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**NPS NRP Executive Summary**
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NAVAL RESEARCH PROGRAM
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MONTEREY, CALIFORNIA

# ANALYSIS OF ALTERNATIVE ELECTROLYZER TECHNOLOGIES TO SUPPORT NEXT GENERATION UAV

## EXECUTIVE SUMMARY

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## Project Summary

Unmanned aerial vehicles (UAV) are strategic tools that boast immense capability; however, these systems are still limited by the logistical demands of fuel production and fuel supply. Naval Air System Command (NAVAIR) and Naval Research Laboratory (NRL) are in search of a capability that would allow unit-based production of hydrogen fuel for hydrogen fuel cells for a next-generation, fixed wing, hydrogen fuel-cell UAV—electrolyzers are the clear answer to this problem. Electrolyzers produce hydrogen and oxygen from water using electricity and are widely used by the United States Navy (USN) submarine service as oxygen generators. This research explored all currently qualified electrolyzer systems in the USN, determined the relevant functional and performance parameters, and developed the most advantageous use-cases from the qualified candidate electrolyzer systems.

The Navy currently uses three qualified oxygen generators: the Low Pressure Electrolyzer (LPE), the Integrated Low Pressure Electrolyzer (ILPE), and the Automatic Electrolytic Oxygen Generator (AEOG). This research utilized the Model Based Systems Engineering Methodology for Employing Architecture for Systems Analysis (MBSE MEASA) in concert with Systems Modeling Language (SysML) to synthesize the requirements from the sponsors into a working architecture that informed the selection of the most preferred functional and performance criteria of the desired system. The culmination of this methodology was a multi-criteria decision-making (MCDM) model based on the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methodology to aid in a system selection recommendation.

The MCDM model resulted in the unanimous selection of the LPE over the other alternatives for all use-cases and each iteration of the model. In continuation of this work, it is recommended to analyze the functional and performance criteria using other forms of multi-criteria decision-making models to verify and validate the results. Additionally, commercial off-the-shelf (COTS) options should be considered regardless of qualification status.

**Keywords:** *unmanned systems, hydrogen fuel cell, electrolyzer, energy optimization, logistical independence, Systems Modeling Language, SysML, Model Based Systems Engineering Methodology for Employing Architecture for Systems Analysis, MBSE MEASA, analysis of alternatives, AoA*

## Background

UAVs are a force multiplier on the battlefield in a multitude of diverse and strategic ways. They enable the operational commander as well as the civilian user to extend their reach with a high level of fidelity without many of the risks that traditional aviation poses to human life. NRL successfully designed, built, and operated the Ion Tiger Hydrogen Fuel cell UAV, which set unofficial endurance records for fuel cell powered flight by flying for 26 hours while carrying a 5-pound payload (Swider-Lyons et al., 2010). Building on experience with the Ion Tiger UAV, NRL is developing prototypes for the next generation fuel cell UAV. A key requirement for the next generation design is the use of a fuel that does not require its own logistics; therefore, electrolyzers, which generate hydrogen fuel from water using electricity, are being explored as a sustainable and logistically independent fuel supply system. Additionally, the electrolyzer must already be qualified for use by the USN.

According to Pollman (2013), "Exponential equipment and capability growth has made us much heavier and much less agile. This equipment growth has come with a commensurate growth in fuel and energy consumption, which ties us to long and vulnerable logistics trains. Our enemies have recognized and successfully exploited this vulnerability" (p. 69). This study aims to link a desired capability of a hydrogen fuel cell to a fuel production method as a system to minimize the logistical burden on the units who operate the system. Additionally, this research is an exercise in utilizing an established method for going from stated requirements to needs, employing an architecture, determining relevant parameters and criteria, and utilizing a model or analysis method to aid in decision-making.

This research utilized the MBSE MEASA process to distill the needs and technical desires of NRL and NAVAIR into clearly defined requirements and subsequently used SysML to transform the requirements into a functional and physical architecture. According to Beery (2016), "The functional architecture specifies what the system must do to satisfy the developed requirements and the physical architecture specifies what system components are necessary to perform the functions identified in the functional architecture" (p. 7). The above represents the first three steps of the MBSE MEASA process. The output of the first three steps of the MBSE MEASA process is a set of critical technical parameters that are then distilled into criteria as the inputs for the MCDM model. Each criterion is given a weight factor based on a unique use case which serves as a preference for one factor over another.

This work directly supports the analysis and assessment needs of Headquarters Marine Corps., Aviation and the Office of the Chief of Naval Operations N94. It also answers the Chief of Naval Operation's call, spelled out in *A Design for Maintaining Maritime Superiority*, to better leverage the Naval Postgraduate School to address long term sustainment and logistics in support of the Distributed Maritime Operations concept (U.S. Navy, 2018).

## Findings and Conclusions

This research implemented the MBSE MEASA process to develop a functional and physical architecture from the sponsors' needs and requirements. The output of the architecture was a set of measurable system parameters that are the input criteria for the MCDM model. Additionally, the requirements analysis resulted in three mission options, or operational settings, in which the system could be used. The first mission option conceptualizes a ship-based system, where it is tied to and derives its power and resources solely from the ship. The second mission option utilizes the system in concert with a mobile unit, either on-foot or as the payload for a multi-purpose vehicle, such as a High Mobility Multipurpose Wheeled Vehicle. This mission option is the most constrained in terms of size and weight. Finally, the third mission option utilizes the system as part of the forward operating base's (FOB) system of systems.

The criteria that were chosen from the output of the functional and physical architecture covered various aspects of the system. The system's operational availability, reliability, and maintainability are of particular importance as they carry heavy implications for the operators and maintainers. The system's power requirements as well as the portability are also key, as this system could be utilized in a forward deployed and isolated environment. Both life-cycle cost and life expectancy are significant from an acquisition and sustainment perspective. Finally, each system's hydrogen-production rate is the chosen performance criteria as this value will drive further fueling and UAV sortie requirements.

The results of the MCDM model were indisputable—the LPE was the most preferred system option for every iteration of the model by at least 35%. This result was due to a few factors. First, the LPE is by far the cheapest option, costing almost half of the other two alternatives over the system's life cycle. Second, the LPE is a much simpler system than either the ILPE or the AEOG, which historically results in longer operational availability, better reliability, and a more maintainable system. Finally, the LPE performs comparably to the highest performing alternative (the ILPE) and requires less power than the other alternatives. In terms of the mission options, the ship-based and FOB-based options are the most viable mission settings for the identified alternatives.

Although the LPE is slightly less than the threshold weight and size for mission option 2, the proximity to the threshold results in an impractical solution. This presents a practical limitation of the effectiveness of the available systems to satisfy the mission options and limits the options available for the analysis of alternatives (AoA). Additionally, the TOPSIS methodology is only one option available to the decision-maker when executing MCDM models, so depending on the methodology used, the results could vary. Lastly, the classified nature of the ILPE precluded a thorough examination of the criteria, which could have presented some amount of error in the results of the AoA.

## Recommendations for Further Research

This research could greatly benefit from future work. The Low Pressure Electrolyzer , Integrated Low Pressure Electrolyzer , and the Automatic Electrolytic Oxygen Generator are the only three systems that are qualified for use in the United States Navy. To integrate these systems in line with the mission options, modifications to the systems as well as the support elements (e.g., ships, base infrastructure, etc.) will have to be made to accommodate these systems. Future work including case studies of complex system modification as well as a determination of the viability of these systems from a ship system's integration perspective would further validate this research.

Aside from the three systems identified in line with the sponsors' qualification requirement, a closer look at the qualification process for a system of this caliber would be beneficial and could minimize the schedule and budget risk if or when new acquisition is executed, or an established system is repurposed to support a new mission. In addition to analyzing the procedure for qualification of a system such as an electrolyzer, an expansion of the alternative space could be advantageous.

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## Acronyms

| | |
|---|---|
| AoA | analysis of alternatives |
| AEOG | Automatic Electrolytic Oxygen Generator |
| COTS | commercial off-the-shelf |
| DOD | Department of Defense |
| FOB | forward operating base |
| ILPE | Integrated Low Pressure Electrolyzer |
| LPE | Low Pressure Electrolyzer |
| MBSE MEASA | Model Based Systems Engineering Methodology for Employing Architecture for Systems Analysis |
| MCDM | multi-criteria decision-making |
| NRL | Naval Research Laboratory |
| SysML | Systems Modeling Language |
| TOPSIS | Technique for Order Preference by Similarity to Ideal Solution |
| USN | United States Navy |
| UAV | unmanned aerial vehicle |