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RENEWABLE ENERGY

3 Underwater Vehicle Charging

Powering the Blue Economy: Exploring Opportunities for Marine Renewable Energy in Maritime Markets

April 2019

3. Underwater Vehicle Charging: Autonomous Underwater Vehicles, Unmanned Underwater Vehicles, and Remotely Operated Vehicles

Key Findings

- Autonomous underwater vehicles (AUVs) and unmanned underwater vehicles (UUVs) are vehicles that perform underwater tasks without a tether or line to a surface ship, carrying instruments and sensors to monitor or inspect underwater environments.
- Although AUVs are a cheaper alternative to traditional vessels, power capacity of the vehicle's battery remains a limiting factor and keeps their missions limited in range and duration, often as little as 24 hours.
- Docking and recharge stations can extend the mission duration of underwater vehicles by recharging their batteries at sea, as well as providing a secure platform to dock vehicles between missions. Underwater docking stations are under development and not yet available commercially as they lack a practical power generation source.
- Powering underwater docking stations and recharging AUVs with marine energy could provide a locally generated reliable power source, smoothed for intermittency by battery backup. Underwater recharging of AUVs would reduce the need to recall vehicles to the surface as frequently; save time and resources; improve human safety on ships at sea; increase mission duration, range, and stealth; and reduce carbon emissions.

Opportunity Summary

AUVs and UUVs are used for observation, surveillance, persistent monitoring, ocean observation, and inspections of subsea infrastructure. These vehicles can also be equipped with ocean sensors to provide ocean observations and measurements. Currently, these vehicles are limited in their range and duration by the capacity of their batteries. Depending on the vehicle sensor payload, they may also have limited data storage space. These operation constraints mean that unmanned underwater vehicles require frequent recovery for recharge and data offload, which generally requires the assistance of a support vessel and crew.

Underwater charging and data offloading for AUVs and UUVs could reduce the reliance on expensive surface vessels and extend mission duration. Marine-energy-powered recharge stations could harvest power continuously as the resource allows, and—when paired with battery banks—allow reliable, on-demand recharging of vehicles. Underwater recharge stations could also be used as intermediate data repositories, effectively increasing data storage capabilities. The global AUV/UUV market is presently valued at $2.6 billion and is expected to double by 2022 (Research and Markets 2017), with customers in the defense, oil and gas, and research industries.

Application

Description of Application

AUVs or UUVs (hereafter called "AUVs") include a range of shapes and sizes, such as torpedoes, small submersibles, and less-hydrodynamic cubes. These vehicles are used in the civilian sector for ocean observations, underwater inspections, monitoring of the seabed and underwater structures, and scientific studies. In the military and security sector, they are used for surveillance, underwater monitoring, mine detection and countermeasures, payload delivery, barrier patrol, and inspection and identification of vessels and structures.

AUVs perform maritime tasks that once took a fleet of ships months to complete, as they can collect data faster and stay at sea longer than traditional vessels (Unmanned Systems Technology 2018). However, power remains a limiting factor, as missions are limited by battery capacity and typically last less than 24 hours. After the battery is spent, the system must be recovered by a vessel for recharging. Most AUVs use onboard stored electric energy for propulsion, powering sensors, and acquiring data. The energy storage system capacity varies with system type, but typically no more than 40% of the interior of AUVs is devoted to the energy storage system. Deployment and recovery efforts for recharging AUVs are time sensitive and often limited by weather conditions, which pose a serious hazard to both the crew and the vehicle (Ewachiw 2014). Marine energy could provide an off-vehicle autonomous power source (i.e., at-sea recharging) for AUV recharging that would reduce the need to recover the vehicle as frequently, as well as reduce the detectability of operations at sea for security and military purposes (Figure 3.1). At-sea recharging could also shorten the distance requirement for the energy storage system, thereby enabling more, smaller, and cheaper AUVs.

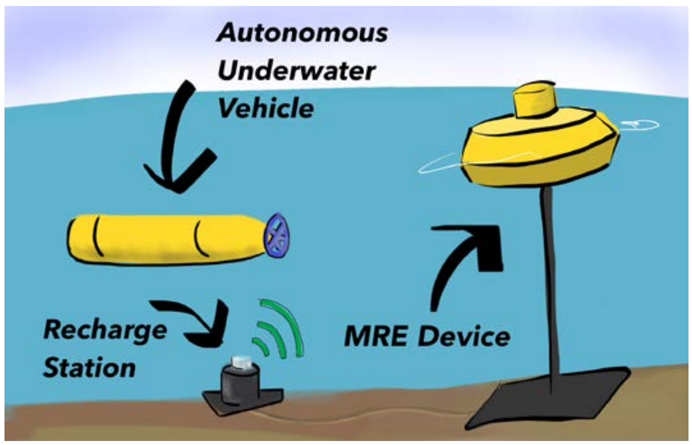

Figure 3.1. Marine energy application overview for underwater recharge of vehicles. *Image courtesy of Molly Grear, Pacific Northwest National Laboratory*

The opportunity to recharge AUVs underwater and to offload payload or data, as well as provide data storage on the recharge station, depends on the availability of robust and efficient recharge technologies. Several such technologies are under development through the U.S. military and its industrial partners, including physical docking stations (Figure 3.2) that use wireless induction charging or plugged-in connections (Shepard News 2015; Townsend and Shenoi 2013). Opportunities for vehicle recharge include, but are not limited to (B. Polagye, personal communication, 2017):

- Locations that do not already have sources of power/communications. Temporary installations may be useful to meet environmental monitoring requirements in areas where industry exploitation may have an impact on the seabed or water quality.
- Long-duration survey operations in which mobile marine energy systems move with AUVs as they conduct mapping or search operations. Such a system would be more cost effective than deploying AUVs with manned vessels and have the potential to cover more area in a shorter period of time than if the vehicle is recovered, recharged, and redeployed every time the batteries are exhausted.
- Permanent installments for a particular purpose (e.g., aquaculture fisheries) that need maintenance, inspection, or monitoring over a long duration from AUVs and do not have access to grid power for vehicle recharge.

Autonomous Underwater Vehicles/Unmanned Underwater Vehicles

AUVs are self-guided, self-powered vehicles that are attractive options for maritime operations because they can reach shallower water than ships and deeper waters than human divers or tethered vehicles. AUVs can operate in intertidal waters, and some can dive up to 6,000 meters (m) deep (National Oceanic and Atmospheric Administration [NOAA] 2017a). Unmanned surface vehicles may be used to launch and recover AUVs and synchronize mission operations (Figure 3.3). Fully autonomous operations have onboard electrical sources to power propellers or thrusters to move the vehicle through the water. Power is also used to operate sensors on the instrument. Most AUVs use specialized batteries, yet some use fuel cells or rechargeable storage with solar power. AUV batteries require recharging, but some sensors can run for months at a time before a recharge is needed (NOAA 2017a). The total energy capacity of a smaller AUV may only be a few kilowatt-hours (kWh); the larger 21-inch-diameter AUVs may have battery packs with capacities on the order of 10 kWh or more (Dhanak and Xiros 2016).

Figure 3.2. Underwater Remus docking station. *Photo courtesy of Woods Hole Oceanographic Institution (WHOI)*

The duration of most AUV missions is typically 24 hours and is related to power consumption of onboard sonar and sensor systems. However, AUV missions have been extended in recent years; power management of systems has helped to extend these ranges. For example, the Monterey Bay Aquarium Research Institute (MBARI) operates a long-range AUV called Tethys that can cover ranges of 1,000 kilometers or more, and can have a mission duration of weeks at a time without returning to the surface (MBARI 2018; A. Hamilton, personal communication, 2017).

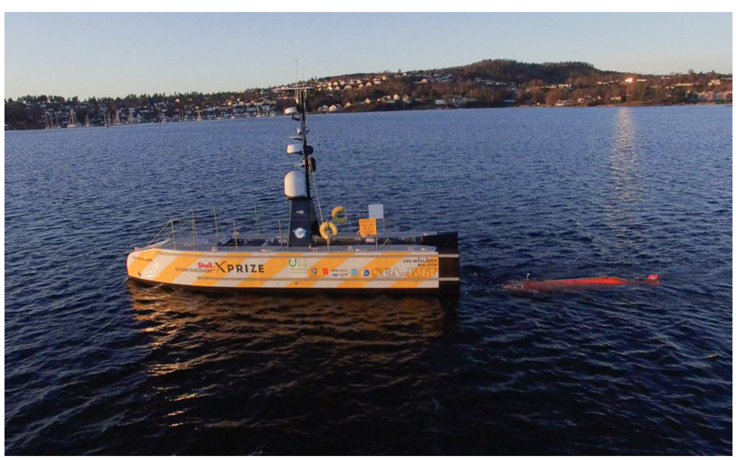

Figure 3.3. USV SEA-KIT, designed by Hushcraft LTd to act as a surface support vessel for the AUV, including the capacity to launch and recover the AUV and to provide subsea communications and positioning.

Source: ©Lew Abramson/lewabramson.com

Appendix A of Button et al. (2009) provides an overview of the AUV market, including an inventory of AUVs that demonstrate critical AUV capabilities (e.g., endurance) or attributes (e.g., maturity). As such, this appendix identifies four general classes of AUVs:

- **Small AUVs**. AUVs between 3 and 10 inches (in.) in diameter. They can be man-portable and capable of deployment from a variety of platforms or even larger AUVs. Submarine deployment is possible. Endurance is typically from 10 to 25 hours, though emerging battery technology will increase this.
- **Medium AUVs**. AUVs between 10 and 21 in. in diameter. Medium AUVs can also be shore-, submarine-, or ship-launched and recovered with handling equipment. Payload volume can be 6 to 12 times larger than the small AUV class. Their endurance is typically double that of the small AUV, but can be even greater for the larger, medium-class AUVs.
- **Large AUVs**. AUVs between 21 and 84 in. in diameter. These AUVs will require appropriate handling equipment to support stowage, launch, and recovery on any seaborne hoist platform. Large AUVs can also be shore- or ship-launched with special handling equipment.
- **Extra-large AUVs**. AUVs with diameters larger than 84 in. Shore- or ship-launched with sufficient handling facilities, such as cranes and well decks. These AUVs likely have a hybrid energy system (diesel and battery) with an endurance measured in weeks.

Gliders

Gliders are AUVs that use buoyancy propulsion to travel through the ocean to gather data on physical, bio-optical, and chemical properties (e.g., temperature, salinity, chlorophyll, or dissolved oxygen). Glider missions may last up to 3 months and cover distances up to 1,800 kilometers (Figure 3.4). However, new commercial gliders are available that can travel 10,000 kilometers (up to a 6,000 m depth), extending their endurance to more than a year of deployment time (J. Sobin, personal communication). The U.S. Navy makes extensive use of gliders as well (Naval Oceanographic Office 2017). While traveling, gliders relay their data to shore via satellite telemetry (Woods Hole Oceanographic Institution 2017). Although some gliders are self-propelled (Liquid Robotics 2018), others operate on stored energy in battery packs, providing opportunities to extend observation campaigns with recharge at sea by marine energy devices operating at sea (NOAA 2017c).

Figure 3.4. Teledyne Webb Research's Slocum glider. *Image courtesy of WHOI*

Remotely Operated Vehicles

Remotely operated vehicles (ROVs) (Figure 3.5) are connected to surface ships by cables or tethers and are remotely controlled by an operator on the surface vessel. Most ROVs are equipped with a still camera, video camera, and lights, but may also be equipped with a manipulator or cutting arm, water samplers, and other sampling instrumentation. ROVs are used for industrial purposes, such as internal and external inspections of underwater pipelines and the structural testing of offshore platforms, and are used for scientific purposes, such as ocean exploration (NOAA 2017b). Recent technological advances have included the development of hybrid ROVs (MODUS 2018) that can be used in traditional tethered mode or disconnected to operate autonomously, like AUVs. By disconnecting from the tether, underwater inspection and monitoring ROVs can work in close quarters with cables and other industrial elements that might entangle a tether. These untethered (or hybrid) ROVs have potential for utilizing underwater recharge, although they are unlikely to become a substantial market.

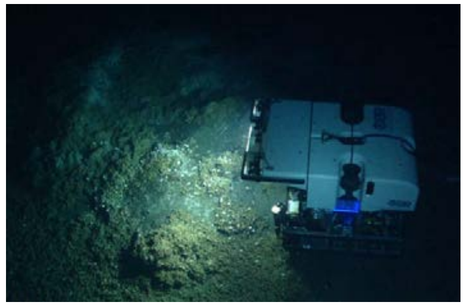

Figure 3.5. NOAA's Deep Discoverer remotely operated vehicle explores during a 2013 expedition to investigate the U.S. Atlantic canyons. *Photo courtesy of NOAA*

Docking Stations

Docking stations for AUVs can be used to extend the mission duration of underwater vehicles by recharging their batteries while at sea. Docking stations provide a secure platform to park vehicles between missions and usually provide power to recharge batteries. Additionally, docking stations may provide for some onboard data storage, as well as provide a gateway for communications to shore (MBARI 2017) and improve launch and recovery operations.

Docking stations include sensors that allow the AUV to home on the dock, mechanisms to mechanically connect the vehicle and the dock, and software that controls the overall process. Some docking stations include one or more communication links between the vehicle and the dock, in addition to power transfer systems that power and recharge the vehicle (Dhanak and Xiros 2016).

As described in Dhanak and Xiros (2016), docking systems can be designed to rest on the seafloor and be connected to a cabled observatory. The system shown in Figure 3.6 includes a flared capture cone, which increases the capture aperture of the dock, and a cylindrical housing section, which encloses the docked AUV. A pin containing an inductive coil is inserted into the vehicle, enabling inductive power transfer. An 802.11 link supports short-range communication through seawater. The entire cone assembly is mounted on a gimbal and counterweighted so that the dock will self-level on deployment. While the co-location of sensors and other technologies could potentially be a development barrier, this could also be an opportunity to co-develop more integrated and efficient devices and systems.

Underwater docking stations have not yet made the transition from demonstration to commercial operations (Dhanak and Xiros 2016), as designs are still undergoing research and development. Factors that have affected the adoption of underwater docking stations include significant investments in infrastructure (moorings with satellite communications and large quantities of batteries), AUV reliability and inherent docking risk, and the comparatively high cost of scientifically equipped AUVs. Additional examples of docking stations are shown in Figure 3.7 and Figure 3.8.

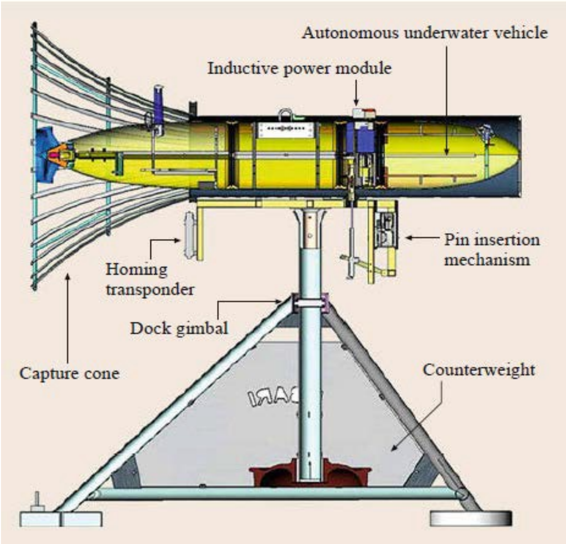

Figure 3.6. Model of a docking station with an AUV captured within the dock. *Image courtesy of Dhanak and Xiros (2016), SolidWorks drawing by Jon Erikson, MBARI*

Figure 3.7. Recovering a docking system for an autonomous underwater vehicle after a test deployment in Monterey Bay. *Photo by Brett Hobson ©2006 MBARI*

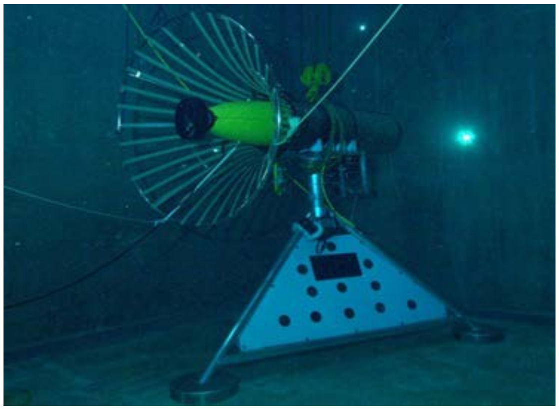

Figure 3.8. A docking system for an autonomous underwater vehicle being tank tested by the Monterey Bay Aquarium Research Institute. *Photo by Brett Hobson ©2006 MBARI*

Power Requirements

It is expected that all AUVs, UUVs, and hybrid ROVs will have similar power requirements. Energy requirements depend on mission requirements and the number of vehicles to service and are estimated to be between 66 kWh and 2.2 megawatt-hours per recharge station. Gish and Hughes (2017) cite that 200–500 watts of power is required for normal charging, yet faster charging is possible with increased power, which may be more desirable for some applications. A typical AUV recharge takes approximately4–8 hours (Gish and Hughes 2017).

Ideally, the power source should be able to operate over a wide depth range that is estimated to be between 50 and 1,000 m. The constant harvest of marine energy, coupled with battery backup, would allow for recharging on demand. Energy storage may be required, as the supply/availability of energy may not always match the immediate demand for power.

A variety of systems and subsystems could use marine energy, including electricity, as shown in Figure 3.9.

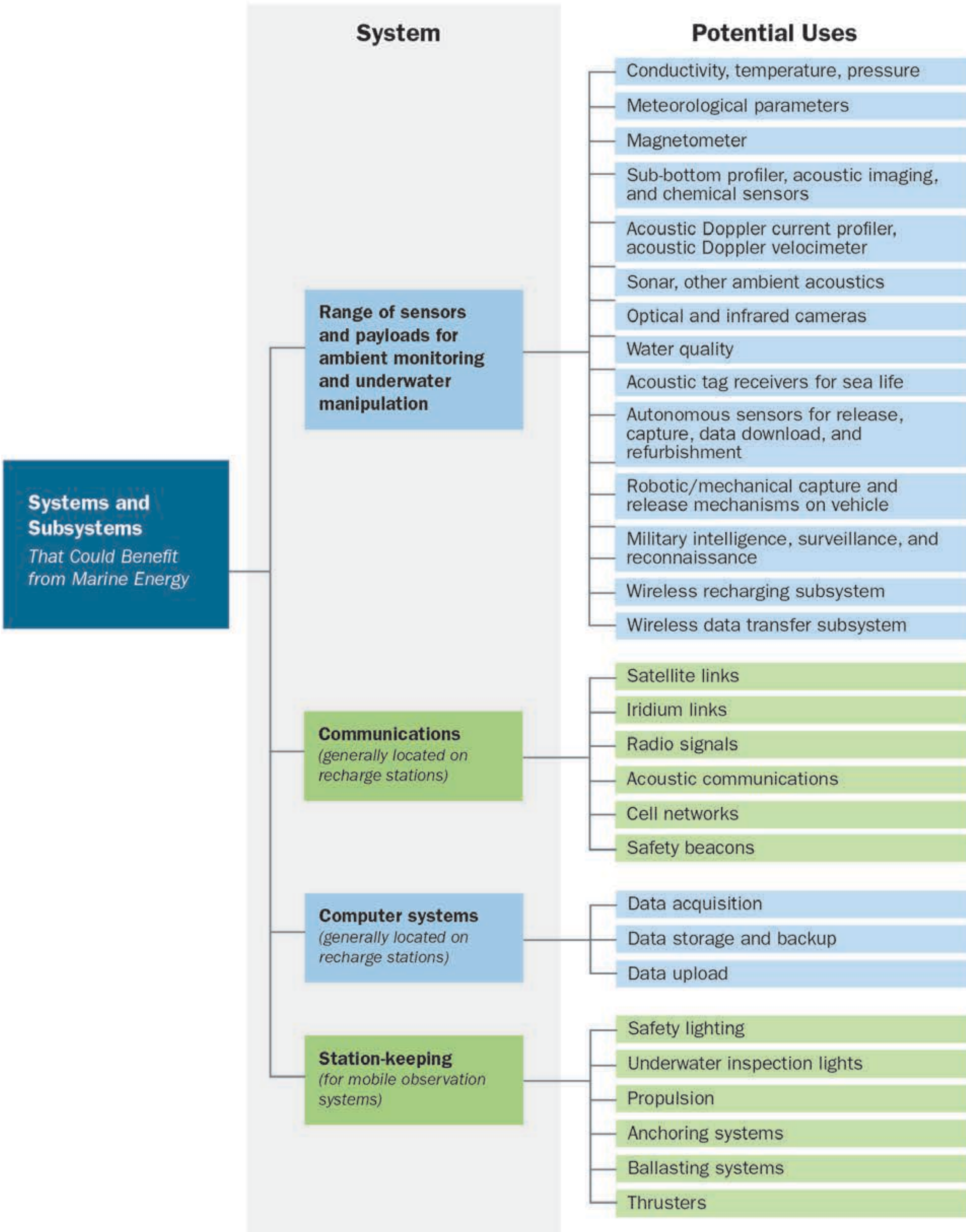

Figure 3.9. Vehicle systems and subsystems that could benefit from marine energy power

In addition, there will be uses for compressed air for active ballasting of recharge systems, which could be generated using mechanical energy from marine energy devices.

Markets

Description of Markets

Globally, the AUV market is estimated at $2.6 billion and it is expected to double by 2022 (Research and Markets 2017). The market for recharging AUVs underwater, which includes the charging stations and associated infrastructure, is not developed and has an unknown valuation, but is expected to have a growth rate similar to the greater AUV market, just on a smaller scale, as the market growth is tied to the AUV market. Small stand-alone underwater recharge stations using undersea currents can produce power of approximately 1,500 watts for local AUV recharging (Ryan Frommelt, personal communication, October 2018).

The AUV market has been growing over the past several years as a result of the increasing demand for commercial, military, and scientific research applications. New investments in the market have been driven largely by the defense industry (Research and Markets 2017). The range of applications is broad and includes intelligence, surveillance, and reconnaissance; antisubmarine warfare; inspection and identification; communications; navigation network nodes; payload delivery; barrier patrol for homeland defense and force protection; and seabase support. The tactical and potential cost advantages of deploying swarms of AUVs that can cover regions of ocean area are huge relative to comparable services offered by a single ship trying to cover the same area.

The AUV market is closely coupled with the oil and gas industry and displays similar trends (Markets and Markets 2017). The demand from underwater exploration outfits will likely drive the need for more AUVs and charging capabilities, in addition to increased depth, endurance, vehicle maneuverability, and real- or near-real-time communications.

The key end users of the AUV market are the commercial sector (e.g., surveying and seabed mapping, offshore drilling, and pipeline inspections), followed by the defense and homeland security sectors (Markets and Markets 2017) and arctic exploration, as well as scientific uses.

As discussed in Shukla and Karki (2016), the oil and gas industry is making automation a priority because of quickly emerging challenges facing the industry, such as a lower recovery rate, exploration of unconventional reserves, operation in extreme environmental conditions, and profitability of the overall business model. As such, the industry will be relying on robotic solutions (including ROVs) for underwater inspections, welding and manipulation, remote sensing, and oil spill prevention.

Additionally, AUVs and ROVs are used in aquaculture operations for underwater object retrieval, monitoring, and net inspection (The Fish Site 2016). Offshore energy operations also use ROVs to aid in the installation, maintenance, and expansion of energy production (AquaBotix 2017), and ROVs are used for surveillance and inspection of port facilities (Gutierrez et al. 2010). In addition, AUVs are heavily used for marine research applications by academia (e.g., WHOI), the federal government (e.g., NOAA), and the military.

The U.S. Department of Defense has identified nine mission categories for AUVs, including intelligence, surveillance, and reconnaissance; mine countermeasures; antisubmarine warfare; inspection/identification; oceanography; communications/navigation network node; payload delivery; information operations; and time-critical strike (Button et al. 2009). In 2016, the U.S. Department of Defense announced that they would be investing $600 million in AUVs over the next 5 years (Pomerleau 2016). Additionally, the United States Department of Homeland Security Science and Technology Directorate is interested in AUV research and has been supporting funding the development of an AUV called the BIOSwimmer that is designed to resemble a tuna and will be used for inspection work in oily or dangerous environments.

Scientific uses of AUVs include a variety of monitoring and exploration uses, generally using commercially available or purpose-built devices in cooperation with companies that also supply the military and industrial oil and gas markets.

Power Options

There are few viable options for powering an underwater vehicle recharge station other than marine energy (see Figure 3.10). Hydrogen-oxygen fuel cells are emerging as a viable underwater vehicle recharge station power source, but require a consistent and reliable supply of hydrogen for fuel. Diesel generator sets must be surface-based and would require frequent refueling and maintenance, leading to poor stealth characteristics, high costs, and risk of spills. Other renewables, such as solar and wind, are less suitable replacements, as AUV charging will likely take place underwater, requiring extensive cabling from any surface power source and reducing stealth as a result of the surface expression. Solar and wind applications must be mounted at the surface. Placing solar photovoltaic panels close to the ocean surface will require frequent cleaning of the panels from salt spray and bird droppings. Wind turbines would have to be surface-based on a platform or bottom-mounted on foundations, making them depth-limited for underwater recharge applications.

Geographic Relevance

The evolving need for energy for underwater charging is worldwide, in all bodies of water. Differing energy demands could make the energy in ocean currents, tidal currents, and waves both near to shore and in the open oceans relevant, providing no geographic constraints.

Tidal resources are most common in inland waters and in shallow constrictions where there is less need for long-duration AUV monitoring. Ocean currents, especially fast-flowing western boundary currents, can approach speeds of 3–4 knots in some areas and could be harnessed for underwater vehicle recharging. However, operating these vehicles in fast-flowing ocean currents may increase operational complexity. Although operating vehicles in fast-moving currents may be problematic, the temporal and spatial (horizontal and depth) variations in their intensity and direction may be used for opportunistic propulsion and may present opportunities for vehicle recharging (B. Polagye, personal communication, 2017). Most tidal and ocean current devices are submerged and may be more useful for stealth or military missions where a surface expression is not preferred.

Marine Energy Potential Value Proposition

AUVs are duration-limited, typically capable of lasting 24 hours before having to surface to offload data via satellite or be recharged by a surface vessel. By surfacing, the AUV is spending time off mission and compromising its stealth. The support vessels that must recover these vehicles are very expensive, charging $30,000 or more per day. Other nonmonetary risks from vessels at sea include additional danger to vessel crews, increased emissions, and the potential for petroleum spills.

If AUVs could be recharged and offload data underwater without surfacing, a sizable portion of the operating costs for a typical mission—estimated at hundreds of thousands of dollars—would be eliminated.

The ability to recharge vehicles underwater will lead to cost savings and safety improvements for deployment and retrieval and will increase the amount of time that a deployed vehicle can spend on the mission by eliminating the need to surface, transit, and redeploy from a mother ship (Button et al. 2009).

Underwater recharge stations are currently under development. These stations are presently relying on battery banks for power. Powering these stations with marine energy would provide a reliable, locally generated power source, smoothed for intermittency by battery backup. Underwater recharging would reduce the need to recall vehicles to the surface as frequently; save time and resources; improve human safety; increase mission duration, range, and stealth; and reduce carbon emissions. Hybrid ROVs—which can be disconnected from the umbilical cable—could also benefit from marine energy.

Gish and Hughes (2017) presented a hypothetical cost-savings scenario for the development of an underwater docking station for small commercial AUVs.

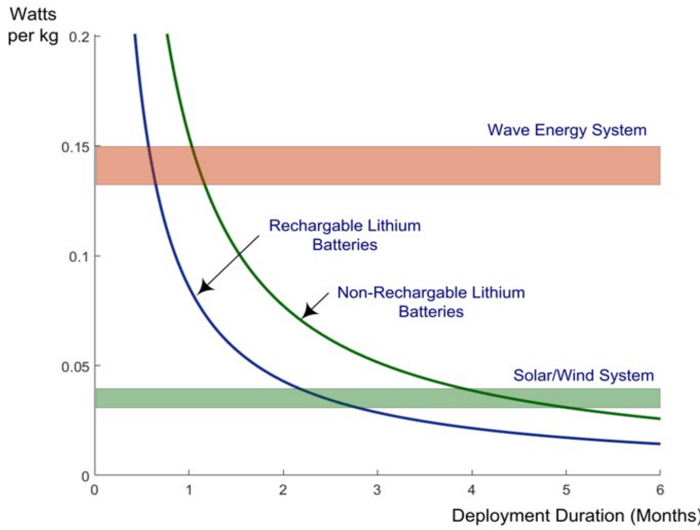

Figure 3.10. Energy requirements for deployment duration. *Image courtesy of Hamilton (2017)*

Opportunities for underwater recharging occur throughout the coastal area and open oceans where there is a need to survey or monitor using AUVs for extended periods of time (i.e., more than 1 month) (Figure 3.11 and Figure 3.12) and where sufficient wave or tidal resources are available. AUV operators typically prefer environments with minimal ocean currents when possible as it is easier for the vehicle to navigate and make headway.

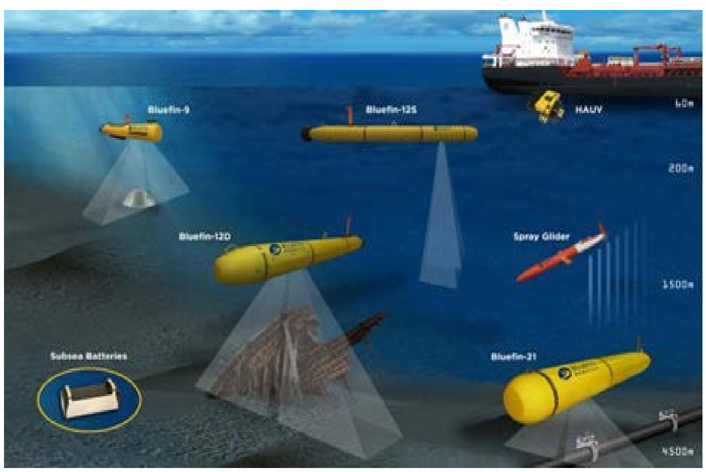

Figure 3.11. Opportunities for underwater recharging in all oceans, at all depths, for a variety of AUVs.
Image courtesy of Bluefin Robotics

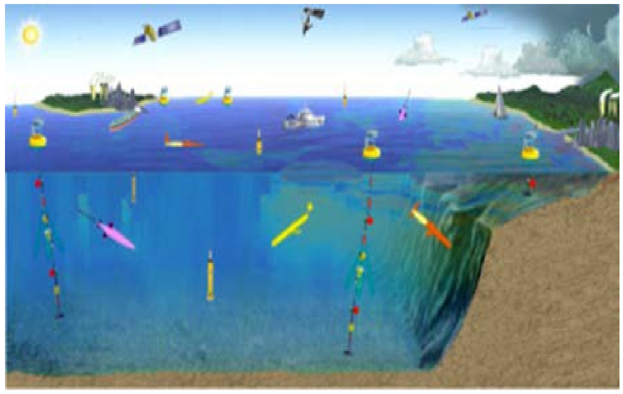

Figure 3.12. Underwater gliders and profiling arrays, representing a variety of AUVs, deployed in different areas of the ocean from shallow waters near land to the deep sea. *Image courtesy of ACSA, SeaExplorer, Creative Commons*

AUVs deployed for extended mission durations (e.g., more than 1 month) and/or those that consume a significant amount of power as a result of onboard instruments (e.g., sonar, sensors) may benefit from underwater recharging opportunities that can be powered using wave energy systems (A. Hamilton, personal communication, 2017); Hamilton (2017) estimates that wave energy systems provide a persistent form of energy that will be useful over AUV instrument deployment cycles. The power provided from wave energy systems is more persistent than that provided by battery power alone and is higher than the solar/wind system, as shown in Figure 3.10, for a recharge station built into an observation buoy. However, battery storage may be appropriate for shorter AUV deployment durations when recharging is unnecessary.

An emerging potential market within the U.S. Department of Defense sector (U.S. Navy and U.S. Air Force) supporting the swarm approach over traditional operations at sea is unmanned aerial vehicles or drones in ocean areas. The unmanned aerial vehicles will need recharging, and the ability to recharge stealthily at sea, rather than returning to a land-based recharging station, thereby enhancing mission success, range, and cost.

Path Forward

Projects will initially be small and bespoke for specific AUVs. Defense contractors and laboratories are and will continue to be early adopters of underwater marine-energy-powered recharge devices. Small-scale wave energy converters and underwater turbines can meet early-development needs for underwater recharging and there is significant opportunity for the two markets (AUV recharge and marine energy) to co-develop. Permitting marine energyuse for underwater recharging will have similar time frames and cost estimates as other small, off-grid marine energy developments. Security and military uses may allow for fasterpermitting.

Research and development in this area should concentrate on the mechanical and electrical coupling of marine energy devices to the recharge stations and the integration with data transfer capabilities. Specific adaptations to existing marine energy designs (wave energy converters in particular) should be developed to eliminate surface expression and optimize for underwater power generation. Efficient low-speed (under one knot) underwater turbines need to demonstrate high reliability and efficiency. Marine energy devices have little deployment experience in deep water; thus, systems need to be reliably demonstrated in these locations with minimal deployment preparation. A potentially large niche within the recharge station arena is a low-visibility, low-surface-expression device that could recharge unmanned aerial vehicles at sea rather than returning to land-based recharge stations.

Efficient underwater charging stations need to be reliably demonstrated. Gish and Hughes (2017) highlight several challenges associated with underwater docking stations for AUV recharging including reliability and robustness, marine fouling, corrosion, wave and current forces, and deployment and recovery. These are all areas that will benefit from additional research to help advance the market. Standardization of recharge stations to accommodate a variety of AUVs will increase adoption and drive down costs. Hamilton (2017) also highlights the need for numerical models for station-keeping system dynamics.

Oceanographic research institutions must continue research and development related to technology and vehicle development, instrumentation development, vehicle and platform reliability, and wave/current energy capture. The University of North Carolina's Coastal Studies Institute has been studying the Gulf Stream to harvest its energy using a submerged turbine. The turbine would be attached to an AUV with the ability to move the turbine to the location of the best resource (Coastal Review Online 2017). Potential market synergies exist between the application of marine energy for underwater vehicle recharging and marine energy's application for ocean observation, navigation markers, growing algae at sea, and aquaculture.

Other synergies exist between marine energy and undersea power generation devices. For example, L3 Open Water Power has developed an aluminum-water platform technology for undersea power generation that provides energy storage with extremely high energy density. The aluminum-water chemistry has been shown to be inherently safer and more stable than many other battery and fuel cell chemistries typically found in maritime use. The device promises a significant improvement in the endurance of AUVs and sensors (L3 2017). Additionally, Teledyne Energy Systems is presently developing the Sea Floor Power Node for deep-water AUV recharging applications using fuel cell power with refillable reactants (Utz et al. 2018). Teledyne is interested in extending this product to include a regenerative capability to reduce the reactant storage volume (M. Miller, personal communication, 2017). Integrating these and similar energy power and storage solutions with marine energy could improve mission operations and durations and allow for the incorporation of more power-demanding instruments.

Potential Partners

For the development of underwater vehicle recharging, potential U.S. mission-driven partners for the marine energy industry include government, academia, and industry. Within the U.S. government, potential partners include the U.S. Department of Defense (U.S. Navy, Defense Advanced Research Projects Agency), Department of Homeland Security, and government-funded ocean observatories, such as the U.S. Integrated Ocean Observing System and regional Ocean Observing Systems.

In academia, potential partners include oceanographic research universities, such as University-National Oceanographic Laboratory System, University of California San Diego's Scripps Institute of Oceanography, Woods Hole Oceanographic Institution, the University of Washington, University of North Carolina, North Carolina State University, and other research institutes, such as MBARI. Oceanographic institutions in other nations are similarly involved with the Global Ocean Observing System and are likely to have interests in underwater recharging of autonomous vehicles as well.

Industry partners could include subsea and observation original equipment manufacturers, defense contractors, oil and gas inspection contractors, pipeline and subsea cable inspection service providers, ocean observation sensor and equipment companies, and navigation and buoy manufacturers.

A number of U.S. and international companies have been identified as interested in the AUV recharge market including Teledyne Technologies (United States), Subsea 7 (United Kingdom), Kongsberg Maritime (Norway), Saab (Sweden), and Oceaneering International Inc. (United States). Other potential vendors include Searobotics, Boeing, Honeywell, Bluefin Robotics, and wireless charging companies, such as Wibotic and AeroJet Rocketdyne.

References

Button, Robert W., John Kamp, Thomas B. Burtin, and James Dryden. 2009. *A Survey of Missions for Unmanned Undersea Vehicles*. RAND National Defense Research Institute. https://www.rand.org/content/dam/rand/pubs/monographs/2009/RAND_MG808.pdf.

Coastal Review Online. 2017. "Project Looks to Tap Gulf's Stream's Energy." Accessed August 30, 2018. https://www.coastalreview.org/2017/05/project-looks-tap-gulf-streams-energy/.

Dhanak, Manhar R., and Xiros, Nikolas I. (Eds.). 2016. *Springer Handbook of Ocean Engineering*. Springer. http://www.springer.com/us/book/9783319166483.

Ewachiw, Mark A., Jr. 2014. "Design of an Autonomous Underwater Vehicle (AUV) Charging System for Underway, Underwater Recharging." *MS Thesis*. Massachusetts Institute of Technology. Cambridge, MA. pp 86. https://calhoun.nps.edu/handle/10945/43069.

Gish, L.A. and Hughes, H. 2017. Presentation: Underwater Recharging for Small Commercial AUVs. DOE Marine Energy Technologies Forum. December 6, 2017.

Gutierrez, Luis B., Carlos A. Zuluaga, Juan A. Ramirez, Rafael E. Vasquez, Diego A. Florez, Elkin A. Taborda, and Raul A. Valencia. 2010. "Development of an Underwater Remotely Operated Vehicle (ROV) for Surveillance and Inspection of Port Facilities." *ASME 2010 International Mechanical Engineering Congress and Exposition*, pp. 631–640. American Society of Mechanical Engineers. http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1617008.

Hamilton, Andy. 2017. "Wave-Energy Conversion for Oceanographic Applications." Presentation at DOE Marine Energy Technologies Forum. December 5–7, 2017.

Huner, J.V. 1985. *Crustacean and Mollusk Aquaculture in the United States*. Springer, New York. 476 pp.

Liquid Robotics. 2018. Energy Harvesting Ocean Robot. https://www.liquid-robotics.com/platform/how-it-works/

L3. 2017. "Open Water Power." http://openwaterpower.com/.

Markets and Markets. 2017. *Unmanned Underwater Vehicles (UUV) Market worth 5.20 Billion USD by 2022*. https://www.marketsandmarkets.com/PressReleases/unmanned-underwater-vehicles.asp.

Monterey Bay Aquarium Research Institute (MBARI). 2017. *Autonomous Underwater Vehicle Docking*. https://www.mbari.org/autonomous-underwater-vehicle-docking/.

MBARI. 2018. "Long-range autonomous underwater vehicle *Tethys*." Accessed August 30, 2018. https://www.mbari.org/at-sea/vehicles/autonomous-underwater-vehicles/long-range-auv-tethys/.

MODUS. 2018. MODUS Seabed Intervention. http://modus-ltd.com/.

National Oceanic and Atmospheric Administration (NOAA). 2017a. "The Tropical Atmosphere Ocean (TAO) Array: Gathering Data to Predict El Niño." https://celebrating200years.noaa.gov/datasets/tropical/welcome.html.

NOAA. 2017b. "Tsunami Messages for the Pacific Ocean (Past 30 days)." http://ptwc.weather.gov/?region=1.

NOAA. 2017c. "What is an Ocean Glider?" https://oceanservice.noaa.gov/facts/ocean-gliders.html.

Naval Oceanographic Office. 2017. Spring WG/CSAB Update. https://www.ofcm.gov/groups/CSAB/Meetings/2017/2017-03/05-NAVO%20Overview%20Brief%20to%20CSAB%20LAR%20input%20Mar17%20v2.pdf.

Pomerleau, Mark. 2016. "DOD plans to invest $600M in unmanned underwater vehicles." *Defense Systems.* https://defensesystems.com/articles/2016/02/04/dod-navy-uuv-investments.aspx.

Research and Markets. 2017. *Global $2.65 Billion Unmanned Underwater Vehicles Market 2017-2021*. https://globenewswire.com/news-release/2017/03/10/934263/0/en/Global-2-65-Billion-Unmanned-Underwater-Vehicles-Market-2017-2021.html.

Shepard News. 2015. "US works on underwater UUV recharging." https://www.shephardmedia.com/news/uv-online/us-works-underwater-uuv-recharging/.

Shukla, Amit, and Hamad Karki. 2016. "Application of robotics in offshore oil and gas industry—A review Part II." *Robotics and Autonomous Systems*. Vol. 75, Part B, 508–524. https://doi.org/10.1016/j.robot.2015.09.013.

The Fish Site. 2016. *Underwater ROVs Making a Splash in Aquaculture*. https://thefishsite.com/articles/underwater-rovs-making-a-splash-in-aquaculture.

Townsend, Nicholas, and Ajit Shenoi. 2013. "Recharging autonomous underwater vehicles from ambient wave induced motions." *Oceans*. San Diego, CA. September 23–27, 2013.

Unmanned Systems Technology. 2018. Combined USV and AUV System Maps Ocean Floor. Accessed 8/30/2018. http://www.unmannedsystemstechnology.com/2018/01/combined-usv-auv-system-maps-ocean-floor/.

Utz, R., R. Wynne, M. Miller, R. Sievers, T. Valdez. 2018. "Lightweight System Design and Demonstration of a High Reliability, Air Independent, PEMFC Power System for an Untethered Subsea Power Node." Proceedings of the 2008 Power Sources Conference. pp. 203-206.

Woods Hole Oceanographic Institution. 2017. Coastal and Global Scale Nodes: Coastal Sliders. http://www.whoi.edu/ooi_cgsn/coastal-gliders.

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