z_2 - nZ_3)$$

The parameter S_y is the yield strength of the material, n (=e/t) is the ratio of radial deviation to thickness (out-of-roundness), and Z_1, Z_2 and Z_3 are collapse pressure formula parameters.

$$Z_1 = \exp\left(-\frac{0.815 m^{1/2}}{k\phi}\right)$$

$$Z_2 = \frac{1}{m^{0.95}(k\phi)^{0.10}}$$

$$Z_2 = \frac{50}{m^{1.95}(k\phi)^{0.10}} - \frac{33}{m^2}$$

The parameter m (=r/t) is the ratio of the mean radius to the thickness, k (=t/h) is the thickness to length ratio, and ϕ (=E/S_y) is the inverse strain parameter.

$$0 \le n \le \frac{m}{100}$$

$$10 \le m \le 100$$

$$0.001 \le k \le 0.200$$

$$100 \le \phi \le 1000$$

<u>Capital Investment at Commencement of Commercial Operations</u>

The cost of an electrical grid on the ocean floor is used as the basis of comparison. Based upon oil company estimates, it is assumed that such a cable will cost approximately $2.5 million per kilometer. The tie-back distance is multiplied by this cost to give an estimate of the total cable cost for a given site. It is further assumed that the cost of one 40 MW substation on the ocean floor is approximately $30 million, with the number of stations determined from the total power required for the site, and with a minimum of one substation per site.

In regard to the hybrid power systems, the total cost of an energy conversion system is estimated from the total power for the site, and the power-specific cost (PSC_{EC}):

$$Cost_{EC} = Power_{Site} \times PSC_{EC}$$

The total cost of an energy conversion system is estimated from the total power for the site, and the power-specific cost (ESC_{ES}):

$$Cost_{EC} = Power_{Site} \times ESC_{ES}$$

The cost for the pressure vessel is calculated from the total weight of the vessel (W_{PV}) is calculated with the following generalized expression [Peters et al.]:

$$Cost_{PV} = A_{PV} \times (W_{PV})^{\alpha_{PV}}$$

The constants $A_{PV} \approx$ 73 $/kg-steel and $\alpha_{PV} \approx$ -0.34 are materials-specific constants for steel, and $B_{PV} \approx$ 11 $-titanium/$-steel is an allowance factor used to account for more expensive materials of construction, such as titanium-based alloys. It is assumed that a protective steel hull structure is built around the pressure vessel, with a weight roughly equivalent to the weight of the pressure vessel, and with a cost factors provided by the oil and gas industry:

$$Cost_{PV-total} = A_{PV} \times B_{PV} \times (W_{PV})^{\alpha_{PV}} + (C_{hull} \times W_{PV}) + D_{hull}$$

The hull cost parameters are: $C_{hull} \approx$ $8/kg-steel and $D_{hull} \approx$ $15 million. The volume of the flotation tank is designed to enable enough water displacement to float the entire hybrid power system, accounting for the weights of the energy conversion device, the energy storage device, the pressure vessels, and the floatation tank. The wall thickness of the floatation tank is designed to prevent collapse at depth, using the same critical wall thickness formulae used to design the pressure vessels. Furthermore, the same cost correlation is used to estimate the cost of the floatation tank.

$$Cost_{FT} = A_{FT} \times (W_{FT})^{\alpha_{FT}}$$

A protective hull structure is also assumed around the floatation tanks.

$$Cost_{FT-total} = A_{FT} \times B_{FT} \times (W_{FT})^{\alpha_{FT}} + (C_{hull} \times W_{FT}) + D_{hull}$$

The total direct cost ($Cost_{direct}$) for the energy conversion and storage components, the pressure vessel, the floatation tanks, and the protective hulls is calculated as follows:

$$Cost_{direct} = Cost_{EC} + Cost_{ES} + Cost_{PV-total} + Cost_{FT-total}$$

Indirect cost factors ($IDFs$) are applied to the total direct cost to account for indirect costs, including: (1) construction services ≈ 10 percent; (2) home office engineering and services ≈ 7 percent; (3) field office engineering and services ≈ 5 percent; (4) owner's costs ≈ 13 percent; and (5) non-NRC licensing and permitting ≈ 1 percent.

$$Cost_{indirect} = Cost_{direct} \times \sum_i IDF_i$$

A contingency allowance of ~10% and an allowance for miscellaneous costs ~1% are included to calculate the total overnight cost. These are accounted for in the allowance factors (AFs).

$$Cost_{overnight} = Cost_{direct} \times \left(1 + \sum_i IDF_i\right) \times \left(1 + \sum_j AF_j\right)$$

A construction escalation allowance of ~5% and an allowance for interest of ~5% are included to calculate the cost at the commencement of commercial operations. These are accounted for in the allowance factors (EFs).

$$Cost_{total} = Cost_{direct} \times \left(1 + \sum_i IDF_i\right) \times \left(1 + \sum_j AF_j\right) \times \left(1 + \sum_k EF_k\right)$$

<u>Annualized Cost at Commencement of Commercial Operations</u>

The annualized cost at the commencement of commercial operations is calculated by applying the annuity present worth factor to the total direct and indirect costs ($A_{PF} \approx$ 9.63% at an optimistic discount rate of approximately 5%, which is customary for projects of relatively low risk). In regard to the calculation of the annualized costs, the compound interest factor (f_i) is:

$$f_i = (1+i)^n$$

The discount factor (f_d) is then:

$$f_d = \frac{1}{f_i}$$

The annuity future worth factor (f_{AF}) is:

$$f_{AF} = \frac{A}{F} = \frac{i}{(1+i)^n - 1}$$

The parameter i is the interest rate, the parameter n is the number of payment periods, A is the annuity, or annualized cost, and the parameter F is the future worth of the money. The annuity present worth factor (f_{AP}) is:

$$f_{AP} = \frac{A}{P} = \frac{i(1+i)^n}{(1+i)^n - 1}$$

The parameter P is the present value of the money. Using this formalism, the total annualized cost ($A \approx Cost_{annualized}$) is then calculated from the cost at the commencement of commercial operations ($Cost_{total}$) as follows:

$$Cost_{annualized} = Cost_{total} \times f_{AP}$$

Assumed values used for the economic analysis are summarized in the appendices (Appendix H, Tables H1 through H5).

Annual Operating Expense

Several contributions to annual operating and maintenance costs are accounted for by applying appropriate factors to the annualized cost at the commencement of commercial operations. These contributions include: (1) chemicals, materials and utilities ≈ 10 percent; (2) spare parts and capital plant upgrades ≈ 10 percent; (3) taxes and insurance ≈ 10 percent; (4) operating cost contingency ≈ 5 percent; (4) general operating and maintenance costs ≈ 2 percent; and (5) miscellaneous operating and maintenance costs ≈ 1 percent; and are accounted for in operation and maintenance factors ($OPFs$).

$$Cost_{operations} = Cost_{annualized} \times \sum_i OPF_i$$

Cost of Electricity

The total annual cost of operation is:

$$Cost_{annual\,total} = Cost_{annualized} + Cost_{operations} = Cost_{annualized}\left(1 + \sum_i OPF_i\right)$$

The cost of electricity (COE) is then calculated by dividing the total annualized cost by the energy generated.

$$COE = \frac{\left(Cost_{annual\ total}\right)}{\left(Power_{total}\right) \times \left(24 \times 365\, hours/year\right)}$$

These formulae have been used to predict the cost-of-electricity from each of the hybrid options, for each of the concept-of-operations sites. The results are summarized in the following section.

Results

Weight of Energy Conversion and Storage Components for Each Site

The estimated weights of the energy conversion and storage components for each hybrid system, evaluated for each concept-of-operations site are summarized in Table 5 and Figure 1, with more detail presented in the appendices (Appendix I).

Total Weight of Hybrid System for Each Site

The estimated total weight for each hybrid system, evaluated for each concept-of-operations site are summarized in Table 5 and Figure 2, with more detail presented in the appendices (Appendix I). The weight of the hybrid energy conversion and storage systems for the three largest sites, Shtokman, Chinook and Ormen Lange, are between 10,000 and 100,000 metric tons. For comparison, the NS Savannah and NS Otto Hahn weighed 25,790 and 22,000 metric tons, respectively. Thus, the largest hybrid systems will have weights comparable to these nuclear powered ships.

Total Volume of Hybrid System for Each Site

The estimated total volume for each hybrid system, evaluated for each concept-of-operations site are summarized in Table 5 and Figure 3, with more detail presented in the appendices (Appendix I). While the hybrid systems are comparable to the commercial nuclear-powered ships in weight, their density is greater, so they occupy less volume than the ships.

Capital Investment at Commencement of Commercial Operations

The estimated capital investment at the commencement of commercial operations for each hybrid system, evaluated for each concept-of-operations site are summarized in Table 6 and Figure 4, with more detail presented in the appendices (Appendix I). The capital costs are dominated by parameters that are insensitive to the size of the site, such as those used to account for the assumed protective hull, and are relatively insensitive to the size of the site. The subsea vehicular options are the most expensive and least practical. The subsea vehicle that ferries stored energy from the surface to the site via batteries is by far the worst option, and is not given any serious consideration.

Annualized Cost at Commencement of Commercial Operations

The estimated annualized cost at the commencement of commercial operations for each hybrid system, evaluated for each concept-of-operations site are summarized in Table 6 and Figure 5, with more detail presented in the appendices (Appendix I). Like the initial capital cost, the annualized costs are dominated by parameters that are insensitive to the size of the site, and are also insensitive to the size of the site.

Cost of Electricity

The estimated cost of electricity (COE) for each hybrid system, evaluated for each concept-of-operations site are summarized in Table 6 and Figure 6, with more detail presented in the appendices (Appendix I). The least expensive option for power at all of the concept-of-operations sites is the electrical grid, with an assumed cost of approximately $2.5 million per kilometer. In regard to the COE, hybrid power options that are comparable with the grid option include the pressurized water reactor (PWR), a fuel cell on the ocean floor fueled with well-head methane and a line to the surface for compressed air (FC1), or a fuel cell on the ocean floor fueled with well-head methane and oxygen brought to the system in submersible tanks (FC2). The team prefers FC1 since FC2 seems impractical from an operational point-of-view.

Economy of Scale

The estimated cost of electricity (COE) as a function of power generation capacity is shown in Figure 7, and shows a clear economy of scale. As the systems become larger, the cost of electricity produced by the system becomes less expensive, regardless of the hybrid system assumed. The two largest sites, Shtokman and Ormen Lange are off sufficient size so that power can be supplied for less than $1 per kilowatt-hour, comparable to the cost for grid power.

Summary

An investment in deep-sea (deep-ocean) hybrid power systems may enable certain off-shore oil and gas exploration and production. Advanced deep-ocean drilling and production operations, locally powered, may provide commercial access to oil and gas reserves otherwise inaccessible. Further, subsea generation of electrical power has the potential of featuring a low carbon output resulting in improved environmental conditions. Such technology therefore, enhances the energy security of the United States in a green and environmentally friendly manner. The objective of this study is to evaluate alternatives and recommend equipment to develop into hybrid energy conversion and storage systems for deep ocean operations. Such power systems will be located on the ocean floor and will be used to power offshore oil and gas exploration and production operations. Such power systems will be located on the oceans floor, and will be used to supply oil and gas exploration activities, as well as drilling operations required to harvest petroleum reserves. The following conceptual hybrid systems have been identified as candidates for powering sub-surface oil and gas production operations:

1. PWR = Pressurized-Water Nuclear Reactor + Lead-Acid Battery
2. FC1 = Line for Surface O_2 + Well Head Gas + Reformer + PEMFC + Lead-Acid & Li-Ion Batteries
3. FC2 = Stored O2 + Well Head Gas + Reformer + Fuel Cell + Lead-Acid & Li-Ion Batteries
4. SV1 = Submersible Vehicle + Stored O_2 + Fuel Cell + Lead-Acid & Li-Ion Batteries
5. SV2 = Submersible Vehicle + Stored O_2 + Engine or Turbine + Lead-Acid & Li-Ion Batteries
6. SV3 = Submersible Vehicle + Charge at Docking Station + ZEBRA & Li-Ion Batteries
7. PWR TEG = PWR + Thermoelectric Generator + Lead-Acid Battery
8. WELL TEG = Thermoelectric Generator + Well Head Waste Heat + Lead-Acid Battery
9. GRID = Ocean Floor Electrical Grid + Lead-Acid Battery
10. DOC = Deep Ocean Current + Lead-Acid Battery

Detailed analyses of each of the eight leading hybrid options, as well as the assumed base case (ocean floor electrical grid) are given in Appendix F. The deep ocean current option was abandoned early, due to the low velocities on the floor of the ocean (less than 0.5 meters per second), and the very large turbine size that would be required with such low velocities (300-foot span).

The weight of the hybrid energy conversion and storage systems for the three largest sites, Shtokman, Chinook and Ormen Lange, are between 10,000 and 100,000 metric tons. For comparison, the NS Savannah and NS Otto Hahn weighed 25,790 and 22,000 metric tons, respectively. Thus, the largest hybrid systems will have weights comparable to these nuclear powered ships. While the hybrid systems are comparable to the commercial nuclear-powered ships in weight, their density is greater, so they occupy less volume than the ships. The capital costs are dominated by parameters that are insensitive to the size of the site, such as those used to account for the assumed protective hull, and are relatively insensitive to the size of the site. The subsea vehicular options are the most expensive and least practical. The subsea vehicle that ferries stored energy from the surface to the site via batteries is by far the worst option, and is not given any serious consideration. Like the initial capital cost, the annualized costs are dominated by parameters that are insensitive to the size of the site, and are also insensitive to the size of the site. The least expensive option for power at all of the concept-of-operations sites is the

electrical grid, with an assumed cost of approximately $2.5 million per kilometer. In regard to the COE, hybrid power options that are considered to be comparable with the grid option are the pressurized water reactor (PWR) and a fuel cell on the ocean floor fueled with well-head methane and a line to the surface for compressed air (FC1). As the systems become larger, the cost of electricity produced by the system becomes less expensive, regardless of the hybrid system assumed. The two largest sites, Shtokman and Ormen Lange are off sufficient size so that power can be supplied for less than $1 per kilowatt-hour, comparable to the cost for grid power.

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Acknowledgements

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Tables

Table 1 – Concept-of-operations sites for evaluation of deep ocean hybrid power systems [Haut 2009]

Field or Project	Owner	Region	Year	Depth	Depth	Tie Back	Tie Back	Liquid	Total Power
name			calendar	meters	feet	km	miles	MBOPD	MW
Shtokman	Gazprorn	Barents Sea	2020	350	1,148	565.0	209.0	NA	240.0
Chinook	Petrobras	GOM	2009	2,682	8,800	19.3	12.0	20	7.2
King	BP	GOM	2007	1,700	5,578	20.0	18.0	83	2.0
Ormen Lange	Hydro	Norway	2011	850	2,789	120.0	193.0	79	60.0
Perdido	Shell	GOM	2010	2,438	7,999	NA	NA	40	5.0
Argonauta	Shell	Brazil	2009	1,900	6,234	9.0	5.6	9.7	2.2
Marimba Field	Petrobras	Campros Basin	2000	395	1,296	1.1	0.7	7	0.1
Pazflor	Total	Angola Blk 17	2011	800	2,625	4.0	3.0	NA	13.8
Hypothetical				1,389	4,559	105.5	63.0		41.3

Table 2 – Summary of deep ocean hybrid generation and storage options considered for study

Description	Nomenclature
PWR = Nuclear Reactor + Pb Acid Battery	PWR
FC1 = Line for Surface O2 + WELL Head Gas + Reformer + PEMFC + Battery	FC1
FC2 = Stored O2 + Well Head Gas + Reformer + Fuel Cell + Battery	FC2
SV1 = Submersible Vehicle + Stored O2 + Fuel Cell + Battery	SV1
SV2 = Submersible Vehicle + Stored O2 + Engine or Turbine + Battery	SV2
SV3 = Submersible Vehicle + Charge at Docking Station + ZEBRA Battery	SV3
PWR TEG = PWR + WELL TEG + Pb Acid Battery	PWR TEG
WELL TEG = Thermoelectric Generator + Well Head Waste Heat + Battery	WELL TEG
GRID = Floor Electrical Grid + Battery	GRID
DOC = Deep Ocean Current + Battery	DOC

Table 3 – Summary of key attributes of power generation options used to assess hybrid system options

Screening Criteria	Units	PWR	FC	TIC	TEG
Specific Power	W/kg	250.0	28.90	1057	8.800
Power Density	W/L	791.6	20.78	3347	2.200
Specific Energy	Wh/kg	10,950,000			
Energy Density	Wh/L	34,672,967			
Overall Device Efficiency	%	0.30	0.60	0.40	0.10
Technology Cost	$/kW	7,500	2,500	500	2,000

Table 4 – Summary of key attributes of energy storage options used to assess hybrid system options

Screening Criteria	Units	Pb Acid	AgZn	NaS	ZEBRA	Li-Ion	Regen FC
Specific Power	W/kg	20	1470	250	169	74	27
Power Density	W/L	51	2520	386	261	147	17
Specific Energy	Wh/kg	20	105	117	94	75	326
Energy Density	Wh/L	50	180	147	148	139	209
Coulombic Efficiency (Ah/Ah)	%	0.80	0.90	0.89	1.00	0.99	0.90
Electrical Efficiency (Wh/Wh)	%	0.70	0.75	0.70	0.70	0.95	0.43
Overall Device Efficiency	%	0.56	0.68	0.62	0.70	0.94	0.38
Technology Cost	$/kWh	150	600	300	220	300	5000

Table 5 – Summary of the predicted mass and volume of deep ocean hybrid power generation and energy storage options, for each of the con-ops cases

Hybrid System Volume (Cubic Meters)									
Site	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID
Shtokman	89,574	185,132	21,126,191	52,815,478	42,795,786	2,433,210	324,766	323,145	92,534
Chinook	3,139	71,237	7,785,692	19,464,230	8,429,285	88,712	12,455	12,397	3,238
King	840	4,642	524,414	1,311,036	921,613	23,442	3,190	3,174	986
Ormen Lange	24,027	69,480	7,953,368	19,883,421	15,506,951	661,517	87,782	87,332	24,551
Perdido	2,112	28,999	3,202,843	8,007,107	4,370,490	59,280	8,313	8,275	2,231
Argonauta	943	6,236	699,846	1,749,614	1,179,736	26,442	3,608	3,590	998
Marimba Field	30	64	7,343	18,358	14,827	817	109	108	38
Pazflor	5,167	15,204	1,760,846	4,402,115	3,447,586	140,892	19,216	19,124	5,108
Hybrid System Weight (Metric Tons)									
Site	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID
Shtokman	56,163	67,923	86,641	216,603	136,060	1,237,266	95,306	94,222	95,938
Chinook	3,476	54,517	45,989	114,973	24,922	85,544	9,018	8,951	4,805
King	736	2,668	2,650	6,625	2,815	17,451	1,654	1,640	2,169
Ormen Lange	16,837	30,173	34,832	87,081	47,791	382,404	32,145	31,818	25,188
Perdido	2,231	20,740	18,208	45,521	13,049	54,117	5,567	5,525	3,584
Argonauta	865	3,810	3,659	9,148	3,597	20,723	2,013	1,996	1,499
Marimba Field	19	24	30	76	47	420	33	32	98
Pazflor	3,732	6,527	7,612	19,030	10,567	83,903	7,001	6,929	3,950
Energy Conversion & Storage Components (Metric Tons)									
Site	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID
Shtokman	49,600	56,866	47,096	117,740	64,762	1,072,340	76,873	75,913	89,499
Chinook	1,488	16,447	8,375	20,937	2,023	32,170	2,306	2,277	2,855
King	413	1,192	732	1,829	546	8,936	641	633	1,852
Ormen Lange	12,400	19,723	14,375	35,937	16,244	268,085	19,218	18,978	20,838
Perdido	1,033	6,879	3,671	9,176	1,388	22,340	1,602	1,582	2,409
Argonauta	455	1,565	924	2,311	602	9,830	705	696	1,097
Marimba Field	17	20	16	40	22	357	26	25	96
Pazflor	2,852	4,396	3,240	8,099	3,735	61,660	4,420	4,365	3,086

Table 6 – Summary of the cost-of-electricity, annualized costs and capital investment for each of the deep ocean hybrid power generation and energy storage options, for each of the con-ops cases

Cost of Electricity at Site ($/kWh-e)									
Site	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID
Shtokman	0.3117	0.4718	0.3986	0.9950	0.4541	5.9075	0.4084	0.1861	0.2565
Chinook	3.5520	8.7727	6.2999	15.6973	8.8381	116.1483	4.8741	3.5773	2.5289
King	11.9500	12.9326	12.3294	30.6352	29.0088	402.2488	15.9392	11.7736	8.7918
Ormen Lange	0.6199	0.9691	0.8028	2.0007	1.2261	16.3595	0.8406	0.5183	0.4424
Perdido	4.9707	7.9399	6.5002	16.1753	12.1636	164.4874	6.7352	4.9529	4.5988
Argonauta	10.8993	12.1912	11.4536	28.4629	26.4802	366.4688	14.5651	10.7602	7.6954
Marimba Field	291.6057	287.7732	286.8783	712.4901	711.8591	9924.6266	386.1943	286.6950	202.4166
Pazflor	1.9239	2.2439	2.0803	5.1735	4.4147	60.7853	2.5704	1.8045	1.2310
Annualized Costs ($M)									
Site	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID
Shtokman	655.8413	992.6223	838.6570	2093.3426	955.4366	12428.4891	859.3045	391.5581	539.6797
Chinook	224.1873	553.6930	397.6164	990.7410	557.8189	7330.7225	307.6329	225.7816	159.6117
King	209.5081	226.7335	216.1588	537.0969	508.5824	7052.2254	279.4467	206.4147	154.1381
Ormen Lange	326.0484	509.7039	422.2295	1052.2736	644.8546	8604.4503	442.1283	272.5999	232.6874
Perdido	217.8670	348.0072	284.9052	708.9631	533.1294	7209.4846	295.2022	217.0847	201.5665
Argonauta	210.1954	235.1104	220.8853	548.9131	510.6751	7067.4240	280.8915	207.5135	148.4081
Marimba Field	204.4973	201.8096	201.1820	499.6550	499.2126	6959.9421	270.8304	201.0535	141.9507
Pazflor	232.7337	271.4513	251.6582	625.8455	534.0504	7353.2505	310.9398	218.2910	148.9160
Initial Capital Investment ($M)									
Site	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID
Shtokman	4916.3574	7449.4530	6291.4042	15728.5106	7169.7609	93464.2259	6446.7038	2928.5533	4042.6487
Chinook	1669.6759	4148.0497	2974.1210	7435.3024	4179.0824	55121.4183	2297.3112	1681.6671	1183.9706
King	1559.2664	1688.8266	1609.2890	4023.2225	3808.7512	53026.7047	2085.3088	1535.9989	1142.8013
Ormen Lange	2435.8227	3817.1859	3159.2479	7898.1198	4833.7209	64701.7509	3308.9171	2033.8102	1733.6090
Perdido	1622.1376	2600.9859	2126.3651	5315.9126	3993.3807	54209.5288	2203.8138	1616.2530	1499.5336
Argonauta	1564.4353	1751.8334	1644.8392	4112.0981	3824.4907	53141.0212	2096.1756	1544.2637	1099.7027
Marimba Field	1521.5770	1501.3618	1496.6415	3741.6037	3738.2758	52332.5971	2020.5010	1495.6746	1051.1340
Pazflor	1733.9574	2025.1713	1876.2977	4690.7443	4000.3081	55290.8623	2322.1835	1625.3267	1103.5230

Figures

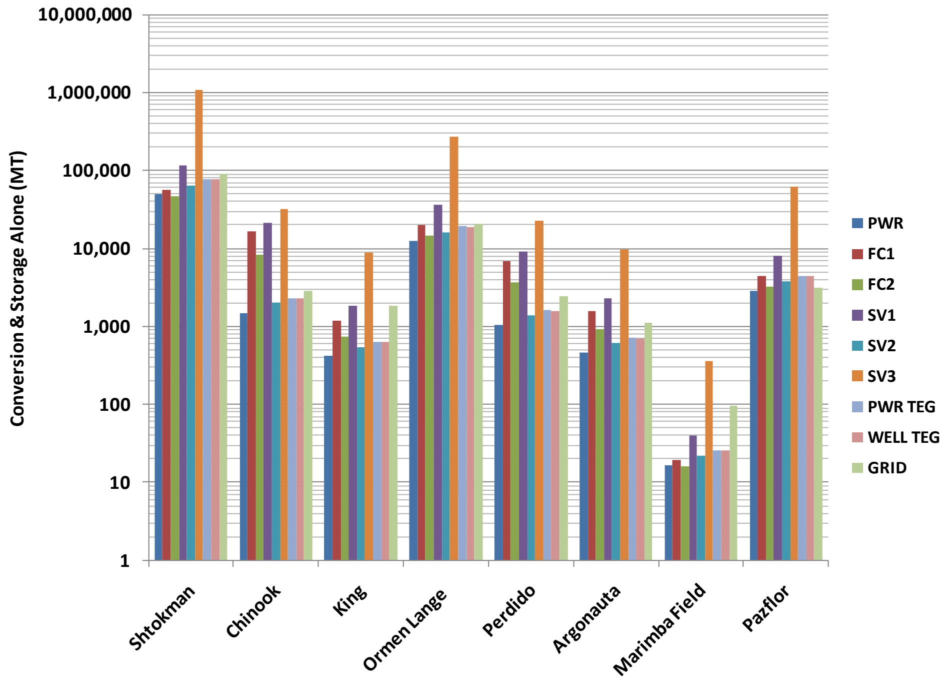

Figure 1 – Graphical comparison of the predicted masses of power generation and energy storage components, for each of the deep ocean hybrid systems, and for each of the con-ops cases

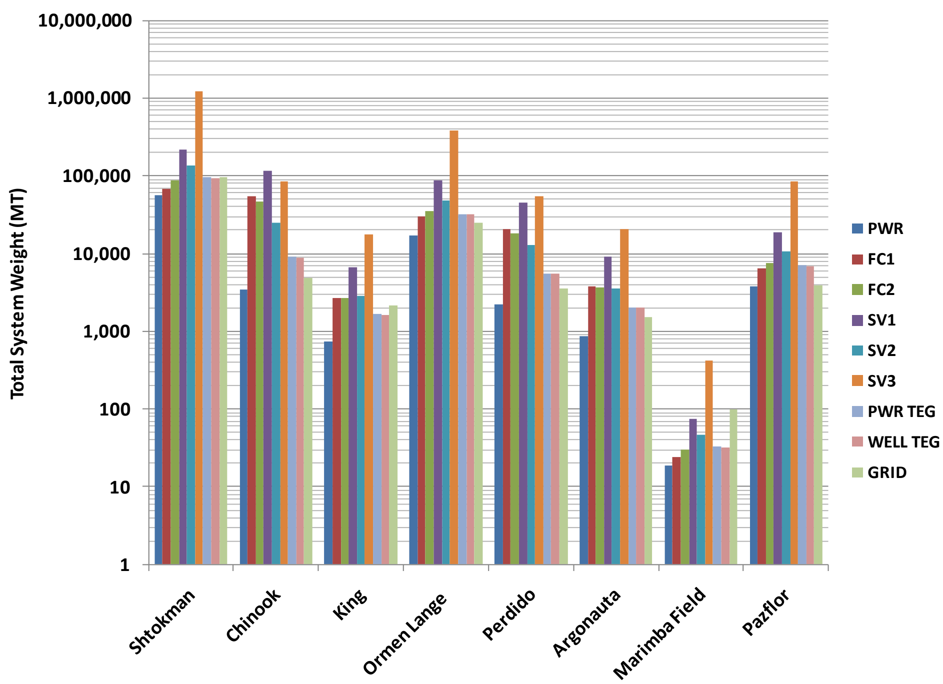

Figure 2 – Graphical comparison of the predicted total masses of the deep ocean hybrid power generation and energy storage options, for each of the con-ops cases

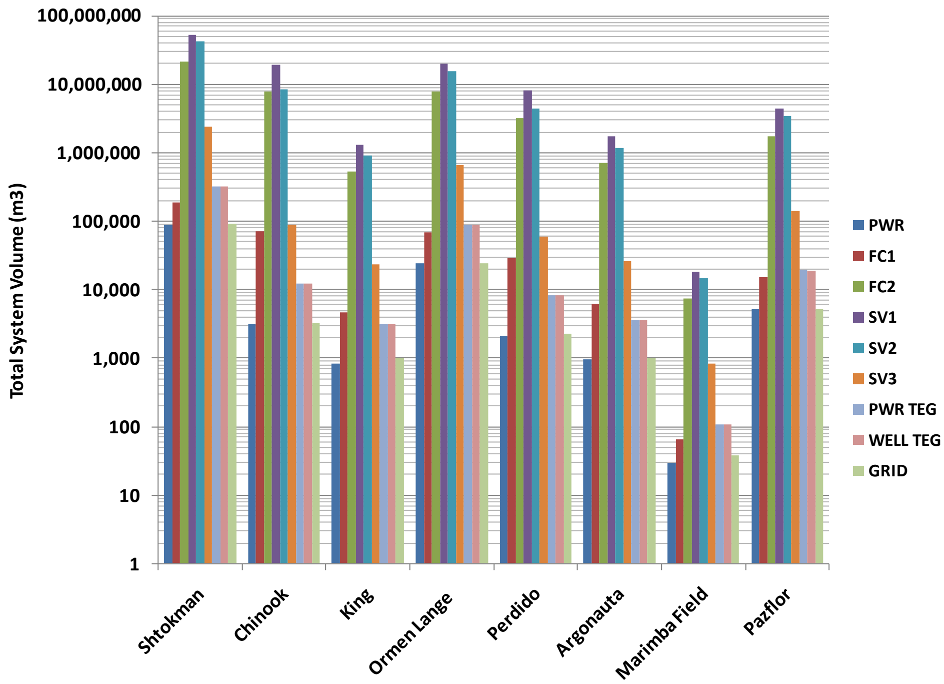

Figure 3 – Graphical comparison of the predicted volumes of the deep ocean hybrid power generation and energy storage options, for each of the RPSEA con-ops cases

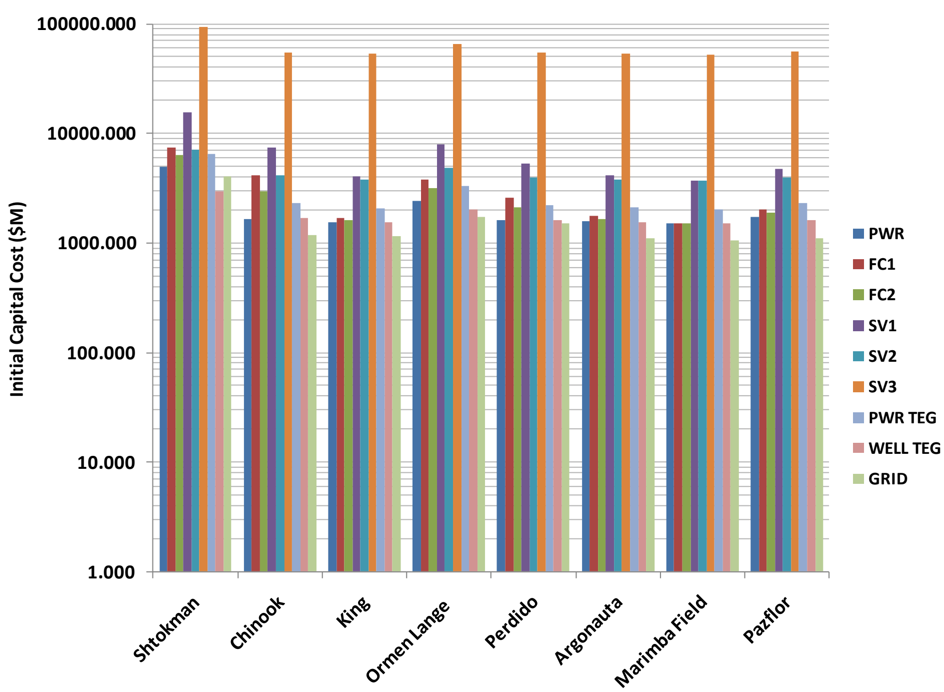

Figure 4 – Graphical comparison of the predicted capital investment required for each deep ocean hybrid power generation and energy storage option, for each of the con-ops cases

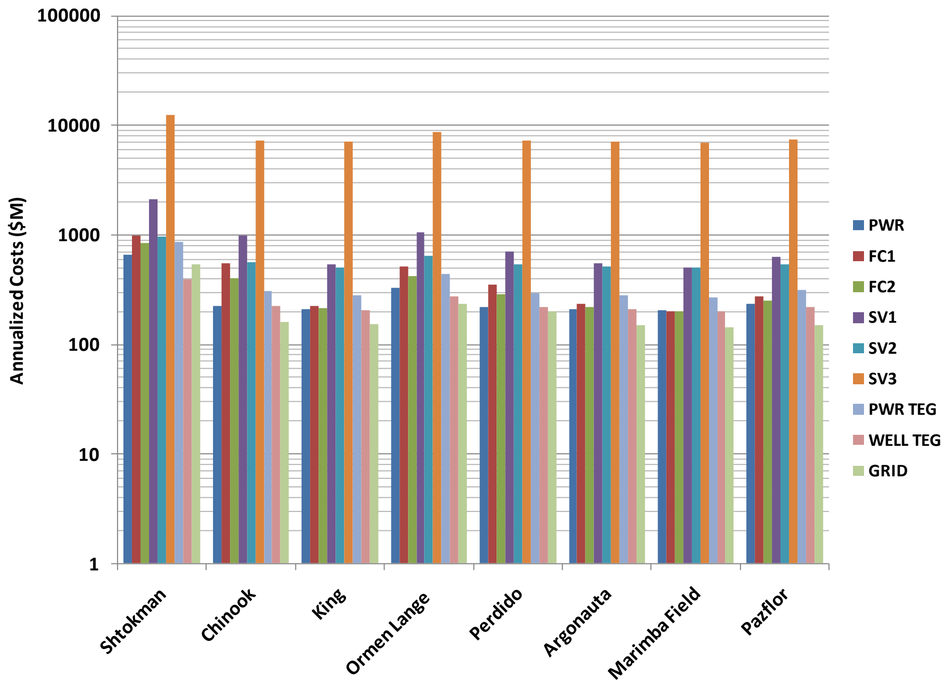

Figure 5 – Graphical comparison of the predicted annualized costs for each deep ocean hybrid power generation and energy storage option, for each of the RPSEA con-ops cases

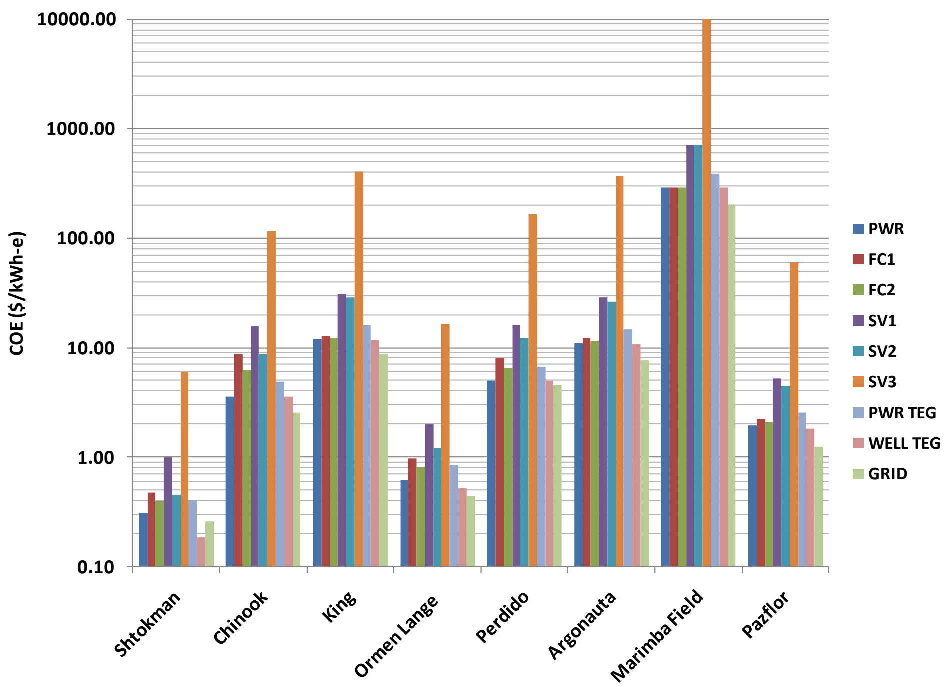

Figure 6 – Graphical comparison of the predicted cost-of-electricity produced by each of the deep ocean hybrid power generation and energy storage systems, at each of the con-ops sites

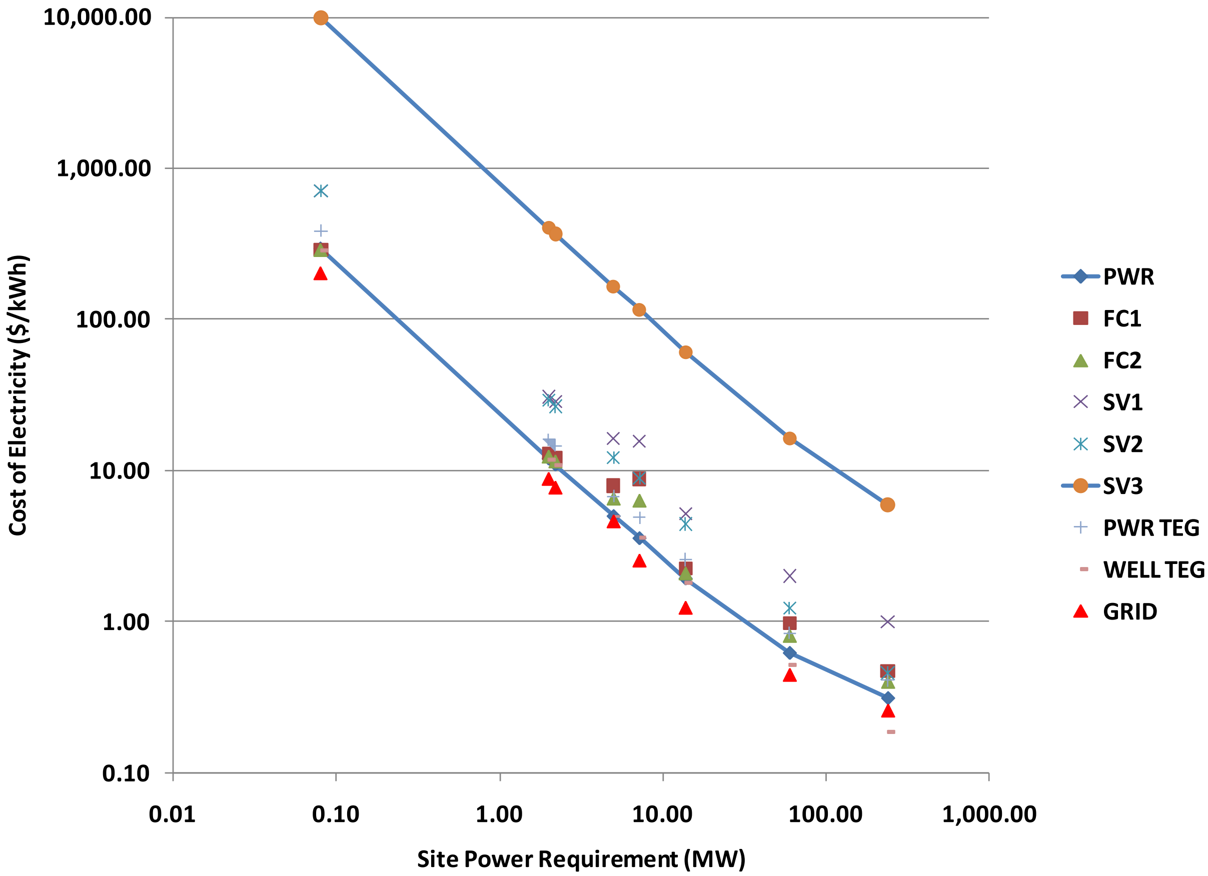

Figure 7 – The cost of electricity shows a very clear economy of scale, with the lowest electricity costs being realized for the largest sites

Appendix A – Background on World-Wide Use of Large and Modular Nuclear Reactors

Table A 1 – The inventory of operating nuclear reactors world-wide, broken down into global regions including: West Europe; East Europe; America (North America); and Asia and Africa [Fukuda]

Worldwide Nuclear Reactors				
	Completed & Operating	Completed & Operating	Under Construction	Under Construction
Regions	Reactors	Total Capacity	Reactors	Total Capacity
	Number	Gwe	Number	Gwe
West Europe	146	125.7	0.0	0.0
East Europe	67	46.1	10.0	8.0
America	124	112.4	1.0	0.7
Asia & Africa	104	74.5	22.0	18.4
World	441	358.7	33.0	27.1

Table A 2 – The inventory of spent nuclear fuel from nuclear reactor operations being stored world-wide, broken down into global regions including: West Europe; East Europe; America (North America); and Asia and Africa [Fukuda]

Spent Nuclear Fuel Inventory	
	SNF
Regions	Total
	t HM
West Europe	36,100
East Europe	27,700
America	83,300
Asia & Africa	23,900
World	171,000

Table A 3 – The world-wide inventory of relatively small modular nuclear reactors is shown with their corresponding country of origin and electrical generating capacity

Reactor	Location	Power
VK-300	Atomenergoproekt, Russia	300 MWe PWR
CAREM	CNEA & INVAP, Argentina	27 MWe PWR
KLT-40	OKBM, Russia	35 MWe PWR
MRX	JAERI, Japan	30-100 MWe PWR
IRIS-100	Westinghouse-led, international	100 MWe PWR
B&W mPower	Babcock & Wilcox, USA	125 MWe PWR
SMART	KAERI, S. Korea	100 MWe PWR
NP-300	Technicatome (Areva), France	100-300 MWe PWR
HTR-PM	INET & Huaneng, China	105 MWe HTR
PBMR	Eskom, South Africa,	165 MWe HTR
GT-MHR	General Atomics (USA), Minatom (Russia) et al	280 MWe HTR
BREST	RDIPE (Russia)	300 MWe LMR
FUJI	ITHMSO, Japan-Russia-USA	100 MWe MSR

Figure A 1 – The commercial NS Savannah nuclear powered ship was built by New York Ship Building in Camden, New Jersey and had a 74 MW PWR built by Babcock & Wilcox (B&W) and sailed from 1970-79

Figure A 2 – The B&W mPower^{TM} reactor, with its scalable, modular design, has the capacity to provide 125 MWe to 750 MWe or more for a five-year operating cycle without refueling, and is designed to produce clean, near-zero emission operations. This PWR is very similar in design to that used for the NS Savannah

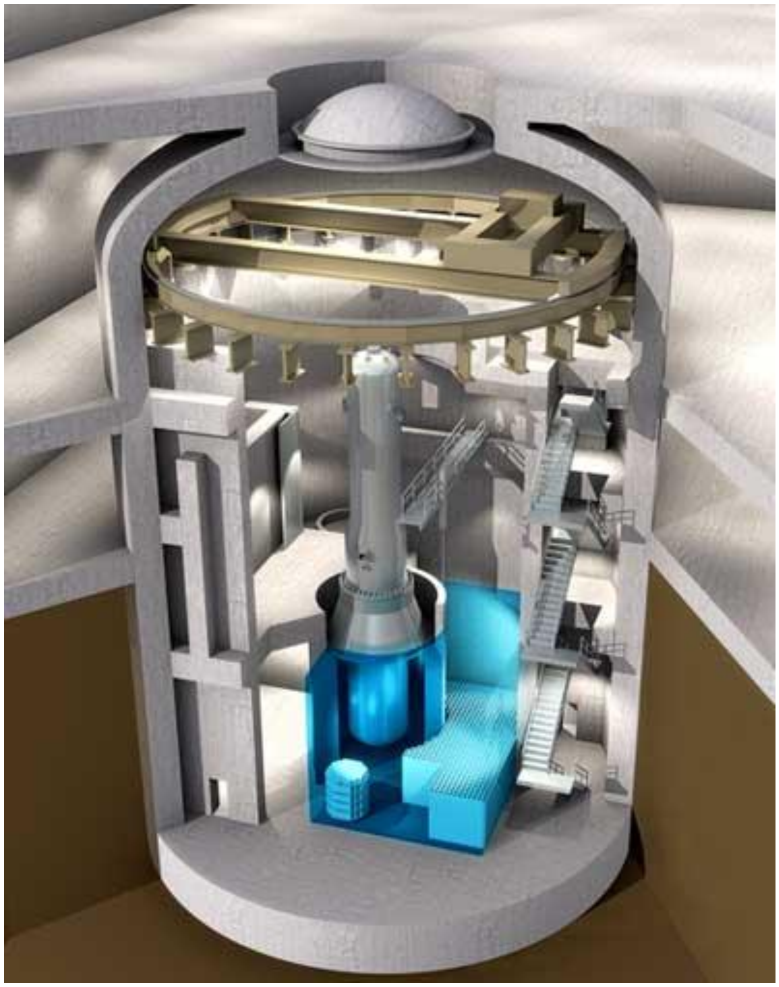

Figure A 3 – A single B&W mPower™ module inside its own independent, underground containment

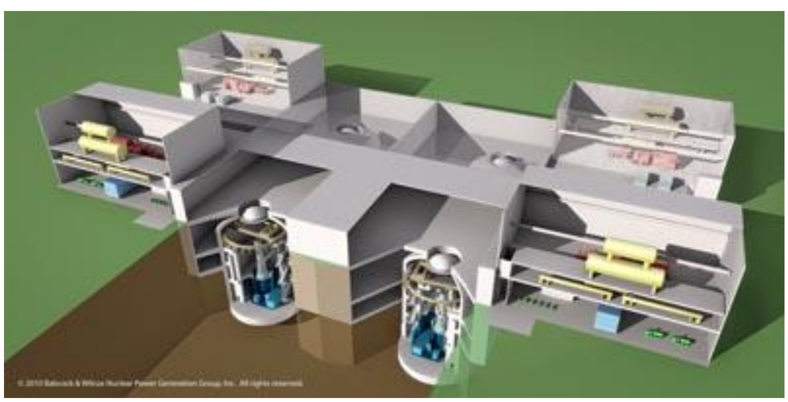

Figure A 4 – Four B&W mPower™ nuclear reactors configured as a 500 megawatt nuclear power plant

Appendix B – Deep Ocean Experience with PEMFC Systems

Figure B 1 – The left image shows the Class 212A fuel-cell powered submarine being constructed by HDW in Kiel, Germany. The center image shows the assembled submarine sitting in dry dock, and the right image shows the vessel after launch

Figure B 2 – Components of the fuel cell system used by HDW shipyard in Kiel, Germany aboard sub-sea vessels

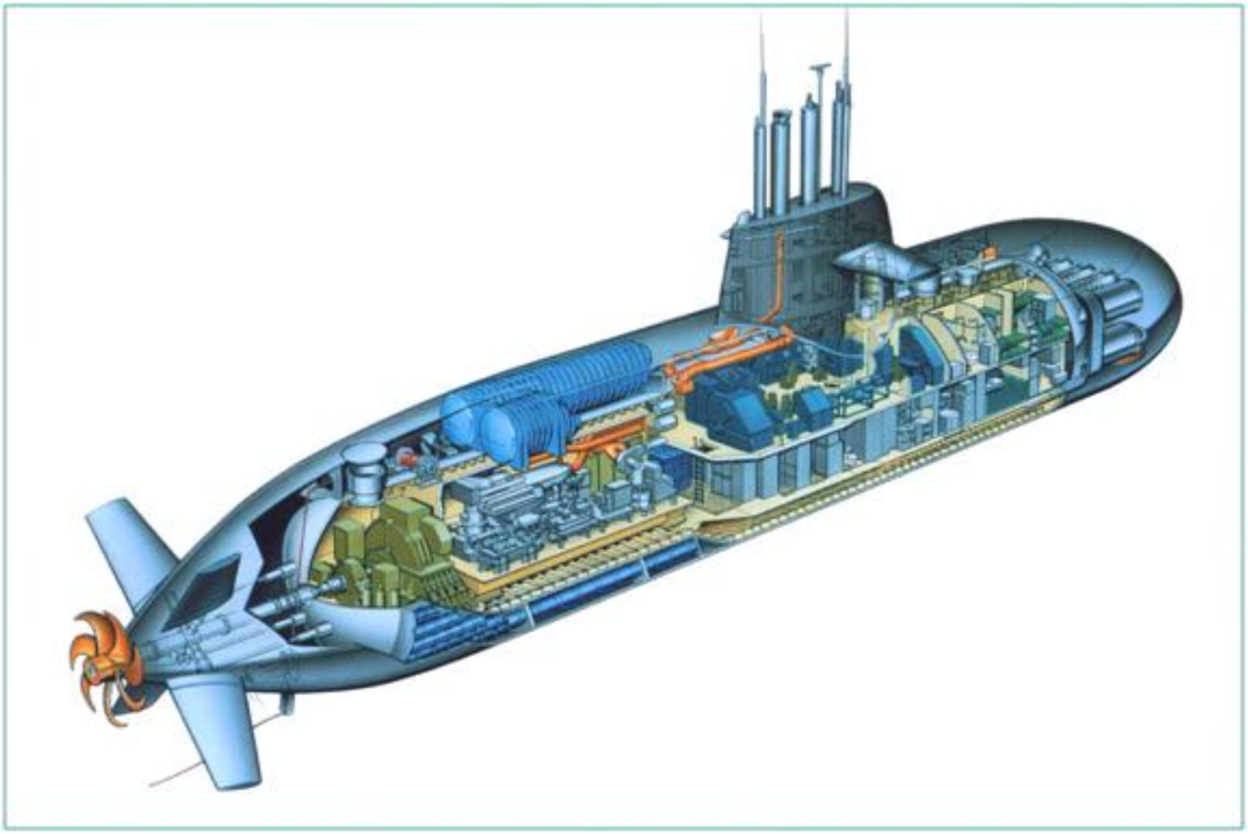

Figure B 3 – Three-dimensional schematic representation of the fuel-cell powered sub-sea vessel

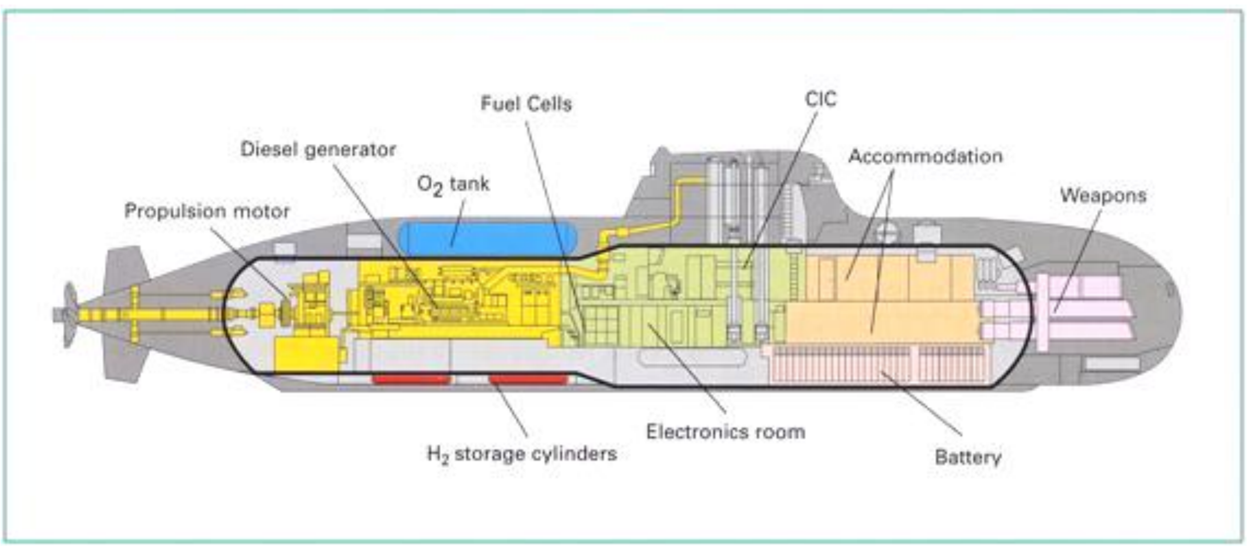

Figure B 4 – Two-dimensional schematic representation of the fuel-cell powered sub-sea vessel, showing the systems required for operation, including the oxygen storage tank, the fuel cells, and the hydrogen storage cylinders

Appendix C – Representative Composition and Properties for Oil and Gas from Well Head

Table C 1 – Composition of typical oil and gas layer from typical deep-ocean well [Gonzalez SPE 110833]

	Oil-Layer Fluid Composition (mole %)				Gas-Layer Fluid Composition (mole %)			
Component	MW	Flashed Gas	Flashed Liquid	Mono-phasic Fluid	MW	Flashed Gas	Flashed Liquid	Mono-phasic Fluid
Carbon Dioxide	44.01	0.07	0	0.05	44.01	0.05	0.00	0.05
Nitrogen	28.01	0.18	0	0.12	28.01	0.00	0.00	0
Methane	16.04	79.53	0	49.6	16.04	96.73	0.00	92.62
Ethane	30.07	7.40	0	4.61	30.07	0.96	0.00	0.92
Propane	44.10	6.49	0.56	4.26	44.10	0.90	0.09	0.87
Butane	58.12	3.93	1.35	2.95	58.12	0.65	0.38	0.65
Pentane	72.15	1.98	2.67	2.24	72.15	0.47	1.27	0.5
C6	86.20	0.26	3.79	1.59	86.20	0.11	2.57	0.22
C-Pentane	84.16	0.00	0.69	0.26	84.16	0.00	0.69	0.03
Benzene	78.11	0.00	0.12	0.05	78.11	0.00	0.05	0.00
Cyclohexane	84.16	0.07	0.46	0.22	84.16	0.04	0.40	0.05
C7	100.20	0.04	4.22	1.61	100.20	0.04	5.80	0.28
C-Hexane	98.19	0.03	1	0.39	98.19	0.02	1.25	0.07
Toluene	92.14	0.00	0.64	0.24	92.14	0.00	0.88	0.04
C8	107.00	0.01	4.97	1.87	107.00	0.01	8.65	0.37
E-Benzene	106.17	0.00	0.37	0.14	106.17	0.00	0.65	0.03
Xylene	106.17	0.00	1.02	0.39	106.17	0.00	1.26	0.06
C9	121.00	0.01	4.25	1.6	121.00	0.01	8.09	0.35
C10	134.00	0.00	5.33	2.01	134.00	0.00	9.16	0.39
C11	147.00	0.00	7.6	2.86	147.00	0.00	8.79	0.37
C12+	291.40	0.00	60.99	19.82	162.65	0.00	50.00	2.12
MW		22.02	221.04	96.91		17.15	177.24	23.95
Mole Ratio		0.6237	0.3763			0.9376	0.0424	

Table C 2 – Physical properties of oil and gas layers from typical deep-ocean (sub-surface) well

	Oil-Lower Layer	Gas-Upper Layer
Reservoir Conditions		
Pressure (psia)	16,990	15,740
Temperature (F)	184	170
Depth (ft MD)	22,700	21,900
Reservoir Fluid Properties		
Oil-Base Mud OBM Contamination (wt. % RF Basis)	20	3.1
Gas-Oil Ratio GOR - Single-Stage Flash (scf/bbl) … original	852	13,693
Gas-Oil Ratio GOR - Single-Stage Flash (scf/bbl) … decontaminated	1,133	15,253
Bubble Point Prtessure at Reservoir Temperature (psia)	3,427	
Bubble Point at 100°F (psia)	2,940	
Dew Point Pressure at Reservoir Temperature (psia)		10,562
Properties at Reservoir Conditions		
Compressibility (1E-6/psi)	4.40	2.10
Density (g/cc)	0.75	0.42
Properties at Saturation Conditions		
Compressibility (1E-6/psi)	12.70	1.60
Density (g/cc)	0.67	0.38
FVF - Single-Stage Flash at Reservoir Temp. & Press.	1,322.00	
Properties at 60°F		
Molar Mass	220.42	176.06
Molar Mass	229.59	177.24
Oil-Base Mud OBM Contamination (wt. % STO Basis)	23.30	9.80
API - Single-Stage STO … Original	36.10	43.50
API - Single-Stage STO … De-Contaminated	32.80	42.50
Density (g/cc) … Original	0.84	0.81
Density (g/cc) … De-Contaminated	0.86	0.81
Gas Gravity	0.76	0.59

Table C 3 – Pressure as a function of time at various points in typical deep-ocean well system

Time	Oil Layer	BHFP	Oil-Lower Layer	Gas-Upper Layer	Comingle Point	Well Head	Separator
years	psi	psi	psi	psi	psi	psi	psi
0	17000	16700	16990	15,740	8,000	2,100	1,200
1	15600	15260	15590	14,300	8,200	2,120	1,200
2	14200	13820	14190	12,860	8,400	2,140	1,200
3	12800	12380	12790	11,420	8,600	2,160	1,200
4	11400	10940	11390	9,980	8,800	2,180	1,200
5	10000	9500	9990	8,540	9,000	2,200	1,200

Table C 4 – Temperature as a function of time at various points in typical deep-ocean well system

Time	Oil Layer	BHFP	Oil-Lower Layer	Gas-Upper Layer	Comingle Point	Well Head	Separator
years	°F	°F	°F	°F	°F	°F	°F
0	180	180	184	170	145	115	100
1	180	180	184	170	144	120	105
2	180	180	184	170	143	125	110
3	180	180	184	170	142	125	110
4	180	180	184	170	141	125	110
5	180	180	184	170	140	125	110

Table C 5 – Gas-to-oil ratios (GORs) for deep-ocean wells at various times

Time	GOR
years	scf/bbl
0	900
1	1,120
2	1,340
3	1,560
4	1,780
5	2,000

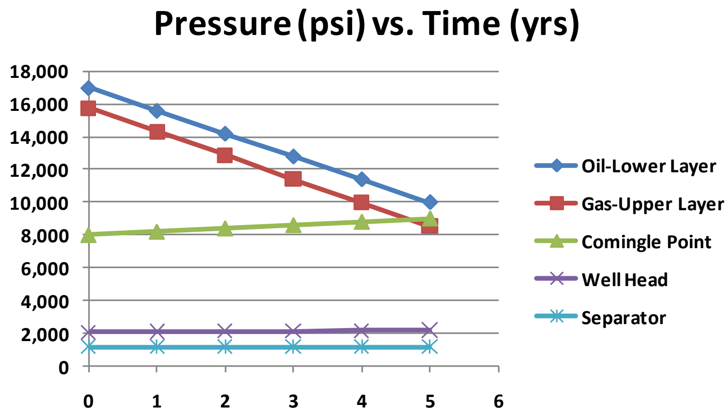

Figure C 1 – Pressure as a function of time at various points in typical deep-ocean well system

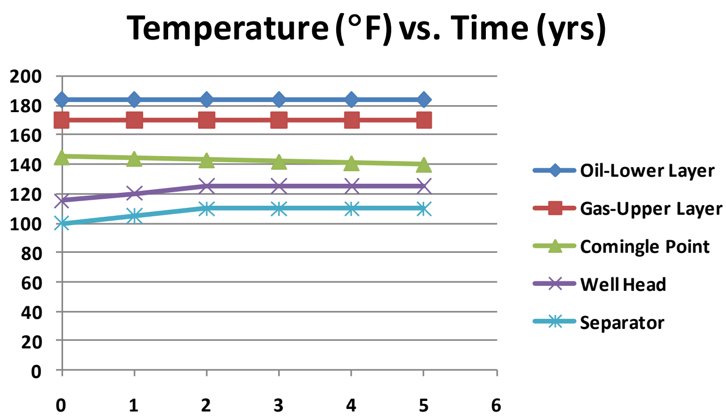

Figure C 2 – Temperature as a function of time at various points in typical deep-ocean well system

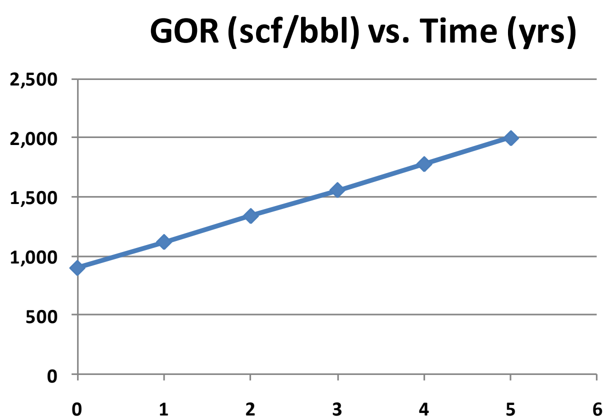

Figure C 3 – Gas-to-oil ratio (GOR) for production from typical deep-ocean well system

Appendix D – Classes of Thermoelectric Materials and Devices

Table D 1 – Summary of practical thermoelectric materials, categorized as tellurides, silicon-germanium alloys, silicides, sulfides, antimonides and superlattices, with their corresponding operating temperature and dimensionless figure of merit, used to estimate the overall device efficiency

Family	Type	Compound	T(K)	ZT	Source
Tellurides	p	25% Bi2Te3 + 75% Sb2Te3	300	0.98	Rosi, 1968
	n	75% Bi2Te3 + 25% Bi2Se3	300	0.72	Rosi, 1968
	p	PbTe	600	1.05	Rosi, 1968
	n	PbTe	600	1.05	Rosi, 1968
	n	Pb0.75Sn0.25Te	900	1.44	Wood, 1988
	p	(GeTe)0.95(Bi2Te3)	750	1.28	Wood, 1988
	p	AgSbTe2	650	1.17	Wood, 1988
Si-Ge Alloys	p	Si70Ge30	1000	1.00	Rosi, 1968
	n	Si70Ge30	1000	1.10	Rosi, 1968
Silicides	n	FeSi2 + 3% Co	1000	0.08	Matsubari, 1992
	p	Ru2Si3	700	0.00	Ohta, 1992
	n	Ru2Si3	500	0.01	Ohta, 1992
Sulfides	p	Ce3-xS4 (0.00 < x < 0.33)	1000	0.43	Cutler, 1964
	p	Ce 3-x S4 (0.30 < x < 0.33)	1000	1.03	Cutler, 1964
	n	LaS1.445	1000	1.53	Kamarzin, 1981
	p	US	573	0.06	Gmelin
Antimonides	p	IrSb3	773	0.50	Caillat, 1992
Superlattice		PbTe/Te	300	1.90	Harman, 1998

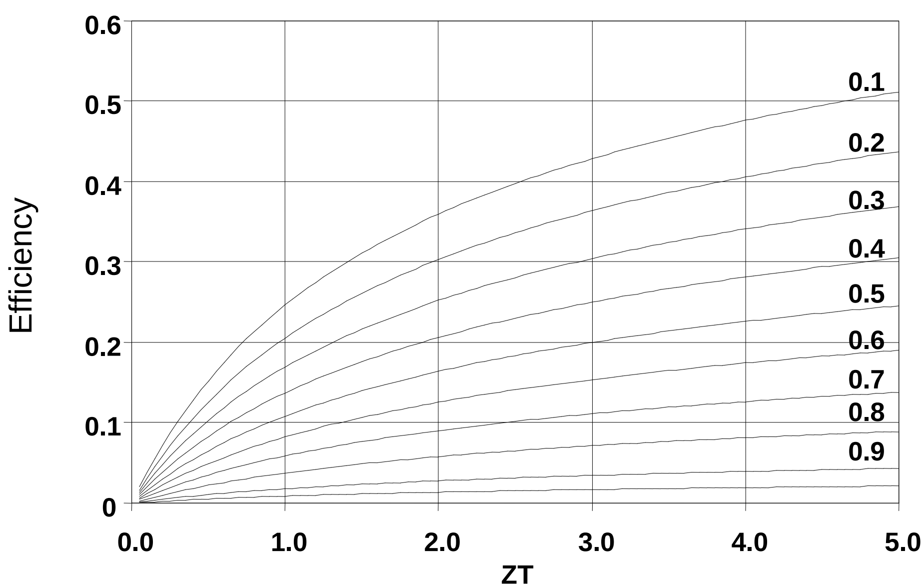

Figure D 1 – Efficiency (η) as a function of ZT for T_c/T_h ratios from 0.1 to 0.9

Appendix E – Deep Ocean Currents

Figure E 1 – Advanced turbine for the conversion of deep ocean current to shaft energy

Appendix F – Energy Storage Technologies

Table F 1 – A comparison of energy storage technologies considered for RPSEA hybrid system

Parameter	Units	Pb Acid	AgZn	NaS	ZEBRA	Li-Ion	Regenerative Fuel Cell
Anode	none		Zn	Na	Na	LiC6	PtRu/C
Cathode	none	PbO_2	AgO/Ag_2O	S	$NiCl_2$	$Li_x(Ni,Co)O_2$	Pt/C
Separator	none	Polyethylene	Cellophane	β''-Al_2O_3	β''-Al_2O_3	Polyethylene	Nafion
Electrolyte Salt	none	H_2SO_4	40% KOH	None	$NaAlCl_4$	1M $LiPF_6$	None
Electrolyte Solvent	none	H_2O	H_2O	None	None	EC:DMC:DEC	H_2O
Toxic Materials Required	elements	Pb, Sb	None	S	Ni	Ni, Co, $LiPF_6$	None
Strategic Materials Required	elements	None	Ag	None	Ni	Ni, Co, $LiPF_6$	Pt, Ru
Minimum Operating Temperature	degrees C	-40	-20	290	220	-30	30
Nominal Operating Temperature	degrees C	30	30	310-350	270-350	30	90
Maximum Operting Temperature	degrees C	60	60	390	450	60	120
Minimum Operating Voltage	V	1.75	1.30	1.78	1.72	3.00	0.50
Nominal Operating Voltage	V	1.90	1.50	1.90	2.25	3.80	0.70
Maximum Operating Voltage	V	2.00	1.70	1.95	2.67	4.00	1.20
Open Circuit Voltage	V	2.10	1.86	2.08	2.58	4.10	1.20
Cell Impedance	milliohms	NA	5 to 15	5 to 32	10 to 45	5 to 10	NA
Peak Specific Power	W/kg	210	5560	215-360	250-390	1,100	NA
Specific Power	W/kg	20	5560-1470	390-250	171-169	1100-74	27
Power Density	W/L	51	9530-2520	604-386	265-261	2270-147	17
Specific Energy	Wh/kg	20-35	105-110	117-226	94-119	75-182	326
Energy Density	Wh/L	50-90	180-300	147-370	148-183	139-359	209
Coulombic Efficiency (Ah/Ah)	%	80-90%	90%	89-92%	~100%	99%	90%
Electrical Efficiency (Wh/Wh)	%	70-75%	75%	NA	NA	95%	43%
Self Discharge Rate	% per mo.	< 3	< 3	< 1	< 1	< 2	NA
Minimum Cycle Life	Cycles	200	10	NA	1,300	300	NA
Nominal Cycle Life	Cycles	400	100	2,250	2,500	500	NA
Maximum Cycle Life	Cycles	1,100	250	NA	3,500	1,500	NA
Mimimum Calendar Life	years	3.0	0.5	NA	5.0	1.0	NA
Nominal Calendar Life	years	5.5	1.0	7.5	7.0	3.0	NA
Maximum Calendar Life	years	8.0	1.5	15.0	9.0	5.0	NA
Technology Cost	$/kWh	150	600	300	220	300	NA
Cost Relative to Pb Acid	none	1.0	4.0	1.5	1.5	2.0	NA

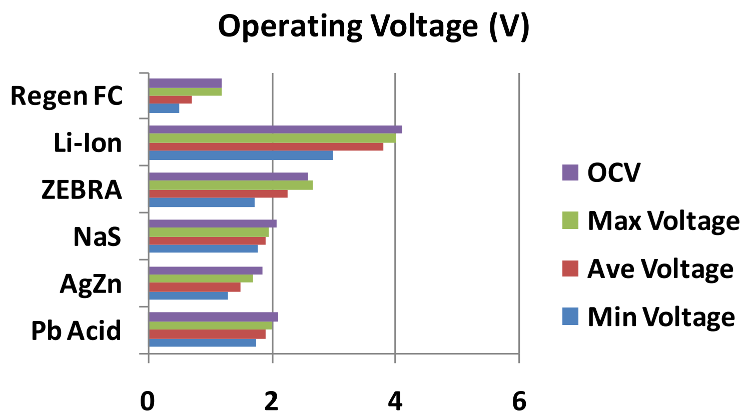

Figure F 1 – Range of cell voltages for energy storage technologies considered for the various hybrid energy conversion and storage systems, ranging from the open circuit voltage (OCV) to the minimum operating voltage

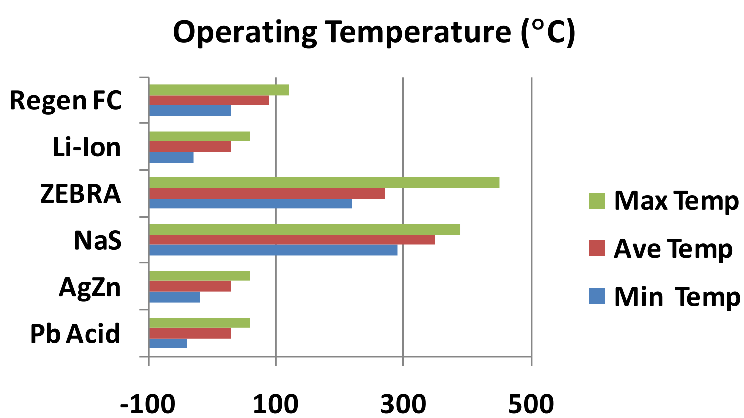

Figure F 2 – Range of operating temperatures possible with the energy storage technologies considered for the various hybrid energy conversion and storage systems

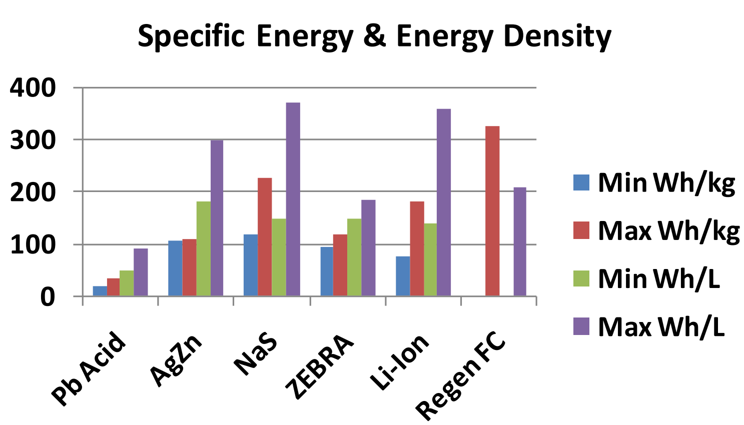

Figure F 3 – A comparison of the specific energies and energy densities for the energy storage technologies considered for the various hybrid energy conversion and storage systems

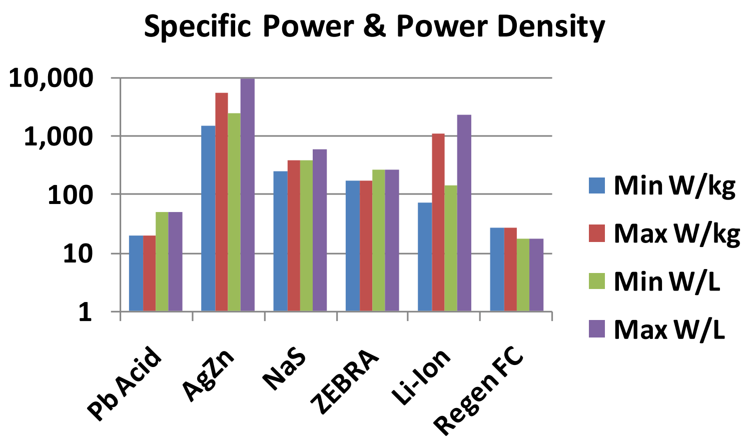

Figure F 4 – A comparison of the specific powers and power densities for the energy storage technologies considered for the various hybrid energy conversion and storage systems

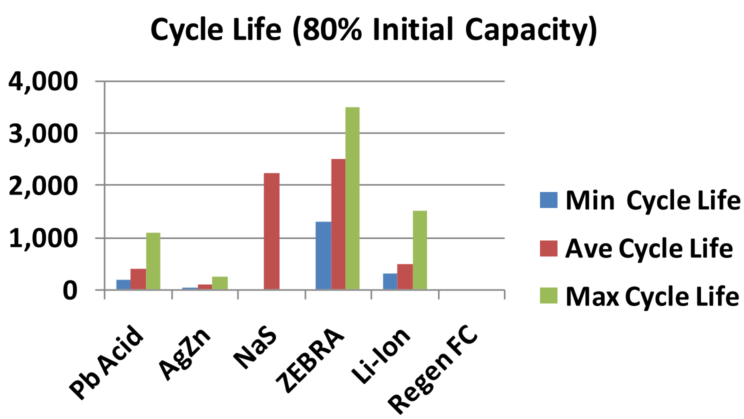

Figure F 5 – A comparison of the charge-discharge cycle lives for the energy storage technologies considered for the various hybrid energy conversion and storage systems

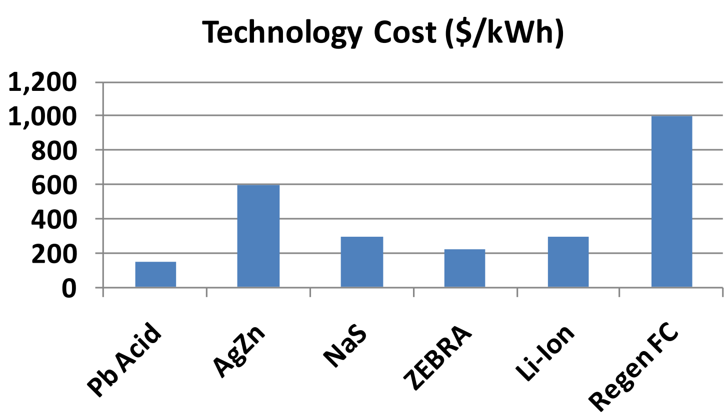

Figure F 6 – A comparison of the cost of energy storage for each of the technologies considered for the various hybrid energy conversion and storage systems

Appendix G – Tradeoff Between Specific Energy & Specific Power

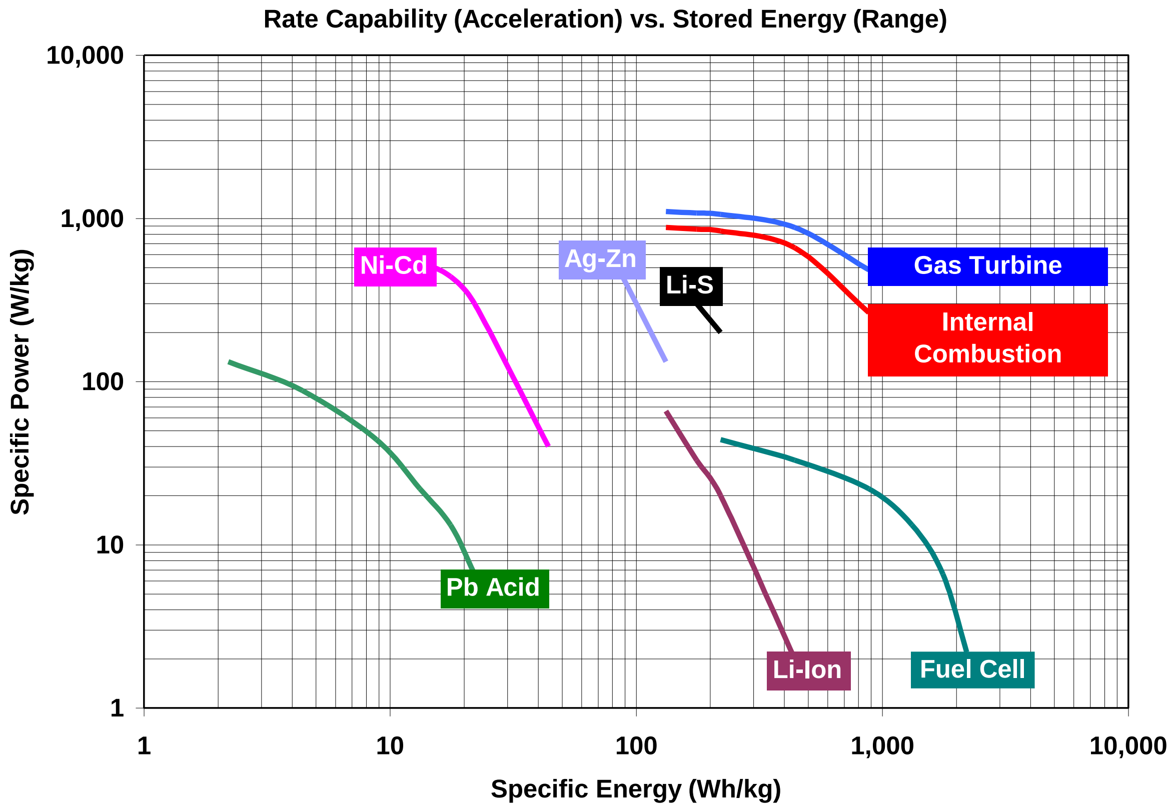

Figure G 1 – Specific power vs. specific energy for competing non-nuclear sub sea energy conversion and storage systems

Appendix H – Summary of Assumptions Underlying Economic Analysis

Table H 1 – Life, interest rate, discount factor, and annuity factor assumptions [Perry's Handbook]

Cost Model Assumptions	Value	Units
Required Power	Site Specific	MW-e
Service Life = n	15	years
Interest Rate = I (Assuming Relatively Low Risk)	5	%
Compound Interest Factor = $f_i = (1+i)^n$	2.0789	factor
Discount Factor = $f_d = 1/f_i$	0.4810	factor
Annuity Future Worth Factor = f_{AF} = A/F = $i/[(1+i)^n-1]$	0.0463	factor
Annuity Present Worth Factor = f_{AP} = A/P = $[i(1+i)^n]/[(1+i)n-1]$	0.0963	factor
Salary & Fringe Benefits - Management	300000	$/year
Salary & Fringe Benefits - Engineer	200000	$/year
Salary & Fringe Benefits - Operations	100000	$/year

Table H 2 – Miscellaneous assumptions impacting ocean floor grid option

Assumed Electrical Grid Concept of Operations	Parameter	Units
Assumed Cost of DC Cables (Onshore to Control Buoy)	2,500,000.00	US $ per km
Assumed Cost of HVDC Station	30,000,000.00	US $ per HVDC Station
Assumed Power Capability of HVDC Station	40.00	MW per HVDC Station
Assumed Cost of Umbilical Riser at Buoy	1,000,000.00	US $ per 1000 ft
Assumed Cost of Remote Control Buoy Station + AD/DC Inverter	1,000,000.00	US $ per unit
Assumed Cable Diameter	4.0000	inches
Assumed Cable Diameter	10.1600	cm
Assumed Cable Diameter - Corresponding Cross-Sectional Area	81.0732	cm2
Estimated Cable Volume Per km - Assumed Cable Diameter	8,107,319.6656	cm3 per km
Assumed Cable Density Equals Copper Density	8.9200	grams per cm3
Estimated Cable Weight Per km - Assumed Cable Density	72,317.2914	kg per km
Assumed Cost of Copper	15.00	US $ per kg
Assumed Cost of $1 Million Per Kilometer - Estimated from Cable Size & Copper Costs	1,084,759.37	US $ per km
Assumed Cable Resistivity Equals Copper Resistivity at 20°	1.6730	microohm-cm
Assumed Cable Temperature Coefficient Equals Copper Temperature Coefficient	0.0068	per °F
Assumed Cable Operating Temperature	40.0000	°F
Assumed Cable Operating Temperature	4.7778	°C
Assumed Cable Resistivity at Operating Temperature	1.4998	microohm-cm
Assumed Cable Resistance per Kilometer	0.0018	ohms per km
Conversion of Mechanical Horsepower (HP) to Watts (W)	745.7000	W per hp
Assumed Pump Power	800.0000	hp per pump
Assumed Pumps per ESP Unit	2.0000	pump per ESP
Estimated Total Pumping Power per ESP Unit	1.1931	MW per ESP
Assumed Cable Current - Two 800-HP Pumps Per ESP (230 Amps per Pump)	460.0000	amps per ESP
Assumed Cable Current - Based Upon 70 MVA & 120 KV	583.3333	amps per site
Assumed Nominal Cable Current	1,000.0000	amps per site
Assumed Cost of Electricity on Shore	0.1000	US $ per kWh

Table H 3 – Assumptions pertaining to the cost and operation of non-grid sub-systems

Miscellaenous Assumptions	Parameter	Units
Service Life	15.00	years
Submersible on Bottom for 7 Days Between Surfacings	168.00	hours
Assume Submersibles Operating in Parallel - One on Surface - One on Bottom	2.00	vehicles
Vehicle to Power System Ratio	1.25	factor
Fraction of Operating Power Required for Control & Communications	0.05	fraction
Full Power Backup Required for Graceful Shutdown - Operating Time on Battery	4.00	hours
Cost of Cryogenic Oxygen at Surface	0.50-0.75	LOX $ per 100 SCF
Cost of Cryogenic Oxygen at Surface	0.50-0.75	LOX $ per gal
Cost of Cryogenic Oxygen at Surface	0.198129	LOX $ per liter
Density of Crygenic Oxygen at Surface	1.149000	LOS kg/L (BP=182.962°C)
Cost of Cryogenic Oxygen at Surface	0.172436	LOX $ per kg
Cost of Cryogenic Oxygen at Surface	0.172436	LOX $/kg
Assumed Cost of Single Stand Pipe from Surface for Oxygen	1,000,000.00	$ per 1000 ft
Assumed Cost of Stand Pipe from Surface for Pressurized Oxygen	1,000.00	$ per ft
Assumed Cost of Double Stand Pipe from Surface for Oxygen & Exhaust	2,000,000.00	$ per 1000 ft
Assumed Cost of Double Stand Pipe from Surface for Oxygen & Exhaust	2,000.00	$ per ft
Pre-Exponential Factor for Carbon Steel PV & FT Cost	73.00	$ per kg
Exponent for Carbon Steel PV & FT Cost	-0.34	none
Escalation Factor for Titanium Fabrication	11.00	$(Ti)/$(CS)
Hull Base Costs	150000000.00	$ per unit
Incremental Hull Costs	8000.00	$ per metric ton
Incremental Hull Costs	8.00	$ per kg
Reformer:Fuel Cell Weight Ratio	2.00	kg per kg
Reformer:Fuel Cell Volume Ratio	2.00	L per L
Reformer:Fuel Cell Cost Ratio	2.00	$ per $
Reformer Efficiency	90%	percent
Fuel Cell Efficiency	67%	percent
Overall Efficiency for Reformer & Fuel Cell System	60%	percent
Assumed Time to License Sub-Surface Nuclear Power Plant	7.00	years
Assumed Licensing Costs Per Year	3.00	$M per year

Table H 4 – Cost factors applied to direct costs to calculate indirect and total overnight costs, and used to calculate the capital cost at the commencement of commercial operations, and the associated annualized costs

RPSEA Concept of Operations Site: Site A	Factor	Units
Energy Conversion & Storage	Site/System Specific	
Oxygen Supply	Site/System Specific	
Pressure Vessels	Site/System Specific	
Flotation Tanks	Site/System Specific	
Miscellaneous	Site/System Specific	
Direct Costs Subtotal (2010 $M)	Site/System Specific	
Construction Services	0.10	
Home Office Engineering & Services	0.07	
Field Office Engineering & Services	0.05	
Owner's Costs	0.13	
Licensing & Permitting	0.01	
Indirect Costs Subtotal (2010 $M)		
Total & Indirect Costs (2010 $M)		
Contingency Allowancy	0.10	
Miscellaneous	0.01	
Total Overnight Costs		
Allowance for Escalation During Construction	0.05	
Allowance for Interest	0.05	
Capital Investment at Commercial Operation (2010 $M)		
Annualized Investment at Commercial Operation (2010 $M/year)	0.0963	

Table H 5 – Assumed labor and salaries for operation, and additional cost factors applied to the annualized investment to calculate various contributions to the annual operating expense

RPSEA Concept of Operations Site: Site A	Manpower	Units
Managers	2	FTE
Engineers	4	FTE
Operators	8	FTE
RPSEA Concept of Operations Site: Site A	**Factor**	**Units**
Salaries & Benefits		
Chemicals, Materials & Utilities	0.10	$/$
Spare Parts & Capital Plant Upgrades	0.10	$/$
Taxes & Insurance	0.10	$/$
Operating Cost Contingency	0.05	$/$
General O&M	0.02	$/$
Miscellaneous	0.01	$/$

Appendix I – Detailed Analyses of Costs for Each Concept of Operations Site

Table I 1 – Summary of the detailed economic analysis performed for the Shtokman site

Assumptions	Value	Units	Reference	Nomenclature	Description of Deep Ocean Hybrid System
Required Power	240.0000	MW-e	Site Dependent	PWR	PWR = Nuclear Reactor + Pb Acid Battery
Service Life = n	15	years	Analyst Estimate	FC1	FC1 = Line for Surface O2 + WELL Head Gas + Reformer + PEMFC + Battery
Interest Rate = i	5	%	Analyst Estimate	FC2	FC2 = Stored O2 + Well Head Gas + Reformer + Fuel Cell + Battery
Compound Interest Factor = $f_i = (1+i)^n$	2.0789	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV1	SV1 = Submersible Vehicle + Stored O2 + Fuel Cell + Battery
Discount Factor = $f_d = 1/f_i$	0.4810	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV2	SV2 = Submersible Vehicle + Stored O2 + Engine or Turbine + Battery
Annuity Future Worth Factor = f_{AF} = A/F = $i/[(1+i)^n-1]$	0.0463	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV3	SV3 = Submersible Vehicle + Charge at Docking Station + ZEBRA Battery
Annuity Present Worth Factor = f_{AP} = A/P = $[i(1+i)^n]/[(1+i)n-1]$	0.0963	factor	Perry's 7th Edition pp. 9-10 to 9-13	PWR TEG	PWR TEG = PWR + WELL TEG + Pb Acid Battery
Salary & Fringe Benefits - Management	300000	$/year	Analyst Estimate	WELL TEG	WELL TEG = Thermoelectric Generator + Well Head Waste Heat + Battery
Salary & Fringe Benefits - Engineer	200000	$/year	Analyst Estimate	GRID	GRID = Floor Electrical Grid + Battery
Salary & Fringe Benefits - Operations	100000	$/year	Analyst Estimate	DOC	DOC = Deep Ocean Current + Battery

Investment at Comencement of Commercial Operations		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Schtokman	Factor	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Energy Conversion & Storage		1958.400	3440.094	2734.187	6835.467	1842.894	22176.000	2438.400	638.400	1750.900	$M
Oxygen Supply		0.000	2.296	4.811	12.028	9.785	0.000	0.000	0.000	0.000	$M
Pressure Vessels		472.561	516.080	504.811	1262.028	1170.441	16639.509	717.680	566.893	321.774	$M
Flotation Tanks		514.260	527.639	544.915	1362.288	1294.556	17469.254	710.725	558.301	361.835	$M
Miscellaneous		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	$M
Direct Costs Subtotal (2010 $M)		2945.221	4486.109	3788.724	9471.811	4317.677	56284.763	3866.806	1763.594	2434.509	$M
Construction Services	0.1	294.522	448.611	378.872	947.181	431.768	5628.476	386.681	176.359	243.451	$M
Home Office Engineering & Services	0.07	206.165	314.028	265.211	663.027	302.237	3939.933	270.676	123.452	170.416	$M
Field Office Engineering & Services	0.05	147.261	224.305	189.436	473.591	215.884	2814.238	193.340	88.180	121.725	$M
Owner's Costs	0.13	382.879	583.194	492.534	1231.335	561.298	7317.019	502.685	229.267	316.486	$M
Licensing & Permitting	0.01	50.452	44.861	37.887	94.718	43.177	562.848	59.668	17.636	24.345	$M
Indirect Costs Subtotal (2010 $M)		1081.280	1614.999	1363.941	3409.852	1554.364	20262.515	1413.050	634.894	876.423	$M
Total & Indirect Costs (2010 $M)		4026.501	6101.108	5152.665	12881.663	5872.040	76547.278	5279.856	2398.488	3310.933	$M
Contingency Allowancy	0.10	402.650	610.111	515.267	1288.166	587.204	7654.728	527.986	239.849	331.093	$M
Miscellaneous	0.01	40.265	61.011	51.527	128.817	58.720	765.473	52.799	23.985	33.109	$M
Total Overnight Costs		4469.416	6772.230	5719.458	14298.646	6517.964	84967.478	5860.640	2662.321	3675.135	$M
Allowance for Escalation During Construction	0.05	223.471	338.611	285.973	714.932	325.898	4248.374	293.032	133.116	183.757	$M
Allowance for Interest	0.05	223.471	338.611	285.973	714.932	325.898	4248.374	293.032	133.116	183.757	$M
Capital Investment at Commercial Operation (2010 $M)		4916.357	7449.453	6291.404	15728.511	7169.761	93464.226	6446.704	2928.553	4042.649	$M
Annualized Investment at Commercial Operation (2010 $M/year)	0.0963	473.653	717.697	606.128	1515.321	690.751	9004.557	621.090	282.144	389.478	$M
Operating & Maintenance Costs		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Schtokman	FTE	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Managers	2	600000	600000	600000	600000	600000	600000	600000	600000	600000	$/year
Engineers	4	800000	800000	800000	800000	800000	800000	800000	800000	800000	$/year
Operators	8	800000	800000	800000	800000	800000	800000	800000	800000	800000	$/year
RPSEA Concept of Operations Site: Schtokman	Factor	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Salaries & Benefits		2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	$M
Chemicals, Materials & Utilities	0.10	47.365	71.770	60.613	151.532	69.075	900.456	62.109	28.214	38.948	$M
Spare Parts & Capital Plant Upgrades	0.10	47.365	71.770	60.613	151.532	69.075	900.456	62.109	28.214	38.948	$M
Taxes & Insurance	0.10	47.365	71.770	60.613	151.532	69.075	900.456	62.109	28.214	38.948	$M
Operating Cost Contingency	0.05	23.683	35.885	30.306	75.766	34.538	450.228	31.055	14.107	19.474	$M
General O&M	0.02	9.473	14.354	12.123	30.306	13.815	180.091	12.422	5.643	7.790	$M
Miscellaneous	0.01	4.737	7.177	6.061	15.153	6.908	90.046	6.211	2.821	3.895	$M
Operating & Maintenance Costs (2010 $M/year)		182.188	274.925	232.529	578.022	264.685	3423.932	238.214	109.415	150.202	$M/year
Estimated Cost of Electricity		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Schtokman		PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Electric Power Generation		240.0000	240.0000	240.0000	240.0000	240.0000	240.0000	240.0000	240.0000	240.0000	MW-e
Hours Per Year		8766	8766	8766	8766	8766	8766	8766	8766	8766	hours/year
Annual Electric Energy Production		2.104E+09	2.104E+09	2.104E+09	2.104E+09	2.104E+09	2.104E+09	2.104E+09	2.104E+09	2.104E+09	kWh-e/year
Annual Production Cost		6.558E+08	9.926E+08	8.387E+08	2.093E+09	9.554E+08	1.243E+10	8.593E+08	3.916E+08	5.397E+08	$/year
Cost of Electricity (COE)		3.117E-01	4.718E-01	3.986E-01	9.950E-01	4.541E-01	5.908E+00	4.084E-01	1.861E-01	2.565E-01	$/kWh-e

Table I 2 – Summary of the detailed economic analysis performed for the Chinook site

Assumptions	Value	Units	Reference	Nomenclature	Description of Deep Ocean Hybrid System
Required Power	7.2000	MW-e	Site Dependent	PWR	PWR = Nuclear Reactor + Pb Acid Battery
Service Life = n	15	years	Analyst Estimate	FC1	FC1 = Line for Surface O2 + WELL Head Gas + Reformer + PEMFC + Battery
Interest Rate = i	5	%	Analyst Estimate	FC2	FC2 = Stored O2 + Well Head Gas + Reformer + Fuel Cell + Battery
Compound Interest Factor = $f_i = (1+i)^n$	2.0789	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV1	SV1 = Submersible Vehicle + Stored O2 + Fuel Cell + Battery
Discount Factor = $f_d = 1/f_i$	0.4810	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV2	SV2 = Submersible Vehicle + Stored O2 + Engine or Turbine + Battery
Annuity Future Worth Factor = f_{AF} = A/F = $i/[(1+i)^n-1]$	0.0463	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV3	SV3 = Submersible Vehicle + Charge at Docking Station + ZEBRA Battery
Annuity Present Worth Factor = f_{AP} = A/P = $[i(1+i)^n]/[(1+i)n-1]$	0.0963	factor	Perry's 7th Edition pp. 9-10 to 9-13	PWR TEG	PWR TEG = PWR + WELL TEG + Pb Acid Battery
Salary & Fringe Benefits - Management	300000	$/year	Analyst Estimate	WELL TEG	WELL TEG = Thermoelectric Generator + Well Head Waste Heat + Battery
Salary & Fringe Benefits - Engineer	200000	$/year	Analyst Estimate	GRID	GRID = Floor Electrical Grid + Battery
Salary & Fringe Benefits - Operations	100000	$/year	Analyst Estimate	DOC	DOC = Deep Ocean Current + Battery

Investment at Comencement of Commercial Operations		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Chinok	**Factor**	**PWR**	**FC1**	**FC2**	**SV1**	**SV2**	**SV3**	**PWR TEG**	**WELL TEG**	**GRID**	**Units**
Energy Conversion & Storage		58.752	1168.302	585.067	1462.668	97.638	665.280	73.152	19.152	83.002	$M
Oxygen Supply		0.000	17.600	1.777	4.444	1.932	0.000	0.000	0.000	0.000	$M
Pressure Vessels		457.217	606.623	535.023	1337.558	1140.615	16043.725	635.339	485.052	306.930	$M
Flotation Tanks		474.080	705.457	669.167	1672.917	1276.486	16485.470	659.524	508.507	323.063	$M
Miscellaneous		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	$M
Direct Costs Subtotal (2010 $M)		**990.048**	**2497.982**	**1791.035**	**4477.587**	**2516.671**	**33194.476**	**1368.015**	**1012.711**	**712.995**	**$M**
Construction Services	**0.1**	99.005	249.798	179.103	447.759	251.667	3319.448	136.801	101.271	71.299	$M
Home Office Engineering & Services	**0.07**	69.303	174.859	125.372	313.431	176.167	2323.613	95.761	70.890	49.910	$M
Field Office Engineering & Services	**0.05**	49.502	124.899	89.552	223.879	125.834	1659.724	68.401	50.636	35.650	$M
Owner's Costs	**0.13**	128.706	324.738	232.835	582.086	327.167	4315.282	177.842	131.652	92.689	$M
Licensing & Permitting	**0.01**	30.900	24.980	17.910	44.776	25.167	331.945	34.680	10.127	7.130	$M
Indirect Costs Subtotal (2010 $M)		**377.417**	**899.274**	**644.773**	**1611.931**	**906.001**	**11950.011**	**513.485**	**364.576**	**256.678**	**$M**
Total & Indirect Costs (2010 $M)		**1367.466**	**3397.256**	**2435.808**	**6089.519**	**3422.672**	**45144.487**	**1881.500**	**1377.287**	**969.673**	**$M**
Contingency Allowancy	**0.10**	136.747	339.726	243.581	608.952	342.267	4514.449	188.150	137.729	96.967	$M
Miscellaneous	**0.01**	13.675	33.973	24.358	60.895	34.227	451.445	18.815	13.773	9.697	$M
Total Overnight Costs		**1517.887**	**3770.954**	**2703.746**	**6759.366**	**3799.166**	**50110.380**	**2088.465**	**1528.788**	**1076.337**	**$M**
Allowance for Escalation During Construction	**0.05**	75.894	188.548	135.187	337.968	189.958	2505.519	104.423	76.439	53.817	$M
Allowance for Interest	**0.05**	75.894	188.548	135.187	337.968	189.958	2505.519	104.423	76.439	53.817	$M
Capital Investment at Commercial Operation (2010 $M)		**1669.676**	**4148.050**	**2974.121**	**7435.302**	**4179.082**	**55121.418**	**2297.311**	**1681.667**	**1183.971**	**$M**
Annualized Investment at Commercial Operation (2010 $M/year)	**0.0963**	**160.860**	**399.633**	**286.534**	**716.334**	**402.622**	**5310.524**	**221.328**	**162.016**	**114.066**	**$M**

Operating & Maintenance Costs		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Chinok	**FTE**	**PWR**	**FC1**	**FC2**	**SV1**	**SV2**	**SV3**	**PWR TEG**	**WELL TEG**	**GRID**	**Units**
Managers	**2**	600000	600000	600000	600000	600000	600000	600000	600000	600000	**$/year**
Engineers	**4**	800000	800000	800000	800000	800000	800000	800000	800000	800000	**$/year**
Operators	**8**	800000	800000	800000	800000	800000	800000	800000	800000	800000	**$/year**
RPSEA Concept of Operations Site: Chinok	**Factor**	**PWR**	**FC1**	**FC2**	**SV1**	**SV2**	**SV3**	**PWR TEG**	**WELL TEG**	**GRID**	**Units**
Salaries & Benefits		2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	$M
Chemicals, Materials & Utilities	**0.10**	16.086	39.963	28.653	71.633	40.262	531.052	22.133	16.202	11.407	$M
Spare Parts & Capital Plant Upgrades	**0.10**	16.086	39.963	28.653	71.633	40.262	531.052	22.133	16.202	11.407	$M
Taxes & Insurance	**0.10**	16.086	39.963	28.653	71.633	40.262	531.052	22.133	16.202	11.407	$M
Operating Cost Contingency	**0.05**	8.043	19.982	14.327	35.817	20.131	265.526	11.066	8.101	5.703	$M
General O&M	**0.02**	3.217	7.993	5.731	14.327	8.052	106.210	4.427	3.240	2.281	$M
Miscellaneous	**0.01**	1.609	3.996	2.865	7.163	4.026	53.105	2.213	1.620	1.141	$M
Operating & Maintenance Costs (2010 $M/year)		**63.327**	**154.060**	**111.083**	**274.407**	**155.196**	**2020.199**	**86.305**	**63.766**	**45.545**	**$M/year**

Estimated Cost of Electricity		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Chinok		**PWR**	**FC1**	**FC2**	**SV1**	**SV2**	**SV3**	**PWR TEG**	**WELL TEG**	**GRID**	**Units**
Electric Power Generation		7.2000	7.2000	7.2000	7.2000	7.2000	7.2000	7.2000	7.2000	7.2000	MW-e
Hours Per Year		8766	8766	8766	8766	8766	8766	8766	8766	8766	hours/year
Annual Electric Energy Production		6.312E+07	6.312E+07	6.312E+07	6.312E+07	6.312E+07	6.312E+07	6.312E+07	6.312E+07	6.312E+07	kWh-e/year
Annual Production Cost		2.242E+08	5.537E+08	3.976E+08	9.907E+08	5.578E+08	7.331E+09	3.076E+08	2.258E+08	1.596E+08	$/year
Cost of Electricity (COE)		**3.552E+00**	**8.773E+00**	**6.300E+00**	**1.570E+01**	**8.838E+00**	**1.161E+02**	**4.874E+00**	**3.577E+00**	**2.529E+00**	**$/kWh-e**

Table I 3 – Summary of the detailed economic analysis performed for the King site

Assumptions	Value	Units	Reference	Nomenclature	Description of Deep Ocean Hybrid System
Required Power	2.0000	MW-e	Site Dependent	PWR	PWR = Nuclear Reactor + Pb Acid Battery
Service Life = n	15	years	Analyst Estimate	FC1	FC1 = Line for Surface O2 + WELL Head Gas + Reformer + PEMFC + Battery
Interest Rate = i	5	%	Analyst Estimate	FC2	FC2 = Stored O2 + Well Head Gas + Reformer + Fuel Cell + Battery
Compound Interest Factor = $f_i = (1+i)^n$	2.0789	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV1	SV1 = Submersible Vehicle + Stored O2 + Fuel Cell + Battery
Discount Factor = $f_d = 1/f_i$	0.4810	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV2	SV2 = Submersible Vehicle + Stored O2 + Engine or Turbine + Battery
Annuity Future Worth Factor = f_{AF} = A/F = $i/[(1+i)^n-1]$	0.0463	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV3	SV3 = Submersible Vehicle + Charge at Docking Station + ZEBRA Battery
Annuity Present Worth Factor = f_{AP} = A/P = $[i(1+i)^n]/[(1+i)n-1]$	0.0963	factor	Perry's 7th Edition pp. 9-10 to 9-13	PWR TEG	PWR TEG = PWR + WELL TEG + Pb Acid Battery
Salary & Fringe Benefits - Management	300000	$/year	Analyst Estimate	WELL TEG	WELL TEG = Thermoelectric Generator + Well Head Waste Heat + Battery
Salary & Fringe Benefits - Engineer	200000	$/year	Analyst Estimate	GRID	GRID = Floor Electrical Grid + Battery
Salary & Fringe Benefits - Operations	100000	$/year	Analyst Estimate	DOC	DOC = Deep Ocean Current + Battery

Investment at Comencement of Commercial Operations		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: King	Factor	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Energy Conversion & Storage		16.320	80.547	47.287	118.218	18.706	184.800	20.320	5.320	81.320	$M
Oxygen Supply		0.000	11.156	0.120	0.299	0.211	0.000	0.000	0.000	0.000	$M
Pressure Vessels		451.825	460.555	457.028	1142.571	1128.989	15826.947	608.266	458.183	301.742	$M
Flotation Tanks		455.414	464.765	464.689	1161.722	1145.749	15921.278	611.759	461.485	305.140	$M
Miscellaneous		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	$M
Direct Costs Subtotal (2010 $M)		**923.559**	**1017.022**	**969.124**	**2422.811**	**2293.655**	**31933.025**	**1240.345**	**924.988**	**688.202**	**$M**
Construction Services	**0.1**	92.356	101.702	96.912	242.281	229.365	3193.303	124.035	92.499	68.820	$M
Home Office Engineering & Services	**0.07**	64.649	71.192	67.839	169.597	160.556	2235.312	86.824	64.749	48.174	$M
Field Office Engineering & Services	**0.05**	46.178	50.851	48.456	121.141	114.683	1596.651	62.017	46.249	34.410	$M
Owner's Costs	**0.13**	120.063	132.213	125.986	314.965	298.175	4151.293	161.245	120.249	89.466	$M
Licensing & Permitting	**0.01**	30.236	10.170	9.691	24.228	22.937	319.330	33.403	9.250	6.882	$M
Indirect Costs Subtotal (2010 $M)		**353.481**	**366.128**	**348.885**	**872.212**	**825.716**	**11495.889**	**467.524**	**332.996**	**247.753**	**$M**
Total & Indirect Costs (2010 $M)		**1277.040**	**1383.150**	**1318.009**	**3295.022**	**3119.370**	**43428.915**	**1707.870**	**1257.984**	**935.955**	**$M**
Contingency Allowancy	**0.10**	127.704	138.315	131.801	329.502	311.937	4342.891	170.787	125.798	93.596	$M
Miscellaneous	**0.01**	12.770	13.832	13.180	32.950	31.194	434.289	17.079	12.580	9.360	$M
Total Overnight Costs		**1417.515**	**1535.297**	**1462.990**	**3657.475**	**3462.501**	**48206.095**	**1895.735**	**1396.363**	**1038.910**	**$M**
Allowance for Escalation During Construction	**0.05**	70.876	76.765	73.149	182.874	173.125	2410.305	94.787	69.818	51.946	$M
Allowance for Interest	**0.05**	70.876	76.765	73.149	182.874	173.125	2410.305	94.787	69.818	51.946	$M
Capital Investment at Commercial Operation (2010 $M)		**1559.266**	**1688.827**	**1609.289**	**4023.222**	**3808.751**	**53026.705**	**2085.309**	**1535.999**	**1142.801**	**$M**
Annualized Investment at Commercial Operation (2010 $M/year)	**0.0963**	**150.223**	**162.705**	**155.043**	**387.606**	**366.944**	**5108.714**	**200.903**	**147.982**	**110.100**	**$M**
Operating & Maintenance Costs		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: King	FTE	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Managers	**2**	600000	600000	600000	600000	600000	600000	600000	600000	600000	**$/year**
Engineers	**4**	800000	800000	800000	800000	800000	800000	800000	800000	800000	**$/year**
Operators	**8**	800000	800000	800000	800000	800000	800000	800000	800000	800000	**$/year**
RPSEA Concept of Operations Site: King	Factor	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Salaries & Benefits		2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	$M
Chemicals, Materials & Utilities	**0.10**	15.022	16.271	15.504	38.761	36.694	510.871	20.090	14.798	11.010	$M
Spare Parts & Capital Plant Upgrades	**0.10**	15.022	16.271	15.504	38.761	36.694	510.871	20.090	14.798	11.010	$M
Taxes & Insurance	**0.10**	15.022	16.271	15.504	38.761	36.694	510.871	20.090	14.798	11.010	$M
Operating Cost Contingency	**0.05**	7.511	8.135	7.752	19.380	18.347	255.436	10.045	7.399	5.505	$M
General O&M	**0.02**	3.004	3.254	3.101	7.752	7.339	102.174	4.018	2.960	2.202	$M
Miscellaneous	**0.01**	1.502	1.627	1.550	3.876	3.669	51.087	2.009	1.480	1.101	$M
Operating & Maintenance Costs (2010 $M/year)		**59.285**	**64.028**	**61.116**	**149.490**	**141.639**	**1943.511**	**78.543**	**58.433**	**44.038**	**$M/year**
Estimated Cost of Electricity		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: King		PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Electric Power Generation		2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	MW-e
Hours Per Year		8766	8766	8766	8766	8766	8766	8766	8766	8766	hours/year
Annual Electric Energy Production		1.753E+07	1.753E+07	1.753E+07	1.753E+07	1.753E+07	1.753E+07	1.753E+07	1.753E+07	1.753E+07	kWh-e/year
Annual Production Cost		2.095E+08	2.267E+08	2.162E+08	5.371E+08	5.086E+08	7.052E+09	2.794E+08	2.064E+08	1.541E+08	$/year
Cost of Electricity (COE)		**1.195E+01**	**1.293E+01**	**1.233E+01**	**3.064E+01**	**2.901E+01**	**4.022E+02**	**1.594E+01**	**1.177E+01**	**8.792E+00**	**$/kWh-e**

Table I 4 – Summary of the detailed economic analysis performed for the Ormen Lange site

Assumptions	Value	Units	Reference	Nomenclature	Description of Deep Ocean Hybrid System
Required Power	60.0000	MW-e	Site Dependent	PWR	PWR = Nuclear Reactor + Pb Acid Battery
Service Life = n	15	years	Analyst Estimate	FC1	FC1 = Line for Surface O2 + WELL Head Gas + Reformer + PEMFC + Battery
Interest Rate = i	5	%	Analyst Estimate	FC2	FC2 = Stored O2 + Well Head Gas + Reformer + Fuel Cell + Battery
Compound Interest Factor = $f_i = (1+i)^n$	2.0789	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV1	SV1 = Submersible Vehicle + Stored O2 + Fuel Cell + Battery
Discount Factor = $f_d = 1/f_i$	0.4810	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV2	SV2 = Submersible Vehicle + Stored O2 + Engine or Turbine + Battery
Annuity Future Worth Factor = f_{AF} = A/F = $i/[(1+i)^n-1]$	0.0463	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV3	SV3 = Submersible Vehicle + Charge at Docking Station + ZEBRA Battery
Annuity Present Worth Factor = f_{AP} = A/P = $[i(1+i)^n]/[(1+i)n-1]$	0.0963	factor	Perry's 7th Edition pp. 9-10 to 9-13	PWR TEG	PWR TEG = PWR + WELL TEG + Pb Acid Battery
Salary & Fringe Benefits - Management	300000	$/year	Analyst Estimate	WELL TEG	WELL TEG = Thermoelectric Generator + Well Head Waste Heat + Battery
Salary & Fringe Benefits - Engineer	200000	$/year	Analyst Estimate	GRID	GRID = Floor Electrical Grid + Battery
Salary & Fringe Benefits - Operations	100000	$/year	Analyst Estimate	DOC	DOC = Deep Ocean Current + Battery

Investment at Comencement of Commercial Operations		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Ormen Lange	Factor	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Energy Conversion & Storage		489.600	1257.904	871.464	2178.659	489.211	5544.000	609.600	159.600	384.600	$M
Oxygen Supply		0.000	5.578	1.813	4.532	3.549	0.000	0.000	0.000	0.000	$M
Pressure Vessels		465.109	509.538	494.091	1235.227	1155.894	16352.419	677.129	526.576	314.556	$M
Flotation Tanks		496.718	525.714	535.152	1337.881	1262.244	17067.394	690.481	538.598	344.834	$M
Miscellaneous		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	$M
Direct Costs Subtotal (2010 $M)		**1451.427**	**2298.734**	**1902.520**	**4756.299**	**2910.898**	**38963.814**	**1977.210**	**1224.774**	**1043.991**	**$M**
Construction Services	0.1	145.143	229.873	190.252	475.630	291.090	3896.381	197.721	122.477	104.399	$M
Home Office Engineering & Services	0.07	101.600	160.911	133.176	332.941	203.763	2727.467	138.405	85.734	73.079	$M
Field Office Engineering & Services	0.05	72.571	114.937	95.126	237.815	145.545	1948.191	98.861	61.239	52.200	$M
Owner's Costs	0.13	188.686	298.835	247.328	618.319	378.417	5065.296	257.037	159.221	135.719	$M
Licensing & Permitting	0.01	35.514	22.987	19.025	47.563	29.109	389.638	40.772	12.248	10.440	$M
Indirect Costs Subtotal (2010 $M)		**543.514**	**827.544**	**684.907**	**1712.268**	**1047.923**	**14026.973**	**732.796**	**440.919**	**375.837**	**$M**
Total & Indirect Costs (2010 $M)		**1994.941**	**3126.278**	**2587.427**	**6468.567**	**3958.821**	**52990.787**	**2710.006**	**1665.692**	**1419.827**	**$M**
Contingency Allowancy	0.10	199.494	312.628	258.743	646.857	395.882	5299.079	271.001	166.569	141.983	$M
Miscellaneous	0.01	19.949	31.263	25.874	64.686	39.588	529.908	27.100	16.657	14.198	$M
Total Overnight Costs		**2214.384**	**3470.169**	**2872.044**	**7180.109**	**4394.292**	**58819.774**	**3008.106**	**1848.918**	**1576.008**	**$M**
Allowance for Escalation During Construction	0.05	110.719	173.508	143.602	359.005	219.715	2940.989	150.405	92.446	78.800	$M
Allowance for Interest	0.05	110.719	173.508	143.602	359.005	219.715	2940.989	150.405	92.446	78.800	$M
Capital Investment at Commercial Operation (2010 $M)		**2435.823**	**3817.186**	**3159.248**	**7898.120**	**4833.721**	**64701.751**	**3308.917**	**2033.810**	**1733.609**	**$M**
Annualized Investment at Commercial Operation (2010 $M/year)	**0.0963**	**234.673**	**367.756**	**304.369**	**760.923**	**465.692**	**6233.515**	**318.789**	**195.942**	**167.020**	**$M**

Operating & Maintenance Costs		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Ormen Lange	FTE	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Managers	2	600000	600000	600000	600000	600000	600000	600000	600000	600000	**$/year**
Engineers	4	800000	800000	800000	800000	800000	800000	800000	800000	800000	**$/year**
Operators	8	800000	800000	800000	800000	800000	800000	800000	800000	800000	**$/year**
RPSEA Concept of Operations Site: Ormen Lange	Factor	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Salaries & Benefits		2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	$M
Chemicals, Materials & Utilities	0.10	23.467	36.776	30.437	76.092	46.569	623.351	31.879	19.594	16.702	$M
Spare Parts & Capital Plant Upgrades	0.10	23.467	36.776	30.437	76.092	46.569	623.351	31.879	19.594	16.702	$M
Taxes & Insurance	0.10	23.467	36.776	30.437	76.092	46.569	623.351	31.879	19.594	16.702	$M
Operating Cost Contingency	0.05	11.734	18.388	15.218	38.046	23.285	311.676	15.939	9.797	8.351	$M
General O&M	0.02	4.693	7.355	6.087	15.218	9.314	124.670	6.376	3.919	3.340	$M
Miscellaneous	0.01	2.347	3.678	3.044	7.609	4.657	62.335	3.188	1.959	1.670	$M
Operating & Maintenance Costs (2010 $M/year)		**91.376**	**141.947**	**117.860**	**291.351**	**179.163**	**2370.936**	**123.340**	**76.658**	**65.668**	**$M/year**

Estimated Cost of Electricity		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Ormen Lange		PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Electric Power Generation		60.0000	60.0000	60.0000	60.0000	60.0000	60.0000	60.0000	60.0000	60.0000	MW-e
Hours Per Year		8766	8766	8766	8766	8766	8766	8766	8766	8766	hours/year
Annual Electric Energy Production		5.260E+08	5.260E+08	5.260E+08	5.260E+08	5.260E+08	5.260E+08	5.260E+08	5.260E+08	5.260E+08	kWh-e/year
Annual Production Cost		3.260E+08	5.097E+08	4.222E+08	1.052E+09	6.449E+08	8.604E+09	4.421E+08	2.726E+08	2.327E+08	$/year
Cost of Electricity (COE)		**6.199E-01**	**9.691E-01**	**8.028E-01**	**2.001E+00**	**1.226E+00**	**1.636E+01**	**8.406E-01**	**5.183E-01**	**4.424E-01**	**$/kWh-e**

Table I 5 – Summary of the detailed economic analysis performed for the Perdido site

Assumptions	Value	Units	Reference	Nomenclature	Description of Deep Ocean Hybrid System
Required Power	5.0000	MW-e	Site Dependent	PWR	PWR = Nuclear Reactor + Pb Acid Battery
Service Life = n	15	years	Analyst Estimate	FC1	FC1 = Line for Surface O2 + WELL Head Gas + Reformer + PEMFC + Battery
Interest Rate = i	5	%	Analyst Estimate	FC2	FC2 = Stored O2 + Well Head Gas + Reformer + Fuel Cell + Battery
Compound Interest Factor = $f_i = (1+i)^n$	2.0789	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV1	SV1 = Submersible Vehicle + Stored O2 + Fuel Cell + Battery
Discount Factor = $f_d = 1/f_i$	0.4810	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV2	SV2 = Submersible Vehicle + Stored O2 + Engine or Turbine + Battery
Annuity Future Worth Factor = f_{AF} = A/F = $i/[(1+i)^n-1]$	0.0463	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV3	SV3 = Submersible Vehicle + Charge at Docking Station + ZEBRA Battery
Annuity Present Worth Factor = f_{AP} = A/P = $[i(1+i)^n]/[(1+i)n-1]$	0.0963	factor	Perry's 7th Edition pp. 9-10 to 9-13	PWR TEG	PWR TEG = PWR + WELL TEG + Pb Acid Battery
Salary & Fringe Benefits - Management	300000	$/year	Analyst Estimate	WELL TEG	WELL TEG = Thermoelectric Generator + Well Head Waste Heat + Battery
Salary & Fringe Benefits - Engineer	200000	$/year	Analyst Estimate	GRID	GRID = Floor Electrical Grid + Battery
Salary & Fringe Benefits - Operations	100000	$/year	Analyst Estimate	DOC	DOC = Deep Ocean Current + Battery

Investment at Comencement of Commercial Operations		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Perdito	**Factor**	**PWR**	**FC1**	**FC2**	**SV1**	**SV2**	**SV3**	**PWR TEG**	**WELL TEG**	**GRID**	**Units**
Energy Conversion & Storage		40.800	483.110	251.284	628.211	59.013	462.000	50.800	13.300	283.300	$M
Oxygen Supply		0.000	15.998	0.731	1.828	1.002	0.000	0.000	0.000	0.000	$M
Pressure Vessels		454.976	515.348	487.509	1218.772	1135.772	15954.585	623.852	473.646	304.770	$M
Flotation Tanks		465.645	551.875	540.987	1352.466	1209.053	16228.744	637.058	486.372	314.959	$M
Miscellaneous		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	$M
Direct Costs Subtotal (2010 $M)		**961.421**	**1566.331**	**1280.511**	**3201.277**	**2404.840**	**32645.330**	**1311.710**	**973.318**	**903.029**	**$M**
Construction Services	0.1	96.142	156.633	128.051	320.128	240.484	3264.533	131.171	97.332	90.303	$M
Home Office Engineering & Services	0.07	67.299	109.643	89.636	224.089	168.339	2285.173	91.820	68.132	63.212	$M
Field Office Engineering & Services	0.05	48.071	78.317	64.026	160.064	120.242	1632.266	65.585	48.666	45.151	$M
Owner's Costs	0.13	124.985	203.623	166.466	416.166	312.629	4243.893	170.522	126.531	117.394	$M
Licensing & Permitting	0.01	30.614	15.663	12.805	32.013	24.048	326.453	34.117	9.733	9.030	$M
Indirect Costs Subtotal (2010 $M)		**367.111**	**563.879**	**460.984**	**1152.460**	**865.742**	**11752.319**	**493.216**	**350.395**	**325.090**	**$M**
Total & Indirect Costs (2010 $M)		**1328.532**	**2130.210**	**1741.495**	**4353.737**	**3270.582**	**44397.648**	**1804.925**	**1323.713**	**1228.119**	**$M**
Contingency Allowancy	0.10	132.853	213.021	174.149	435.374	327.058	4439.765	180.493	132.371	122.812	$M
Miscellaneous	0.01	13.285	21.302	17.415	43.537	32.706	443.976	18.049	13.237	12.281	$M
Total Overnight Costs		**1474.671**	**2364.533**	**1933.059**	**4832.648**	**3630.346**	**49281.390**	**2003.467**	**1469.321**	**1363.212**	**$M**
Allowance for Escalation During Construction	0.05	73.734	118.227	96.653	241.632	181.517	2464.069	100.173	73.466	68.161	$M
Allowance for Interest	0.05	73.734	118.227	96.653	241.632	181.517	2464.069	100.173	73.466	68.161	$M
Capital Investment at Commercial Operation (2010 $M)		**1622.138**	**2600.986**	**2126.365**	**5315.913**	**3993.381**	**54209.529**	**2203.814**	**1616.253**	**1499.534**	**$M**
Annualized Investment at Commercial Operation (2010 $M/year)	**0.0963**	**156.280**	**250.585**	**204.859**	**512.147**	**384.731**	**5222.670**	**212.320**	**155.714**	**144.468**	**$M**
Operating & Maintenance Costs		**Hybrid Power Generation Option**									
RPSEA Concept of Operations Site: Perdito	**FTE**	**PWR**	**FC1**	**FC2**	**SV1**	**SV2**	**SV3**	**PWR TEG**	**WELL TEG**	**GRID**	**Units**
Managers	2	600000	600000	600000	600000	600000	600000	600000	600000	600000	$/year
Engineers	4	800000	800000	800000	800000	800000	800000	800000	800000	800000	$/year
Operators	8	800000	800000	800000	800000	800000	800000	800000	800000	800000	$/year
RPSEA Concept of Operations Site: Perdito	**Factor**	**PWR**	**FC1**	**FC2**	**SV1**	**SV2**	**SV3**	**PWR TEG**	**WELL TEG**	**GRID**	**Units**
Salaries & Benefits		2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	$M
Chemicals, Materials & Utilities	0.10	15.628	25.058	20.486	51.215	38.473	522.267	21.232	15.571	14.447	$M
Spare Parts & Capital Plant Upgrades	0.10	15.628	25.058	20.486	51.215	38.473	522.267	21.232	15.571	14.447	$M
Taxes & Insurance	0.10	15.628	25.058	20.486	51.215	38.473	522.267	21.232	15.571	14.447	$M
Operating Cost Contingency	0.05	7.814	12.529	10.243	25.607	19.237	261.134	10.616	7.786	7.223	$M
General O&M	0.02	3.126	5.012	4.097	10.243	7.695	104.453	4.246	3.114	2.889	$M
Miscellaneous	0.01	1.563	2.506	2.049	5.121	3.847	52.227	2.123	1.557	1.445	$M
Operating & Maintenance Costs (2010 $M/year)		**61.587**	**97.422**	**80.046**	**196.816**	**148.398**	**1986.815**	**82.882**	**61.371**	**57.098**	**$M/year**
Estimated Cost of Electricity		**Hybrid Power Generation Option**									
RPSEA Concept of Operations Site: Perdito		**PWR**	**FC1**	**FC2**	**SV1**	**SV2**	**SV3**	**PWR TEG**	**WELL TEG**	**GRID**	**Units**
Electric Power Generation		5.0000	5.0000	5.0000	5.0000	5.0000	5.0000	5.0000	5.0000	5.0000	MW-e
Hours Per Year		8766	8766	8766	8766	8766	8766	8766	8766	8766	hours/year
Annual Electric Energy Production		4.383E+07	4.383E+07	4.383E+07	4.383E+07	4.383E+07	4.383E+07	4.383E+07	4.383E+07	4.383E+07	kWh-e/year
Annual Production Cost		2.179E+08	3.480E+08	2.849E+08	7.090E+08	5.331E+08	7.209E+09	2.952E+08	2.171E+08	2.016E+08	$/year
Cost of Electricity (COE)		**4.971E+00**	**7.940E+00**	**6.500E+00**	**1.618E+01**	**1.216E+01**	**1.645E+02**	**6.735E+00**	**4.953E+00**	**4.599E+00**	**$/kWh-e**

Table I 6 – Summary of the detailed economic analysis performed for the Argonauta site

Assumptions	Value	Units	Reference	Nomenclature	Description of Deep Ocean Hybrid System
Required Power	2.2000	MW-e	Site Dependent	PWR	PWR = Nuclear Reactor + Pb Acid Battery
Service Life = n	15	years	Analyst Estimate	FC1	FC1 = Line for Surface O2 + WELL Head Gas + Reformer + PEMFC + Battery
Interest Rate = i	5	%	Analyst Estimate	FC2	FC2 = Stored O2 + Well Head Gas + Reformer + Fuel Cell + Battery
Compound Interest Factor = $f_i = (1+i)^n$	2.0789	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV1	SV1 = Submersible Vehicle + Stored O2 + Fuel Cell + Battery
Discount Factor = $f_d = 1/f_i$	0.4810	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV2	SV2 = Submersible Vehicle + Stored O2 + Engine or Turbine + Battery
Annuity Future Worth Factor = f_{AF} = A/F = $i/[(1+i)^n-1]$	0.0463	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV3	SV3 = Submersible Vehicle + Charge at Docking Station + ZEBRA Battery
Annuity Present Worth Factor = f_{AP} = A/P = $[i(1+i)^n]/[(1+i)n-1]$	0.0963	factor	Perry's 7th Edition pp. 9-10 to 9-13	PWR TEG	PWR TEG = PWR + WELL TEG + Pb Acid Battery
Salary & Fringe Benefits - Management	300000	$/year	Analyst Estimate	WELL TEG	WELL TEG = Thermoelectric Generator + Well Head Waste Heat + Battery
Salary & Fringe Benefits - Engineer	200000	$/year	Analyst Estimate	GRID	GRID = Floor Electrical Grid + Battery
Salary & Fringe Benefits - Operations	100000	$/year	Analyst Estimate	DOC	DOC = Deep Ocean Current + Battery

Investment at Comencement of Commercial Operations		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Argonauta	Factor	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Energy Conversion & Storage		17.952	106.917	60.666	151.666	21.560	203.280	22.352	5.852	53.952	$M
Oxygen Supply		0.000	12.468	0.160	0.399	0.270	0.000	0.000	0.000	0.000	$M
Pressure Vessels		452.145	464.580	459.368	1148.421	1129.685	15840.088	609.801	459.705	302.049	$M
Flotation Tanks		456.575	471.000	470.338	1175.846	1151.618	15958.499	614.736	464.408	306.248	$M
Miscellaneous		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	$M
Direct Costs Subtotal (2010 $M)		**926.672**	**1054.965**	**990.533**	**2476.332**	**2303.133**	**32001.868**	**1246.889**	**929.966**	**662.248**	**$M**
Construction Services	0.1	92.667	105.497	99.053	247.633	230.313	3200.187	124.689	92.997	66.225	$M
Home Office Engineering & Services	0.07	64.867	73.848	69.337	173.343	161.219	2240.131	87.282	65.098	46.357	$M
Field Office Engineering & Services	0.05	46.334	52.748	49.527	123.817	115.157	1600.093	62.344	46.498	33.112	$M
Owner's Costs	0.13	120.467	137.146	128.769	321.923	299.407	4160.243	162.096	120.896	86.092	$M
Licensing & Permitting	0.01	30.267	10.550	9.905	24.763	23.031	320.019	33.469	9.300	6.622	$M
Indirect Costs Subtotal (2010 $M)		**354.602**	**379.788**	**356.592**	**891.480**	**829.128**	**11520.672**	**469.880**	**334.788**	**238.409**	**$M**
Total & Indirect Costs (2010 $M)		**1281.274**	**1434.753**	**1347.125**	**3367.812**	**3132.261**	**43522.540**	**1716.770**	**1264.753**	**900.657**	**$M**
Contingency Allowancy	0.10	128.127	143.475	134.712	336.781	313.226	4352.254	171.677	126.475	90.066	$M
Miscellaneous	0.01	12.813	14.348	13.471	33.678	31.323	435.225	17.168	12.648	9.007	$M
Total Overnight Costs		**1422.214**	**1592.576**	**1495.308**	**3738.271**	**3476.810**	**48310.019**	**1905.614**	**1403.876**	**999.730**	**$M**
Allowance for Escalation During Construction	0.05	71.111	79.629	74.765	186.914	173.840	2415.501	95.281	70.194	49.986	$M
Allowance for Interest	0.05	71.111	79.629	74.765	186.914	173.840	2415.501	95.281	70.194	49.986	$M
Capital Investment at Commercial Operation (2010 $M)		**1564.435**	**1751.833**	**1644.839**	**4112.098**	**3824.491**	**53141.021**	**2096.176**	**1544.264**	**1099.703**	**$M**
Annualized Investment at Commercial Operation (2010 $M/year)	**0.0963**	**150.721**	**168.776**	**158.468**	**396.169**	**368.460**	**5119.728**	**201.950**	**148.778**	**105.948**	**$M**
Operating & Maintenance Costs		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Argonauta	FTE	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Managers	2	600000	600000	600000	600000	600000	600000	600000	600000	600000	**$/year**
Engineers	4	800000	800000	800000	800000	800000	800000	800000	800000	800000	**$/year**
Operators	8	800000	800000	800000	800000	800000	800000	800000	800000	800000	**$/year**
RPSEA Concept of Operations Site: Argonauta	Factor	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Salaries & Benefits		2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	$M
Chemicals, Materials & Utilities	0.10	15.072	16.878	15.847	39.617	36.846	511.973	20.195	14.878	10.595	$M
Spare Parts & Capital Plant Upgrades	0.10	15.072	16.878	15.847	39.617	36.846	511.973	20.195	14.878	10.595	$M
Taxes & Insurance	0.10	15.072	16.878	15.847	39.617	36.846	511.973	20.195	14.878	10.595	$M
Operating Cost Contingency	0.05	7.536	8.439	7.923	19.808	18.423	255.986	10.098	7.439	5.297	$M
General O&M	0.02	3.014	3.376	3.169	7.923	7.369	102.395	4.039	2.976	2.119	$M
Miscellaneous	0.01	1.507	1.688	1.585	3.962	3.685	51.197	2.020	1.488	1.059	$M
Operating & Maintenance Costs (2010 $M/year)		**59.474**	**66.335**	**62.418**	**152.744**	**142.215**	**1947.696**	**78.941**	**58.736**	**42.460**	**$M/year**
Estimated Cost of Electricity		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Argonauta		PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Electric Power Generation		2.2000	2.2000	2.2000	2.2000	2.2000	2.2000	2.2000	2.2000	2.2000	MW-e
Hours Per Year		8766	8766	8766	8766	8766	8766	8766	8766	8766	hours/year
Annual Electric Energy Production		1.929E+07	1.929E+07	1.929E+07	1.929E+07	1.929E+07	1.929E+07	1.929E+07	1.929E+07	1.929E+07	kWh-e/year
Annual Production Cost		2.102E+08	2.351E+08	2.209E+08	5.489E+08	5.107E+08	7.067E+09	2.809E+08	2.075E+08	1.484E+08	$/year
Cost of Electricity (COE)		**1.090E+01**	**1.219E+01**	**1.145E+01**	**2.846E+01**	**2.648E+01**	**3.665E+02**	**1.457E+01**	**1.076E+01**	**7.695E+00**	**$/kWh-e**

Table I 7 – Summary of the detailed economic analysis performed for the Marimba Field site

Assumptions	Value	Units	Reference	Nomenclature	Description of Deep Ocean Hybrid System
Required Power	0.0800	MW-e	Site Dependent	PWR	PWR = Nuclear Reactor + Pb Acid Battery
Service Life = n	15	years	Analyst Estimate	FC1	FC1 = Line for Surface O2 + WELL Head Gas + Reformer + PEMFC + Battery
Interest Rate = i	5	%	Analyst Estimate	FC2	FC2 = Stored O2 + Well Head Gas + Reformer + Fuel Cell + Battery
Compound Interest Factor = $f_i = (1+i)^n$	2.0789	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV1	SV1 = Submersible Vehicle + Stored O2 + Fuel Cell + Battery
Discount Factor = $f_d = 1/f_i$	0.4810	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV2	SV2 = Submersible Vehicle + Stored O2 + Engine or Turbine + Battery
Annuity Future Worth Factor = f_{AF} = A/F = $i/[(1+i)^n-1]$	0.0463	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV3	SV3 = Submersible Vehicle + Charge at Docking Station + ZEBRA Battery
Annuity Present Worth Factor = f_{AP} = A/P = $[i(1+i)^n]/[(1+i)n-1]$	0.0963	factor	Perry's 7th Edition pp. 9-10 to 9-13	PWR TEG	PWR TEG = PWR + WELL TEG + Pb Acid Battery
Salary & Fringe Benefits - Management	300000	$/year	Analyst Estimate	WELL TEG	WELL TEG = Thermoelectric Generator + Well Head Waste Heat + Battery
Salary & Fringe Benefits - Engineer	200000	$/year	Analyst Estimate	GRID	GRID = Floor Electrical Grid + Battery
Salary & Fringe Benefits - Operations	100000	$/year	Analyst Estimate	DOC	DOC = Deep Ocean Current + Battery

Investment at Comencement of Commercial Operations		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Marimba Field	Factor	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Energy Conversion & Storage		0.653	1.192	0.933	2.331	0.618	7.392	0.813	0.213	32.803	$M
Oxygen Supply		0.000	2.592	0.002	0.004	0.003	0.000	0.000	0.000	0.000	$M
Pressure Vessels		450.063	450.158	450.136	1125.341	1125.143	15752.790	600.249	450.246	300.059	$M
Flotation Tanks		450.147	450.188	450.217	1125.541	1125.450	15754.847	600.256	450.246	300.137	$M
Miscellaneous		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	$M
Direct Costs Subtotal (2010 $M)		**900.862**	**904.130**	**901.287**	**2253.218**	**2251.214**	**31515.029**	**1201.318**	**900.705**	**633.000**	**$M**
Construction Services	0.1	90.086	90.413	90.129	225.322	225.121	3151.503	120.132	90.070	63.300	$M
Home Office Engineering & Services	0.07	63.060	63.289	63.090	157.725	157.585	2206.052	84.092	63.049	44.310	$M
Field Office Engineering & Services	0.05	45.043	45.206	45.064	112.661	112.561	1575.751	60.066	45.035	31.650	$M
Owner's Costs	0.13	117.112	117.537	117.167	292.918	292.658	4096.954	156.171	117.092	82.290	$M
Licensing & Permitting	0.01	30.009	9.041	9.013	22.532	22.512	315.150	33.013	9.007	6.330	$M
Indirect Costs Subtotal (2010 $M)		**345.310**	**325.487**	**324.463**	**811.158**	**810.437**	**11345.411**	**453.474**	**324.254**	**227.880**	**$M**
Total & Indirect Costs (2010 $M)		**1246.173**	**1229.617**	**1225.751**	**3064.377**	**3061.651**	**42860.440**	**1654.792**	**1224.959**	**860.880**	**$M**
Contingency Allowancy	0.10	124.617	122.962	122.575	306.438	306.165	4286.044	165.479	122.496	86.088	$M
Miscellaneous	0.01	12.462	12.296	12.258	30.644	30.617	428.604	16.548	12.250	8.609	$M
Total Overnight Costs		**1383.252**	**1364.874**	**1360.583**	**3401.458**	**3398.433**	**47575.088**	**1836.819**	**1359.704**	**955.576**	**$M**
Allowance for Escalation During Construction	0.05	69.163	68.244	68.029	170.073	169.922	2378.754	91.841	67.985	47.779	$M
Allowance for Interest	0.05	69.163	68.244	68.029	170.073	169.922	2378.754	91.841	67.985	47.779	$M
Capital Investment at Commercial Operation (2010 $M)		**1521.577**	**1501.362**	**1496.641**	**3741.604**	**3738.276**	**52332.597**	**2020.501**	**1495.675**	**1051.134**	**$M**
Annualized Investment at Commercial Operation (2010 $M/year)	**0.0963**	**146.592**	**144.645**	**144.190**	**360.475**	**360.154**	**5041.842**	**194.660**	**144.097**	**101.269**	**$M**
Operating & Maintenance Costs		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Marimba Field	FTE	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Managers	2	600000	600000	600000	600000	600000	600000	600000	600000	600000	**$/year**
Engineers	4	800000	800000	800000	800000	800000	800000	800000	800000	800000	**$/year**
Operators	8	800000	800000	800000	800000	800000	800000	800000	800000	800000	**$/year**
RPSEA Concept of Operations Site: Marimba Field	Factor	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Salaries & Benefits		2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	$M
Chemicals, Materials & Utilities	0.10	14.659	14.464	14.419	36.047	36.015	504.184	19.466	14.410	10.127	$M
Spare Parts & Capital Plant Upgrades	0.10	14.659	14.464	14.419	36.047	36.015	504.184	19.466	14.410	10.127	$M
Taxes & Insurance	0.10	14.659	14.464	14.419	36.047	36.015	504.184	19.466	14.410	10.127	$M
Operating Cost Contingency	0.05	7.330	7.232	7.209	18.024	18.008	252.092	9.733	7.205	5.063	$M
General O&M	0.02	2.932	2.893	2.884	7.209	7.203	100.837	3.893	2.882	2.025	$M
Miscellaneous	0.01	1.466	1.446	1.442	3.605	3.602	50.418	1.947	1.441	1.013	$M
Operating & Maintenance Costs (2010 $M/year)		**57.905**	**57.165**	**56.992**	**139.180**	**139.059**	**1918.100**	**76.171**	**56.957**	**40.682**	**$M/year**
Estimated Cost of Electricity		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Marimba Field		PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Electric Power Generation		0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	MW-e
Hours Per Year		8766	8766	8766	8766	8766	8766	8766	8766	8766	hours/year
Annual Electric Energy Production		7.013E+05	7.013E+05	7.013E+05	7.013E+05	7.013E+05	7.013E+05	7.013E+05	7.013E+05	7.013E+05	kWh-e/year
Annual Production Cost		2.045E+08	2.018E+08	2.012E+08	4.997E+08	4.992E+08	6.960E+09	2.708E+08	2.011E+08	1.420E+08	$/year
Cost of Electricity (COE)		**2.916E+02**	**2.878E+02**	**2.869E+02**	**7.125E+02**	**7.119E+02**	**9.925E+03**	**3.862E+02**	**2.867E+02**	**2.024E+02**	**$/kWh-e**

Table I 8 – Summary of the detailed economic analysis performed for the Pazflor site

Assumptions	Value	Units	Reference	Nomenclature	Description of Deep Ocean Hybrid System
Required Power	13.8000	MW-e	Site Dependent	PWR	PWR = Nuclear Reactor + Pb Acid Battery
Service Life = n	15	years	Analyst Estimate	FC1	FC1 = Line for Surface O2 + WELL Head Gas + Reformer + PEMFC + Battery
Interest Rate = i	5	%	Analyst Estimate	FC2	FC2 = Stored O2 + Well Head Gas + Reformer + Fuel Cell + Battery
Compound Interest Factor = $f_i = (1+i)^n$	2.0789	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV1	SV1 = Submersible Vehicle + Stored O2 + Fuel Cell + Battery
Discount Factor = $f_d = 1/f_i$	0.4810	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV2	SV2 = Submersible Vehicle + Stored O2 + Engine or Turbine + Battery
Annuity Future Worth Factor = f_{AF} = A/F = $i/[(1+i)^n-1]$	0.0463	factor	Perry's 7th Edition pp. 9-10 to 9-13	SV3	SV3 = Submersible Vehicle + Charge at Docking Station + ZEBRA Battery
Annuity Present Worth Factor = f_{AP} = A/P = $[i(1+i)^n]/[(1+i)n-1]$	0.0963	factor	Perry's 7th Edition pp. 9-10 to 9-13	PWR TEG	PWR TEG = PWR + WELL TEG + Pb Acid Battery
Salary & Fringe Benefits - Management	300000	$/year	Analyst Estimate	WELL TEG	WELL TEG = Thermoelectric Generator + Well Head Waste Heat + Battery
Salary & Fringe Benefits - Engineer	200000	$/year	Analyst Estimate	GRID	GRID = Floor Electrical Grid + Battery
Salary & Fringe Benefits - Operations	100000	$/year	Analyst Estimate	DOC	DOC = Deep Ocean Current + Battery

Investment at Comencement of Commercial Operations		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Pazflor	Factor	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Energy Conversion & Storage		112.608	279.154	195.636	489.090	111.815	1275.120	140.208	36.708	49.108	$M
Oxygen Supply		0.000	5.250	0.401	1.003	0.789	0.000	0.000	0.000	0.000	$M
Pressure Vessels		454.405	465.809	462.049	1155.122	1134.319	15931.707	620.969	470.784	304.221	$M
Flotation Tanks		461.746	469.359	471.832	1179.580	1162.088	16089.689	621.816	471.290	311.220	$M
Miscellaneous		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	$M
Direct Costs Subtotal (2010 $M)		**1028.759**	**1219.571**	**1129.919**	**2824.797**	**2409.012**	**33296.516**	**1382.993**	**978.782**	**664.549**	**$M**
Construction Services	0.1	102.876	121.957	112.992	282.480	240.901	3329.652	138.299	97.878	66.455	$M
Home Office Engineering & Services	0.07	72.013	85.370	79.094	197.736	168.631	2330.756	96.809	68.515	46.518	$M
Field Office Engineering & Services	0.05	51.438	60.979	56.496	141.240	120.451	1664.826	69.150	48.939	33.227	$M
Owner's Costs	0.13	133.739	158.544	146.889	367.224	313.171	4328.547	179.789	127.242	86.391	$M
Licensing & Permitting	0.01	31.288	12.196	11.299	28.248	24.090	332.965	34.830	9.788	6.645	$M
Indirect Costs Subtotal (2010 $M)		**391.353**	**439.046**	**406.771**	**1016.927**	**867.244**	**11986.746**	**518.877**	**352.362**	**239.238**	**$M**
Total & Indirect Costs (2010 $M)		**1420.113**	**1658.617**	**1536.689**	**3841.723**	**3276.256**	**45283.262**	**1901.870**	**1331.144**	**903.786**	**$M**
Contingency Allowancy	0.10	142.011	165.862	153.669	384.172	327.626	4528.326	190.187	133.114	90.379	$M
Miscellaneous	0.01	14.201	16.586	15.367	38.417	32.763	452.833	19.019	13.311	9.038	$M
Total Overnight Costs		**1576.325**	**1841.065**	**1705.725**	**4264.313**	**3636.644**	**50264.420**	**2111.076**	**1477.570**	**1003.203**	**$M**
Allowance for Escalation During Construction	0.05	78.816	92.053	85.286	213.216	181.832	2513.221	105.554	73.878	50.160	$M
Allowance for Interest	0.05	78.816	92.053	85.286	213.216	181.832	2513.221	105.554	73.878	50.160	$M
Capital Investment at Commercial Operation (2010 $M)		**1733.957**	**2025.171**	**1876.298**	**4690.744**	**4000.308**	**55290.862**	**2322.183**	**1625.327**	**1103.523**	**$M**
Annualized Investment at Commercial Operation (2010 $M/year)	**0.0963**	**167.053**	**195.110**	**180.767**	**451.917**	**385.399**	**5326.848**	**223.724**	**156.588**	**106.316**	**$M**

Operating & Maintenance Costs		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Pazflor	FTE	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Managers	2	600000	600000	600000	600000	600000	600000	600000	600000	600000	**$/year**
Engineers	4	800000	800000	800000	800000	800000	800000	800000	800000	800000	**$/year**
Operators	8	800000	800000	800000	800000	800000	800000	800000	800000	800000	**$/year**
RPSEA Concept of Operations Site: Pazflor	Factor	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Salaries & Benefits		2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	2.200	$M
Chemicals, Materials & Utilities	0.10	16.705	19.511	18.077	45.192	38.540	532.685	22.372	15.659	10.632	$M
Spare Parts & Capital Plant Upgrades	0.10	16.705	19.511	18.077	45.192	38.540	532.685	22.372	15.659	10.632	$M
Taxes & Insurance	0.10	16.705	19.511	18.077	45.192	38.540	532.685	22.372	15.659	10.632	$M
Operating Cost Contingency	0.05	8.353	9.755	9.038	22.596	19.270	266.342	11.186	7.829	5.316	$M
General O&M	0.02	3.341	3.902	3.615	9.038	7.708	106.537	4.474	3.132	2.126	$M
Miscellaneous	0.01	1.671	1.951	1.808	4.519	3.854	53.268	2.237	1.566	1.063	$M
Operating & Maintenance Costs (2010 $M/year)		**65.680**	**76.342**	**70.891**	**173.928**	**148.652**	**2026.402**	**87.215**	**61.703**	**42.600**	**$M/year**

Estimated Cost of Electricity		Hybrid Power Generation Option									
RPSEA Concept of Operations Site: Pazflor		PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID	Units
Electric Power Generation		13.8000	13.8000	13.8000	13.8000	13.8000	13.8000	13.8000	13.8000	13.8000	MW-e
Hours Per Year		8766	8766	8766	8766	8766	8766	8766	8766	8766	hours/year
Annual Electric Energy Production		1.210E+08	1.210E+08	1.210E+08	1.210E+08	1.210E+08	1.210E+08	1.210E+08	1.210E+08	1.210E+08	kWh-e/year
Annual Production Cost		2.327E+08	2.715E+08	2.517E+08	6.258E+08	5.341E+08	7.353E+09	3.109E+08	2.183E+08	1.489E+08	$/year
Cost of Electricity (COE)		**1.924E+00**	**2.244E+00**	**2.080E+00**	**5.174E+00**	**4.415E+00**	**6.079E+01**	**2.570E+00**	**1.804E+00**	**1.231E+00**	**$/kWh-e**