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Hydrogen Fuel in Support of Unmanned Operations in an EABO Environment

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NAVAL POSTGRADUATE SCHOOL

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HYDROGEN FUEL ENABLING UNMANNED CAPABILITIES

by

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ABSTRACT

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.

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I. INTRODUCTION

A. 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 provides specificity regarding the concept for logistical support to multiple EABO sites. Those 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. Those 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 is motivated by that guidance and conducts an operational assessment of hydrogen requirements for use as a fuel in an EABO environment.

Use of hydrogen as a fuel in both EABO and LOCE requires consideration of several factors. 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. A potential solution to decreasing the stress on fuel distribution networks that may come from increased use of unmanned systems is the employment of alternative fuels that can be generated in theater. 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 for conventional fuels. A major challenge is generation of electricity to power hydrogen fuel generation. Additionally, the method of hydrogen generation and storage must be investigated, with focus on strategies that are viable within the EABO and LOCE concepts. This study develops an operational simulation model of unmanned system operation in an EABO environment. That simulation model explicitly models the generation of hydrogen fuel using technologies that are viable for fielding to support EABO in a near term (five to ten year) timeframe. The simulation model is subsequently exercised across a range of environmental conditions and operational employment decisions to produce recommendations for the utilization of hydrogen as an alternative fuel source for both EABO and LOCE.

B. OBJECTIVES

This work applies a systems engineering approach to develop a finite set of scenarios for hydrogen use as a fuel in an EABO environment. Those 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. The goal is to investigate benefits and system of systems trade-offs with the objective of delaying fuel resupply to the greatest extent possible. This will inform identification of Doctrine, Organization, Training, Materiel, Leadership, Personnel, and Facilities (DOTMLPF) gaps to hydrogen adoption as an enabler of EABO and LOCE. In support of that broader goal, this research has the following objectives:

- Create a set of scenarios or operational concepts for use of hydrogen fuel in an EABO environment.
- In terms of a single chosen scenario, assess requirements for hydrogen fuel generation, storage, and distribution.
- Provide recommendations that balance system development with operational employment while considering the potential impact of environmental factors

C. APPROACH

The research investigates future hydrogen requirements for use as a fuel in an EABO environment, with the ultimate outcome of making recommendations to inform development of a capability evolution plan. The systems engineering approach presented in (Van Bossuyt et al. 2019), complemented by the mission engineering approach described in (Beery and Paulo 2019), is used. The approach is well suited to assessment of systems during the conceptual development phase of the systems engineering process. Stakeholders were engaged to help better understand the problem and desired capability. Stakeholder input was used to frame the capability and better understand the state of the art. Scenarios were developed to communicate the desired capability and highlight how it differs from how business is done today. Based on these scenarios, a functional architecture was developed, and that architecture mapped to a physical architecture. Based on these architectures, a discrete-event simulation model was developed using the software program ExtendSim to address the research questions and better understand the system of system trade-offs for implementation of the desired capability. Architecture and simulation development for this work is described in detail in (Meyen-Faria et al. 2022). Analysis of the results is used to inform development of the hydrogen fuel concept for EABO and LOCE.

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II. MODELING AND ANALYSIS

A. INTRODUCTION AND DESIGN CONSIDERATIONS

The focus of this research is assessment of the viability of hydrogen fuel in both EABO and LOCE. EABO and LOCE are both defined by multiple, mobile, low-signature systems deployed across a large area in a contested environment. The contested nature of these operations will require systems that are sustainable, reliable, and maintainable with limited support from traditional infrastructure. Given those demands, there is a need to investigate the utility of alternative fuel types, which may allow operational forces to operate for extended durations with limited reliance on external logistics support. Hydrogen fuel may enable this decoupling from fuel chain because it can be generated from widely available natural resources. Specifically, hydrogen fuel can be generated using seawater, which is abundantly available in both EABO and LOCE locations.

Generation of hydrogen in contested environments requires a design concept that considers several important factors. A major design consideration in this report is the ability to deploy the hydrogen generation system to an EABO site. This report assumes that the hydrogen generation system must be able to be deployed on a CH-53 helicopter inside of 45-foot shipping containers. This creates design constraints on the size and weight of the hydrogen generation system. The report assumes that the hydrogen generation system must be able to perform four primary functions, listed below along with the system components that exist to support each function:

- Seawater Intake
    - Hoses, Intake Pump, Filtration System
- Electricity Generation
    - Electricity Harvester (ex: Solar Panels, Wind Turbines, Tidal Buoy)
- Hydrogen Fuel Generation and Storage
    - Electrolysis Components, Storage Tanks, Battery, Compressor
- Hydrogen Fuel Distribution
    - Hoses, Unmanned System Interface

Definition of these four primary functions highlighted three important processes that the hydrogen generation system must support. The system must be able to: 1) generate electricity, 2) generate hydrogen, and 3) store hydrogen. Figure 1 presents a visualization of these four primary functions, coupled with these three essential processes.

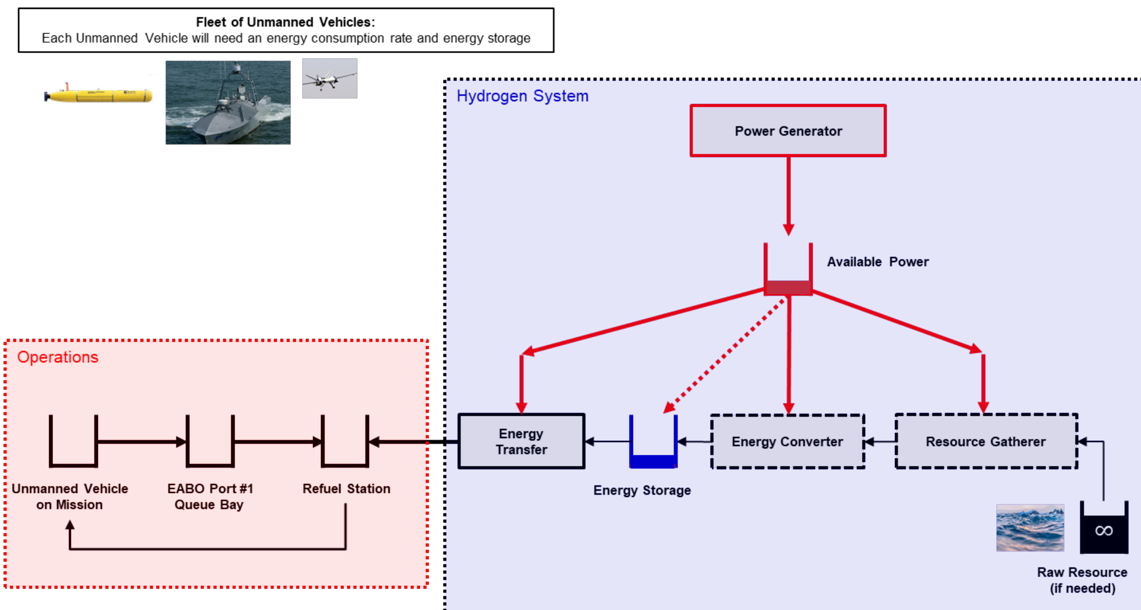

Figure 1. Hydrogen Generation System Process Diagram

Figure 1 is intentionally generic in terms of resources available and energy generation technique. An important observation from Figure 1 is that the hydrogen generation system (shaded in blue) must be modeled independently from the operations system (highlighted in red). The essential activities within the hydrogen generation system are:

- Collection of raw resource into a resource gatherer (for the hydrogen generation system this is likely a pump that may also be capable of filtering or chemical cleansing)
- Transitioning of the raw resource into an energy converter that separates the raw resource into useful components
- Storage of extracted fuel until the initiation of energy transfer
- Delivery of fuel from the storage system to unmanned systems

A persistent activity that must be conducted throughout the process is power generation. That power generation may be possible via multiple technologies or systems. A preliminary review of relevant literature suggested that the following techniques may be capable of providing power to the hydrogen generation system: coal, natural gas, solar, geothermal, hydroelectric, biomass, wave, wind, and nuclear. That preliminary list was assessed against four criteria: 1) the viability of implementing while decoupled from a logistics chain, 2) size or transportability, 3) time to start up the system and shut down the system, and 4) raw resource location. Coal, natural gas, and biomass were eliminated from consideration based on the ability to decouple from the logistics chain. Hydroelectric was eliminated based on size. Nuclear was eliminated based on start up and shut down time. Geothermal was eliminated based on the availability of the raw resource since it requires consistent sunlight. That elimination left three viable sources of power generation for the hydrogen fuel system: solar, wave, and wind. Each of those alternatives are considered as part of this research and the differences between each are modeled explicitly for analysis.

An additional factor that required preliminary assessment prior to model construction was the technique employed to generate hydrogen. This project considered the viability of hydrocarbons, biohydrogen, photocatalytic, and electrolysis as alternatives for hydrogen generation. While each technique was assessed as technological viable, electrolysis appears to be the most economically and operationally viable in the near term and was selected as the sole alternative for hydrogen generation in this research.

The final factor that required preliminary consideration prior to modeling was the storage mechanism for hydrogen fuel. There is substantial active research in this area studying the viability of hydrogen storage as gas, liquid, and metal hydrides. Review of that research and associated literature suggested that each may be worthy of investigation, but that storage as metal hydrides will likely require twenty years to be operationally viable, storage as liquid will likely require ten years to be operationally viable, and storage as gas will likely require five years to be operationally viable. Given the expected timeline for this study, gas is the only option considered as part of the analysis of alternatives.

B. MODEL OVERVIEW

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 is not the detailed representation of the unmanned vehicles, the performance and operational characteristics of the unmanned systems at each site are randomized and each vehicle is treated as a generic unmanned system, termed a UxV. At each site the model simulates generation of hydrogen fuel and refueling of UxVs. The model assumes 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 has the capability to generate electricity and subsequently power the electrolysis of seawater into fuel. Additionally, there is an assumed constraint on the size of the hydrogen generation system. The model assumes that the system has a weight limit of 30,000 pounds, which means it can be transported in a 45-foot shipping container using a CH-53 helicopter. Presentation of the simulation model is separated into the two categories described in Figure 1, the hydrogen generation system and the operational system.

1. Hydrogen Generation System

The representation of the hydrogen generation system in the ExtendSim model is split into two primary sub-functions: electricity generation/storage and hydrogen generation/storage. As discussed in the previous section, three techniques for electricity generation are considered for this project: solar, wind, and wave. Review of existing systems suggested that definition of two different wind generation systems was necessary due to substantial differences in performance. Accordingly, wind electricity generation is modeled using two alternative physical systems, one with a rating of one kW and a second with a rating of three kW. Figure 2 presents an overview of the four systems considered for electricity generation as part of this project. The performance characteristics, detailed in Meyen-Faria et al. (2022), of the solar generation system are from (ShopSolarKits.com 2022), for the 1kW wind generation system are from (Aeolos Wind Turbine Company 2022), the 3kW wind generation system are from (Aeolos Wind Turbine Company 2022), and the wave generation system are from (Ocean Power Technologies 2022).

1. Solar		**2. Wind**	
12*365W Solar Panels Output = 0.365kW per panel Dimensions: 69in x 40in x 1.5in Weight: 19.5kg (43lbs) per panel		Rated Power: 1kW Maximum Output Power 1.5kW Height: 2.8m (9.2ft) Radius: 2.0m (6.6ft) Rated Wind Speed: 10m/s (22.3mph) Weight: 28kg (61.6lbs)	
3. Wind-3kW		**4. Wave**	
Rated Power: 3kW Maximum Output Power: 3.6kW Height: 3.6m (11.8ft) Diameter: 2.8m (9.2ft) Rated windspeed: 11m/s (24.6mph) Weight: 106kg (233.7lbs)		Height: 13.3m Float Diameter: 2.65m Weight: 8,300kg Min Mooring Depth: 25m Max Morring Depth: 1,000m Continuous Average Power: 8.4kWh/day	

Figure 2. Electricity Generation Alternatives

Within the model the physical characteristics of the electricity generation systems are not modeled directly. Rather, because the model is focused on the transfer of hydrogen fuel to unmanned systems, the power generated from each of the candidate systems is modeled as an input to the hydrogen generation system. Power generation is modeled using an underlying function to alter the amount of power provided the hydrogen generation system over time. Figure 3 presents a graphical overview of this implementation.

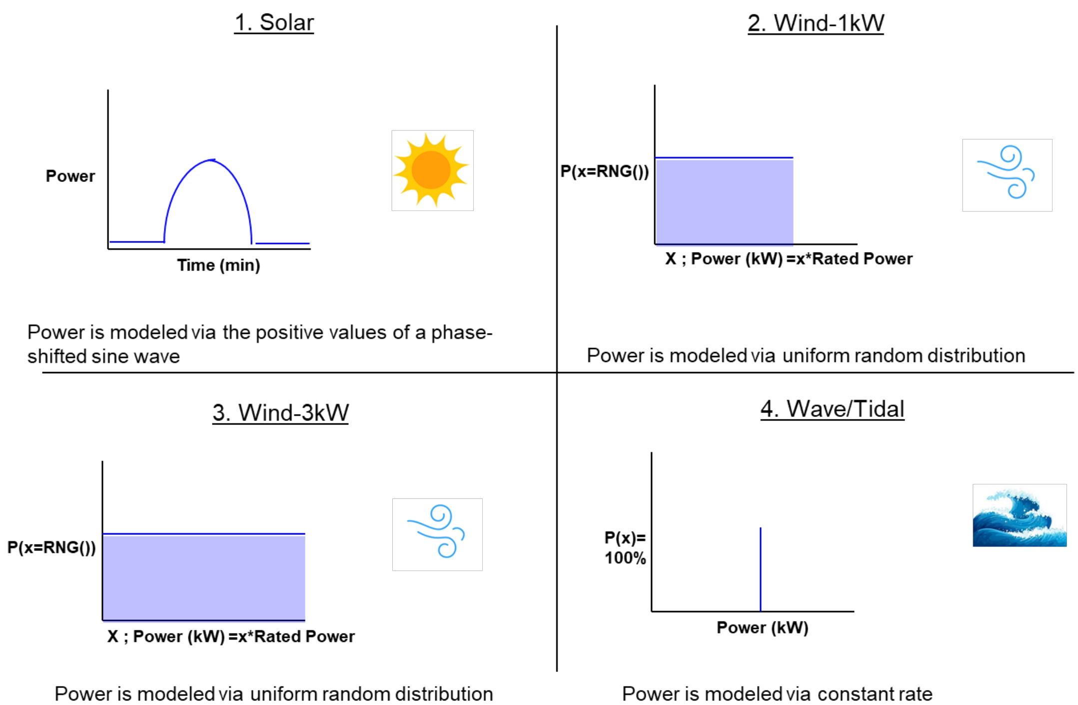

Figure 3. Implementation of Electricity Generation Alternatives (after Meyen-Faria et al. 2022)

Solar electricity generation is 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). As noted, wind electricity generation is 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 is 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 are modeled similar to the wind systems with the note that power is generated as pulses, rather than constants.

Once electricity is generated the model simulates electrolysis when there is sufficient electricity to perform electrolysis for one minute (the time step used in the model). The model assumes that each hydrogen generation system is equipped with nine-kilogram tanks for storage of hydrogen fuel with a compression of 1.35 kilowatts per kilogram. The stored hydrogen fuel is used to refuel UxVs, which are deployed for operational use and arrive at the system at random intervals. Figure 4 presents a graphical representation, assuming solar power for power generation, of the electrolysis and power storage system.

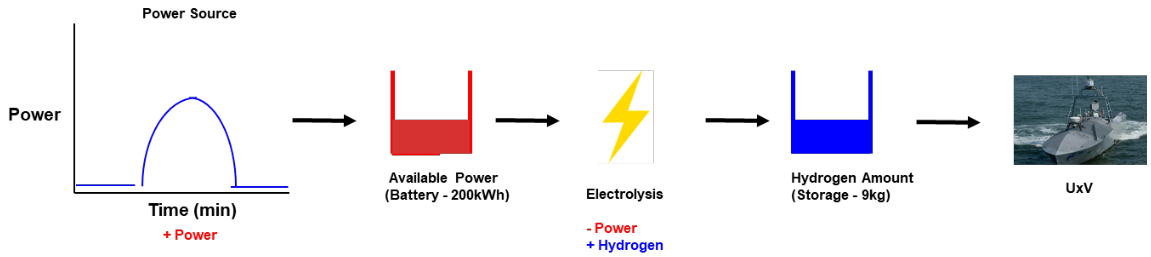

Figure 4. Electrolysis and Power Storage (Meyen-Faria et al. 2022)

2. Operational System

The operation of a group of UxVs is modeled independently from the hydrogen generation and storage system. The operational system requires initialization, where input variables for the impact of weather, mission duration, distance from the refueling site to the operational area, and refueling rate are defined and randomized using normal distributions. UxVs are assumed to be deployed with full fuel tanks at the start of each model run. Subsequently, UxVs follow a sequential process of:

- Travel to operational area
- Conduct mission
- Travel to refueling station
- Queue
- Begin refueling
- Subtract hydrogen from reserves
- Complete refueling

After completing this sequence each UxV loops for the duration of the simulation model. Note that there are several important assumptions made within the model. Notably, each UxV refuels to 100%, there is no loss of electricity due to connections or interfaces, electricity does not experience storage or aging loss, the fuel burn rate for each UxV is constant over time, UxVs do not experience maintenance downtime, there is a single compressor, the hydrogen storage system does not leak, no power is used during standby mode, and UxVs in queue do not continue to burn hydrogen fuel. Note that the model is configured to run for a one-week time period and increments time with a time step of one minute.

C. BASELINE ANALYSIS

Preliminary investigation of the model was conducted to visualize the impact of several factors within the model. For this analysis, the average queue time for each UxV waiting to be refueled was used as the measure of effectiveness. Fifteen model runs were conducted, each using solar power generation. For the first five model runs a single generator was used, for the second five runs two generators were used, and for the third group of five runs three generators were used. The model simulated two unmanned systems with a constant fuel burn rate of 3g/minute. Figure 5 presents the results of these fifteen runs, annotated to denote the grouping into the five runs for each power configuration type.

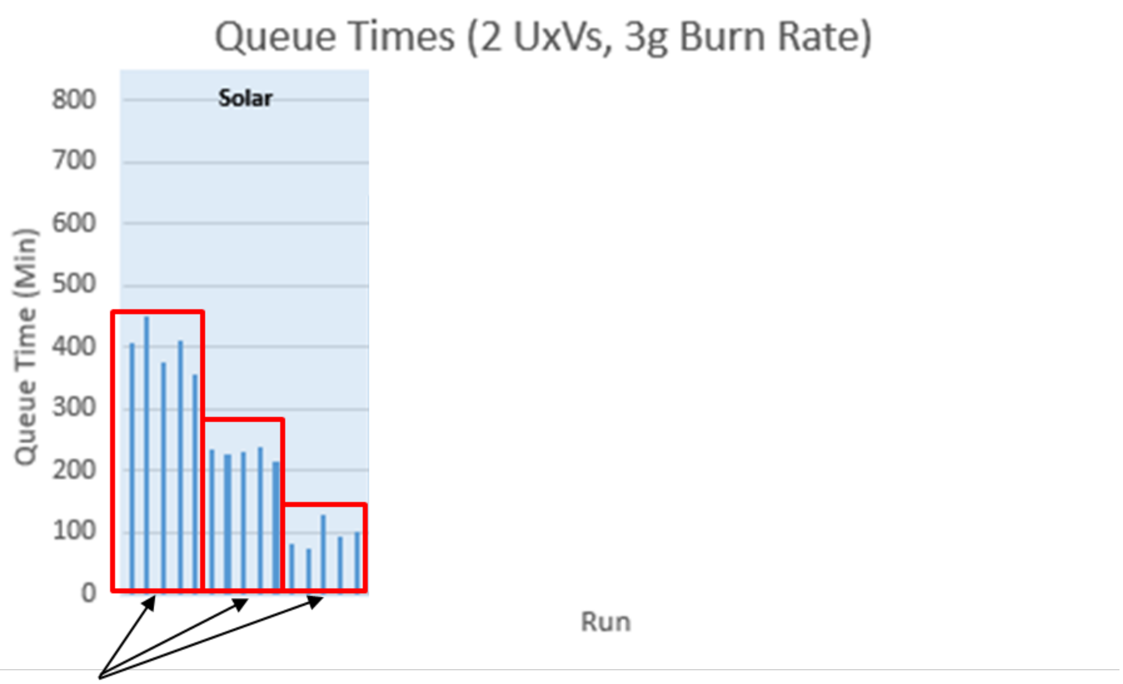

Figure 5. Average Queue Time for Three Preliminary Design Configurations (after Meyen-Faria et al. 2022)

Figure 5 suggests that the change to number of power generation systems is working as expected. The configurations which utilize a single power generation system are associated with substantially longer queue times than those with two systems, which are associated with longer wait time than those with three systems. This strategy was applied to the three other power generation systems to ensure that they are also functioning properly within the model. Figure 6 presents a similar set of fifteen model runs for each of the four power generation types modeled in the simulation.

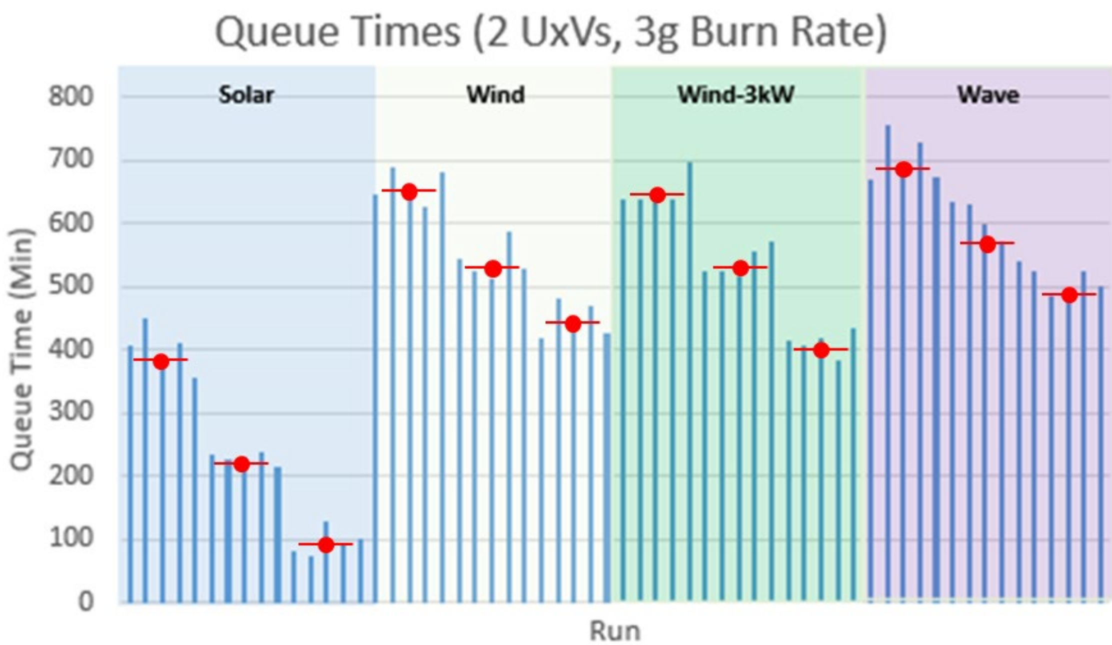

Figure 6. Average Queue Time for Four Power Generation Types (after Meyen-Faria et al. 2022)

Figure 6 suggests that there is a potentially interesting difference between the performance of the solar powered system and each of the three alternative power generation systems, which are each associated with substantially higher queue times than the solar power system.

Before proceeding to a formal experimental design, the impact of changing both the number of UxVs and the burn rate of each UxV was investigated independently from the power type. Using a similar strategy, where fifteen runs are conducted for each power generation type, the number of UxVs was varied (from 1 to 2) and the burn rate of each UxV was varied (from 2.5 to 3). This resulted in a total of 240 simulation runs. The results are summarized in Figure 7.

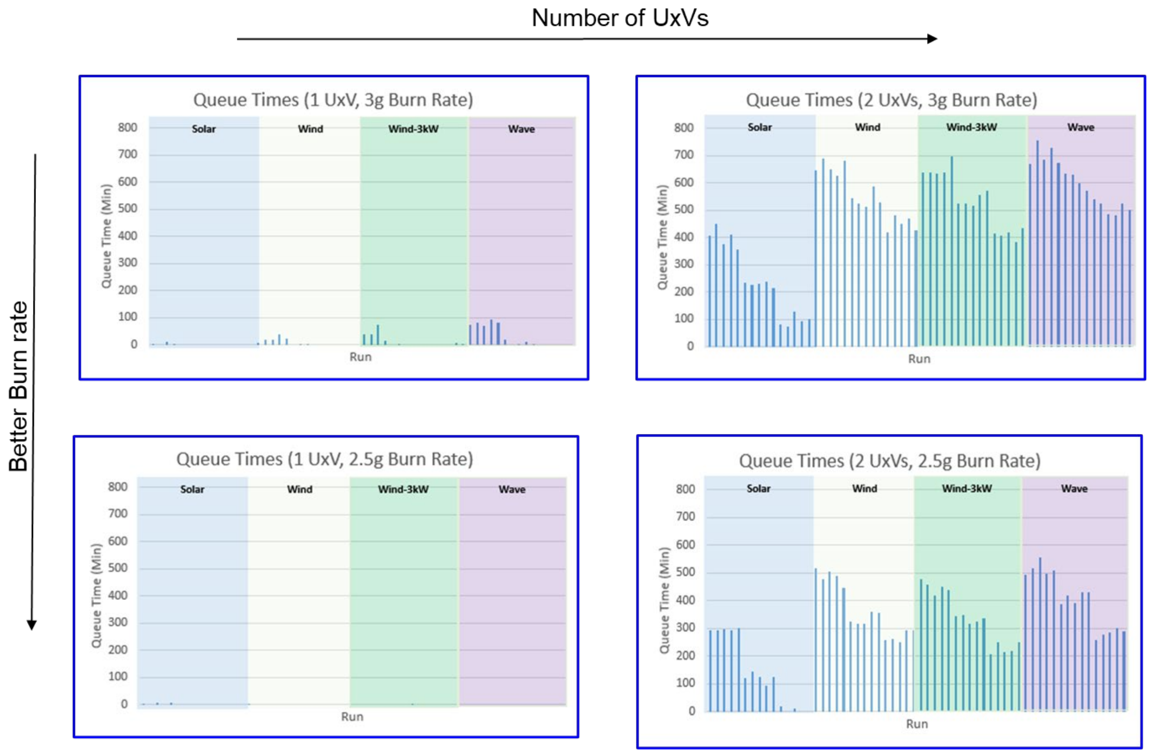

Figure 7. Impact of UxV Quantity and Burn Rate on Queue Time (after Meyen-Faria et al. 2022)

As with the previous analysis, the results suggests that the model is working properly. Increasing the number of UxVs increases the average queue time across all power generation configurations and burn rates. Similarly, increasing the fuel burn rate increases the queue time across all power generation configurations and UxV quantities. This suggests that each of these design considerations are working as expected within the ExtendSim model and provides preliminary direction for more detailed experimentation.

D. EXPERIMENTAL DESIGN STRATEGY

To investigate the design and operational factors that have the largest impact on performance a nearly orthogonal nearly balanced design was generated using (Vieira 2012). Table 1 summarizes the factors and levels considered in this study. A total of 512 design combinations were generated. Note that the power type was not treated as a variable within the experimental design, rather the entire design was repeated for each power type. This resulted in a total of 2,048 design points for examination within the

ExtendSim model. To account for the stochastic nature of the simulation each design point was replicated 30 times, resulting in a total of 61,440 simulation model runs.

Factor	**Minimum**		**Maximum**	
Number of UxVs	1		4	
Tank Size (g of H_2)	4000		6000	
Burn Rate (g/minute)	2.5		3.5	
Travel Duration (min)	40		80	
Mission Time (min)	500		700	
Refueling rate (g of H_2)	0.0005		0.001	
Number of Generators	5		30	
Power Type	Solar - 27kW/day	Wind - 3kW/day	Wind-3k - 9kW/day	Wave - 9kW/day

Table 1. Experimental Design Factors and Levels (after Meyen-Faria et al. 2022)

E. REGRESSION ANALYSIS

To assess the factors from Table 1 that had the largest impact on system performance a single evaluation measure, the number of unmanned systems refueled during the simulation run, was chosen. Stepwise regression and least squares regression were conducted to generate a regression equation. The candidate model included all first order terms, all second order terms, and all two-way interactions. Figure 8 presents a simplified regression equation with all parameters sorted by LogWorth. The associated regression equation has an r-square value of 0.91, indicating a quality model fit.

Source	LogWorth		PValue
Power Type	29076.42		0.00000
Number of Devices	15768.53		0.00000
Burn Rate	1415.772		0.00000
Number of Devices*Number of Devices	1031.482		0.00000
Number of UxVs*Mission Time (Mean)	426.029		0.00000
Mission Time (Mean)	177.716		0.00000
Mission Time (Mean)*Power Type	153.026		0.00000
Number of UxVs*Number of UxVs	86.087		0.00000
Number of UxVs*Power Type	48.990		0.00000
Number of UxVs	16.239		0.00000
Mission Time (Mean)*Mission Time (Mean)	2.058		0.00874
Number of UxVs*Number of Devices	1.455		0.03509
Number of UxVs*Burn Rate	0.744		0.18038

Figure 8. Sorted Parameter Estimates from Regression Analysis (after Meyen-Faria et al. 2022)

Review of Figure 8 suggests several important findings. First, the power type dominates the equation. This suggest that the selection of solar, 1 kW wind, 3 kW wind, or wave power generation has the largest impact on model variability. Second, the number of devices has the second largest impact on variability, followed by the UxV burn rate. This suggests that, once the appropriate power type is identified, system design should focus on the number of devices employed at each location and, subsequently, the fuel burn rate of individual UxVs. Figure 8 also shows that there are several statistically significant interactions between factors that warrant additional exploration. The three interactions that have the largest impact on model variability are the interaction between the number of UxVs and the mission time, the interaction between the mission time and the power type, and the interaction between the number of UxVs and the power type. To visualize the impact that two factor interactions have on mission performance Figure 9 presents interaction plots.

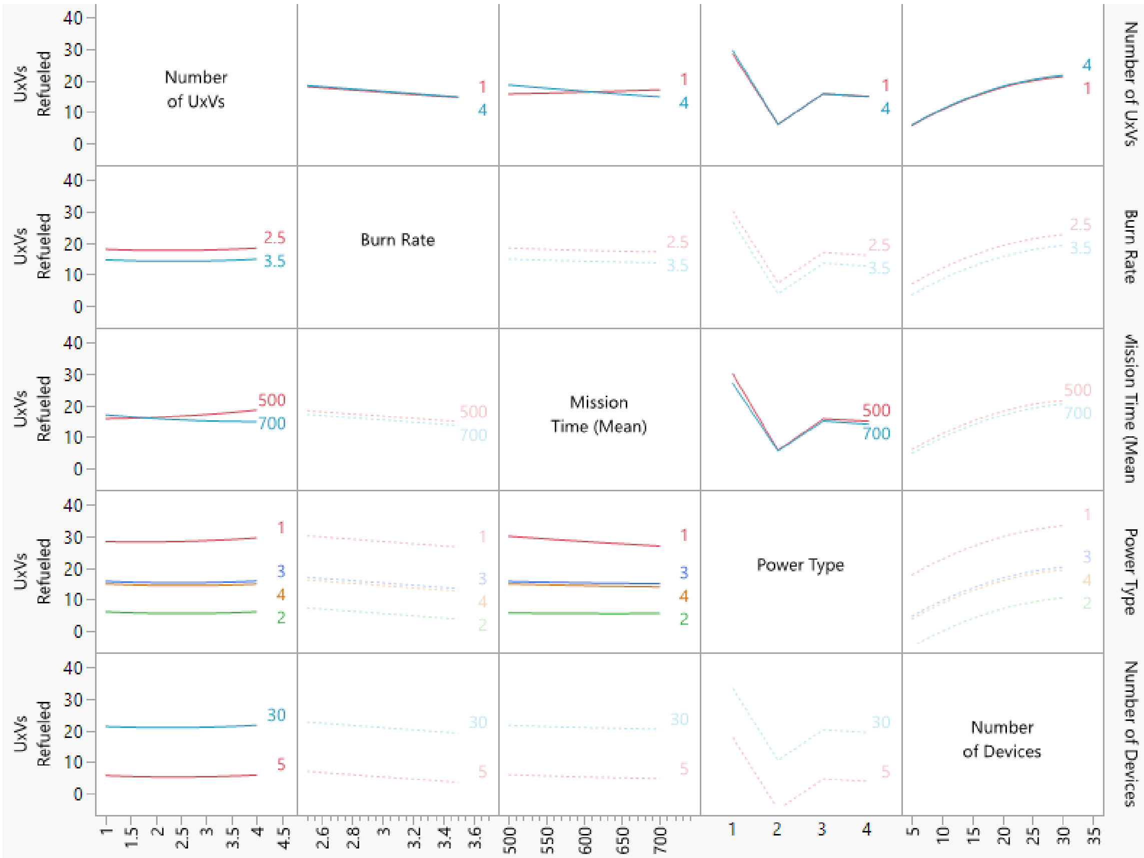

Figure 9. Interaction Plots for Number of UxVs Refueled (after Meyen-Faria et al. 2022)

Review of Figure 9 demonstrates that, while there are several statistically significant interactions, those interactions appear to have almost zero operational significance. The only interaction that may be interesting is the interaction between the number of UxVs and the mission time. Review of that interaction plot (third plot on the first column from the left) suggests that an increase from a single UxV to four UxVs has a more pronounced impact on the number of UxVs refueled when the mission time is 500 minutes when compared to mission times of 700 minutes. This suggests that increasing the number of UxVs has a more pronounced impact when the mission time is short. This finding is potentially interesting but is more likely a function of the specific scenario examined in this analysis and may not be generalizable to other scenarios. Additional investigation may choose to focus on this interaction during analysis to determine whether or not the finding is generalizable. For the recommendations of this analysis the conclusion is that there are no operationally generalizable interactions that need to be considered despite the presence of multiple statistically significant interactions.

To develop specific design and operational recommendations beyond the sorted parameter estimates presented in Figure 8 a partition tree was created. The partition tree segments the dataset into groups based on grouping of candidate decision variables. Figure 10 presents a partition tree analysis using the number of UxVs refueled as the output variable.

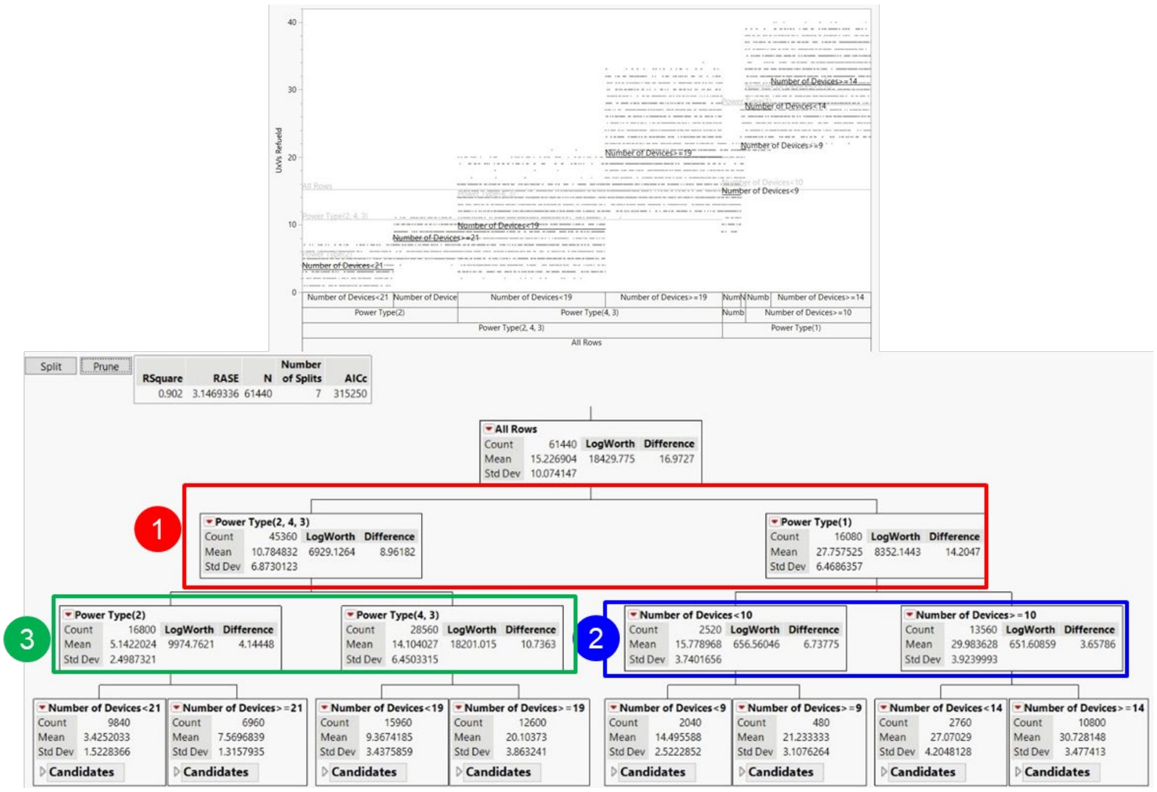

Figure 10. Partition Tree Analysis for Number of UxVs Refueled (after Meyen-Faria et al. 2022)

Review of Figure 10 suggests several interesting conclusions. Beyond the finding presented in Figure 8 that the power type has the largest impact on performance, Figure 8 demonstrates that the selection of Power Type 1 (coding for solar power generation) has the largest impact on performance. This split is highlighted in red and denoted as split one in Figure 10. Notice that the mean number of UxVs refueled is given for model runs with Power Type 1 (solar) and Power Types 2, 3, and 4 (all other types). For model runs using solar power there was an average of 27.7 UxVs refueled over the simulated one-week timeframe. This is a substantial difference from the performance when any other power generation system is used, where there is an average of 10.7 UxVs refueled. This adds specificity to the finding from the original regression analysis, which demonstrated that the power type has the largest impact on performance and demonstrates that the development of a hydrogen fueling system should focus on the use of solar power generation over any other design choice. Figure 10 also shows additional findings that decompose the design decisions for the hydrogen fueling system contingent on the selection of solar power generation. The right side of Figure 10, highlighted in blue and denoted with the number two, shows that when solar power generation is selected, the next choice that should be made is the use of at least 10 devices. In configurations where at least 10 solar power generation systems are used there is an average of 29.9 UxVs refueled, compared to 15.7 UxVs refueled for configurations with fewer than 10 solar power generation systems. The left side of Figure 10, highlighted in green and denoted with the number three provides a similar decomposition for configurations where solar power generation is not selected (Power Type 2, 3, or 4 is selected). The partition analysis shows that the decision that has the largest impact on variability, contingent on solar power generation not being selected, is the use of Power Type 2 (the coding for 1 kW wind power generation). The analysis shows that when Power Type 2 (1 kW wind turbine) is selected there are an average of 5.1 UxVs refueled, compared to 14.1 UxVs refueled for configurations with Power Types 3 and 4. This suggests that, if solar power generation is not possible, the next choice that should be made is avoiding a 1 kW wind turbine if either wave power generation or a 3 kW wind turbine are available. One additional layer of decomposition is shown for reference to provide specificity regarding the number of devices of each type that should be utilized contingent on power type selection.

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III. CONCLUSIONS

A. SUMMARY AND FINDINGS

As the Navy and Marine Corps mature the EABO and LOCE concepts there will be increased emphasis on the ability to sustain unmanned systems. Both EABO and LOCE will require platforms that can operate without reliance on traditional petroleum supply chains. To inform development of those concepts this study conducted an operational assessment of hydrogen requirements for use as a fuel in EABO and LOCE. This research examines multiple aspects of hydrogen fuel that may impact implementation, specifically generation of electricity to power hydrogen fuel generation, as well as hydrogen generation and storage. Additionally, this project examined the impact of design characteristics of the hydrogen generation system, design characteristics of unmanned systems that may utilize hydrogen fuel, and operational and environmental considerations to develop recommendations that are applicable across a range of potential employment strategies.

This project used a discrete-event simulation model to assess alternative strategies for the use of hydrogen fuel in an EABO environment. The model was exercised for a 7-day timeframe (10,080 minutes) and systematically varied the following as part of a designed experiment:

- Quantity of UxVs
- UxV tank size
- UxV hydrogen burn rate
- UxV travel time to mission area
- UxV operational deployment duration
- Hydrogen refuel rate
- Electricity generation type
- Number of electricity generation systems

The analysis showed 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. As comparison, the next highest performing alternative, a 3 kW rated wind turbine, requires approximately 20 systems to refuel 20 UxVs over the simulation timeframe. 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 over the simulation timeframe.

Beyond the type and quantity of electricity generation system used to power hydrogen generation 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 in 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.

B. FUTURE WORK RECOMMENDATIONS

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.

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