2022

Hydrogen Fuel in Support of Unmanned Operations in an EABO Environment

Pollman, Anthony G.; Beery, Paul T.; Lussier, Jonathan

Monterey, California: Naval Postgraduate School

https://hdl.handle.net/10945/71957

NAVAL RESEARCH PROGRAM
NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

HYDROGEN FUEL ENABLING UNMANNED CAPABILITIES

EXECUTIVE SUMMARY

Principal Investigator (PI): Dr. Paul Beery, Systems Engineering (SE) and Dr. Anthony Pollman, SE

Additional Researcher(s): No additional researchers participated in this research project.

Student Participation: Ms. Rachel Meyen-Faria, CIV, SE; Mr. Bradley G. Petersen, CIV, SE; Ms. Vanny Prak, CIV, SE; Mr. Jonathan R. Schweichler, CIV, SE

Prepared for:
Topic Sponsor Lead Organization: N9 - Warfare Systems
Topic Sponsor Name(s): Mr. Cayle Bradley, USN
Topic Sponsor Contact Information: cayle.a.bradley@navy.mil; 703-614-0184

This research is supported by funding from the
Naval Postgraduate School, Naval Research Program (PE 0605853N/2098).

Project Summary
This project conducted an operational analysis of the utility of hydrogen fuel to support unmanned systems in an Expeditionary Advanced Base Operations (EABO) context. The project developed a systems architecture to identify the relevant subsystems and design considerations for the construction of a hydrogen generation system. A discrete-event simulation model was created, using the ExtendSim software, to examine alternative system configurations and assess the sensitivity of candidate designs to alternative unmanned system operational concepts. Particular focus was given to the electrolysis power source; the study considered solar generation, low performance (rated for one kW) wind generation, high performance (rated for three kW) wind generation, and tidal/wave generation. Additionally, the project systematically varied both unmanned system and environmental characteristics as part of a designed experiment. Results indicate that the power generation type has a larger impact on operational performance than any environment factors, as well as the design or employment of the associated unmanned systems. Specifically, solar generation is the preferred alternative for hydrogen generation.

Keywords: *hydrogen fuel, hydrogen generation, alternative fuel, discrete-event simulation, expeditionary advance base operations, Littoral Operations in a Contested Environment, LOCE, Expeditionary Advanced Base Operations, EABO*

Background

Navy and Marine Corps planners developed the Expeditionary Advanced Base Operations (EABO) concept of operations to provide maritime commanders with more options for future sea control operations. EABO is envisioned as complementary to Littoral Operations in a Contested Environment (LOCE), which provide specificity regarding the concept for logistical support to multiple EABO sites. These concepts align with recent guidance, notably NAVPLAN 2021 and the Tri-Service Maritime Strategy, which detail the importance of unmanned systems capabilities to future warfighting. Many unmanned undersea and aerial systems currently in development are looking to alternative energy sources, including hydrogen, to maximize operational reach and persistence. These concepts and directions define a future combat environment that demands risk-worthy platforms to perform sea denial as a low-signature "inside force" that is untethered from a large petroleum supply chain. This study was motivated by that guidance and assessed hydrogen requirements for use as a fuel in an EABO environment to inform development of a capability evolution plan.

Use of hydrogen as a fuel in both EABO and LOCE requires consideration of several importation design considerations. The EABO and LOCE concepts both rely on mobile, low-signature forces. An idea that is repeated in both concepts is the distribution of unmanned systems across multiple sites. While there are numerous operational advantages to this distribution, it creates challenges for logistics and support. Specifically, each concept has the potential to create substantial stress on the fuel distribution network for both the Navy and Marine Corps. Employment of alternative fuels that can be generated in theater represents a potential solution to decreasing the stress on fuel distribution networks that may come from increased use of unmanned systems. Because hydrogen fuel can be generated through harvesting of seawater, it is a particularly attractive alternative fuel type. However, realization of hydrogen as a fuel for unmanned systems presents challenges that do not exist with conventional fuels. A major challenge is generation of electricity to power the hydrogen fuel generation. This report preliminarily considered the following electricity generation techniques: coal, natural gas, solar, geothermal, hydroelectric, biomass, wave, wind, and nuclear and directly implements solar, wind, and wave electricity generation techniques into the analysis of alternatives. Additionally, hydrogen fuel use requires a defined strategy for hydrogen generation. This report considered the viability of hydrocarbons, biohydrogen, photocatalytic solar, and electrolysis solar as alternatives, with electrolysis being the option considered as part of the analysis of alternatives. Finally, hydrogen storage was considered, with gas, liquid, and metal hydrides examined as potential alternatives. Given the expected timeline for this study, gas was the only option considered as part of the analysis of alternatives.

Using that expected timeline as a starting point, this work examines scenarios for hydrogen use as a fuel in an EABO environment. These scenarios model a hydrogen fuel distribution system with an emphasis on hydrogen generation and storage, the electrolysis mechanism employed to support hydrogen generation, the number of employed hydrogen generation systems, and the operational employment of unmanned vehicles that utilize hydrogen fuel.

Findings and Conclusions

To assess the viability of hydrogen fuel, this project utilized a discrete-event simulation in a software program called ExtendSim. The ExtendSim model simulates multiple EABO operational sites distributed across an island chain. Each site utilizes a combination of Unmanned Surface Vehicles (USVs), Unmanned Undersea Vehicles (UUVs), and Unmanned Aerial Vehicles (UAVs). Because the focus of this project was not the detailed representation of the unmanned vehicles, the performance and operational characteristics of the unmanned systems at each site were randomized and each vehicle was treated as a generic Unmanned Vehicle (UxV). At each site, the model simulated generation of hydrogen fuel and refueling of UxVs. The model assumed that, since the EABO and LOCE concepts emphasize distributed operations, each hydrogen generation system can operate without demand for external resources. This means that each hydrogen generation system had the capability to generate electricity and subsequently power the electrolysis of seawater into fuel. Additionally, there was an assumed constraint on the size of the hydrogen generation system. The model assumed that the system was transported to the site by a CH-53 helicopter, which dictated limitations on both size and weight.

Generation of hydrogen fuel using seawater was modeled as a series of five events: generation of electricity, processing of seawater, performing electrolysis, storing of hydrogen, and transfer of hydrogen to each UxV. Electricity generation was modeled in particular detail to represent three alternative generation techniques: solar, wind, and wave. Solar electricity generation was modeled using a sine wave and an assumption of a ratio of 12 hours of sunlight to 12 hours of zero sunlight (corresponding to a 50% duty cycle). Wind electricity generation was modeled using two alternative physical systems, one with a rating of one kW and a second with a rating of three kW. The electricity generated by each wind system was modeled by surveying candidate wind turbine systems, observing daily averages for power generation, dividing by time to get an average power by minute, and multiplying by a uniform distribution to introduce randomness. Finally, wave systems were modeled similar to the wind systems, with the note that power was generated as pulses, rather than constants. Once electricity was generated, the model simulated electrolysis when there was sufficient electricity to perform electrolysis for one minute (the time step used in the model). The model assumed that each hydrogen generation system was equipped with nine-kilogram tanks for storage of hydrogen fuel with a compression of 1.35 kilowatts per kilogram. The stored hydrogen fuel was used to refuel UxVs, which were deployed for operational use and arrived at the system at random intervals. 61,440 runs of the simulation were conducted across the following set of input variables: number of UxVs, UxV tank size, UxV hydrogen burn rate, UxV operational duration, UxV travel time to operational locations, electricity generation type, and number of electricity generation systems. Analysis suggests that solar electricity generation has the largest impact on mission success.

Recommendations for Further Research

This work used a discrete-event simulation model tailored to assess alternative strategies for the use of hydrogen fuel in an Expeditionary Advanced Base Operations (EABO) environment. The model assessed the viability of alternative electricity generation strategies to support hydrogen generation that is decoupled from traditional fuel chains via harvesting of hydrogen from seawater. The model was exercised for a sevenday timeframe (10,080 minutes) and systematically varied the following as part of a designed experiment: quantity of Unmanned Vehicles (UxV), UxV tank size, UxV hydrogen burn rate, UxV travel time to mission area, UxV operational deployment duration, hydrogen refuel rate, electricity generation type, and number of electricity generation systems. The analysis shows the use of solar electricity generation, rather than wind or wave approaches, has the largest impact on operational performance. Notably, approximately 10 solar devices are able to keep 30 UxVs refueled over a one-week timeframe. In comparison, the next-highest performing alternative, a 3 kW-rated wind turbine, requires approximately 20 systems to refuel 20 UxVs. The other electricity generation types considered (a 1kW rated wind turbine and a wave generator) are only able to support an average of 14 UxVs.

Beyond the type of electricity generation system, there were limited operational insights that warrant further investigation. Statistical analysis indicated that the hydrogen burn rate for individual UxVs was statistically significant; however, the operational impact appears to be minimal. Hydrogen burn rate was modeled from 2.5 grams per minute to 3.5 grams per minute, and the reduction from the maximum to the minimum value only allowed support of a single additional UxV. The interaction between input variables was also assessed with similar results. The only interaction that resulted in potentially actionable operational recommendations was the interaction between the number of UxVs and the operational employment duration of each UxV. The results indicate that in extreme scenarios, specifically a single UxV operating with a very short mission duration, the hydrogen generation system may not be able to generate hydrogen quickly enough to support refueling at the rate which the UxV will require. This suggests that, in scenarios where missions are expected to be extremely short, it may be beneficial to have additional UxVs on hand to serve as spares, rather than waiting for refueling.

Direct follow-on research can be dedicated to a comparison of the preferred solution from this project to other alternatives that were beyond the scope of this research. Solar appears to be a more promising technology in the near term than either wind or wave for hydrogen generation and may warrant additional emphasis. The results suggest investigation that compares hydrogen fuel to other potential fuel types, especially nuclear, may be worthwhile using a similar approach. Particular interest exists in the development of an operational effectiveness model to compare alternative strategies for the harvesting or generation of alternative fuels in theater, with emphasis on comparison of alternative (e.g., hydrogen, nuclear) fueled unmanned systems to conventionally fueled unmanned systems.

Acronyms

EABO	Expeditionary Advance Base Operations
LOCE	Littoral Operations in a Contested Environment
UAV	unmanned aerial vehicle
USV	unmanned surface vehicle
UUV	unmanned undersea vehicle
UxV	unmanned vehicle