Large-Scale Energy Delivery to Enable Persistent Monitoring Subsea


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Abstract
The objective of this paper is to inform the autonomous subsea robotic community of a recently fielded fuel cell-based large-scale energy storage system developed by Teledyne Energy Systems, Incorporated (TESI). This large-scale energy storage system, the TESI Subsea Supercharger prototype (TSS), has been developed as an energy storage system that can enable the un-tethered delivery of power to ocean observatories, un-manned underwater vehicle (UUV) recharging systems, and resident remotely operated vehicles (ROVs). To date, untethered subsea power has been provided by batteries. Batteries are limited in energy, particularly in cold environments, and, if rechargeable, require access to power to recharge. A TSS enables UUVs and ROVs to operate free of interaction with any established subsea resources such as those installed by operators of subsea oilfields as well as in locations where power would be otherwise impractical to deploy. A TSS prototype was used to power two ROVs; one ROV performed ship husbandry simulations and the other performed UUV capture and recharging simulations. During the ship husbandry simulations, an ROV would traverse a dock and then inspect a simulated ship hull. All the power required for the operation was delivered by the TSS prototype. The TSS prototype was able to be fueled dockside and performed a dockside deployment, recovery, and redeployment activity. Similarly, the TSS prototype was able to power an ROV, while operating on solid-state reactants, as it performed a UUV capture and recharging simulation. For this demonstration, the TSS prototype was shipped across the United States, unpacked, fueled, and deployed. The TSS prototype is sufficiently mature to be shipped to a demonstration location without extensive preparation and checkout prior to operation. It is envisioned that one application for the subsea power node would be to allow resident ROVs to traverse and inspect pipelines, specifically during the discovery/development or decommissioning of oilfields. This system can also provide subsea robotic vehicles, tasked to patrol harbors and waterways, with the power to provide persistent surveillance. This paper will review the field-testing of a TSS prototype.
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1.0 Introduction
Unmanned underwater vehicles (UUVs) and remotely operated vehicles (ROVs) have gained a level of autonomy that now allows them to traverse great distances and operate independently on routine tasks subsea [1-3]. Vehicle power remains a major limitation to the operating time of subsea vehicles [4]. To address the limitation of vehicle power, Teledyne Energy Systems, Incorporated, (TESI) has developed an energy storage system that is capable of providing megawatt-hours of energy subsea. This energy storage system, the TESI Subsea Supercharger (TSS), is fuel cell-based and is fed with either gaseous, cryogenic, or solid-state reactants. It is envisioned that a TSS powered subsea recharging dock would enable the untethered recharging of UUVs and ROVs for persistent operation [5-6]. Such capability could allow seabed mapping, ocean thermocline analysis, subsea telecommunication inspection, subsea oil field inspection, search and recovery expeditions, and the autonomous robotic traversing of the seas. This paper will discuss the validation tests TESI has completed for the TSS.

1.1 The TESI Subsea Supercharger (TSS)
The TSS is comprised of a fuel cell system module, a hybridization/power conditioning module, a thermal subsystem, and a reactant storage subsystem. The separation between the fuel cell system module and reactant storage system is the greatest distinction between a battery and a fuel cell system. The fuel cell reactants and fuel cell system are not co-located and thus can be kept separated in the case of an anomaly. The reactant storage subsystem feeds the fuel cell system with hydrogen and oxygen. The hydrogen and oxygen are converted into electrical power and heat at the fuel cell system. The byproduct of the fuel cell reaction is water. The water can either be stored or expelled to the environment. The heat of the fuel cell system is used to maintain operating temperature. As such, fuel cell-based energy storage systems can be designed to operate in very cold (< -40 °C) environments. The TSS is designed for operation just above freezing and is projected to survive storage at temperatures in the range of -20 to +70 °C. The hybridization/power conditioning module is customer specified and can include a hybridizing battery and custom voltage conditioning electronics. A TSS in a 100 kWh configuration is shown as Figure 1. The TSS skid is designed as a mounting platform for the components, the configuration is modular and flexible. As the TSS is modular in design, it can be configured to be integrated into a host skid to meet the requirements of a target application.

Figure 1: The Teledyne Subsea Supercharger (TSS) in 100 kWh energy storage configuration.
1.2 The TSS Fuel Cell System Module

The fuel cell system module is comprised of an ejector driven reactant (EDR) fuel cell system, reactant control subsystem, product management subsystem, and thermal subsystem. The thermal subsystem is comprised of a coolant pump, thermal regulation valve, and radiator. The coolant pump circulates fuel cell product water through the fuel cell system and radiator to allow for cooling. Temperature is controlled via a thermal regulation valve, which passively diverts the cooling water exiting the fuel cell system to a radiator immersed in the environment (pool, lake, or ocean).

The product management subsystem is comprised of a water collection system and product exhaust pump. The product exhaust pump will either store or discharge fuel cell product water. In an application in which system buoyancy must be maintained, the fuel cell product water may be required to be stored. For the TSS target applications, both fuel cell product water storage and expulsion can be employed. The fuel cell system module is designed to support both product water storage and expulsion with the product exhaust pump sized to expel water at select operating ocean depth. The function of the water collection system is to provide the cooling water used in the thermal management subsystem.

The reactant control subsystem consists of inlet solenoid valves, pressure regulators, purge solenoid valves, and reactant recirculation solenoid valves. The reactant control subsystem supports three functions in the TSS. The first function allows for gas to be fed to the fuel cell system, the second function allows for the fuel cell system to purge, and the third function is a feature of the EDR fuel cell system that allows for passive recirculation of reactants within the fuel cell stack [7-9]. The inlet solenoid valves allow the reactant gas to be fed into the fuel cell stack and work as a reactant feed shutoff. If an anomaly is detected, the reactant solenoid valves will close and isolate the reactants from the fuel cell system. If the anomaly is cleared, the solenoid valves can be re-opened and the system can continue operation. The reactant solenoid valves are designed to be normally closed. They will close if power to the fuel cell system controller is lost or if the fuel cell system controller becomes unresponsive. The TSS features a second passive system that will mechanically shut the reactant inlet if the reactant flow to the fuel cell system is higher than expected. The mechanical shut-off valves are not remotely resettable and would require the TSS to be retrieved if activated. The mechanical shut-off valves

Figure 2: The Teledyne Subsea Supercharger (TSS) fuel cell system module.
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provide the TSS with dual redundancy with respect to reactant feed. The pressure regulators regulate the pressure being fed to the fuel cell from the reactant storage subsystem. The purge solenoids allow for the priming and reactant bleed of the fuel cell system. Priming is required when the fuel cell system is taken from an off or hibernate state to an operational one. Reactant bleed is required to remove any inerts found in the reactants. The third function of the reactant control system is to maintain reactant circulation in the fuel cell stack as power is being drawn. As power draw is increased or decreased, the reactant solenoids are opened and closed to maintain the desired flow rate of reactants in the fuel cell stack. The reactant flow allows for the removal of water produced by the fuel cell reaction in the fuel cell stack.

The Ejector Driven Reactant (EDR) Fuel Cell System

The EDR fuel cell system is shown as Figure 3. This system was developed for space applications and designed for operation in a zero-g environment [10-11]. It features an integrated balance of plant, which allows for the passive removal of fuel cell product water. Short fuel cell stacks have been subjected to a failure modes and effects analysis (FMEA) study including durability, freeze-thaw cycling, reactant regulation failure, and cooling failure. The fuel cell stack has met the success criteria for each failure mode to which it has been exposed. Short stacks have been exposed to durability studies (short-term, 2,000 hours) with one short stack being taken to failure. The short stack failed at greater than 14,000 hours.

![Figure 3: Teledyne ejector driven reactant fuel cell system.](image)

1.3 Concept of Operation (CONOP)

The TSS may enable several concept of operations (CONOPs) shown in Figure 4. One CONOP would be for the TSS to power a UUV recharge dock as well as a communication hub to support high-speed data transfer from the surface to a subsea vehicle. In this CONOP, a UUV would dock and transfer data through the dock to a surface communication buoy. In a second CONOP, the TSS would simply power a recharging dock without any surface expression. In this CONOP, a UUV would surface and signal for retrieval once data acquisition is complete. In each of the described CONOPS, the TSS-powered recharging dock could also serve as a long-term subsea positioning system to recalibrate a UUVs guidance system subsea. A third CONOP would be for a vehicle to be continually tethered to the TSS. This CONOP would be compatible with the resident ROV model being developed by the subsea commercial oil and gas market [12]. In the resident ROV model, an ROV is continuously tethered to a
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surface communication buoy and operated remotely. The objective of each of the described CONOPS is to minimize the ship time required for monitoring ocean assets. Minimizing ship time may result in significant reduction in cost for ocean operations [1].

Figure 4: Enabling large-scale untethered subsea power and communications.

1.4 Teledyne Subsea Supercharger Prototype
A validation prototype of the TSS (TSS prototype) was built and field-tested by TESI. The TSS prototype featured a 64-cell EDR fuel cell system that was capable of generating greater than 3.5 kW of power, supporting up to 75 A of discharge current. The EDR fuel cell system was hybridized with a 30 Ah nickel metal hydride (NiMH) battery for start-up and pulse-power operation. The TSS prototype also featured an in-house designed power management system, which delivered a constant 52.5 V dc with 100 A current capability. The power from the TSS prototype was taken dockside to a power inverter where it was converted from 52.5 V dc to 120 V ac. Loads were drawn through the power inverter during field-testing. The goal of the TSS prototype was to demonstrate a lithium-free rechargeable energy storage system that could feature greater energy than an equivalent lithium ion battery. The fuel cell system and hybridization/power conditioning electronics were both housed in individual Prevco pressure housings. The TSS prototype can be seen in Figure 5.
Figure 5: Subsea Supercharger prototype.

2.0 Results
2.1 Testing
A sample of the current-voltage performance testing of the TSS prototype is shown as Figure 6. In this test, the TSS prototype is discharged through resistive loads powered through a power inverter. At start-up, reactants are introduced into the fuel cell system and the system is pressurized to approximately 30 psig with balanced reactants. A shunt regulator is then activated to control the fuel cell stack voltage. The shunt regulator draws approximately 600 W from the fuel cell system to maintain the fuel cell stack voltage to approximately $55 \text{ V}_{dc}$. As power is drawn from the fuel cell system, the shunt regulator shunts less power. If the fuel cell stack voltage is below $53 \text{ V}_{dc}$, the shunt regulator will not draw any power. The TSS prototype delivers a fixed voltage of $52.5 \text{ V}_{dc}$ for loads up to 100 A, this is highlighted by the curve labeled “Conditioned Output Voltage (V)”. Once the shunt regulator is activated, the output relay of the TSS prototype can be closed and power can be drawn. The resistive loads were selected to simulate the power draw of a Teledyne Seabotix Little Benthic Crawler ROV (LBC ROV). The resistive loads consumed 1,480 and 2,350 W from the TSS prototype, which simulated the power from traversing as well as the activation of the LBC ROV hull inspection system. As the resistive loads consumed power, the fuel cell stack voltage dropped from 50 to $48 \text{ V}_{dc}$ for loads of 1,480, and 2,350 W, respectively. As the stack voltage was pulled below $55 \text{ V}_{dc}$, the TSS conditioned output voltage remained a constant $52.5 \text{ V}_{dc}$. 
2.2 Demonstration Scenarios
A TSS prototype has been field tested under three demonstration scenarios. The first demonstration scenario was a validation test of the TSS prototype for operation at 7m depth. The test facility featured a test tank and control room. Power from the TSS prototype was delivered topside and discharged through resistive heaters as previously described. In these tests, the TSS prototype was lowered into the test tank and then run through checkouts. The checkouts included a system reactant purge as well as status of the fuel cell system and hybridization/power conditioning module’s state-of-health. The fuel cell system and hybridization/power conditioning module states-of-health included hydrogen leak detection, water sensors (to detect a water breach), and temperature. The success criteria for the first test scenario included validating safety, handling, system integrity at depth, reactant purging, power output, and establishing the system could be controlled remotely. The prototype TSS met the success criteria for the first test scenario with operation for approximately 2 hours at depth. The prototype TSS operating in the test tank is shown in Figure 7. This field test was completed in preparation for demonstrating the TSS prototype at the 2018 Advanced Naval Technology Exercise (ANTX) held in Newport, Road Island.

In the second demonstration scenario, the TSS prototype powered a LBC ROV while it performed a ship husbandry simulation at ANTX. The ship husbandry simulation consisted of the resident ROV traversing a pier and inspecting a simulated ship hull. As in the first demonstration scenario, power from the TSS prototype was delivered dockside where it fed a power inverter that then fed power to the LBC ROV. In this demonstration scenario, the LBC ROV as well as all of its top-board control electronics were powered by the TSS prototype. The top-board control electronics were comprised of a manual navigation controller and requisite monitor for displaying video information transmitted from the LBC ROV. The data captured during a ship hull inspection is shown in Figure 8. During the initial traverse,
the LBC drew less than 600 W of power. The maximum power recorded during the LBC ROV operation was approximately 1,300 W while the hull inspection system was active. This power included charging of the battery in the hybridization/power conditioning module as well as the operation of other ancillaries during the traverse. The power required by the LBC ROV is approximately 1,000 W lower than anticipated.

In the third demonstration scenario, the TSS prototype was to produce power while being fed reactants from a solid-state reactant management system developed by General Atomics (GA). The solid-state reactant management system generated hydrogen based on the hydrolysis of aluminum and generated oxygen based on the hydrolysis of potassium superoxide [13-15]. Power generated from the TSS prototype was used by an ROV-based charge station (RCS). The function of the RCS is to capture a vehicle and recharge it. The advantage of an RCS versus a static charge dock is it can readily capture vehicles “in flight”. The RCS operates by locking on to a marker on a target vehicle. When a target vehicle is in range, the RCS will capture it. The RCS can enable the subsea recharging of various AUVs. To date, most recharging docks are developed for one specific vehicle. In addition, the RCS can use internal navigation and homing to capture a target vehicle. The target vehicle does not need to support dock-homing autonomy. In the demonstration scenario, the RCS as well as all of its top-board control electronics were powered by the TSS prototype while it was fed reactants from the GA solid-state reactant management system. The top-board control electronics included the RCS manual navigation controller and monitors. The monitors displayed video transmitted by the RCS during operation. For this demonstration scenario, the RCS captured a simulated target vehicle. No power was transferred once the simulated target vehicle was captured. The demonstration of the RCS being powered by the TSS prototype fed by a solid-state reactant management system is shown as Figure 9.

Figure 7: Subsea Supercharger prototype testing at 7m depth.
Figure 8: Subsea Supercharger test data while powering a Teledyne Seabotix LBC ROV during ship husbandry exercises.

Figure 9: Subsea Supercharger resident ROV demonstration.
2.3 Durability Testing
The TSS prototype is being subjected to short-term durability testing. The test is focused on the fuel cell system module. The goals of this test are to measure fuel cell system degradation as well as demonstrate environmental control in the fuel cell system module. Environmental control of the fuel cell system module is of great importance as reactants leaking from both the reactant feed plumbing and fuel cell system can accumulate in the pressure vessel; reactant leaks must be managed. The fuel cell system module incorporates a reactant leakage management subsystem that allows for operation without the accumulation of reactants. A plot of the durability testing is shown as Figure 9. The durability test show the TSS prototype operating through three different load profiles. The first load profile was constant power (not available), the TSS ran for approximately 60 hours at approximately 940 W. The second load profile was also at constant power, the TSS prototype supported a load of approximately 1,600 W for approximately 24 hours. The third load profile included cycling. The TSS would operate at a base load of 940 W and then under an increased load of 1,940 W for 30 minutes every 6 hours. The sharp vertical lines on the plot mark stop-start cycles during the durability testing. The TSS prototype was cycled through a stop-start activity so various components could be checked. The TSS prototype has been able to operate for durations greater than 1000 hours. During all operation, the fuel cell system has been sealed in the fuel cell system module. Fuel cell system module environmental control has been demonstrated. The fuel cell system has registered no measurable degradation during the durability testing to date. The TSS prototype is projected to operate for greater than 10,000 hours.

Figure 9: Subsea Supercharger short-term durability testing with current pulses of up to 40 A.
3.0 Discussion

3.1 Maturity

A TSS prototype has been field tested under three demonstration scenarios and is, at the time of this writing, operating under short-term durability testing. Each of the tests have been selected to demonstrate an increased level of maturity. The first demonstration scenario demonstrated the capability of the TSS prototype to operate in a submerged environment. The second demonstration scenario demonstrated dockside powering of a resident ROV. The last demonstration scenario required the TSS prototype to be shipped across the United States. The TSS prototype performed as expected in each of the demonstration scenarios, the last only requiring the system to be unpacked, fueled, and deployed for power delivery. The TSS is being manufactured to meet the American Petroleum Institute (API) 17 specifications [16]. Having successfully completed each demonstration scenario, we believe the TSS has reached a maturity of API TRL 3/4. The TSS concept has been demonstrated in a relevant environment and a second prototype is being developed for operation at depths greater than 1,000 m. A technology qualification program (TQP), per the API 17 standards, will be initiated in Q4 of 2019. A second-generation prototype of the TSS is shown as Figure 10. This system will be operated at 1000 m with a pathway for demonstration at 4,000 m. We anticipate the vast majority of the applications of the TSS will be in the range of 1,000 to 4,000 m. These depths encompass what is typical for deep-water commercial oil and gas platforms [17].

Figure 10: Second-generation Teledyne Subsea Supercharger prototype.

3.2 Fuel Cell-Based Energy Storage Systems

The value proposition for fuel cell systems for use in subsea applications include: safety, logistics, durability, temperature of operation, and cost. As reactants are not co-located with the fuel cell system, they are safer than other energy storage solutions such as batteries. When a fuel cell system statuses a safety fault, the reactants being fed to the fuel cell system can be physically stopped. With the fuel cell reactants physically stopped, any hazards that the reactants may present can be more easily mitigated. Logistically, fuel cell systems can be transported when un-fueled without the requirement for special safety regulations. As hydrogen and oxygen have established supply chains, fuel cell systems may be readily fueled prior to deployment. In addition, fuel cell systems do not have a shelf life. Their degradation is based on hours of operation and not date of manufacture [18]. As such, issues of degradation during storage are not found in fuel cell systems. Fuel cells generate heat as a byproduct...
during operation. This heat can be harnessed to allow fuel cell systems to readily operate at cold temperatures (-40 °C). These temperatures may cause the energy delivery capacity of batteries to drop by greater than 50 percent [19]. Lastly, fuel cell systems are price competitive to pressure-tolerant batteries used in subsea applications for energy storage requirements above 600 kWh. To increase the capacity in a fuel cell-based energy storage system, only an increase in reactant storage capacity is required. The cost of additional reactant storage to increase required capacity is sufficiently less than the cost of additional batteries. Thus, fuel cell systems present an excellent solution to addressing energy storage system capital cost for deep-sea applications.

4.0 Conclusions
Teledyne Energy Systems, Incorporated (TESI), have developed a fuel cell-based large-scale energy storage system. The target applications for the energy storage system are focused on the commercial oil and gas arena, specifically in the operation of resident ROVs, mapping UUVs, and supporting the development of all-electric subsea oilfields. TESI has fielded a Subsea Supercharger prototype, TSS prototype. The TSS prototype has matured through concept development, concept demonstration and is currently at a TRL 3/4, prototype development, as defined by the API maturation assessment. The TSS will complete a technology qualification program (TQP), per the API 17 standards, to achieve a higher maturity. To date, the TSS prototype has demonstrated that it is sufficiently mature for shipping across the United States and then being deployed without the requirement of extensive preparation. The TSS prototype has demonstrated the capability to be fueled and deployed, both in a test pool and dockside ocean. The TSS is also being durability tested; no degradation is noted after more than 1,000 hours of operation. Through durability testing, the TSS prototype has also demonstrated complete control of the environment of the fuel cell system module. Environmental control of the fuel cell system module is a requirement for prolonged operation either in a contained or in subsea environments. TESI is committed to continuing the development of its fuel cell technologies. We expect to complete a TQP to meet API 17 standards and allow a commercial oil and gas operator to field the unit in a subsea oilfield by Q4 2020. We anticipate the first applications of this technology would be to enhance the operating time of resident ROVs followed by extending the operating time of UUVs.

5.0 Acknowledgments
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6.0 References
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