Deep Sea Hybrid Power Systems (Initial Study)

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Final Report

October 12, 2010

Houston Advanced Research Center

Lawrence Livermore National Laboratory

Naval Facilities Engineering Service Center

Yardney Technical Products

Shell

Total

Chevron

GE

Curtiss-Wright

Deep Sea Hybrid Power Systems (Initial Study)

This report includes various documents that together give the final report for the Deep Sea Hybrid Power Systems (Initial Study). The initial study considered numerous power generation/energy conversion and energy storage technologies to support the exploration and production of oil and gas reserves remotely located off shore in the deep ocean. Detailed analyses of the technologies were then conducted. The parameters evaluated at each site included the following: estimated component weight, total weight, and total volume; initial investment, annual cost, and cost of electricity; and the economy of scale.

Based upon the Initial Study, the following conclusions were made:

- The top two candidates for power generation are both based on the small modular pressurized water reactor. One candidate couples the pressurized water reactor with a secondary steam-turbine-generator system, whereas the other candidate couples the pressurized water reactor with a solid-state thermoelectric generator.
- The leading candidates for energy storage are both versions of sodium-beta batteries: sodium/sulfur and sodium/nickel-chloride (also known as ZEBRA batteries).

The recommendation for the initial near-term efforts is to focus on conducting a detailed feasibility and implementation study; including technical approach, cost, and schedule. Additional recommendations regarding specific features that the study should address are provided in the report.

Attached are all the reports developed during Phase I:

1. Proposed Phase 2 Scope of Work
2. Conclusions and Recommendations Regarding the Deep Sea Hybrid Power Systems Initial Study (TM-2413-OCN)
3. Functional Requirements – Basis of Design
4. Subsurface Hybrid Power Options for Oil & Gas Production at Deep Ocean Sites (LLNL-TR-424663)
5. Energy Storage for Oil & Gas Production at Deep Ocean Sites

Deepwater Hybrid Power Systems Project
Phase 2 Scope of Work

The Initial Study considered numerous power generation/energy conversion and energy storage technologies to support the exploration and production of oil and gas reserves remotely located offshore in the deep ocean. Detailed analyses of the technologies were then conducted. The parameters evaluated at each site included the following: estimated component weight, total weight, and total volume; initial investment, annual cost, and cost of electricity; and the economy of scale. The Initial Study constrained the work to focus on systems that are completely subsea and have no associated ocean surface equipment.

Based upon the Initial Study, the following conclusions were made:

- The top two candidates for power generation are both based on the small modular pressurized water reactor. One candidate couples the pressurized water reactor with a secondary steam-turbine-generator system, whereas the other candidate couples the pressurized water reactor with a solid-state thermoelectric generator.

- The leading candidates for energy storage are both versions of sodium-beta batteries: sodium/sulfur and sodium/nickel-chloride (also known as ZEBRA batteries).

Discussions were held with Shell after the Initial Study final report was issued. Although having a completely subsea system is desirable, comparison of the systems identified during the Initial Study with modular gas turbine system(s) along with supporting energy storage and combined heat and power cycle as well as to the use of fuel cells is of interest. In addition, the focus for Phase 2 should take into consideration the following:

- The power system should be scalable. The system should be designed to provide approximately 5-10 megawatts of power and be designed to add increments of 5 megawatts stages (modules).

- The power system should be designed as a 'utility hub', located at 50+ kilometers from a legacy host, and rated for operation in water depths +3,000 meters.

Taking these factors into account, the Phase 2 scope of work will focus on conducting a detailed feasibility and implementation study; including technical approach, cost, and schedule. Work will include:

<u>Comparison of Pure Subsea Systems with Other Systems</u>. Two other systems will be defined: 1) a pure ocean surface system consisting of gas turbine(s) along with associated energy storage and combined heat and power technologies, and 2) a hybrid ocean surface – subsea system consisting of fuel cell technologies along with associated energy storage. A comparison of the systems identified in the Initial Study to these two systems will be performed.

<u>Detailed Operational Requirements and Interface Specifications</u>. Stakeholder (deepwater operators and service providers) will define baseline operational requirements and interface specifications: notional/representative production field specifications, including representative relative geometrical locations and electrical requirements for each power point, thereby incorporating the power distribution requirements.

Design. The detailed design of local area power generation and distribution network systems that are based on a standard subsea power cable system and the top candidate power/storage system (from the comparison) will be developed. Design considerations will include achieving a modularized approach that can be installed, assembled, and operated remotely in the deep ocean (e.g. 12,000 fsw). A conceptual design for the entire system will be developed.

Deployment, Installation/Assembly, and Recovery Plans and Procedures. Notional plans and procedures for deployment, installation/assembly, and recovery that provide a detailed overview of the necessary support vessels and equipment, personnel, logistics, and timelines, and as well as limitations and restraints associated with the subject efforts will be identified.

Operation, Maintenance, and Emergency Response Requirements. The operation and maintenance requirements of such a power network, including monitoring protocols and necessary response capability will be identified. Issues include maintaining a near continuous system health status, and the capability to appropriately respond (e.g., intervening) in a timely manner.

Approval, Licensing, and Operations Program Plan. A plan that identifies the detailed requirements, organizational roles, and responsibilities associated with obtaining approval and licensing, as well as operating such a power plant will be identified. Relevant to note is the gas and oil industry's desire not to operate such a power plant, but merely to purchase the power from the power plant owner/operator. Therefore, the intention is for this plan to address such issues. Companies that may want to own and operate the system will be identified.

Socialization Strategy. A strategic plan purposely developed towards addressing the various nontechnical barriers associated with the implementation of a remote deep ocean power plant will be developed.

ENGINEERING SERVICE CENTER
Port Hueneme, California 93043-4370

TECHNICAL MEMORANDUM

TM-2413-OCN

CONCLUSIONS AND RECOMMENDATIONS REGARDING THE DEEP SEA HYBRID POWER SYSTEMS INITIAL STUDY

By:

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June 2010

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14. ABSTRACT

This report summarizes the conclusions made during the Initial Study regarding Deep Sea Hybrid Power Systems, and provides recommendations regarding a path forward. The Initial Study considered numerous power generation/energy conversion and energy storage technologies to support the exploration and production of oil and gas reserves remotely located off shore in the deep ocean. Detailed analyses of the technologies were then conducted. The parameters evaluated at each site included the following: estimated component weight, total weight, and total volume; initial investment, annual cost, and cost of electricity; and the economy of scale.

Based upon the Initial Study, the following conclusions were made:

• The top two candidates for power generation are both based on the small modular pressurized water reactor. One candidate couples the pressurized water reactor with a secondary steam-turbine-generator system, whereas the other candidate couples the pressurized water reactor with a solid-state thermoelectric generator.

• The leading candidates for energy storage are both versions of sodium-beta batteries: sodium/sulfur and sodium/nickel-chloride (also known as ZEBRA batteries).

The recommendation for the initial near-term efforts is to focus on conducting a detailed feasibility and implementation study; including technical approach, cost, and schedule. Additional recommendations regarding specific features that the study should address are provided in the report.

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EXECUTIVE SUMMARY

The Naval Facilities Engineering Service Center (NAVFAC ESC) provides ocean engineering program management and technical services to the Department of Energy (DOE) for matters regarding underwater power systems. As part of this support; NAVFAC ESC in collaboration with Lawrence Livermore National Laboratory (LLNL), Yardney Technical Products, Incorporated (YTP), and the Houston Advanced Research Center (HARC) were tasked to summarize conclusions made during an Initial Study regarding Deep Sea Hybrid Power Systems and provide recommendations regarding a path forward.

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 and energy storage equipment on the ocean floor. Locally powered advanced deep ocean drilling operations will provide access to oil and gas reserves otherwise inaccessible. Such technology will therefore enhance the energy security of the United States.

In order to begin the initial study, the need for system requirements was recognized. The system requirements were defined through a series of meetings with the deepwater operators that are members of the research team, followed by further review with service providers. The intent is to locate the power system in remote deepwater production sites. The power system will supply all power needs for the location so that there will be no electrical umbilical from a 'host' platform. Water depths of interest range from 8,500 to 12,000 feet. Eight representative deep ocean sites with a wide range of locations, depths, tie-back distances, and power requirements, were identified.

The Initial Study considered numerous power generation/energy conversion and energy storage technologies to support the exploration and production of oil and gas reserves remotely located off shore in the deep ocean. Based upon a preliminary screening of power generation and energy storage technologies, ten conceptual hybrid energy conversion and storage systems were developed for evaluation at each of the eight representative deep ocean sites. Detailed analyses of the technologies were then conducted. The parameters evaluated at each site included the following: estimated component weight, total weight, and total volume; initial investment, annual cost, and cost of electricity; and the economy of scale.

Based upon the Initial Study, the following conclusions can be made:

1. The top two candidates for power generation are both based on the small modularized pressurized water reactor. One candidate couples the pressurized water reactor with a secondary steam-turbine-generator system, whereas the other candidate couples the pressurized water reactor with a solid-state thermoelectric generator.

2. The leading candidates for energy storage are both versions of sodium-beta batteries: sodium/sulfur and sodium/nickel-chloride (also known as ZEBRA batteries), due to the exceptional cycle life possible with this technology (3,000 to 4,500 charge-discharge cycles). Due to a long and successful history with lead acid batteries in maritime application, extending back for decades, it is believed that this technology should also be considered for actual system designs.

Although it has been more than fifty-two years since the world's first operational nuclear submarine (USS Nautilus) completed the first successful submerged voyage around the North Pole and at present time there are more than 441 light water reactors worldwide, the research team understands that there are extreme differences between a nuclear powered manned submarine operating in relatively shallow water and an unmanned nuclear power plant operating in the remote deep ocean. Systems operating remotely

on the ocean floor require special engineering to optimize reliability, minimize maintenance requirements, and to the extent possible, minimize all failure modes. Furthermore, these remote systems must be specifically designed to facilitate the installation, operation, and required maintenance procedures being conducted through remote operations (e.g., via ROVs).

The research team is also aware of existing barriers regarding nuclear power:

- Public perceptions.
- Domestic and international politics.
- U.S. Nuclear Regulatory Commission (NRC) design, siting, construction, and operation requirements, and approval and licensing timelines.
- National security.
- The Three Mile Island, and Chernobyl events occurring decades ago.
- The current ongoing events with the Deepwater Horizon drilling rig in the Gulf of Mexico (GOMEX).

Taking all these factors into account, the following recommendations are made. The initial near-term efforts should focus on conducting a detailed feasibility and implementation study; including technical approach, cost, and schedule; associated with each of the following:

Detailed Operational Requirements and Interface Specifications. Stakeholder (deepwater operators and service providers) defined baseline operational requirements and interface specifications: notional/representative exploration or production field specifications for all three identified power range requirements, including representative relative geometrical locations and electrical requirements for each power point, thereby incorporating the power distribution requirements.

Design. The design of local area power generation and distribution network systems that are based on a standard submarine power cable system, as well as a small modularized pressurized water reactor. With the pressurized water reactor and for the actual electrical power generation, both the traditional turbine-generator, and the thermoelectric should be investigated. Design considerations should include achieving a modularized approach that can be installed, assembled, and operated remotely in the deep ocean (e.g., 12,000 fsw).

Deployment, Installation/Assembly, and Recovery Plans and Procedures. Notional plans and procedures for deployment, installation/assembly, and recovery that provide a detailed overview of the necessary support vessels and equipment, personnel, logistics, and timelines, and as well as limitations and restraints associated with the subject efforts.

Operation, Maintenance, and Emergency Response Requirements. The operation and maintenance requirements of such a power network, including monitoring protocols and necessary response capability. Issues include maintaining a near continuous system health status, and the capability to appropriately respond (e.g., intervening) in a timely manner.

Approval, Licensing, and Operations Program Plan. A plan that identifies the detailed requirements, organizational roles, and responsibilities associated with obtaining approval and licensing, as well as operating such a power plant. Relevant to note is gas and oil industry's desire not to operate such a power plant, but merely to purchase the power from the power plant owner/operator. Therefore, the intention is for this plan to address such issues.

Socialization Strategy. A strategic plan purposely developed towards addressing the various non-technical barriers associated with the implementation of a remote deep ocean nuclear power plant.

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1.0 INTRODUCTION

The Naval Facilities Engineering Service Center (NAVFAC ESC) provides ocean engineering program management and technical services to the Department of the Navy (DON) and the Department of Energy (DOE) for matters regarding underwater power systems, including deep submergence batteries. As part of the NAVFAC ESC support to DOE; NAVFAC ESC in collaboration with Lawrence Livermore National Laboratory (LLNL), Yardney Technical Products, Incorporated (YTP), and the Houston Advanced Research Center (HARC) were tasked to summarize conclusions made during an Initial Study regarding Deep Sea Hybrid Power Systems and provide recommendations regarding a path forward. This report is the deliverable for that tasking.

2.0 BACKGROUND

The Energy Policy Act of 2005 established a natural gas supply research and development program associated with Ultra-deepwater and Unconventional Onshore Hydrocarbon Resources to be funded over the next 10 years. The legislation identified the National Energy Technology Laboratory (NETL) as the DOE entity responsible for review and oversight of this program, and the NETL Ultra-deepwater and Unconventional Natural Gas and Other Petroleum Resources Program is the implementation of this legislative direction.

In January 2007, NETL contracted the management of these funds to the Research Partnership to Secure Energy for America (RPSEA). RPSEA is a non-profit corporation established to help meet the nation's growing need for hydrocarbon resources produced from reservoirs in America. The RPSEA corporation is formed by a consortium of U.S. energy research universities, industry, and independent research organizations.

NAVFAC ESC, through tasking received from the DOE National Nuclear Security Administration (NNSA), has been supporting the following RPSEA program: Deep Sea Hybrid Power Systems (Initial Study). The following list summarizes the primary organizations/members of the research team that have been collaborating on this program. Relevant to note is that HARC has been serving as the Program Manager / Prime Contractor, thereby providing direction to the other organizations:

- Houston Advanced Research Center (HARC)
- Lawrence Livermore National laboratory (LLNL)
- Yardney Technical Products, Incorporated (YTP)
- Lithion, Incorporated (Lithion)
- Chevron Energy Technology Company (Chevron)
- Shell Exploration and Production (Shell)[1]
- Total Exploration and Production Research and Technology USA (Total)
- Curtiss-Wright Electro-Mechanical Corporation (Curtiss-Wright)

[1] Elected not to be included in the Confidential Disclosure Agreement executed December 18, 2009.

3.0 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 and energy storage equipment on the ocean floor. Locally powered advanced deep ocean drilling operations will provide access to oil and gas reserves otherwise inaccessible. Such technology will therefore enhance the energy security of the United States.

4.0 FUNCTIONAL REQUIREMENTS – BASIS OF DESIGN

In order to begin the initial study, the need for system requirements and the establishment of quantitative and qualitative selection criteria was recognized. The system requirements were defined through a series of meetings with the deepwater operators that are members of the research team, followed by further review with service providers.

The intent is to locate the power system in remote deepwater production sites. The power system will supply all power needs for the location so that there will be no electrical umbilical from a 'host' platform. The power system would be sized to supply the site specific needs. Three (3) power ranges of interest were identified:

- Mid-power, 1 to 10 MW (AC), for small scale multiphase pumps.
- Large-power, 10 to 30 MW (AC), for gas compression and satellite field installations.
- Mega-power, 30 to 200 MW (AC), for cold-ironing of drilling vessel.

Water depths of interest range from 8,500 to 12,000 feet, with the nominal water temperature at these depths being 39.4 °F. System redundancy and reliability of the subsea power supply is critical. System designs must consider shock loads that may occur during installation. Small equipment must be able to withstand a shock load of up to 3g. Larger equipment must be able to withstand a shock load of 5g.

Eight representative deep ocean sites with a wide range of locations, depths, tie-back distances, and power requirements were selected 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 were included in the study to provide a wide range of scenarios. Reference (1) is the Functional Requirements – Basis of Design document developed in December 2008.

TABLE 1

EIGHT (8) REPRESENTATIVE DEEP OCEAN SITES

Field or Project	Owner	Region	Year	Depth	Depth	Tie Back	Tie Back	Total Power
name			calendar	meters	feet	km	miles	MW
Shtokman	Gazprorn	Barents Sea	2020	350	1,148	909.0	565.0	240.0
Chinook	Petrobras	GOM	2009	2,682	8,800	19.3	12.0	0.0
King	BP	GOM	2007	1,700	5,578	29.0	18.0	0.0
Ormen Lange	Hydro	Norway	2011	850	2,789	193.0	120.0	60.0
Perdido	Shell	GOM	2010	2,438	7,999	NA	NA	0.0
Argonauta	Shell	Brazil	2009	1,900	6,234	9.0	5.6	0.0
Marimba Field	Petrobras	Campros Basin	2000	395	1,296	1.1	0.7	0.0
Pazflor	Total	Angola Blk 17	2011	800	2,625	9.0	6.0	0.0
Hypothetical				1,389	4,559	167.1	103.9	37.5

5.0 SUMMARY OF INITIAL STUDY

Energy storage combined with energy conversion/power generation must be integrated, thereby creating a hybrid system capable of providing a constant source of electrical power, as well as enabling either sustained operation or graceful shutdown in the event that the primary power generation systems fails.

As part of the initial study, numerous energy conversion technologies have been considered: (1) proton-exchange membrane fuel cells (PEMFC) 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 (ICE) 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 (TEG) powered with natural gas from deep ocean wells, geothermal sources, and radioisotopes; (6) renewable energy sources at the surface, including solar, wind and wave powered generators; (7) renewable energy sources on the seafloor, including turbines powered with ocean current; and (8) small pressurized-water reactors (PWR) with low-enrichment fuel, similar to those used on the NS Savannah and NS Otto Hahn commercial ships.

Energy storage technologies that were explored included: mechanical flywheels, compressed-gas storage; regenerative liquid redox batteries; regenerative fuel cells; and both secondary batteries in sealed pressure vessels as well as pressure-tolerant secondary batteries. Battery chemistries included a wide range of other conventional and unconventional batteries such as lead-acid, silver-zinc, sodium-beta, and lithium-ion.

Based upon a preliminary screening of power generation and energy storage technologies, ten conceptual hybrid energy conversion and storage systems were developed for evaluation at each of the eight (8) representative deep ocean sites listed in Table 1. These conceptual hybrid systems are summarized in Table 2.

TABLE 2

SUMMARY OF DEEP OCEAN HYBRID GENERATION AND STORAGE OPTIONS CONSIDERED FOR INITIAL STUDY

NO.	NOMENCLATURE	DESCRIPTION
1	PWR	Nuclear Reactor + Battery
2	FC1	PEMFC + Line for surface O_2 + Wellhead Gas + Reformer + Battery
3	FC2	PEMFC + Stored O_2 + Wellhead Gas + Reformer + Battery
4	SV1	PEMFC + Submersible Vehicle for O_2 Transport + Wellhead Gas + Reformer + Battery
5	SV2	ICE or Turbine + Submersible Vehicle for O_2 + Wellhead Gas + Reformer + Battery
6	SV3	Submersible Vehicle with Large Capacity Batteries + Surface Charging Station
7	PWR TEG	Thermoelectric Generator Powered by Heat from Nuclear Reactor + Battery
8	WELL TEG	Thermoelectric Generator Powered by Heat from Combustion of Wellhead Gas + Battery
9	GRID	Ocean Floor Electrical Grid + Battery
10	DOC	Deep Ocean Current + Battery

The deep ocean current option was abandoned early due to the low ocean floor current velocities (less than 0.5 meters per second), and the very large turbine size required (300-foot span). The submersible vehicle options, subsequent to the detailed analysis described below, were later abandoned due to cost and impracticalities.

Detailed Analysis

Detailed analyses of the technologies were conducted and are formally documented in references (2), (3), and (4). The following provides a summary of the areas of investigation:

Estimated Component Weight, Total Weight, and Total Volume for Each Site

The estimated weights of the energy conversion and storage components for each hybrid system, the estimated total weight for each hybrid system, and the estimated total volume for each hybrid system were evaluated for each of the eight representative sites. The estimated 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. Table 3 and Figures 1 through 3 summarize these evaluations.

TABLE 3

SUMMARY OF THE ESTIMATED WEIGHTS AND VOLUMES

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

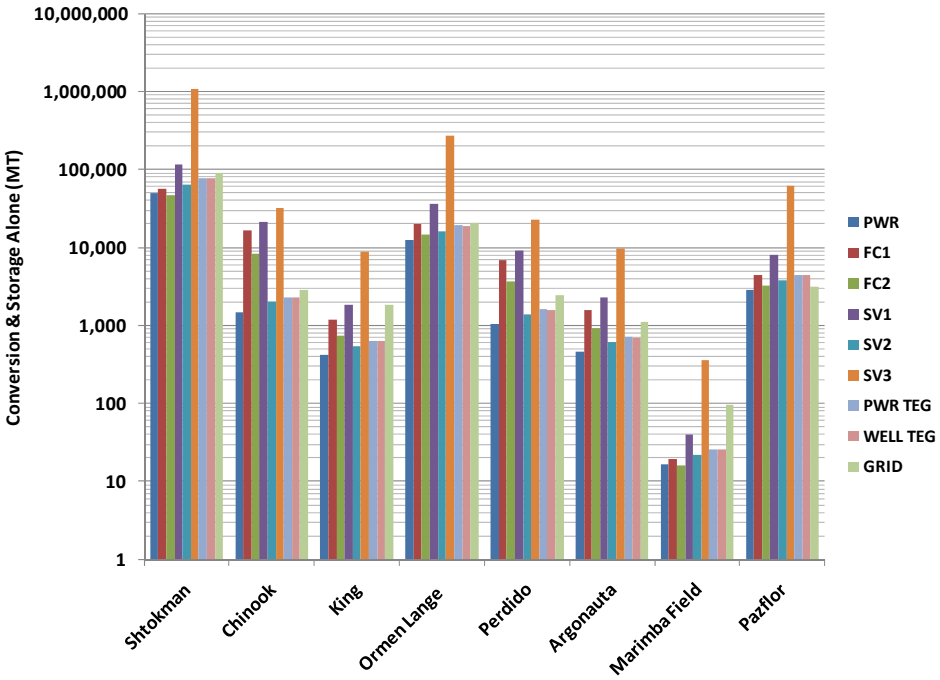

FIGURE 1: Graphical Comparison of Estimated Weights of Power Generation and Energy Storge Components.

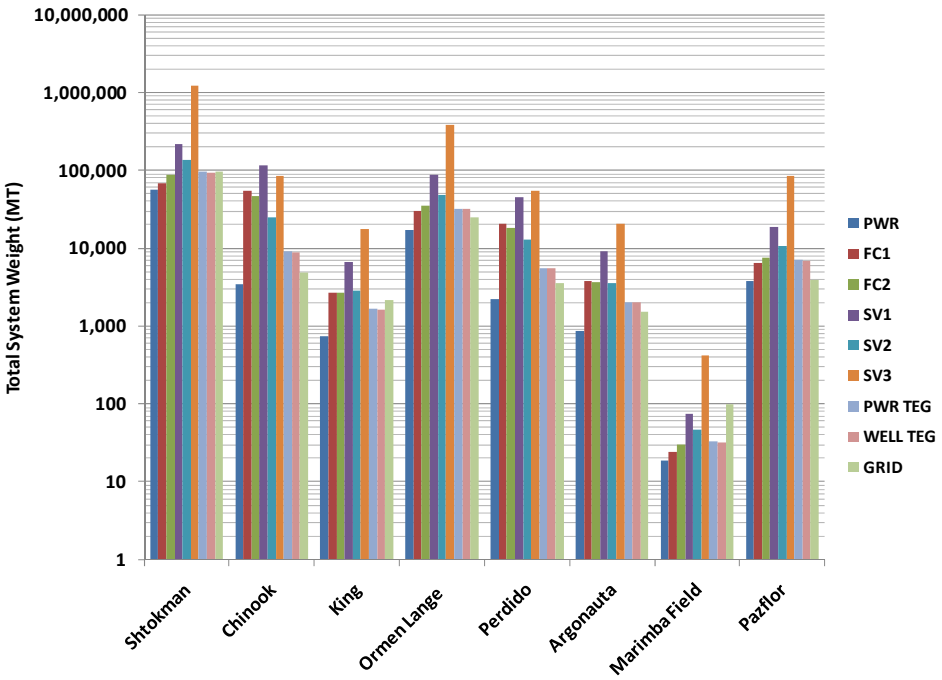

FIGURE 2: Graphical Comparison of Estimated Total Weights of the Hybrid Power Systems.

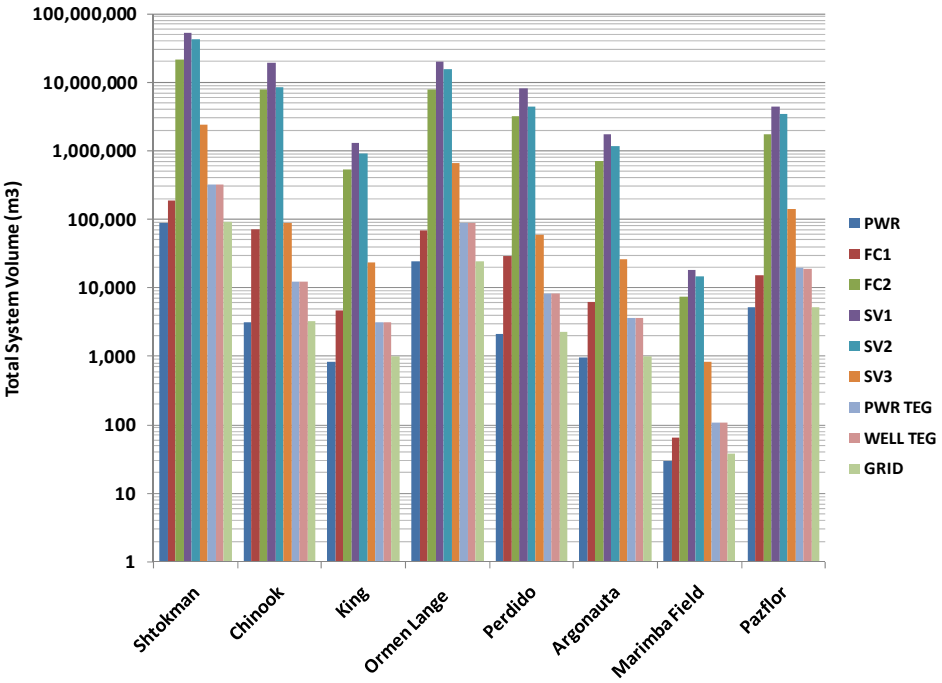

FIGURE 3: Graphical Comparison of Estimated Total Volumes of the Hybrid Power Systems.

Initial Investment, Annual Cost, and Cost of Electricity

The estimated initial capital investment at the commencement of commercial operations, the estimated annualized costs, and the estimated cost of electricity were evaluated for each site, and are summarized in Table 4 and Figures 4 through 6. 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. 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 therefore was subsequently 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. The least expensive option for power at all of the representative sites is the electrical grid, with an assumed cost of approximately $2.5 million per kilometer. In regard to the cost of electricity, 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 wellhead methane and a line to the surface for compressed air (FC1), or a fuel cell on the ocean floor fueled with wellhead methane and oxygen brought to the system in submersible tanks (FC2). That said the research team considers FC2 impractical from an operational point-of-view.

TABLE 4

SUMMARY OF THE INITIAL INVESTMENT, ANNUAL COST, AND COST OF ELECTRICITY

Cost of Electricity at Site ($/kWh-e)									
Site	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID
Shtokman	0.31	0.47	0.40	1.00	0.45	5.91	0.41	0.19	0.26
Chinook	3.55	8.77	6.30	15.70	8.84	116.15	4.87	3.58	2.53
King	11.95	12.93	12.33	30.64	29.01	402.25	15.94	11.77	8.79
Ormen Lange	0.62	0.97	0.80	2.00	1.23	16.36	0.84	0.52	0.44
Perdido	4.97	7.94	6.50	16.18	12.16	164.49	6.74	4.95	4.60
Argonauta	10.90	12.19	11.45	28.46	26.48	366.47	14.57	10.76	7.70
Marimba Field	291.61	287.77	286.88	712.49	711.86	9924.63	386.19	286.69	202.42
Pazflor	1.92	2.24	2.08	5.17	4.41	60.79	2.57	1.80	1.23
Annualized Costs ($M)									
Site	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID
Shtokman	655.84	992.62	838.66	2093.34	955.44	12428.49	859.30	391.56	539.68
Chinook	224.19	553.69	397.62	990.74	557.82	7330.72	307.63	225.78	159.61
King	209.51	226.73	216.16	537.10	508.58	7052.23	279.45	206.41	154.14
Ormen Lange	326.05	509.70	422.23	1052.27	644.85	8604.45	442.13	272.60	232.69
Perdido	217.87	348.01	284.91	708.96	533.13	7209.48	295.20	217.08	201.57
Argonauta	210.20	235.11	220.89	548.91	510.68	7067.42	280.89	207.51	148.41
Marimba Field	204.50	201.81	201.18	499.66	499.21	6959.94	270.83	201.05	141.95
Pazflor	232.73	271.45	251.66	625.85	534.05	7353.25	310.94	218.29	148.92
Initial Capital Investment ($M)									
Site	PWR	FC1	FC2	SV1	SV2	SV3	PWR TEG	WELL TEG	GRID
Shtokman	4916.36	7449.45	6291.40	15728.51	7169.76	93464.23	6446.70	2928.55	4042.65
Chinook	1669.68	4148.05	2974.12	7435.30	4179.08	55121.42	2297.31	1681.67	1183.97
King	1559.27	1688.83	1609.29	4023.22	3808.75	53026.70	2085.31	1536.00	1142.80
Ormen Lange	2435.82	3817.19	3159.25	7898.12	4833.72	64701.75	3308.92	2033.81	1733.61
Perdido	1622.14	2600.99	2126.37	5315.91	3993.38	54209.53	2203.81	1616.25	1499.53
Argonauta	1564.44	1751.83	1644.84	4112.10	3824.49	53141.02	2096.18	1544.26	1099.70
Marimba Field	1521.58	1501.36	1496.64	3741.60	3738.28	52332.60	2020.50	1495.67	1051.13
Pazflor	1733.96	2025.17	1876.30	4690.74	4000.31	55290.86	2322.18	1625.33	1103.52

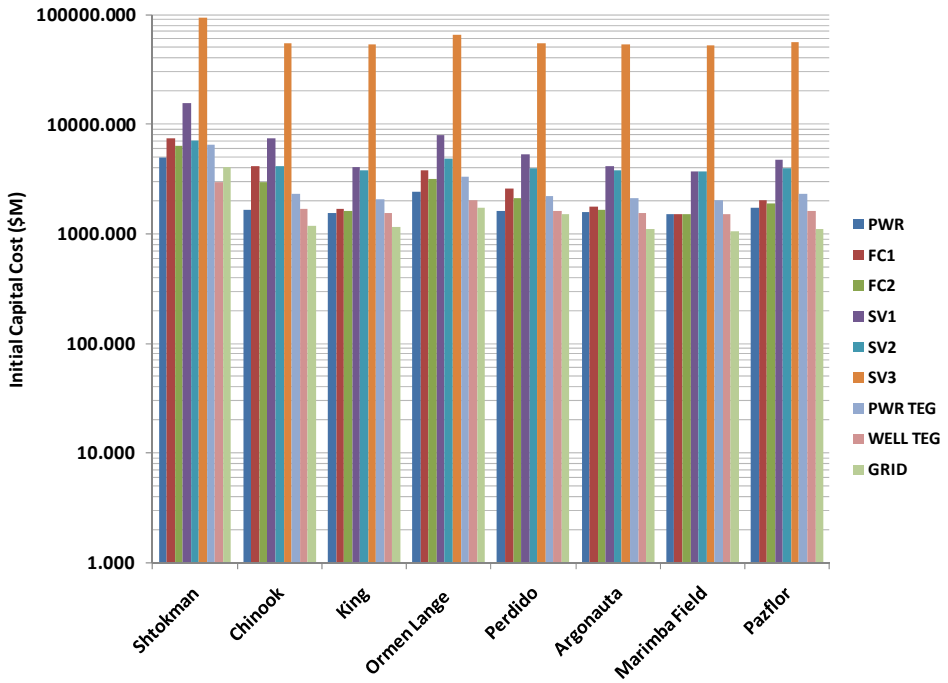

FIGURE 4: Graphical Comparison of the Estimated Initial Capital Investment Required for Each Site.

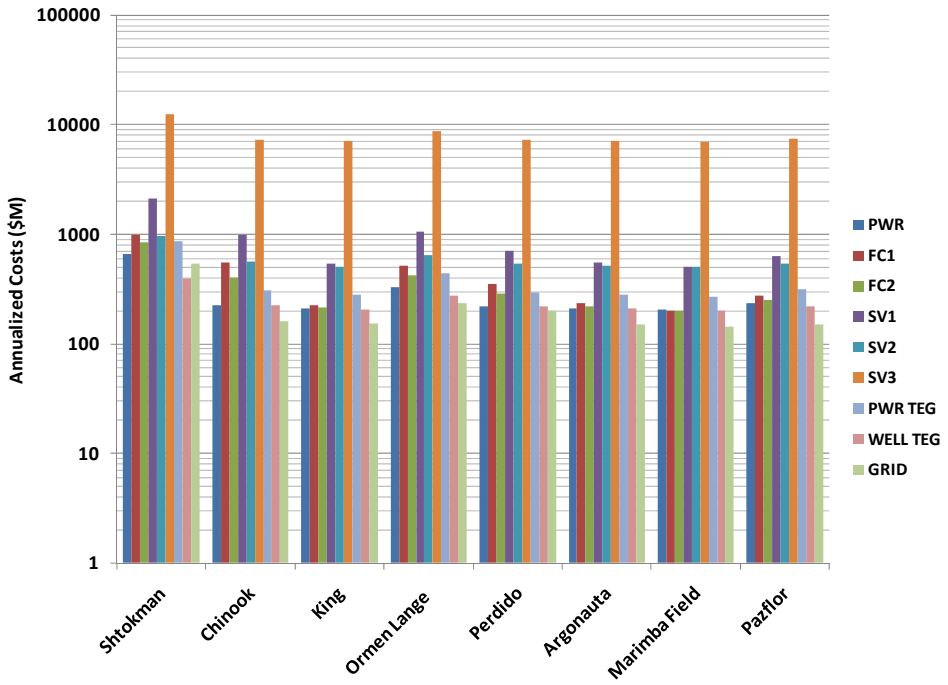

FIGURE 5: Graphical Comparison of the Estimated Annualized Costs for Each Site.

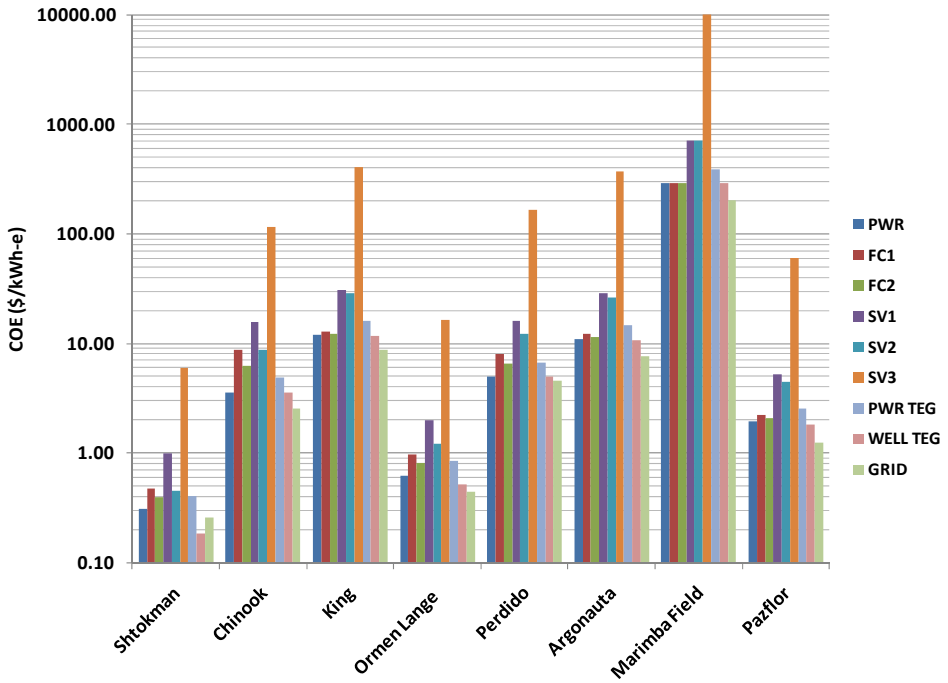

FIGURE 6: Graphical Comparison of the Estimated Cost of Electricity for Each Site.

Economy of Scale

The estimated cost of electricity 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 of sufficient size so that power can be supplied for less than $1 per kilowatt-hour, comparable to the cost for grid power.

The power generation systems that have been identified for more detailed evaluation include: small modular pressurized water reactors (PWR); proton-exchange membrane fuel cells (PEMFC), located on the ocean floor and fed with hydrogen produced by reforming natural gas available at subsea wellheads; thermoelectric generators (TEG), powered from heat generated by small pressurized water reactors, or waste heat from subsea wellheads; and subsea electrical grids carrying power from power plants located on shore. From the initial list of energy storage technologies, only rechargeable batteries: lead-acid, sodium-sulfur, ZEBRA, and lithium-ion were identified for more detailed evaluation.

In the case of power generation systems relying on the oxidation of natural gas or hydrogen derived from subsea wells, oxygen from the surface will have to be supplied to the system, either from tanks used to transport it to the site, or via a pipe in communication with the surface. Obviously, the air supply problem is a major impediment for the use of wellhead gas as an energy source.

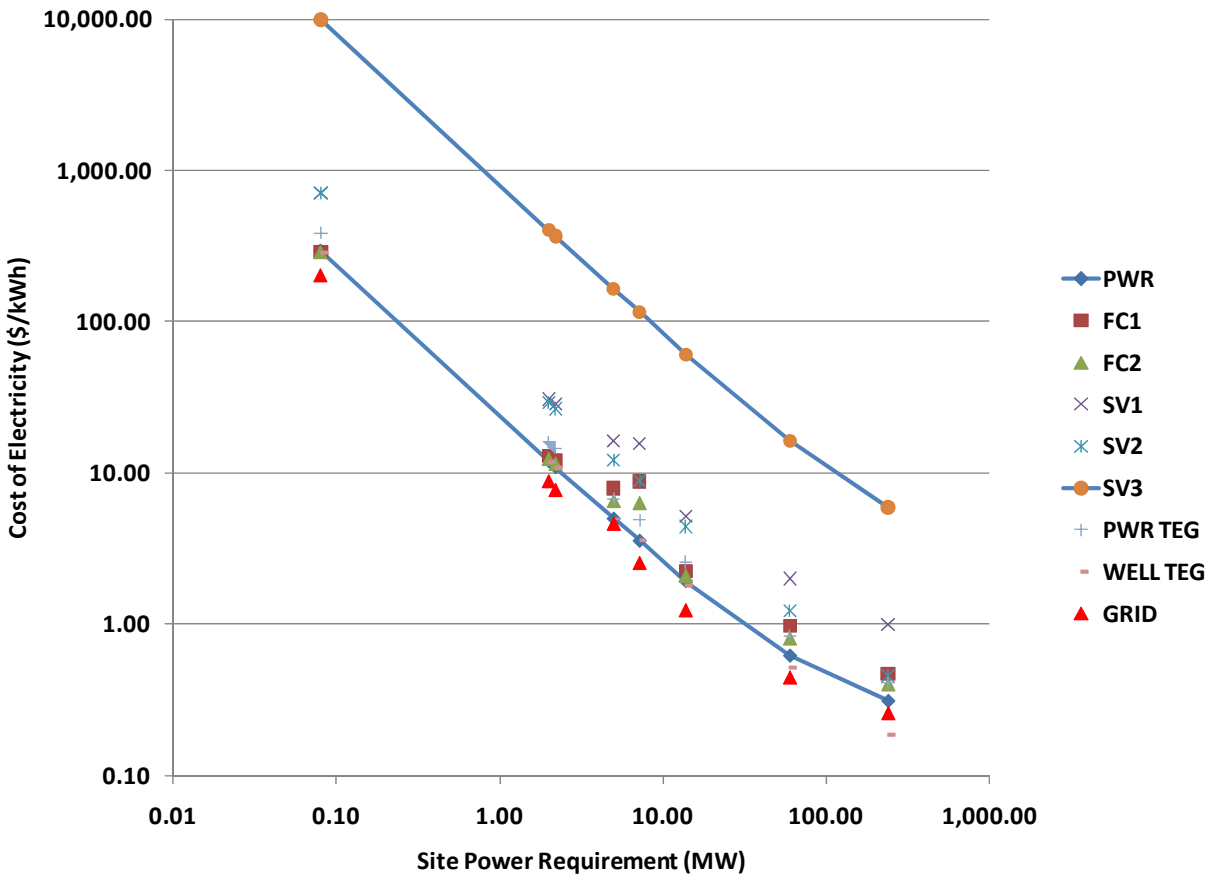

FIGURE 7: Estimated Cost of Electricity as a Function of Power Generation Capacity

Power Generation Technologies

Small Modular Nuclear Reactors

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.

At the present time, there are more than 441 light water reactors (LWRs) worldwide with a total generating capacity of 358.7 GWe. Table 5 summarizes this inventory by global region, and Table 6 provides insight regarding the types and locations of relatively small modular reactors.

TABLE 5

INVENTORY OF NUCLEAR REACTORS WORLD-WIDE BY GLOBAL REGIONS

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 6

COUNTRY OF ORIGIN AND ELECTRICAL GENERATING CAPACITY OF SMALL NUCLEAR REACTORS

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

The mPower™ reactor being developed by Babcock and Wilcox (B&W) of Lynchburg, Virginia leverages a long history of success with earlier designs. This small PWR has a power of 125 megawatts, 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 mPower 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.

Pressurized water reactors (PWR) were the focus of this study, since much of our experience at sea involves this type of technology. However, as actual designs are developed for deep-ocean systems, other new reactor technologies should also be considered. For example, pebble-bed reactors (PBRs) and very high temperature reactors (VHTRs) are designed to use TRISO (tri-structural isotropic) type fuels, which are capable of being operated at extremely high temperature (up to 1,600°C), with correspondingly high thermal-to-electric efficiency, with relatively high burn-up of the nuclear fuel.

Proton-Exchange Membrane Fuel Cell (PEMFC)

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 subsea 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 providing air-independent propulsion (AIP) for non-nuclear submarines (212 and 214 Classes). These small, relative to the typical U.S. submarines, and efficient submarines have now been produced in relatively large numbers. Thus, the viability of subsea fuel cell systems for demanding large scale applications has been unambiguously demonstrated.

Natural gas from deep ocean wells would be a logical energy source for supplying subsurface fuel cells at deep ocean production sites. 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.

Thermoelectric Generator Powered by Heat from Wellhead 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 seafloor 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. 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.

Energy Storage Technologies

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 high 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 relatively inexpensive, and is therefore considered as a potential candidate for the subject application.

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 sub-surface applications, but will require insulated battery bottles, and auxiliary heating equivalent to approximately 10% of the batteries stored energy.

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 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, ZEBRA batteries are proven technology, with a solid history of applications in transportation, and deep ocean applications. The ZEBRA battery is a reasonable contender for sub-surface applications, but will require insulated battery bottles, and auxiliary heating equivalent to approximately 10% of the batteries stored energy.

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 polyvinylidene fluoride (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^{TM}. 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-ion 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.

Based upon the analyses conducted in references (2) through (4), the conceptual hybrid systems listed in Table 7 have evolved as the leading candidates for powering sub-surface oil and gas production operations. Performance characteristics of these leading candidates are provided in Tables 8 and 9.

TABLE 7

SUMMARY OF DEEP OCEAN HYBRID POWER GENERATION AND ENERGY STORAGE LEADING CANDIDATES

NO.	NOMENCLATURE	DESCRIPTION
1	PWR	Nuclear Reactor + Battery
2	FC1	PEMFC + Line for surface O_2 + Wellhead Gas + Reformer + Battery
3	PWR TEG	Thermoelectric Generator Powered by Heat from Nuclear Reactor + Battery
4	WELL TEG	Thermoelectric Generator Powered by Heat from Combustion of Wellhead Gas + Battery
5	GRID	Ocean Floor Electrical Grid + Battery

TABLE 8

SUMMARY OF KEY ATTRIBUTES OF POWER GENERATION OPTIONS

Screening Criteria	Units	PWR	FC	TEG
Specific Power	W/kg	250.0	28.9	8.8
Power Density	W/L	791.6	20.8	2.2
Specific Energy	Wh/kg	10,950,000		
Energy Density	Wh/L	34,672,967		
Overall Device Efficiency	%	30	60	10
Technology Cost	$/kWh	7,500	2,500	2,000

TABLE 9

SUMMARY OF KEY ATTRIBUTES OF ENERGY STORAGE OPTIONS

Screening Criteria	Units	Pb Acid	NaS	ZEBRA	Li-Ion
Specific Power	W/kg	20	250	169	74.0
Power Density	W/L	51	386	261	147.0
Specific Energy	Wh/kg	20	117	94	75.0
Energy Density	Wh/L	50	147	148	139.0
Coulombic Efficiency (Ah/Ah)	%	80	89	~100	99
Electrical Efficiency (Wh/Wh)	%	70	70	70	95
Overall Device Efficiency	%	56	62	70	94
Technology Cost	$/kWh	150	300	220	300

6.0 RELATIVE RANKING OF THE LEADING CANDIDATES

Based upon the analyses conducted in references (2) through (4), the five conceptual hybrid systems listed in Table 7 have evolved as the leading candidates for powering sub-surface oil and gas exploration and production operations.

Qualitative Ranking

The relative ranking of the candidate hybrid options is clearly dominated by the energy conversion/power generation technology as opposed to the technology for energy storage. This statement by no means is meant to infer that energy storage is not absolutely critical and necessary for enabling sustained operation or graceful shutdown in the event that the primary power generation system fails. The statement is made because the selection of any of the four (4) leading energy storage candidates, all rechargeable/secondary batteries, has little to no impact on the ranking of the energy conversion/power generation technology, and subsequently little to no impact on the ranking of the hybrid system.

With specific regards to the four leading energy storage candidates, the two sodium-beta batteries were identified as the two most promising. Although the two sodium-beta battery technologies share obvious performance advantages over competing systems, the lead acid system also exhibits many advantages based on its significant historical baseline, low cost, and operation at great ocean depths while configured in a pressure tolerant battery design configuration. The primary factors leading to this determination included the following:

- Cycle Life. Lead-acid as high as 1,100; lithium-ion ranging from 300 to 1,500, but being very dependent upon build quality; sodium/sulfur approximately 2,500; and ZEBRA as high as 3,500.
- Safety. Unfortunately, lithium-ion batteries have been plagued by a history of significant safety issues, including relatively recent events.
- Technology/Manufacturing Readiness Level.
  - » Sodium/sulfur. Several utilities are putting sodium/sulfur technology to work in the U.S. A variety of large-scale sodium/sulfur load leveling battery systems varying in size between 400 kWh (50 kW) and 64 MWh (8 MW) have been manufactured and placed in operation in Japan by NGK Insulators Ltd (NGK). Manufacturing operations capable of fabricating on the order of 400,000 load leveling sodium sulfur cells per year have been installed by NGK in Japan.
  - » ZEBRA (sodium/nickel-chloride). Manufacturing operations of sodium/nickel-chloride cells for electric vehicle applications capable of fabricating a number of cells similar to NGK's 400,000 per year have been installed by MES-DEA in Switzerland. The sodium/nickel-chloride battery has been developed almost exclusively for electric vehicle applications. The main component of the North Atlantic Treaty Organization (NATO) Submarine Rescue System (NSRS) is the Submarine Rescue Vehicle (SRV), a battery powered manned submersible. The batteries are sodium/nickel-chloride manufactured by MES-DEA in Switzerland. Reportedly, there is also a Chinese SRV that has recently entered service and utilizes the same type of batteries as the NATO SRV.

With regards to energy conversion/power generation, two out of the five options include the utilization of wellhead gas for fuel, and the need for a line to the surface for air/oxidant: #2 FC1 and #4 WELL TEG. As the intent is to avoid an electrical umbilical from a host platform, the need for any above surface infrastructure was identified as undesirable early on in the program. The research team and the deep water operators revisited the system requirements, and concluded that the requirement to avoid any above surface infrastructure is sufficient cause to not consider the WELL TEG or the FC1 any further.

Therefore, the five (5) conceptual hybrid systems listed in Table 7 can initially be reduced to the following three (3): GRID, PWR, and PWR TEG.

With regards to energy conversion/power generation, two out of these three leading candidate approaches include a nuclear reactor, namely PWR and PWR TEG, and the one remaining candidate, GRID, derives power from shore via submarine power cable (e.g., high voltage direct current transmission).

The ranking between either an on-site nuclear reactor or power transmission via submarine cable is likely not an absolute, but rather dependent upon variables that include the following:

- Total targeted power range (e.g., economy of scale).
- Site location/remoteness, including water depth and tie back distance.

In order to further differentiate between the three candidates, cost data from reference (3) can be factored in. Taking into account the initial investment cost, the annual operating cost, and the cost of electricity (see Table 4 and Figures 4, 5, and 6) justifies the following relative ranking from 1 to 3, 1 being most preferred:

#1: GRID
#2: PWR
#3: PWR TEG

Quantitative Ranking

Although the research team is of the opinion that the current resolution level of the information developed so far makes it challenging to develop any significantly more meaningful insights without inducing a level of subjectivity, the team is also of the opinion that at this time it is of significant value to develop a relative quantitative ranking of the three leading candidates.

The approach commenced with the development of selection criteria with assigned weight factors, see Table 10. The weight factors range from 1 to 3, with 3 being high/most desirable.

Relative rankings ranging from 1 to 3, 3 being high/most desirable were then assigned.

TABLE 10

SELECTION CRITERIA AND ASSIGNED WEIGHT FACTORS

No.	CRITERIA	WEIGHT FACTOR (1-LOW, 3- HIGH)
1	System Volume	2
2	System Weight	2
3	Initial Capital Investment	3
4	Annual Operating Cost	3
5	Cost of Electricity	3
6	Reliability	3
7	Lifetime	3
8	Maintenance	2
9	Complexity	2
10	Regulatory Requirements	2
11	Supply Chain	1
12	Safety	3
13	Technology Readiness Level (TRL)	3
14	Manufacturing Readiness Level (MRL)	2

System Volume, Weight, and Costs

Assigned rankings for each candidate for criterion numbers 1 through 5 were based on the values resulting from the previous detailed analyses. The values shown for each of the eight (8) site locations in Tables 3 and 4 for system volume, system weight, initial capital investment, annual operating cost, and cost of electricity were merely summed; and then a relative comparison among the three candidates was made. These summations are shown in Tables 11 and 12.

TABLE 11

SUMMATIONS OF VOLUME AND WEIGHT VALUES

Hybrid System Volume (Cubic Meters)			
Site	PWR	PWR TEG	GRID
Shtokman	89,574	324,766	92,534
Chinook	3,139	12,455	3,238
King	840	3,190	986
Ormen Lange	24,027	87,782	24,551
Perdido	2,112	8,313	2,231
Argonauta	943	3,608	998
Marimba Field	30	109	38
Pazflor	5,167	19,216	5,108
SUM TOTAL	**125,832**	**459,438**	**129,683**
Hybrid System Weight (Metric Tons)			
Site	PWR	PWR TEG	GRID
Shtokman	56,163	95,306	95,938
Chinook	3,476	9,018	4,805
King	736	1,654	2,169
Ormen Lange	16,837	32,145	25,188
Perdido	2,231	5,567	3,584
Argonauta	865	2,013	1,499
Marimba Field	19	33	98
Pazflor	3,732	7,001	3,950
SUM TOTAL	**84,059**	**152,736**	**137,231**

TABLE 12

SUMMATION OF COST VALUES

Cost of Electricity at Site ($/kWh-e)			
Site	**PWR**	**PWR TEG**	**GRID**
Shtokman	0.3117	0.4084	0.2565
Chinook	3.5520	4.8741	2.5289
King	11.9500	15.9392	8.7918
Ormen Lange	0.6199	0.8406	0.4424
Perdido	4.9707	6.7352	4.5988
Argonauta	10.8993	14.5651	7.6954
Marimba Field	291.6057	386.1943	202.4166
Pazflor	1.9239	2.5704	1.2310
SUM TOTAL	**326**	**432**	**228**
Annualized Costs ($M)			
Site	**PWR**	**PWR TEG**	**GRID**
Shtokman	655.8413	859.3045	539.6797
Chinook	224.1873	307.6329	159.6117
King	209.5081	279.4467	154.1381
Ormen Lange	326.0484	442.1283	232.6874
Perdido	217.8670	295.2022	201.5665
Argonauta	210.1954	280.8915	148.4081
Marimba Field	204.4973	270.8304	141.9507
Pazflor	232.7337	310.9398	148.9160
SUM TOTAL	**2,281**	**3,046**	**1,727**
Initial Capital Investment ($M)			
Site	**PWR**	**PWR TEG**	**GRID**
Shtokman	4916.3574	6446.7038	4042.6487
Chinook	1669.6759	2297.3112	1183.9706
King	1559.2664	2085.3088	1142.8013
Ormen Lange	2435.8227	3308.9171	1733.6090
Perdido	1622.1376	2203.8138	1499.5336
Argonauta	1564.4353	2096.1756	1099.7027
Marimba Field	1521.5770	2020.5010	1051.1340
Pazflor	1733.9574	2322.1835	1103.5230
SUM TOTAL	**17,023**	**22,781**	**12,857**

Reliability

For a truly qualified system-level ranking, detailed designs including the reliability of individual subsystems and components is necessary. The absence of such details provides room for subjectivity, and the rankings of the systems below that are based on to-be-developed technology (i.e., all candidates except GRID), were developed based upon the expectations of the future systems. Assigned reliability rankings were based on the following:

- GRID: Assigned a ranking of 3. The power requirements for the deep sea production equipment are considered to be compatible with standard submarine power and telecommunications cable systems, for which a wide range of industry-approved techniques and equipment exists (e.g., cable burial techniques, standard connection boxes, couplings and penetrators, etc…). All components must survive both the mechanical rigors of installation, and have high reliability and long lifetime under deep ocean conditions (high hydrostatic pressure, corrosive environment, forces and effects of ocean current, etc…). As an industry standard, submarine power or telecommunications cables target a service life of at least 25 years, and must be able to be easily deployed and repaired at sea. Cable ships equipped with remotely operated vehicles (ROVs) provide installation and repair capability. Historically, most reported submarine cable failures occur in shallow water due to fishing/trawling activity

and anchors dropped from ships; although natural chaffing, abrasion, and earthquake/volatile seabed related failures occasionally occur in deep water. The most serious limitation with obtaining power at remote deep ocean depths is associated with mechanical and electrical problem areas with underwater electrical connectors and hull/junction box penetrations used to transmit power to submerged loads housed in one atmosphere internal pressure vessels/enclosures. Relative to the other four candidates, the reliability of GRID is considered to be the highest.

- PWR TEG: Assigned a ranking of 2. Thermoelectric generators have a very high level of reliability and proven record of long life space and terrestrial applications. For example, Voyager 1 and Voyager 2 were launched in 1977 and are currently on course to exit the solar system. The solid-state technology is highly scalable and modular, and has no moving parts. It has been more than 52 years since the world's first operational nuclear submarine (USS Nautilus) completed the first successful submerged voyage around the North Pole, and at present time there are more than 441 LWRs worldwide. That said, the reliability of the remote deep ocean PWR TEG is considered second to the GRID.
- PWR: Assigned a ranking of 1. The relative reliability between the PWR TEG and the PWR is based on the relative difference between the solid-state thermoelectric generator and the steam turbine generator system. In future deep-ocean nuclear reactor designs that substitute solid-state thermoelectric generators for conventional Rankine steam-cycle thermal-to-electric converters, a conscious decision will have to be made to trade the higher efficiency of the Rankine cycle for the higher reliability of the thermoelectric generator. By eliminating moving parts and improving reliability, the probability of long-term trouble-free unattended operation should increase.

Lifetime

Assigned rankings for system lifetime were based on the following:

- PWR and PWR TEG: Both assigned a rating of 1. The lifetime of both these systems was based on the reported 5 year capacity (time between refueling) of the B&W mPower™ reactor.
- GRID: Assigned a rating of 3, based on the nominal industry standard 25 years service life for submarine power and telecommunication cable systems.

Maintenance

Effective maintenance is essential for the safe and reliable operation of any power plant. The system must be continuously monitored, and periodically inspected, tested, assessed, and maintained to ensure that the structures, systems, and components (SSCs) function in accordance with the design intents and requirements. The majority of maintenance activities are related to the concept of preventative maintenance, but when the performance or condition of an SSC does not allow it to function per design, corrective maintenance must take place.

Systems operating remotely on the ocean floor require special engineering to optimize reliability, minimize maintenance requirements, and eliminate to the extent possible mechanical parts that can fail. Furthermore, these remote systems must be specifically designed to facilitate the required maintenance operations being carried out via remotely operated vehicles (ROVs).

Assigned rankings for maintenance were based on the following:

- PWR: Assigned a ranking of 1. Extensive preventative maintenance and testing/surveillance programs exist and are necessary for current nuclear power plants to ensure the continued availability, as well that the significant nuclear safety equipment will function when and how it is intended. Due to both the system complexity and the safety issues (both discussed below), the maintenance (both time between and ease of) associated with the PWR relative to the other two candidates is considered to be the most complex, and elaborate.
- PWR TEG: Assigned a ranking of 2. Other than the maintenance associated with the turbine-generator, the PWR TEG maintenance requirements are the same as those for the PWR. Therefore, the PWR TEG maintenance is considered to be the second most complex.
- GRID: Assigned a ranking of 3, considered the least high maintenance item of all the candidates.

<u>System Complexity</u>

Assigned rankings for system complexity were based upon the following:

- PWR: Assigned a ranking of 1. As evident from the following outline of the major systems, the PWR is the most complex of the three options:
  - » Primary System/Reactor Coolant System.
    - Reactor vessel and internals, including fuel rods, and control rods and drive system.
    - Primary cooling system, reactor coolant pump and pressurizer to circulate the reactor coolant heated by the core, transfer heat to the secondary system, and act as a neutron moderator.
    - Chemical and Volume Control System/Makeup and Purification System for coolant makeup to the primary cooling system, removal of corrosion and fission products from the coolant, adjustment of the boric acid concentration, and supply of cooling and lubrication of reactor coolant pump seals.
  - » Secondary system with steam generator and condensate/feedwater system.
  - » Reactor Containment System and Emergency Core Cooling System to provide core cooling following a loss of coolant accident and extra neutron poisons to ensure reactor remains shutdown following the cool down associated with a main steam line rupture.
  - » Turbine-Generator System
- PWR TEG: Assigned a ranking of 2. Other than the lack of a turbine-generator, the PWR TEG requires all of the above systems. Therefore, the PWR TEG is considered to be the second most complex.
- GRID: Assigned a ranking of 3, considered the least complex of all the candidates.

<u>Supply Chain</u>

The Supply Chain was reviewed for each of the options that represent the system of organization, personnel, technology, information, and resources involved in moving a product or service to a customer.

Based on this, the assigned rankings for supply chain were as follows:

- GRID: Assigned a ranking of 3. Relative to the other two candidates, the supply chain is considered the most complete. As indicated earlier, the power requirements for the deep sea production equipment are considered to be compatible with standard submarine power and telecommunications cable systems, for which a wide range of industry-approved techniques

and equipment exists (e.g., cable burial techniques, standard connection boxes, couplings and penetrators, etc…).

- PWR: Assigned a ranking of 2. The supply chain is considered less complete than that for the GRID, but more complete than that for the PWR TEG. Specific areas where suppliers are yet to be identified include sources associated with the to-be-determined ocean engineering methods to ensure compatibility with the remote deep ocean environment (e.g., pressure compensation, pressure tolerance, and 1 atmosphere enclosures, as well as methods to enable in-situ maintenance via ROVs).
- PWR TEG: Assigned a ranking of 1. All the deficiencies associated with PWR supply chain apply, as well as those associated with a large scale thermoelectric generator. Although the technology associated with thermoelectric generators is relatively mature, one of this scale designed for the remote deep ocean environment has never been developed.

Safety

When assessing safety, two specific categories are typically considered:

- Hazard Severity. Assessing the worst potential consequence, defined by degree of injury, occupational illness, or an environmental release.
- Mishap Probability. The probability that a hazard will result in a mishap, based on an assessment of such factors as location, exposure limits, and affected population.

Although land-based nuclear power plants and nuclear power submarines and ships have achieved very high standards of safety performance, and the Generation 3+ LWR power plants may claim to have reached the goal of safety assurance, the potential risk to the persons and environment in the vicinity is undeniable:

> Back in MAR 1979, the Three Mile Island heat removal degradation accident became a turning point in history. Caused by equipment failure coupled with faulty operator actions, the accident resulted in at least half of the core melting. The accident caused no injuries, deaths, nor property damage; and it also did not release sufficient fission products to contaminate the soil around, except slightly within the exclusion area..
>
> In APR 1986, the Chernobyl reactivity increase accident occurred resulting in 50 direct deaths, with estimates of another 4,000 additional cancer deaths among the 600,000 of the most highly exposed people near the reactor.

Therefore, both PWR and PWR TEG were assigned a rating of 1. The GRID option was considered the most relatively benign, and therefore assigned a rating of 3.

Technology Readiness Level

Assigned rankings for technology readiness levels (TLR) were based upon the following:

- GRID: Assigned a ranking of 3. Submarine power cables have traditionally been used to link existing land-based power distribution systems whenever the economic advantages have outweighed the cost of the submarine link. Actual subsea power transmission systems have been “flight proven” through successful operations (TRL 9). Relative to the other three candidates, this is clearly the most mature.

- PWR: Assigned a ranking of 2. Nuclear powered submarines of several countries have now operated in the oceans of the world for nearly fifty years. Although such submarines facilitate putting a man in the various operation and maintenance loops, which in comparison differs significantly with the subject application, this technology can be considered "flight qualified" through test and evaluation (TRL 8), and considered second to GRID in maturity.
- PWR TEG: Assigned a ranking of 1. Very similar to the PWR. Both the pressurized water reactor and thermoelectric generator technologies are mature. Estimated to be at a TRL no higher than six: system/subsystem model or prototype demonstration in a relevant environment. The primary areas in need of attention are the engineering related to the deep ocean environment and the system-level integration aspects associated with the targeted application, as well as the scaling up of the thermoelectric generator to meet the subject requirements.

<u>Manufacturing Readiness Level</u>

Assigned rankings for the manufacturing readiness levels (MRL) were based upon the following:

- GRID: Assigned a ranking of 3. Actual subsea power transmission systems have been "flight proven" through successful operations (TRL 9), and an existing manufacturing capability is in place for "full rate production" (MRL 9). Relative to the other two candidates, this is clearly the most mature.
- PWR: Assigned a ranking of 2. This technology can be considered "flight qualified" through test and evaluation (TRL 8), and an existing manufacturing capability to produce actual product in a low rate initial production is in place (MRL 7), and considered second to GRID in maturity.
- PWR TEG: Assigned a ranking of 1. Very similar to the PWR. MRL is estimated to be at or near MRL 7.

Table 13 summarizes the rankings. The admittedly somewhat subjective rating approach described results with the maximum and minimum achievable scores being 102 and 34, respectively. The following summarizes the resulting scores for the three candidate approaches:

- GRID……98…….. 96%
- PWR…….57…….. 56%
- PWR TEG…… 41……40%

TABLE 13

SUMMARY OF RELATIVE RANKINGS

CRITERIA		WEIGHT FACTOR (1-3)	GRID		PWR		PWR TEG	
			RAW (1-5)	WEIGHED	RAW (1-5)	WEIGHED	RAW (1-5)	WEIGHED
1	System Volume	2	2	4	3	6	1	2
2	Total Weight of System	2	2	4	3	6	1	2
3	Initial Capital Investment	3	3	9	2	6	1	3
4	Annual Operating Cost	3	3	9	2	6	1	3
5	Cost of Electricity	3	3	9	2	6	1	3
6	Reliability	3	3	9	1	3	2	6
7	Lifetime	3	3	9	1	3	1	3
8	Maintenance	2	3	6	1	2	2	4
9	System Complexity	2	3	6	1	2	2	4
10	Regulatory Requirements	2	3	6	1	2	1	2
11	Supply Chain	1	3	3	2	2	1	1
12	Safety	3	3	9	1	3	1	3
13	Technology Readiness Level (TRL)	3	3	9	2	6	1	3
14	Manufacturing Readiness Level (MRL)	2	3	6	2	4	1	2
TOTAL		34	40	**98**	24	**57**	17	**41**

7.0 CARBON EMISSION REPORT

Reference (5) was generated in an effort to document a comparison of the carbon emissions that various alternative power systems may provide if deployed.

The first approach was to investigate various carbon calculators (internet applications that ask various questions about energy use, daily habits, and other important factors and calculates a carbon footprint).

Generally speaking ‘carbon footprint’ is used as a generic synonym for emissions of carbon dioxide or greenhouse gases expressed in CO_2 equivalents, and may be defined as the amount of greenhouse gases, in carbon dioxide equivalent, that an individual, household, or other entity produces in a year. This definition was deemed sufficient because it is the general definition that consumers and the carbon calculators use. This usually means that a carbon calculator will ask for information about electricity usage, household heating, travel by car, and travel by air.

Originally, twelve calculators were examined, chosen from a large list of online calculators. These twelve calculators were then short listed to only include calculators that were from companies or organizations that sold offsets. The carbon calculators considered were: Bonneville Environmental Foundation, Carbon Fund, The Climate Trust, and Native Energy.

The four calculators all required the same input data. For electricity, the calculators asked for the number of kilowatt hours consumed in a year. For a given electricity usage, the calculators varied by as much as 12 percent. This discrepancy is due to the fact that the different carbon calculators rely on different underlying emission factors, largely determined by assumptions made about the mix of energy received in a region. For instance, if most of a company's electricity comes from a coal-fired power plant, there will be significantly more emissions per kWh than if the electricity came from a wind farm or a natural gas fired power plant. This discrepancy can cause large differences because many states have a very different mix of electricity than the national average. As a result, a different method of determining carbon emissions that is directly related to the most realistic solutions was selected.

The realistic options for subsea power generation are nuclear. Cost estimates have been developed and resulted in an estimate between $0.10 and $0.20 per kWh for power delivery. Nuclear energy solutions produce low levels of carbon dioxide emissions from their full life cycle. Nuclear may be comparable with renewables such as wind, solar and hydro in this respect.

In recent years, some utilities generating electricity have undertaken Life Cycle Analysis (LCA) studies as part of their social accountability. The principal focus of LCA for energy systems today is their contribution to climate change. There is an obvious linkage between energy inputs to any life cycle and carbon dioxide emissions, depending on what fuels those inputs. LCA includes mining, fuel preparation, plant construction, transport, decommissioning and managing wastes. In the nuclear fuel cycle energy inputs are low, even with diminishing ore grades. Its very large low carbon advantage over fossil fuels will remain even if very lowgrade ores are used.

LCA data from the following was evaluated:

- Vattenfall's 2002 Environmental Product Declaration for its 3,090 MWe power plant in Forsmark, Sweden.
- The 2005 Environmental Product Declaration for British Energy's Torness 1,250 MWe power station in the United Kingdom (UK).
- The World Nuclear Association's *Energy Analysis* paper.
- Figures published in 2006 for Japan.
- The UK Sustainable Development Commission report in 2006.

All of these suggest a very favorable energy balance for nuclear power, by any criteria, and a very modest carbon dioxide output from the whole fuel cycle, even if moving to very low-grade ores. It is difficult to get simple figures for coal and gas, since so much of the energy input (beyond the fuel itself) is often in transport, which varies from very little to a lot. Energy input figures ranging from 3.5% to 14.0% of lifetime output are published for coal, and 3.8% to 20% or natural gas. Conservatively, the LCA carbon output for nuclear power is about 3% of coal or around 6% of gas. The U.S. Environmental Protection Agency has published annual output emission rates for greenhouse gases (GHG) for the year 2005. The GHG are listed by subregions which are shown in Figure 8. Also listed in this figure are the annual output emission rates for the Electric Reliability Council of Texas (ERCOT) and the Sustainable Energy Research Center (SERC) Mississippi Valley eGRID subregion. These values are listed since they are the

subregions that may supply electricity to the western Gulf of Mexico. With nuclear power production generating between 20 and 30 g/kWh of CO2, this would be approximately 3 – 5% of the CO2 generated by ERCOT and approximately 4.3 – 6.5% of the CO2 generated by SERC Mississippi Valley for the same amount of electricity.

Figure 1. US eGRID subregions.

eGRID subregion acronym	eGRID subregion name	Annual output emission rates		
		Carbon dioxide (CO_2) (g/kWh)	Methane (CH_4) (g/MWh)	Nitrous oxide (N_2O) (g/MWh)
ERCT	ERCOT All	600.3	8.5	6.9
SRMV	SERC Mississippi Valley	462.5	11.0	5.3

FIGURE 8: Subregions for which greenhouse gas emission rates are published, and annual output emission rates for the Electric Reliability Council of Texas (ERCOT) and the Sustainable Energy Research Center (SERC) Mississippi Valley eGRID subregion for 2005.

8.0 BUSINESS CASE

As near shore oil and gas reserves are exhausted, it will be necessary to develop fields further from shore and at greater depths. Locally powered advanced deep ocean drilling operations, may provide access to oil and gas reserves otherwise inaccessible. An investment in subsea (deep ocean) hybrid power systems may enable offshore oil and gas exploration and production in such remote, deepwater locations. Such technology will therefore enhance the energy security of the United States.

According to The Economist (September 8th – 14th 2007), there is a "sea change" in offshore drilling 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 place 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 Sea 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 remote 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 field called Snøhvit, which lies 143 km offshore, 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 Norwegian 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 liquefy 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 capabilities for operations in remote, deepwater locations. Such facilities will require ample supplies of local power to operate machinery, ranging from drilling rigs to pumps and compressors.

9.0 SUMMARY / CONCLUSIONS

The Initial Study regarding Deep Sea Hybrid Power Systems considered numerous power generation/energy conversion and energy storage technologies to support the exploration and production of oil and gas reserves remotely located off shore in the deep ocean. Based upon a preliminary screening of power generation and energy storage technologies, ten conceptual hybrid energy conversion and storage systems were developed for evaluation at each of the eight (8) representative deep ocean sites. Detailed analyses of the technologies were then conducted. The following parameters were evaluated for each site: estimated component weight, total weight, and total volume; initial investment, annual cost, and cost of electricity; and the economy of scale. With regards to energy storage technologies, only rechargeable batteries: lead-acid, sodium-sulfur, ZEBRA, and lithium-ion were identified for more detailed evaluation. Based upon the analyses conducted, the five (5) conceptual hybrid power systems listed in Table 7 were identified as the leading candidates for powering the sub-sea operations.

Obviously, the air supply problem is a major impediment for the use of wellhead gas as an energy source. As the intent is to avoid an electrical umbilical from a host platform, the need for any above surface infrastructure was identified as undesirable early on in the program. Therefore, the research team and the deep water operators concluded that the requirement to avoid any above surface infrastructure, including an air supply line to the surface, was sufficient cause to not consider the WELL TEG or the FC1 any further.

Therefore, the five (5) conceptual hybrid systems was reduced to the following three (3): GRID, PWR, and PWR TEG.

The estimated weights 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. Like the initial capital cost, the annualized costs are dominated by parameters that are 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. 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 of sufficient size so that power can be supplied for less than $1 per kilowatt-hour, comparable to the cost for grid power.

The research team acknowledged that the current level of resolution of the information developed made it challenging to rank the candidate systems without inducing a level of subjectivity, but was also of the opinion that there was significant value to develop a relative quantitative ranking of the three leading candidates. The approach commenced with the development of selection criteria with assigned weight factors, see Table 8. The weight factors range from 1 to 3, with 3 being high/most desirable. Relative rankings ranging from 1 to 3, 3 being high/most desirable were then assigned.

Table 13 summarizes the rankings. The rating approach described results with the maximum and minimum achievable scores being 102 and 34, respectively. The following summarizes the resulting scores for the three candidate approaches:

- GRID…….98……. 96%
- PWR……..57……. 56%
- PWR TEG…….41……. 40%

Relevant to note is that (1) the GRID option is considered as the baseline for which any alternative option must meet or exceed from both a performance and cost perspective, and (2) the primary objective of the Initial Study was to identify the most promising alternative candidates. Therefore, based upon the Initial Study, the following conclusions that can be made:

1. The top two candidates for power generation are both based on the small modularized pressurized water reactor. One candidate couples the pressurized water reactor with a secondary steam-turbine-generator system, whereas the other candidate couples the pressurized water reactor with a solid-state thermoelectric generator.

2. The two leading candidates for energy storage are both versions of sodium-beta batteries: sodium/sulfur and sodium/nickel-chloride (ZEBRA), noting that depending upon the final system requirements (e.g., cycle life) a lead acid system may also provide a suitable solution for energy storage.

10.0 RECOMMENDATIONS

Although it has been more than fifty-two years since the world's first operational nuclear submarine (USS Nautilus) completed the first successful submerged voyage around the North Pole and at present time there are more than 441 light water reactors worldwide, the research team understands that there are extreme differences between a nuclear powered manned submarine operating in relatively shallow water and an unmanned nuclear power plant operating in the remote deep ocean. Systems operating remotely on the ocean floor require special engineering to optimize reliability, minimize maintenance requirements, and to the extent possible, minimize all failure modes. Furthermore, these remote systems must be specifically designed to facilitate the installation, operation, and required maintenance procedures being conducted through remote operations (e.g., via ROVs).

The research team is also aware of existing barriers regarding nuclear power:

- Public perceptions.
- Domestic and international politics.
- U.S. Nuclear Regulatory Commission (NRC) design, siting, construction, and operation requirements, and approval and licensing timelines.
- National security
- The Three Mile Island, Chernobyl events occurring decades ago.
- The current ongoing events with the Deepwater Horizon drilling rig in the Gulf of Mexico (GOMEX).

Taking all these factor into account, the following recommendations are made. The initial near-term efforts should focus on conducting a detailed feasibility and implementation study addressing the following:

Detailed Operational Requirements and Interface Specifications. Stakeholder (deepwater operators and service providers) defined baseline operational requirements and interface specifications: notional/representative exploration or production field specifications for all three identified power range requirements, including representative relative geometrical locations and electrical requirements for each power point, thereby incorporating the power distribution requirements.

Design. The design of local area power generation and distribution network systems that are based on a standard submarine power cable system, as well as a small modularized pressurized water reactor. With the pressurized water reactor and for the actual electrical power generation, both the traditional turbine-generator, and the TEG should be investigated. Design considerations should include achieving a modularized approach, that can be installed, assembled, and operated remotely in the deep ocean (e.g., 12,000 fsw).

Deployment, Installation/Assembly, and Recovery Plans and Procedures. Notional plans and procedures for deployment, installation/assembly, and recovery that provide a detailed overview of the necessary support vessels and equipment, personnel, logistics, and timelines, as well as limitations and restraints associated with the subject efforts.

Operation, Maintenance, and Emergency Response Requirements. The operation and maintenance requirements of such a power network, including monitoring protocols and necessary response capability. Issues include maintaining a near continuous system health status, and the capability to appropriately respond (e.g., intervening) in a timely manner.

Approval, Licensing, and Operations Program Plan. A plan that identifies the detailed requirements, organizational roles, and responsibilities associated with obtaining approval and licensing, as well as operating such a power plant. Relevant to note is gas and oil industry's desire not to operate such a power plant, but merely to purchase the power from the power plant owner/operator. Therefore, the intention is for this plan to address such issues.

Socialization Strategy. A strategic plan purposely developed towards addressing the various non-technical barriers associated with the implementation of a remote deep ocean nuclear power plant.

11.0 REFERENCES

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2. LLNL Report, “Power Generation for Oil and Gas Production at Deep Ocean Sites”, 18 FEB 2010.

3. LLNL Report, “Energy Storage for Oil and Gas Production at Deep Ocean Sites”, 18 FEB 2010.

4. LLNL Report LLNL-TR-424663 Rev. 1, “Subsurface Hybrid Power Options for Oil and Gas Production at Deep Ocean Sites”, 25 APR 2010.

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Deep Sea Hybrid Power Systems (Initial Study)

Subcontract 07121-1902

Functional Requirements – Basis of Design

Deep sea hybrid power systems may enable cost effective offshore oil and gas exploration and production. Advanced deep-ocean drilling operations, locally powered, may provide access to oil and gas reserves otherwise inaccessible and could decrease the air emissions associated with offshore operations. Such technology will therefore enhance the energy security of the United States. There is a strong driving force for the development of subsea capabilities on the ocean floor. Such facilities will require ample supplies of local power to operate machinery on the floor, ranging from control modules to pumps and compressors to supplying power for an entire drilling vessel.

This initial study will systematically screen several potential systems for energy generation and storage technologies for unattended environmentally-friendly deep-sea applications. To begin the screening process, a definition of systems requirements and the establishment of quantitative and qualitative selection criteria are required. These criteria will be used to guide the development of subsea hybrid power system suitable for powering oil and gas equipment. The existing knowledge base of high-performance energy conversion and storage systems, appropriate for underwater applications, will be used as the basis of several conceptual designs, and then those conceptual designs will be systematically screened for the best hybrid system.

The systems requirements were defined through a series of meetings with the deepwater operators that are members of the research team. The requirements were then reviewed with service providers.

The vision is to locate the power system in remote deepwater production sites. The power system would supply all power needs for the location so that there would be no electrical umbilical from a 'host' platform. The power system would be sized to supply the site specific needs.

- ***Low power***: trickle charging of battery packs for satellite well control modules
- ***Mid-power***: small scale multiphase pumps
- ***Large-power***: gas compression, satellite field installations
- ***Mega-power***: cold-ironing of drilling vessel (for example, a semi-submersible drilling rig where the rig may shut down all power plants on the vessel after it plugs into the subsea power plant), large subsea facilities

Water depths for the location of the power system may range from 8,500 ft to 12,000 ft. At these depths the water temperature is 39.4° F.

System redundancy and reliability of the subsea power supply may also be critical. Small equipment must be able to withstand a shock load of up to 3g. Larger equipment must be able to withstand a shock load of 5g.

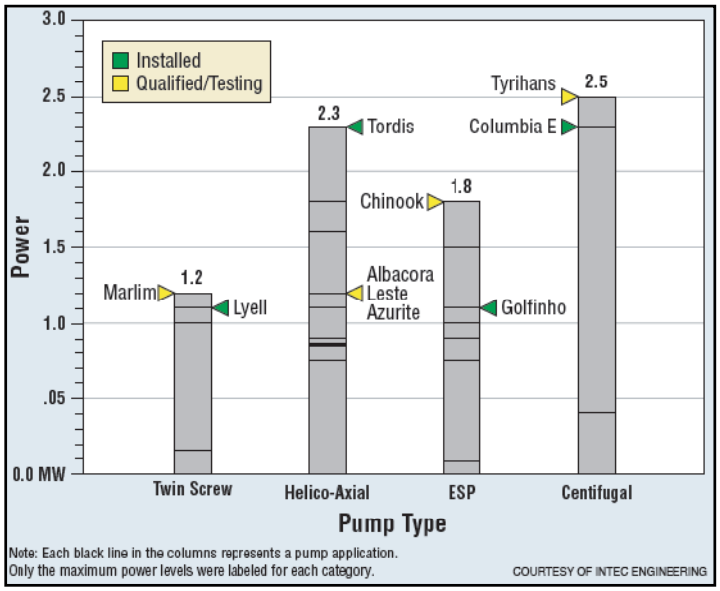
Additional functional requirements are summarized in the following table.

System	Output	Redundancy/Reliability Issues	Comments
Low Power	Less than 5kW (potentially DC)	• Prefer 100% backup or hot standby.	• May be able to cover control modules for a cluster of wells (6 – 8 trees that are of a typical electrical-hydraulic type). • May be able to trickle charge control modules. • May be able to handle small chemical injection pumps. • Multiphase flow meter would need 30 to 100 watts. • Overall – not of much interest.
Mid Power	1 to 10 MW (AC)	• Prefer 100% backup or hot standby.	• Small scale multiphase pumps (up to 3 MW each). • Small wet gas compressor (approx. 5 MW) • Direct electric heating of flowlines and jumpers (approx. 10 MW) • Example: BP King Booster Station (1 MW for each pump, 6.6 kilovolts)
Large Power	10 to 30 MW (AC)	• Prefer 100% backup or hot standby.	• Larger compression (20 MW each) • Example: Ormen Lange (60 MW total, 20 MW for each compressor) • Currently require 6.6 kV. Future requirements could be 13.8 kV or higher. • Prefer to be modular in concept (smaller units connected in parallel).
Mega Power	30 to 200 MW (AC)	• Prefer fail-safe system • Greater than 25 year life	• Prefer 100% backup or hot standby. • Could serve as a subsea utility hub. • As a stretch target, could consider a drilling vessel coming to location under its own power, then, cold-ironing into subsea power plant for drilling operations. A drilling vessel could require a maximum of 50 MW, including o 8 x 4 MW for thrusters o Approx. 5 MW for draw works (6,900 HP) o Approx. 7 MW for mud pumps (4 x 2,200 HP) o Two pedestal electric cranes and two electric knuckle boom cranes. • Prefer to be modular in concept (smaller units connected in parallel).

Vision of Power Generation Systems

The vision is to have a range of sizes of various power generation systems. Based on the discussions held with operating companies, it is desirable to have systems that are sized on a fit-for-purpose basis.

A summary of subsea processing power requirements was published in March 2008.[1] Power requirements for multiphase pumps are illustrated in the graph while the table on the next page summarizes the various installed systems along with the power requirements.

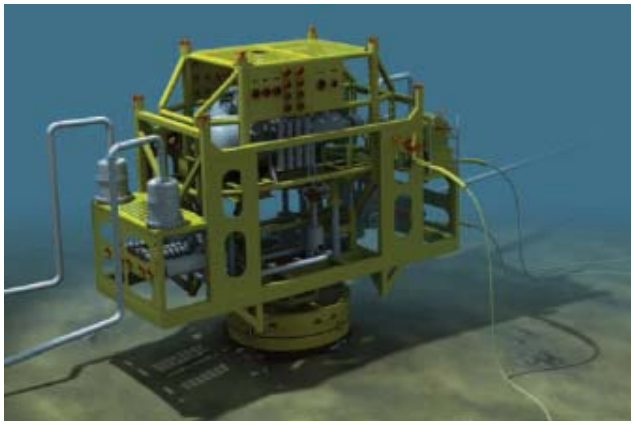


Based on the information gathered from interviews with operators, a review of the current systems installed and a review of the literature, the recommendation is made to focus on three ranges of power requirements: mid, large and mega. The low power range (less than 5 kW) is adequately handled through technology currently available today.

Mid-Power Vision

An example of a mid-power requirement is the BP King Project as discussed in the sidebar.[2]

The mid-power vision is to supply power to remote subsea facilities. Facilities could include multiphase pumping units, water injection units, small wet gas compressors, direct electric heating of flowlines or jumpers.



BP King Project

- Water depth of 5,575 ft, 18 miles from host platform.
- Two twin screw pumps
  - Bornemann MPC-335 units
  - Screw diameter of 13 in
  - Can create required differential pressure over a range of gas void fractions from 0-98 percent
- Each pump installed on own skid
  - 13 x 16 ft
  - 55 tons
  - Separately retrievable
- Manifold
  - 33 x 20 ft
  - 22 tons
- Power supplied at high voltage: 6.6 kilovolts
- Throughput: 83,000 BOPD

[1] Choate, T.; Padilla, M.; McKee, M.; Turner, T; and Albaugh, E.K.: "*2008 Worldwide Survey of Subsea Processing: Separation, Compression, and Pumping Systems,*" **Offshore Magazine**, March 2008.
[2] Aker Kvaerner: "*BP King Development,*" **Solutions**, 1-2006, www.akerkvaerner.com.

PROCESSING DISCIPLINE	COUNT	FIELD OR PROJECT	STATUS	COMMENTS	YEAR	OWNER/ FIELD OPERATOR	REGION	WATER DEPTH		TIEBACK DISTANCE		SYSTEM LIQUID THROUGHPUT		DIFFERENTIAL PRESSURE		POWER	GAS VOLUME FRACTION	SYSTEM PACKAGER	NO. OF PUMPS	PUMP TYPE	PUMP MANUFACTURER
					Yr. (11)	COMPANY		Meters	Feet	Km	Miles	M3/Hr.	MBOPD MBWPD	BAR (3)	PSI (3)	MW (2)	% OF VOL.	COMPANY	PUMPS	TYPE	COMPANY
SUBSEA GAS COMPRESSION	1	DEMO 2000	Q	Statoil K-Lab Test	2001	Statoil	Norway									3.60		Framo Engineering			Framo
	2	Ormen Lange (4)	Q		2011	Hydro	Norway	850	2,789	120	193	520	79	60	870	60		Aker Kvaerner	4		Aker Kvaerner/GE
	3	Asgard	D		2012	StatoilHydro	Norway	250	820	53	85					16		TBA	2		TBA
	4	Troll	C		2016	StatoilHydro	Norway	340	1,116	4	6							TBA			TBA
	5	Shtokman	C		2020	Gazprom	Barents Sea	350	1,148	565	909					240		TBA			TBA
	6	Snohvit	C		2020	Statoil	Barents Sea	345	1,132	143	230					60		TBA			TBA
FULL WELLSTREAM SUBSEA BOOSTING	1	★ Prezioso (20)	I	MPP @ Base of Platform	1994	AGIP	Italy	50	164	0	0	65	10	40	580	0.15	30-90%	Nuovo Pignone (8)	1	Twin-Screw	GE Oil & Gas
	2	Draugen Field	I	SMUBS Project	1994	A/S Norske Shell	Norway	270	886	6	3.7	193	29	53	773	0.75	42%	Framo Engineering	1	Helico-Axial	Framo
	3	Gela Field	I		1994	AGIP															
	4	★ Lufeng 22/1 Field (9)(19)	O	Tieback to FPSO	1998	StatoilHydro	South China Sea	330	1,083	1	0.6	860	130	35	508	0.40	3%	FMC Technologies	5+2 Spare	Centrifugal (1P)	Framo
	5	Machar Field (ETAP Project)	I		1999	BP Amoco	North Sea	85	277	35.2	21.9	555	84	22	319	0.90	64%	Framo Engineering	2+1 Spare	Helico-Axial	Framo
	6	Topacio Field	O	Tieback to Zafiro FPSO	2000	ExxonMobil	Equatorial Guinea	500	1,641	9	5.6	470	71	35	508	0.86	75%		2+1 Spare	Helico-Axial	Framo
	7	Ceiba C3 and C4	O		2002	Triton E.G.	Equatorial Guinea	750	2,461	7.5	4.7	450	68	45	653	0.84	50%	Framo Engineering	2+1 Spare	Helico-Axial	Framo
	8	Ceiba Field (FFD)	O	Full Field Development	2003	Triton E.G.	Equatorial Guinea	700	2,297	7.5	4.7	1,800	272	40	580	0.85	75%	Framo Engineering	4+1 Spare	Helico-Axial	Framo
	9	Mutineer/Exeter	O	Well ESPs+MPP on seafloor	2004	Santos	W. Australia	140	459	7	4.3	600	91	30	435	1.10	0-40%	Framo Engineering	2+1 Spare	Helico-Axial	(16)
	10	Brenda Field	O	For Framo MultiManifold	2005	OILEXCO N.S.	North Sea	145	476	8.5	5.3	750	113	35	508	1.10	40-65%	Framo Engineering	1+1 Spare	Helico-Axial	Framo
	11	Lyell	O	SS Tieback to Ninian South	2005	CNR	North Sea	140	459	11	6.8	200	30	20	290	1.10	0-90%	Aker Kvaerner	1	Twin-Screw	Bornemann
	12	Jubarte Field	O	Uses BCSS (14)	2007	Petrobras	Espirito Santo Basin	1,350	4,429	4	2.5	146	22	138	2,002	1.10	10-40%	FMC Technologies	4	ESP	BH Centrilift
	13	Schiehallion	I	2 Systems	2006	BP	West of Shetlands	400	1,312	3	1.9	2x1,350	2x204	26	377	1.80	74%	Framo Engineering	4	Helico-Axial	Framo
	14	★ King (7)	O	SS Tieback to Marlin TLP	2007	BP	GOM, MC Blks	1,700	5,578	29	18	550	83	50	725	1.00	0-95%	Aker Kvaerner	2+1 Spare	Twin-Screw	Bornemann
	15	Nicol Field	I		2007	OILEXCO N.S.	North Sea	145	476	18.5	11.5	338	51					Framo Engineering	1	Helico-Axial	Framo
	16	Navajo Field (17)	O	ESP in Flowline Riser	2007	Anadarko	GOM	1,169	3,834	6.7	4.2	24	4	40	583	0.75	57%	Centrilift	1	ESP	BH Centrilift
	17	Vincent	I		2008	Woodside	W. Australia	475	1,558	3	1.9	1,250	189	42	609	1.80	25-70%	Framo Engineering	2+2 Spare	Helico-Axial	Framo
	18	Marlim	Q	SBMS-500 SS Field Test	2008	Petrobras	Campos Basin	640	2,100	3.1	1.9	500	75	60	870	1.20	0-100%	Curtiss-Wright/Kvaerner	1	Twin-Screw	Leistritz
	19	Brenda #2	Q		2008	OILEXCO N.S.	North Sea	145	476	8.5	5.3	750	113	35	508	1.10	40-65%	Framo Engineering	1	Helico-Axial	Framo
	20	Argonauta (BC-10)	Q	Caisson /Artifical Lift Manifold	2009	Shell	Brazil	1,900	6,234	9	5.6	64	9.7	165	2,393	1.10	30%	FMC Technologies	2	ESP	BH Centrilift
	21	Golfinho Field	Q	ESP in Caisson (BCSS)	2009	Petrobras	Espirito Santo Basin	1,350	4,429			146	22	138	2,002	1.10	10-40%	FMC Technologies	4	ESP	
	22	Azurite Field	Q		2009	Murphy Oil	Congo, W. Africa	1,338	4,390					40	580	1.20		Framo Engineering	2+1 Spare	Helico-Axial	Framo
	23	Cascade	Q	Horizontal ESP on Skid	2009	Petrobras	GOM	2,484	8,150	8	5	135	20	163	2,357	1.50	20%	FMC Technologies	4	ESP	BH Centrilift
	24	Chinook	Q	Horizontal ESP on Skid	2009	Petrobras	GOM	2,682	8,800	19.3	12	135	20	160	2,326	1.80	0%	FMC Technologies	4	ESP	BH Centrilift
	25	Espadarte	Q	Horizontal ESP on Skid	2009	Petrobras	Brazil	1,400	4,593			83	13	120	1,740	0.90	10-40%		1	ESP	
	26	Jubarte Field	Q	Phase 2 - Uses BCSS (14)	2010	Petrobras	Espirito Santo Basin	1,193	3,914			145	22				30-40%	Aker Kvaerner	8	ESP	
SUBSEA WATER INJECTION	1	★ Troll C Pilot (15)	O	SUBSIS (SS Sep.& WI Sys.)	2000	NorskHydro AS	Norway	340	1,116	4	2.5	250	38	151	2,190	1.60		ABB/Framo	1+1 Spare	Helico-Axial	Framo
	2	★ Tordis Field (13)	I	SS Sep. + MPP + WI	2007	StatoilHydro	North Sea	200	656	11	6.8	650	98	100	1,450	2.30		FMC Technologies	(12)	Helico-Axial	Framo/FMC
	3	Columba E.	I	SS Water Injection	2007	CNR	North Sea	145	476			331	50	305	4,424	2.30		Framo Engineering	2	Centrifugal	Framo
	4	Albacora Leste Field	Q	Raw Water Injection	2009	Petrobras	Brazil	1,240	4,068			375	57	80	1,160	.5-1.2		Framo Engineering	3+1 Spare	Helico-Axial	Framo
	5	Tyrihans	Q	SS Raw Sea WI System	2009	StatoilHydro	Norway	300	984	31	19.3	710	107	190	2,756	2.50		Aker Kvaerner	2+1 Spare	Centrifugal	Aker Kvaerner
SUBSEA SEPARATION	1	SPS Project	O		1968	Exxon	GOM	610	2,001			80	12								
	2	Zakum	I		1970	BP	Abu Dhabi	22	72	0	0										
	3	Argyll	I		1989	BOET (6)	North Sea	75	246												
	4	★ Troll C Pilot (15)	O	SUBSIS (SS Sep.& WI Sys.)	2000	NorskHydro AS	Norway	340	1,116	4	2.5	250	38	15-25	218-363	1.60		ABB/Framo	1+1 Spare	Helico-Axial	Framo
	5	Marimba Field	O	VASPS Field Test	2000	Petrobras	Campos Basin	395	1,296	1.1	0.7	46	7	10	145	0.08		Cameron	1	ESP	Reda
	6	★ Tordis Field (13)	I	SS Sep. + MPP + WI	2007	StatoilHydro	North Sea	200	656	11	6.8	596	120	16	232	2.30		FMC Technologies	(12)	Helico-Axial	Framo/FMC
	7	Perdido	Q	Caisson Sep. & Boosting	2010	Shell	GOM	2,438	7,999				20-40	159	2,303	1.00	15%	FMC Technologies	5	ESP	BH Centrilift
	8	Ostra/Abalone (BC 10)	Q	Caisson/Artifical Lift Manifold	2010	Shell	Brazil	1,900	6,234	9	6	185	28	152	2,205	1.10	5%	FMC Technologies	4	ESP	BH Centrilift
	9	Pazflor (5)	Q	Gas/Liq. Sep.	2011	Total	Angola, Blk 17	800	2,625	4	3			100	1,450	2.30	<16%	FMC Technologies	6+2 Spare		
	10	Canapu Field	Q	Twister Separation Technology		Petrobras	Espirito Santo Basin	1,700	5,578	21	13.1							TwisterBV	none		

LEGEND ("stop Light")
- C Conceptual Project
- Q Qualified/Testing
- I Installed
- O Installed & Currently Operating
- ★ Indicates a World Record

NOTES:
1. See information accuracy statement below title block.
2. Power for gas compression is for the entire compression station. All other power listed is for an individual pump motor.
3. DP values are for individual pumps.
4. Ormen Lange is pumping low volumes of condensate
5. According to Total the Pazflor development will utilize seabed gas/liquid separation next to the production well, which will be the world's first application of this approach.
6. British Offshore Engineering Technology
7. King project utilizes the world's first umbilical to combine with HV cables with the service umbilical.
8. Nuovo Pignone is now part of GE Oil & Gas.
9. Low wellhead pressure of 100 psig at seabed dictated that artificial lift was required.
10. WI - Water Injection and WIP - Water Injection Pump
11. Year indicates first year of operation for the SS processing system.
12. Tordis Field: 1+1 Spare Multi-Phase Boosting Pumps, and 1+1 Spare Water Injection Pumps
13. Tordis Field - Statoil hopes to increase oil recovery from 49% to 55%, an additional 36 MMBO due to the world's first commercial subsea separation, boosting, and injection system.
14. BCSS - Centrifugal Subsea Submersible Pumps. They are placed in protective holes in the seabed 200m from the producing wells.
15. Troll SUBSIS - The world's longest operating SS separation system and world's first SS water injection pump system.
16. Manufacturers are: Framo and Centrilift. There are 2 ESPs per well feeding Framo MPP on seafloor.
17. Navajo field is a SS tieback to Anadarko's Nansen spar.
18. BH Centrilift = Baker Hughes Centrilift
19. World Record - 7 years of operation without intervention
20. World's first deployment of an electrically driven twin screw MPP operating on a live well. Testing occurred in '94 and '95 for a total of 7,850 hours of operation at base of platform on seafloor.

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Large-Power Vision

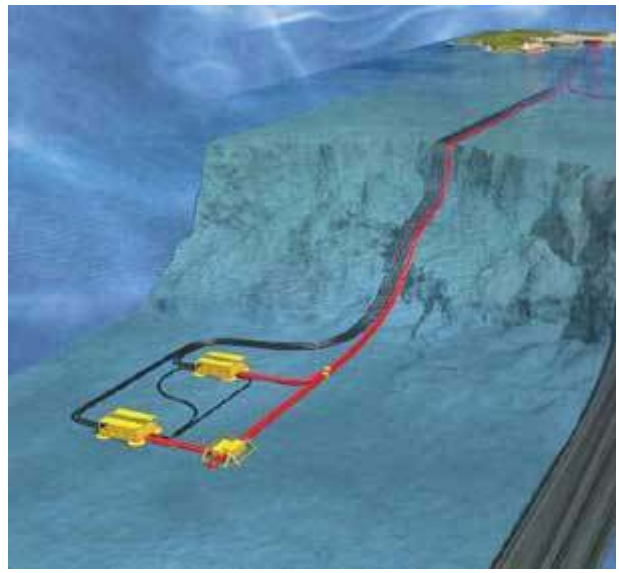
An example of a large-power requirement is the Ormen Lange Project. Specifics about the Ormen Lange field are discussed in the sidebar.

Subsea gas compression would require total installed power in excess of 50 MW to handle the large throughput (60 Mcm/d). The system under development includes the following:[3]

- Long step-out power supply (120 km offset, 70 MVA, 120 kV)
- Subsea power distribution to 22-kV level (circuit breakers, variable speed drives)
- Four off 12.5 MW centrifugal gas compressors with gas-filled, high-speed motors and magnetic bearings
- Four off liquid pumps
- Four off separators
- Other equipment (coolers, control system, instrumentation, valves, process piping, various connections)

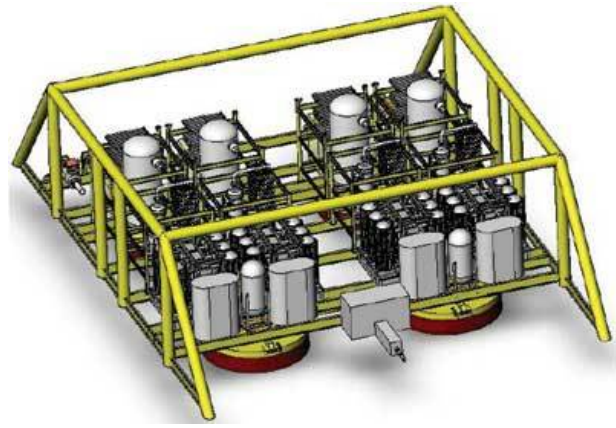
A generic system arrangement for the subsea compression system is illustrated to the right.

The large-power vision is to supply power to remote subsea developments that include large gas compression requirements.



Ormen Lange

Ormen Lange is a large natural gas field located 120 km northwest of Kristiansund, Norway, where water depths vary between 800 and 1,100 meters. Gas from the field will be able to meet up to 20% of the British gas demand for 40 years. The field will be developed through 24 subsea wells in four subsea templates connected by two 30-inch pipelines to an onshore processing terminal.



Ormen Lange System Arrangement.

[3] Eriksen, R.; Gustavsson, F.; Poorte, E.; and Bjerkreim, B.: "*Performance Evaluation of Ormen Lange Subsea Compression Concepts,*" **Offshore**, May 1, 2006, volume 66, issue 5. http://www.offshore-mag.com/articles/article_display.cfm?RTICLE_ID=254789&p=9.

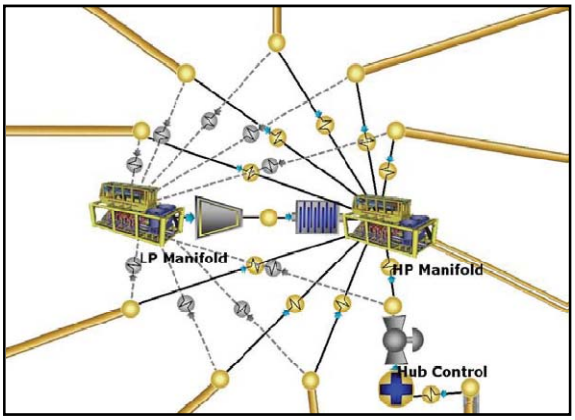
Mega-Power Vision

There are three different scenarios related to the mega-power vision:

- Large subsea development in remote location
- Centralized subsea utility hub
- Any subsea development that would incorporate cold-ironing of drilling vessel

Large Subsea Development

An example of a large subsea development is the Shtokman field, located 342 miles from the Kola Peninsula in the Barents Sea in 1,148 feet of water. Initial gas in place is estimated at 134.2 Tcf and at full field development is expected to produce 3.2 Tcf/year in 2028. The development will have three subsea production facilities and three production platforms. Phase one will include 20 wells arranged over three subsea templates. If subsea compression is used at Shtokman, power requirements will be significant.



The subsea hub is a large gas-gathering network with multiple drill centers. Illustrated are various small gas reservoirs (in this example, there are eight) tied back to a processing and compression facility (illustrated is the compression system).

Centralized Subsea Utility Hub

A centralized subsea utility hub, supplying power, chemicals (corrosion inhibitors, methanol, etc.), water injection, gas compression, etc. could be located in a deepwater remote site to service various subsea developments that are within a certain distance, for example, perhaps a 200 – 250 km radius. This subsea hub vision is similar to that described in the sidebar.[4] Although the figure illustrates only the compression, the hub could include other power requirements such as multiphase pumps and water injection facilities.

Complete cold ironing of a deepwater drilling vessel would require approximately 50 MW.

Cold-Ironing of a Deepwater Drilling Vessel

Cold ironing is a cost effective method currently used to reduce shipping emissions in port for container, cruise and reefer vessels.[5] The vision is to enable a deepwater drilling vessel to arrive on location under its own power. Once at the drill center, the vessel would be able to hook up to the subsea power generator facility and shut down the vessel's power plant. Turning off engines and plugging into the subsea facility would eliminate all

[4] Watson, M.J.; Hawkes, N.J.; Pickering, P.F. and Brown, L.D.: "*Efficient Conceptual Design of an Offshore Gas-Gathering Network,"* SPE 116593, prepared for the 2008 SPE Asia Pacific Oil & Gas Conference and Exhibition, Perth, Australia, 20-22 October 2008.

[5] California Air Resources Board: "*Evaluation of Cold-Ironing Vessels in California*," Draft Report, March 6, 2006, http://www.arb.ca.gov.msprog.offroad.marinevess.docments.coldironing0306/report.pdf

emissions associated with power generation on the vessel. The vessel would have its own power plant system as a back-up. Power requirements could require a maximum of 50 MW, including

- 8 x 4 MW for thrusters
- Approx. 5 MW for draw works (6,900 HP)
- Approx. 7 MW for mud pumps (4 x 2,200 HP)
- Two pedestal electric cranes and two electric knuckle boom cranes.

The mega-power vision would be to enable the option of cold-ironing of the drilling vessel at the various drill centers that are located at various reservoirs that are tied to a central utility hub, or the various drill centers associated with a large subsea field development. The mega-power vision would include powering of all subsea facilities associated with the utility hub requirements. To enable back-up systems for reliability/redundancy the vision would be to have multiple subsea power generation facilities that are tied together to create the mega-power facility. For example, a 200 MW facility could consist of four 50 MW facilities that are tied together in a common control methodology.

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

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February 26, 2010

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[1]Lawrence Livermore National Laboratory, [2]Houston Advaced Research Center, [3]Yardney Technical Products, [4]Babcock & Wilcox, [5]Naval Facilities Engineering Service Center, [6]General Electric Global Research, [7]Chevron Energy Technology Company, [8]Curtiss-Wright Electro-Mechanical Corporation, [9]Total Exploration & Production USA LLC, [10]Shell Oil Company

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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."*
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> *"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."*
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> *"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.

Concept-of-Operation Sites Serving as Basis for Study

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.

Hybrid Energy Conversion and Storage Systems Considered

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
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
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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.

<u>Adjusted Power Requirements for Site Accounting for Compression of Air from Surface</u>

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:

$$P_{CR} = S_y Z_1 \left(Z_2 - n Z_3 \right)$$

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.

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

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

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

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.]:

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

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:

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

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.

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

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

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

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).

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

Annualized Cost at Commencement of Commercial Operations

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

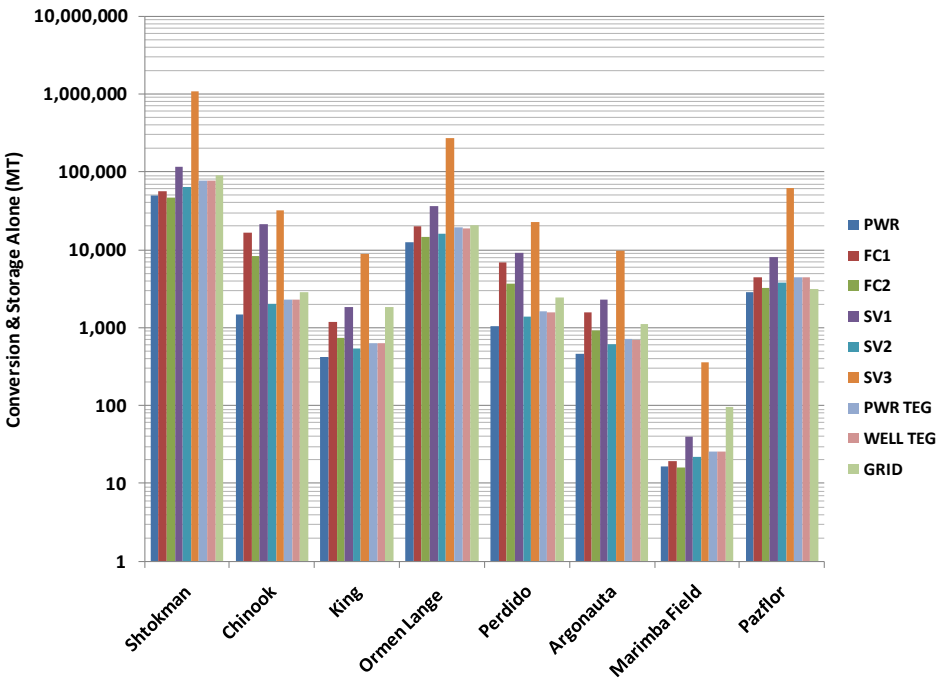

Figure 1 – Graphical comparison of the predicted masses of power generation and energy storage components, for each of the deep ocean hybrid systems, and for each of the con-ops cases

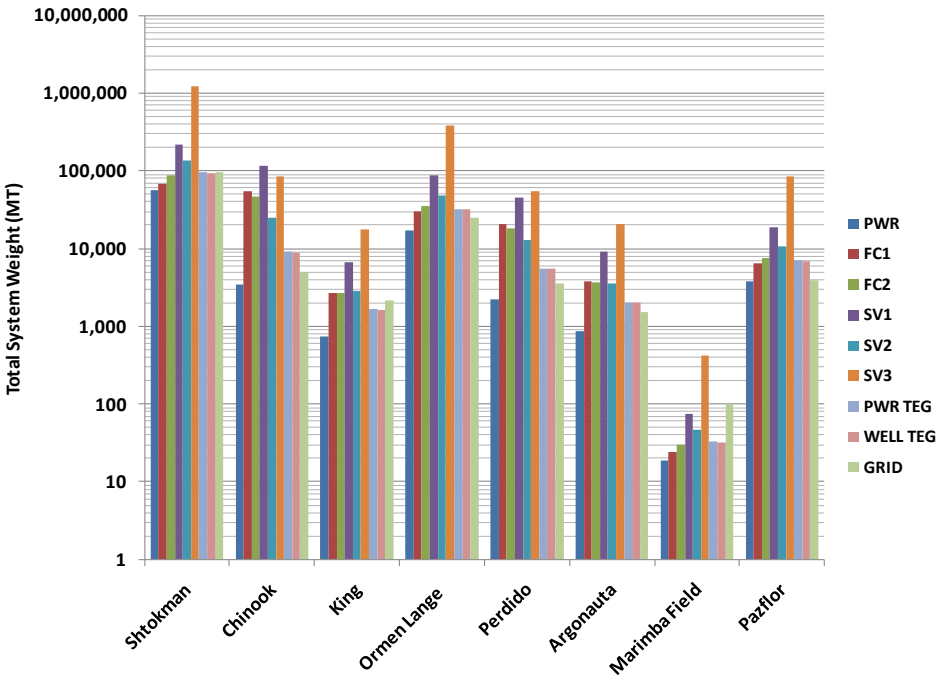

Figure 2 – Graphical comparison of the predicted total masses of the deep ocean hybrid power generation and energy storage options, for each of the con-ops cases

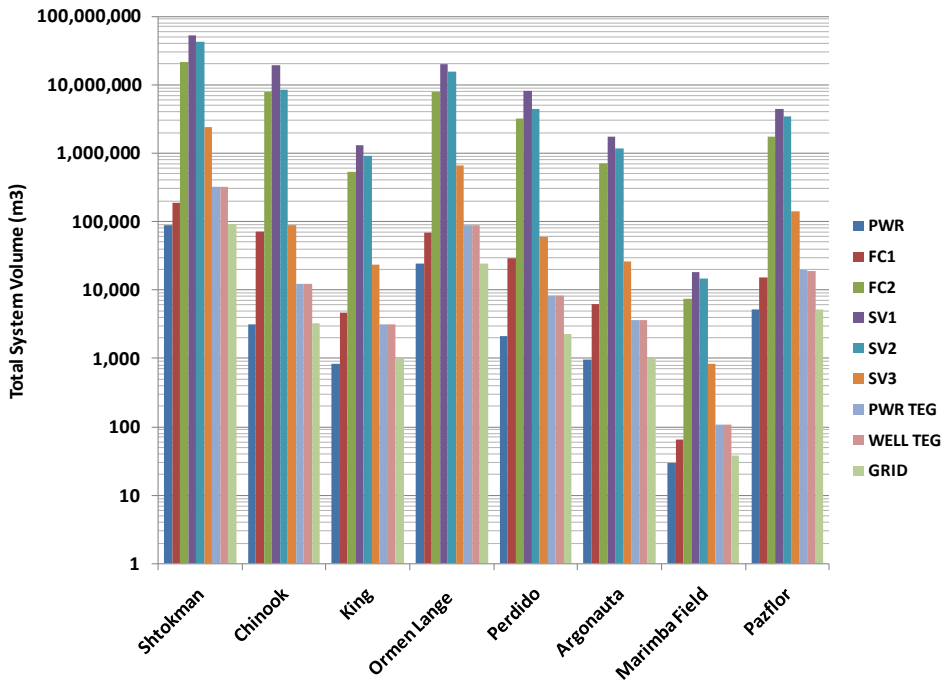

Figure 3 – Graphical comparison of the predicted volumes of the deep ocean hybrid power generation and energy storage options, for each of the RPSEA con-ops cases

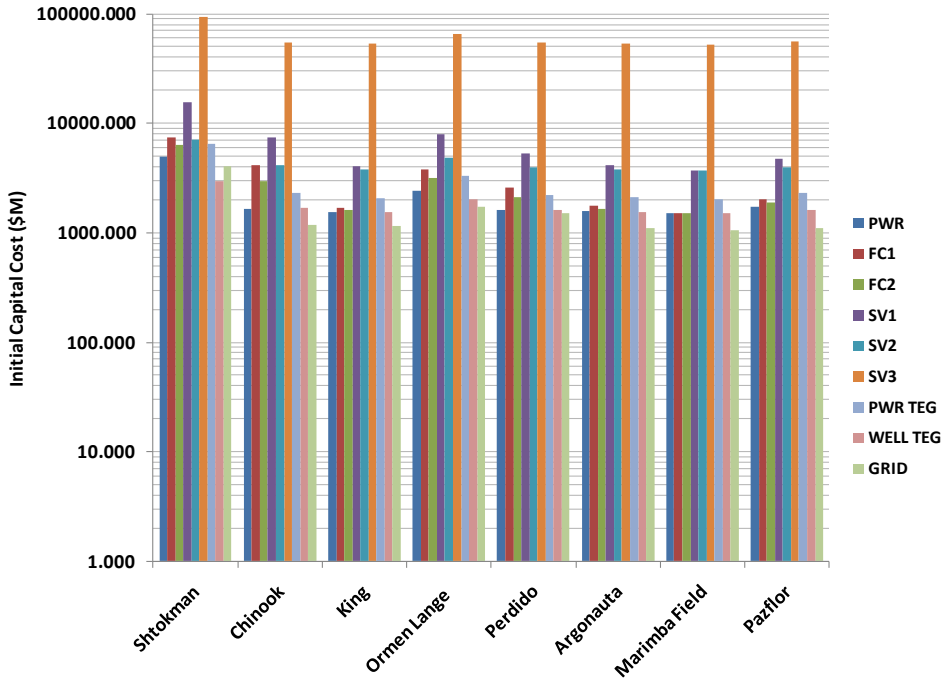

Figure 4 – Graphical comparison of the predicted capital investment required for each deep ocean hybrid power generation and energy storage option, for each of the con-ops cases

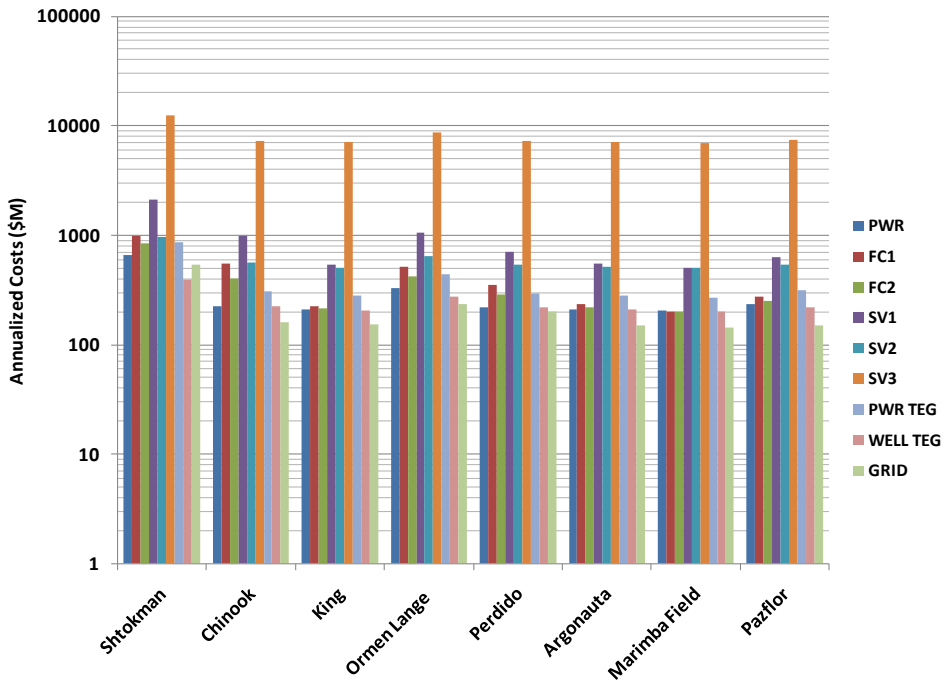

Figure 5 – Graphical comparison of the predicted annualized costs for each deep ocean hybrid power generation and energy storage option, for each of the RPSEA con-ops cases

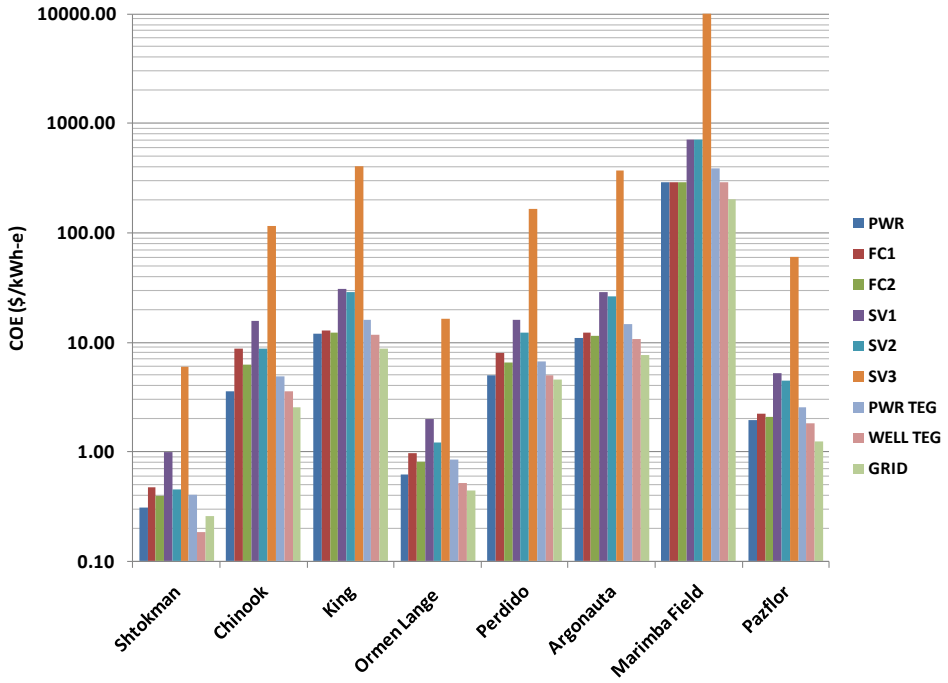

Figure 6 – Graphical comparison of the predicted cost-of-electricity produced by each of the deep ocean hybrid power generation and energy storage systems, at each of the con-ops sites

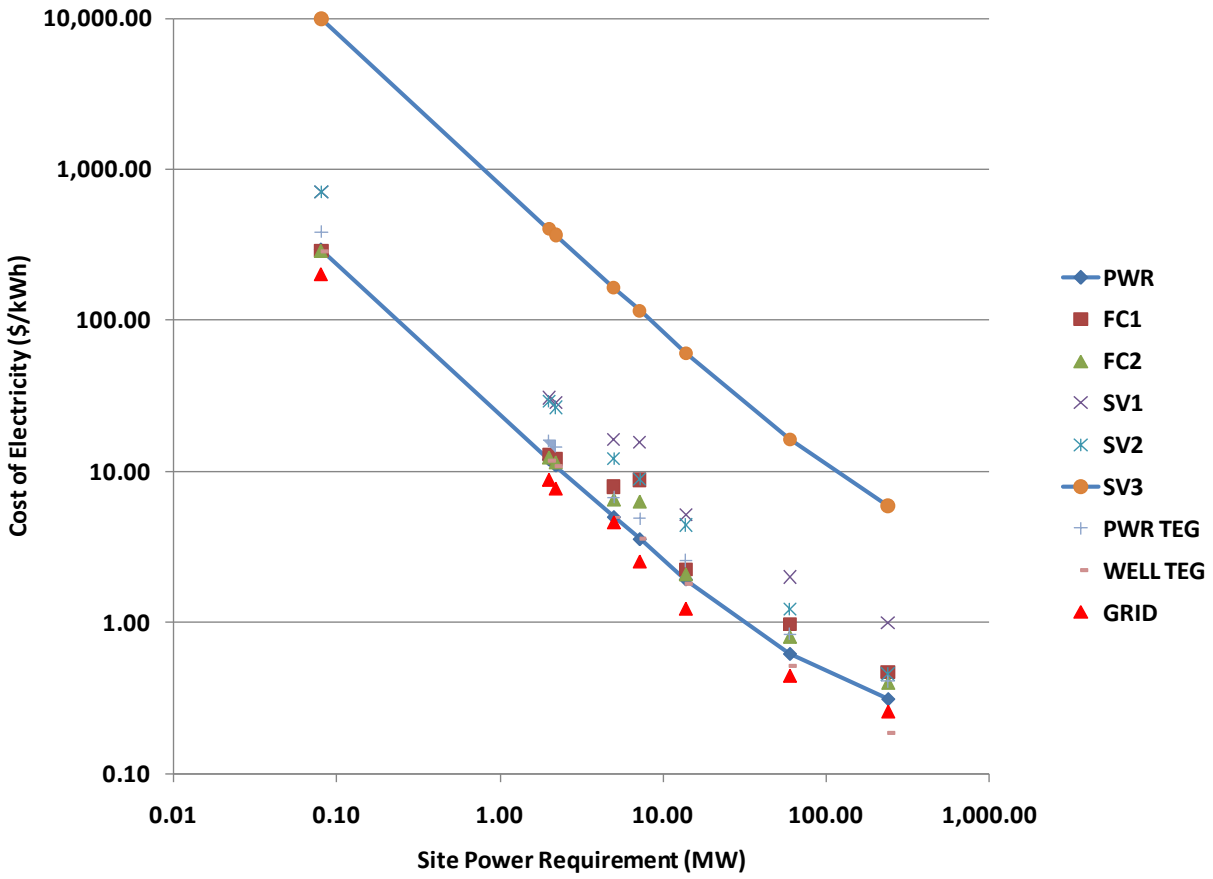

Figure 7 – The cost of electricity shows a very clear economy of scale, with the lowest electricity costs being realized for the largest sites

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

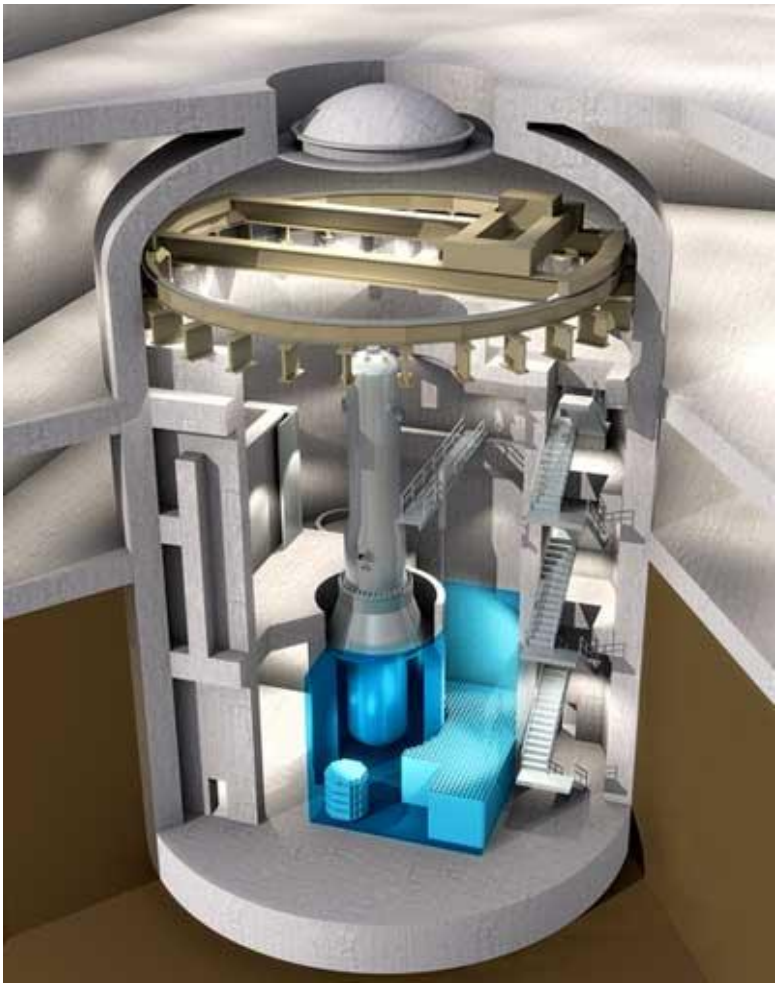

Figure A 3 – A single B&W mPower™ module inside its own independent, underground containment

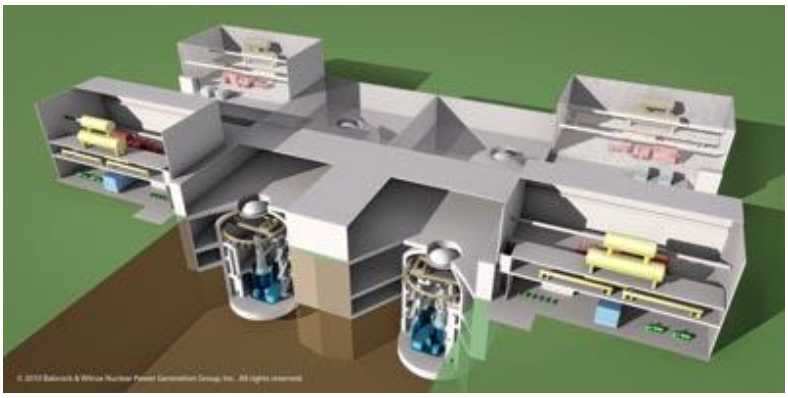

Figure A 4 – Four B&W mPower™ nuclear reactors configured as a 500 megawatt nuclear power plant

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

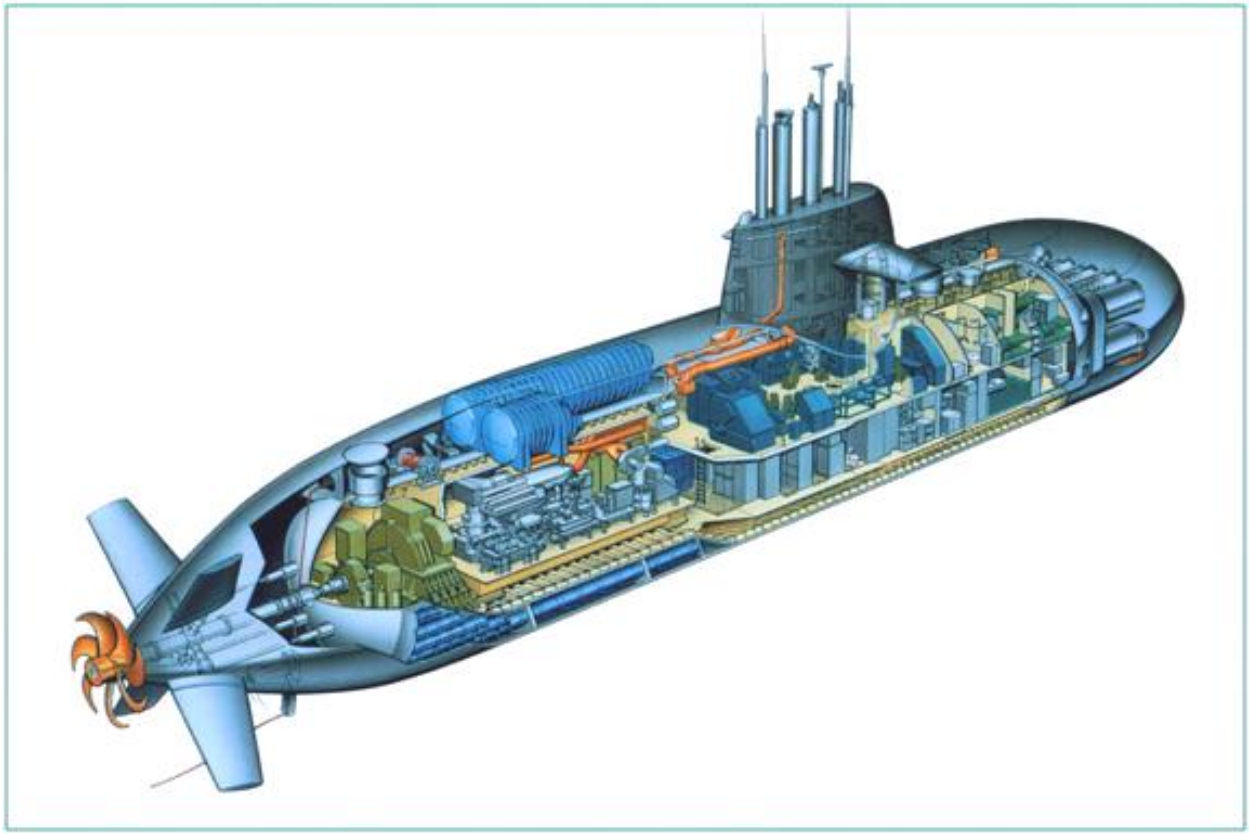

Figure B 3 – Three-dimensional schematic representation of the fuel-cell powered sub-sea vessel

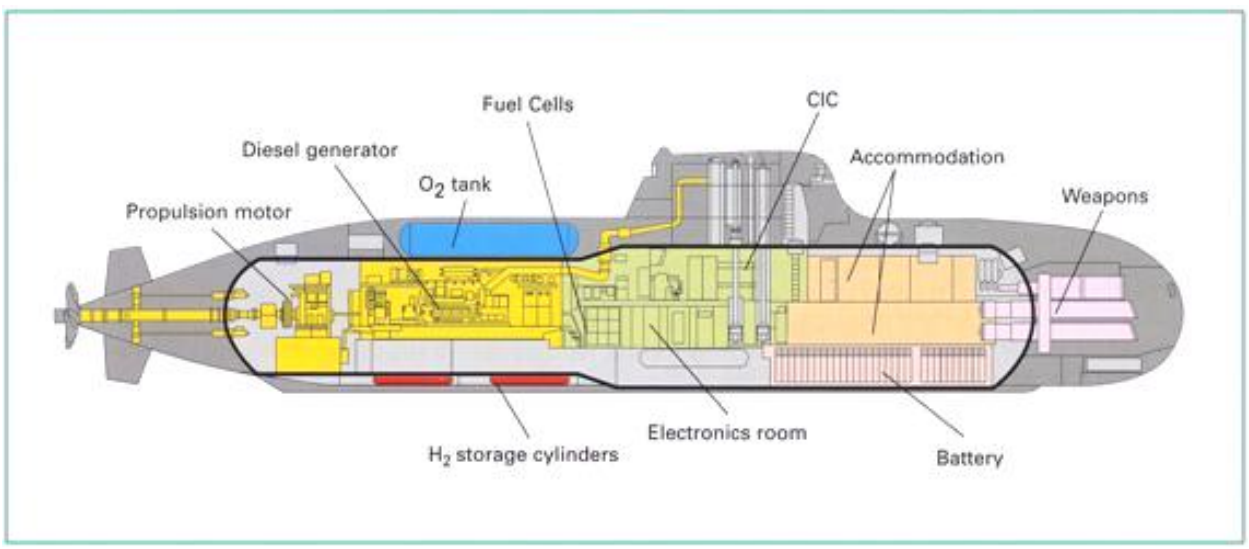

Figure B 4 – Two-dimensional schematic representation of the fuel-cell powered sub-sea vessel, showing the systems required for operation, including the oxygen storage tank, the fuel cells, and the hydrogen storage cylinders

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

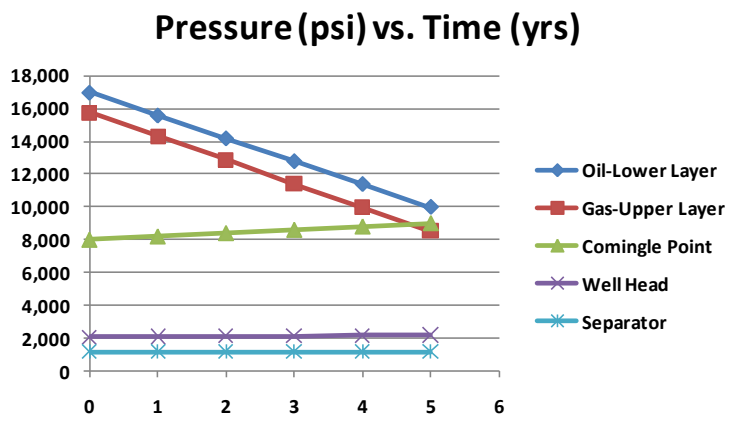

Figure C 1 – Pressure as a function of time at various points in typical deep-ocean well system

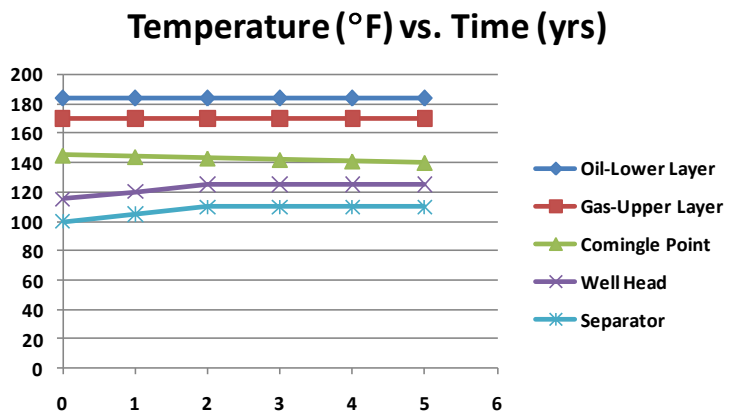

Figure C 2 – Temperature as a function of time at various points in typical deep-ocean well system

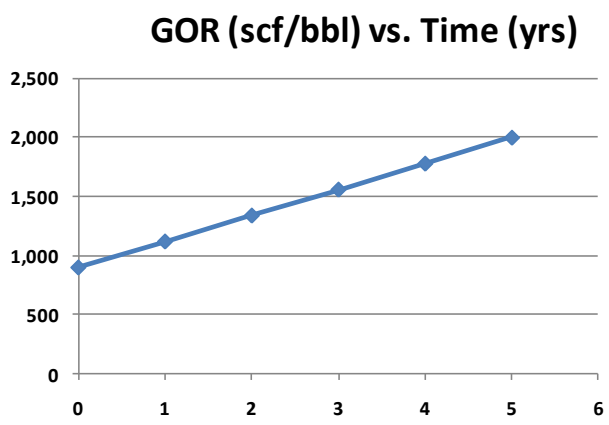

Figure C 3 – Gas-to-oil ratio (GOR) for production from typical deep-ocean well system

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

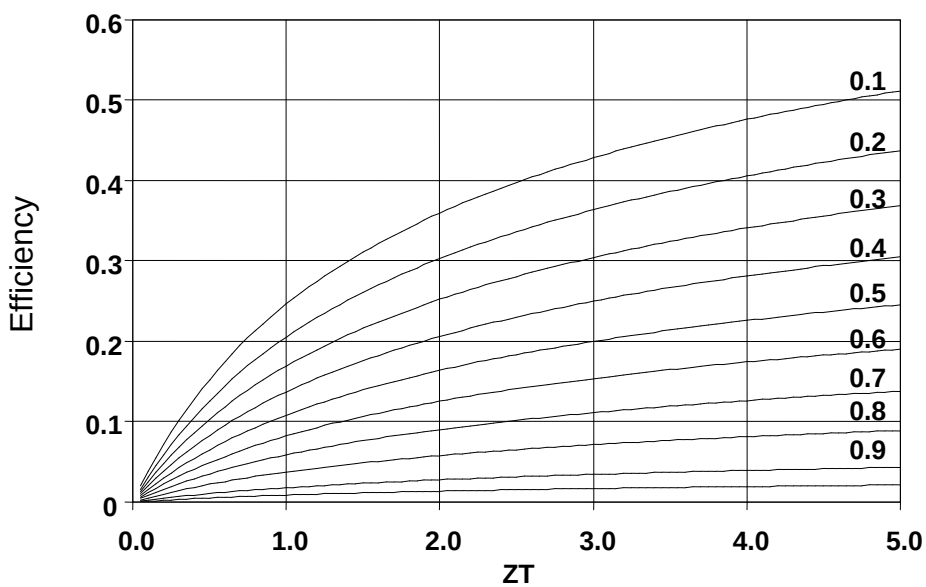

Figure D 1 – Efficiency (η) as a function of ZT for T_c/T_h ratios from 0.1 to 0.9

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

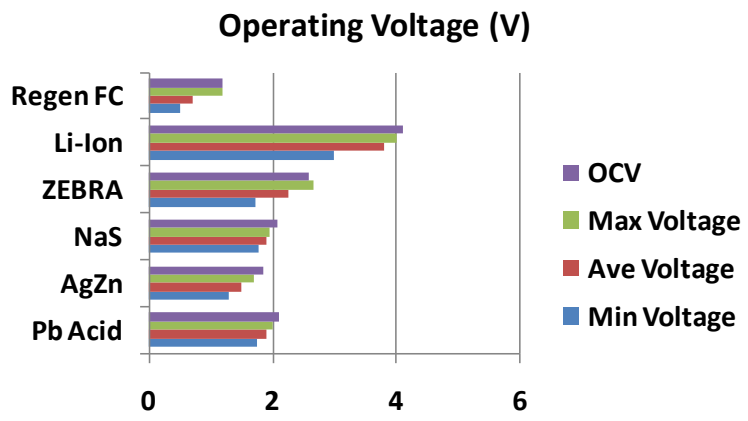

Figure F 1 – Range of cell voltages for energy storage technologies considered for the various hybrid energy conversion and storage systems, ranging from the open circuit voltage (OCV) to the minimum operating voltage

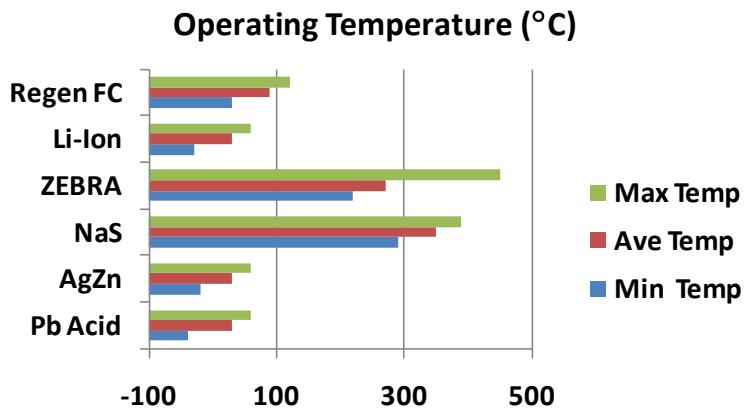

Figure F 2 – Range of operating temperatures possible with the energy storage technologies considered for the various hybrid energy conversion and storage systems

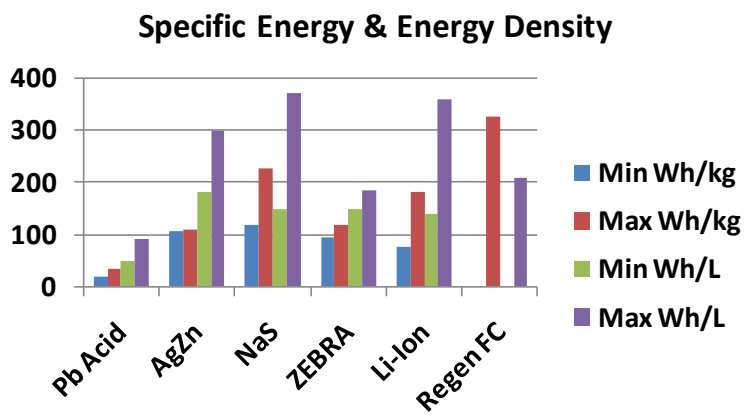

Figure F 3 – A comparison of the specific energies and energy densities for the energy storage technologies considered for the various hybrid energy conversion and storage systems

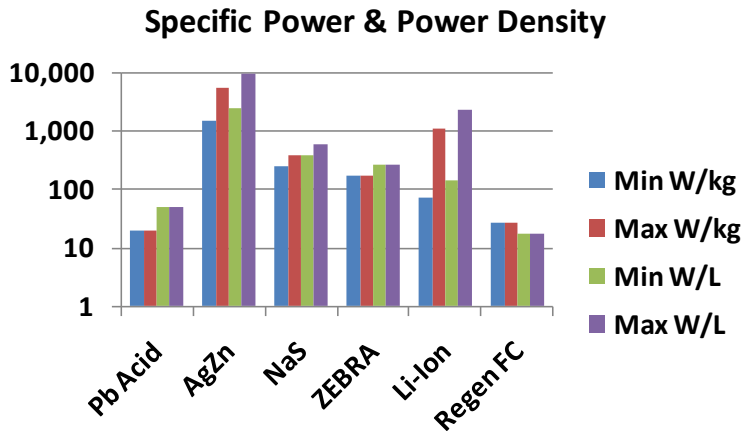

Figure F 4 – A comparison of the specific powers and power densities for the energy storage technologies considered for the various hybrid energy conversion and storage systems

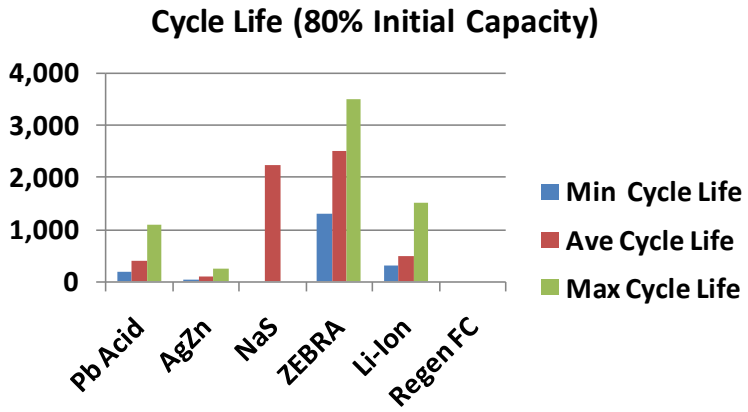

Figure F 5 – A comparison of the charge-discharge cycle lives for the energy storage technologies considered for the various hybrid energy conversion and storage systems

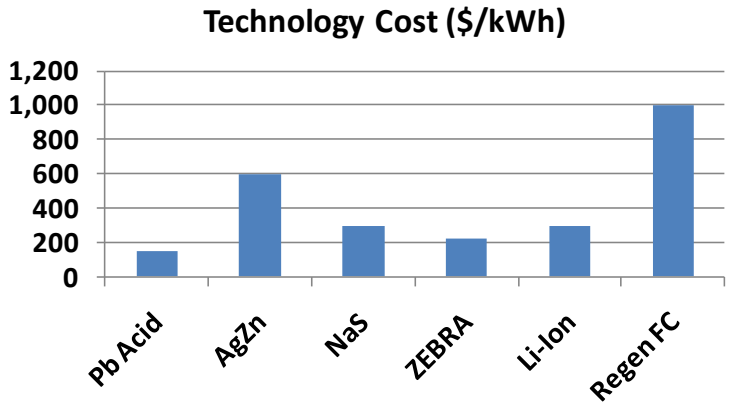

Figure F 6 – A comparison of the cost of energy storage for each of the technologies considered for the various hybrid energy conversion and storage systems

Appendix G – Tradeoff Between Specific Energy & Specific Power

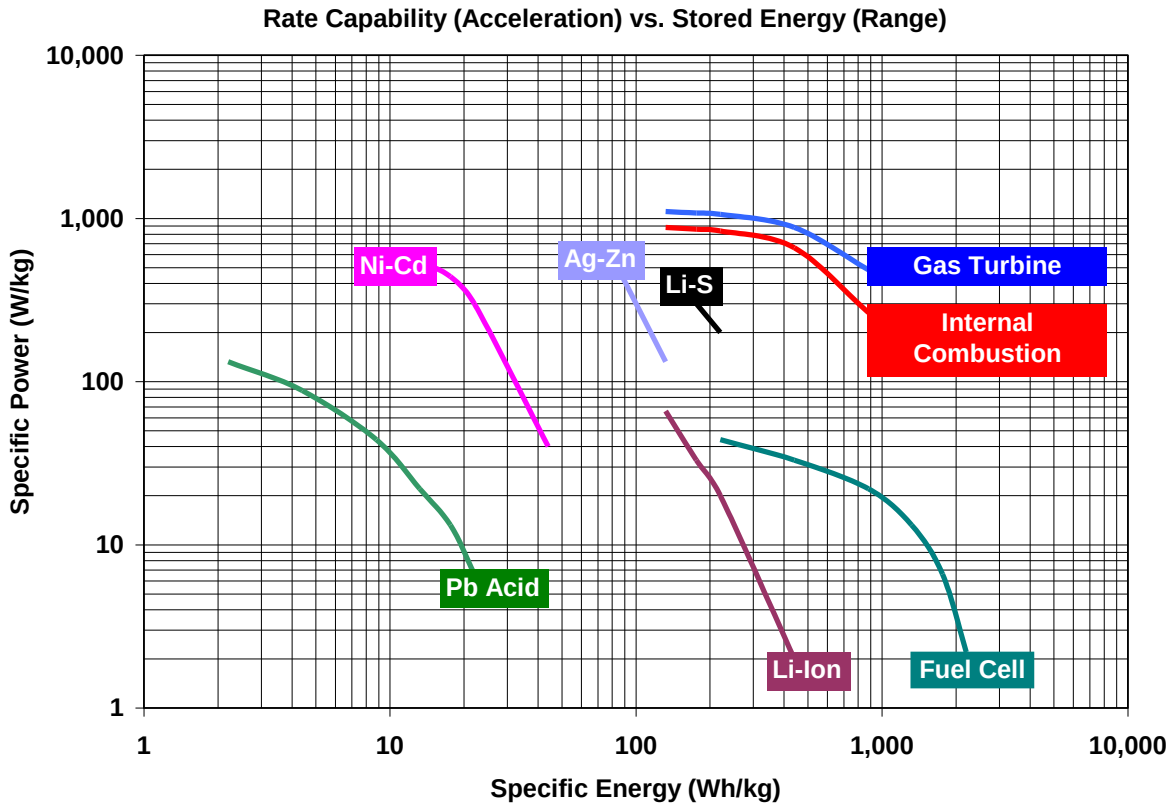

Figure G 1 – Specific power vs. specific energy for competing non-nuclear sub sea energy conversion and storage systems

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 = $f_{afw} = A/F = i/[(1+i)^n-1]$	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 = $f_{afp} = A/P = [i(1+i)^n]/(1+i)n-1]$	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
Required Power	60.0000	MW-e	Site Dependent
Service Life = n	15	years	Analyst Estimate
Interest Rate = i	5	%	Analyst Estimate
Compound Interest Factor = $f_i = (1+i)^n$	2.0789	factor	Perry's 7th Edition pp. 9-10 to 9-13
Discount Factor = $f_d = 1/f_i$	0.4810	factor	Perry's 7th Edition pp. 9-10 to 9-13
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
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
Salary & Fringe Benefits - Management	300000	$/year	Analyst Estimate
Salary & Fringe Benefits - Engineer	200000	$/year	Analyst Estimate
Salary & Fringe Benefits - Operations	100000	$/year	Analyst Estimate

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

Energy Storage for Oil & Gas Production at Deep Ocean Sites

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

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Abstract

By combining the availability and power density of an energy conversion component with the reliability, continuity and storage capability of an energy storage component, hybrid systems can be built for continuous operation, with the characteristics of high power and energy densities, as well as outstanding reliability. Such systems could be built with the capability 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 that 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. In the event of a failure of a primary power generation system, such as a small modular reactor, a proton exchange membrane fuel cell or engine being powered with natural gas from subsea well-heads, there must be enough stored electrical energy to enable continued operation of sensor, control, and communications networks, to enable a gradual and graceful shutdown of operations.

The energy storage technologies that were explored included: mechanical flywheels; compressed-gas storage; liquid red-ox batteries; lead-acid batteries; silver-zinc batteries; sodium-beta batteries; lithium-ion batteries; regenerative fuel cells. Of these, only the lead-acid, sodium-beta and lithium ion batteries were carried forward for consideration as energy storage options for the deep ocean hybrid energy conversion and storage systems being evaluated.

Background

The energy storage technologies that were explored for the deep ocean hybrid energy conversion and storage system included: mechanical flywheels; compressed-gas storage; 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. By combining the power density of the energy conversion component with the energy storage and reliability of the energy storage component, hybrid systems can be built with high power and energy densities, as well as outstanding reliability. A summary of key attributes of energy storage options used to assess hybrid system options is presented in Table 1 and Figures 1 through 6.

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 relatively inexpensive and should therefore 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, silver-zinc 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-ion 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. 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

Summary

By combining the power density of the energy conversion component with the energy storage and reliability of the energy storage component, hybrid systems can be built with high power and energy densities, as well as outstanding reliability. Such systems must be 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. In the event of a failure of a primary power generation system, such as a small modular reactor, a proton exchange membrane fuel cell or engine being powered with natural gas from subsea well-heads, there must be enough stored electrical energy to enable continued operation of sensor, control, and communications networks, to enable a gradual and graceful shutdown of operations.

The energy storage technologies that were explored included: mechanical flywheels; compressed-gas storage; liquid red-ox batteries; lead-acid batteries; silver-zinc batteries; sodium-beta batteries; lithium-ion batteries; regenerative fuel cells. The practicality of compressed-gas storage was site specific, and

not considered viable for most concept-of-operations sites under consideration. The silver-zinc batteries were considered too limited in cycle life and too expensive to include in the final evaluation. Similarly, the regenerative fuel cell was considered too expensive, and had a high level of complexity. Of these, only the lead-acid, sodium-beta and lithium ion batteries were carried forward for consideration as an energy storage option for the deep ocean hybrid energy conversion and storage system.

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Tables & Figures

Table 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

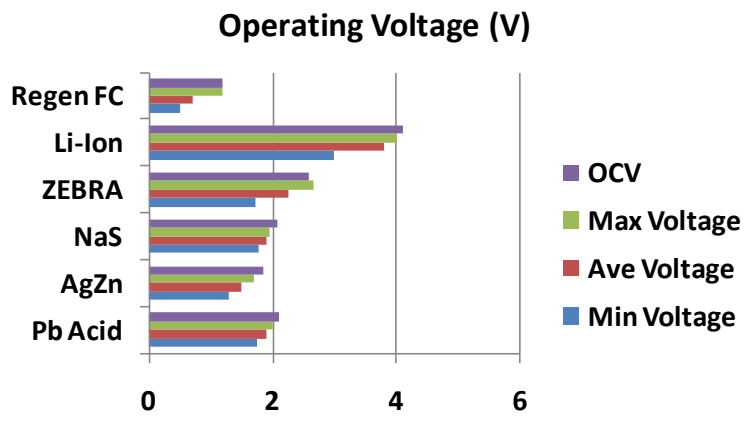

Figure 1 – Range of cell voltages for energy storage technologies considered for the various hybrid energy conversion and storage systems, ranging from the open circuit voltage (OCV) to the minimum operating voltage

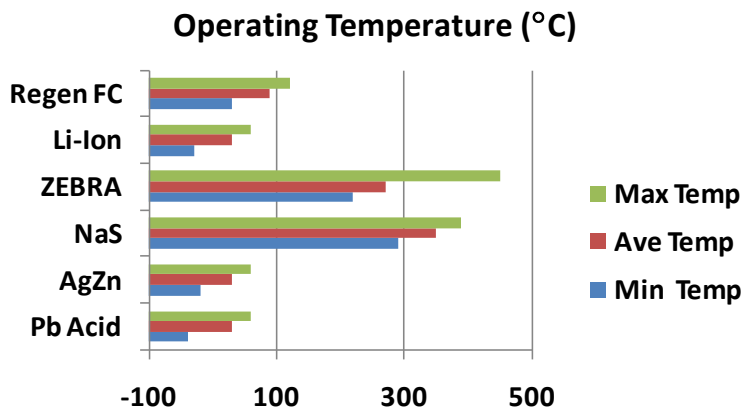

Figure 2 – Range of operating temperatures possible with the energy storage technologies considered for the various hybrid energy conversion and storage systems

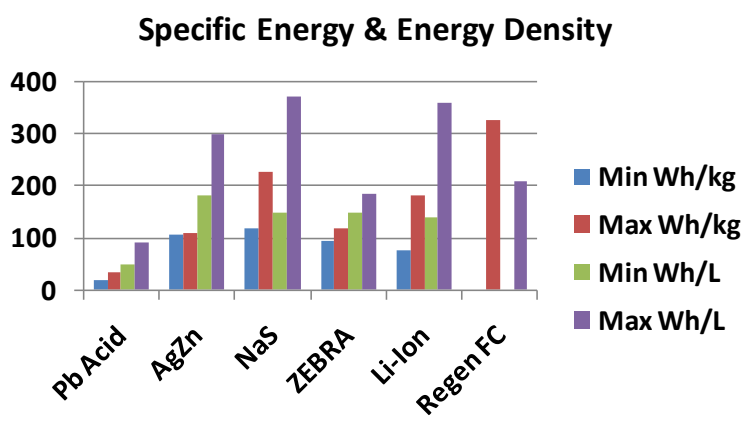

Figure 3 – A comparison of the specific energies and energy densities for the energy storage technologies considered for the various hybrid energy conversion and storage systems

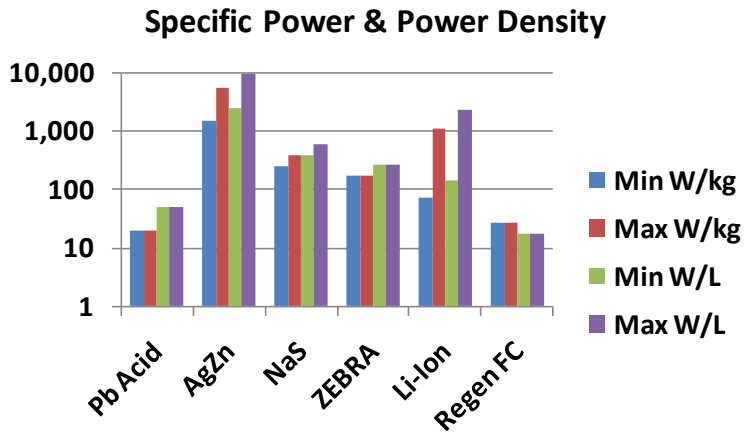

Figure 4 – A comparison of the specific powers and power densities for the energy storage technologies considered for the various hybrid energy conversion and storage systems

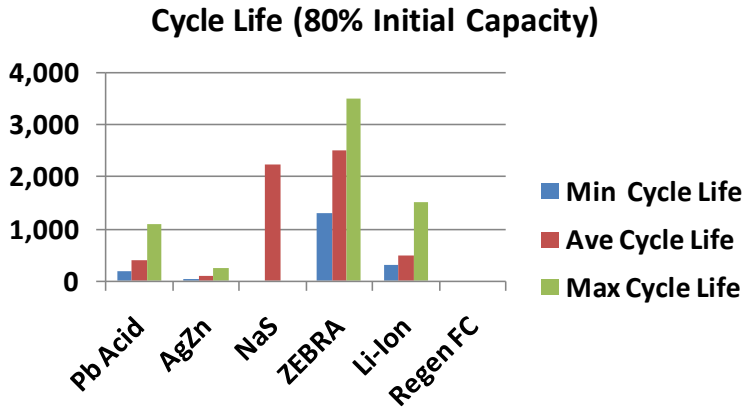

Figure 5 – A comparison of the charge-discharge cycle lives for the energy storage technologies considered for the various hybrid energy conversion and storage systems

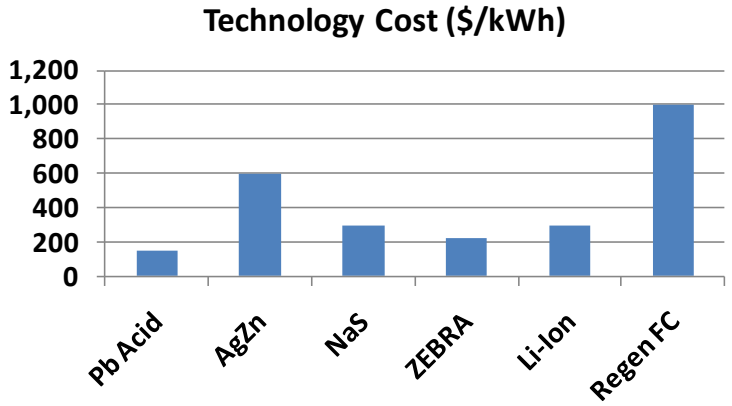

Figure 6 – A comparison of the cost of energy storage for each of the technologies considered for the various hybrid energy conversion and storage systems