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HYDROGEN FUEL SYSTEM FOR NAVY UNMANNED SYSTEMS IN AN EXPEDITIONARY ADVANCED BASING OPERATIONS ENVIRONMENT (EABO)

Meyen-Faria, Rachel; Petersen, Bradley G.; Prak, Vanny; Schweichler, Jonathan R.

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SYSTEMS ENGINEERING CAPSTONE REPORT

HYDROGEN FUEL SYSTEM FOR NAVY UNMANNED SYSTEMS IN AN EXPEDITIONARY ADVANCED BASING OPERATIONS ENVIRONMENT (EABO)

by

Rachel Meyen-Faria, Bradley G. Petersen, Vanny Prak,
and Jonathan R. Schweichler

June 2022

Advisor: Paul T. Beery
Co-Advisor: Anthony G. Pollman

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Many unmanned undersea and aerial systems currently in development are looking for alternative energy sources, including hydrogen, to maximize operational reach and persistence. Current Expeditionary Advance Base Operations (EABO) processes are heavily reliant on logistics and depleting petroleum sources. This capstone project will analyze the potential use of hydrogen fuel generated via a mobile, independent system to address logistics and fuel depletion concerns for EABO.

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Rachel Meyen-Faria, Bradley G. Petersen, Vanny Prak, and Jonathan R. Schweichler

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Lead Editor: Bradley G. Petersen

Reviewed by:	
Paul T. Beery	Anthony G. Pollman
Advisor	Co-Advisor

Accepted by:
Oleg A. Yakimenko
Chair, Department of Systems Engineering

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ABSTRACT

Many unmanned undersea and aerial systems currently in development are looking for alternative energy sources, including hydrogen, to maximize operational reach and persistence. Current Expeditionary Advance Base Operations (EABO) processes are heavily reliant on logistics and depleting petroleum sources. This capstone project will analyze the potential use of hydrogen fuel generated via a mobile, independent system to address logistics and fuel depletion concerns for EABO.

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LIST OF ACRONYMS AND ABBREVIATIONS

DoE	design of experiments
DOTMLPF	doctrine, organization, training, materiel, leaderships and education, personnel, and facilities
EABO	expeditionary advance base operations
IPR	interim progress report
K	kelvin
kg	kilogram(s)
kW	kilowatt(s)
kWh	kilowatt-hour(s)
LOCE	littoral operations in a contested environment
min	minute(s)
ONR	Office of Naval Research
OPT	ocean powered technologies
PSI	pressure per square inch
NAWCAD	Naval Air Warfare Center - Patuxent River
NAVPLAN	navigation plan
NPS	Naval Postgraduate School
NUWCDIVNPT	Naval Undersea Warfare Center - Division Newport
RNG	random number
SMR	steam methane reforming
STDEV	standard deviation
UAV	unmanned aerial vehicle
USMC	United States Marine Corps
USN	United States Navy
USV	unmanned surface vehicle
UUV	unmanned undersea vehicle
UxV	unmanned vehicle of any type (e.g., UAV, USV, UUV)
WEZ	weapon engagement zone

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EXECUTIVE SUMMARY

The future fleet envisioned by the Navy and Marine Corps involves focused capabilities to combat adversarial powers in contested littoral environments. (Chief of Naval Operations and M Gilday 2021). Expeditionary Advanced Based Operations (EABO) is one example of the types of operations planned for these littoral environments. Additionally, plans from the Navy incorporate increasing the size of the future fleet and include having larger number of unmanned systems (Quigley 2020). With goals to improve the readiness and capabilities of Navy ships, submarines, and unmanned systems; there are challenges that need to be addressed (Chief of Naval Operations and M Gilday 2021). For EABO, one of the challenges is logistics support because the operational environment necessitates mobility, sustainability, and low-signature systems (United States Marine Corps 2021). An approach is needed to utilize sustainable resources in an EABO environment that supports the desired capabilities of the future Navy's integrated unmanned systems.

This capstone report discusses the initial systems engineering design phases for a system that generates hydrogen fuel within an Expeditionary Advanced Based Operations (EABO) environment. A hydrogen fuel generation system addresses needs of Navy and Marine Corps operations in such contested environments. These environments require independence from traditional logistics supply chains and therefore require investigation of alternative fuels, such as hydrogen, which may increase the operational reach of EABO forces. This report presents a conceptual hydrogen generation system and investigates the design and utility of that system through modeling and simulation that informs recommendations for Navy and Marine Corps usage in the future combat environment. The modeled hydrogen fuel generation system is assessed in a representative operational environment where it is used for refueling of unmanned systems deployed in an EABO environment.

Four major drivers impact the utility of a hydrogen generation system: the EABO environment, electricity generation, hydrogen generation, and hydrogen storage/ distribution. Starting with the environment where the hydrogen system will operate, the unique characteristics of an EABO site were assessed. Central to EABO is the littoral environment where the operations take place, which can be described as multiple, mobile sites across small-island chains that are within reach of adversarial weapons. The use of unmanned vehicles across a network of EABO sites promotes the desired mobility and low-signature forces. In addition to the importance of transportable systems in an EABO environment, minimizing the required external logistics support is a vital concern. EABO being performed on small-island chains may result in limited availability of fuel resources, particularly traditional petroleum sources. Hydrogen fuel can be generated from a renewable and abundant resource in this environment: seawater. The EABO environment will have influence on various aspects of the hydrogen system; one example is the distance between islands and necessary covertness impacting size and storage requirements. Another example is the hydrogen generation system having to include means for sustainable electricity generation. Power is needed to start and maintain the fuel generation process.

There are a range of options for electricity generation in an unconstrained environment. An evaluation of multiple traditional methods (coal, natural gas, solar, tidal, wave, etc.) identified that solar, tidal/wave, and wind are the most promising candidates for the hydrogen fuel system. For the purposes of this report, each method was constrained based on implementation in an EABO environment. The solar power option is based on an assumption of 6 hours of sunlight per day and is assumed to utilize panels that provide 25.8 kW per day (ShopSolarKits.com 2022). The tidal power option involves a power-absorber buoy that can produce 8.4 kWh per day (Ocean Power Technologies 2022). For wind power, turbines are the best option for the environment. However, turbines may vary in sizes/forms and can produce significantly different amounts of energy. To account for the large variety of options, two wind turbines were selected for the hydrogen system model: a turbine that yields 1 kW and a turbine option that yields 3 kW. The power generation setup consists of the electrical generator (e.g., solar panel) with an electrical controller to determine where the electrical energy is routed. Batteries are used to store surplus electrical energy, as needed.

The basis of the hydrogen fuel generation system is that hydrogen fuel is produced from the seawater surrounding EABO sites. There are several methods that can be used to produce hydrogen. Based on assessment of the hydrogen production methods, the electrolysis-based hydrogen generation method was chosen and analyzed in this report. Once hydrogen is separated into its natural state, there are challenges to storing the hydrogen gas. For this reason, storing hydrogen as a gas, liquid, and in solid material were all assessed as options for the system. After comparing the different methods and considering the key concerns in an EABO environment, storing hydrogen as a gas is the chosen method for this project.

Alternative configurations for the hydrogen fuel generation system are modeled in the software program ExtendSim. The discrete-event model is composed of elements related to three main functions: electricity generation and electrolysis; hydrogen generation, storage, and transfer; and UxV activities. There are multiple model inputs that the user is able to change, most of these inputs are divided into UxV parameters and mission parameters. There are also user changes that involve specific model elements and scenario parameters. Model outputs and all recorded data is stored into tables in the model database. The outputs are: number of UxVs refueled, total hydrogen generated, total electricity generated, and UxV average queue time. The main functions mentioned above each contain multiple lower-level design elements within the model. Electricity generation begins with the electrical energy generation from one of the four renewable source options (wind 1 kW, wind 3kW, solar, or tidal) and includes the electrical energy storage and electrolysis of seawater. The hydrogen generation and storage portion of the model is a function of the power available to generate hydrogen and the available storage to hold generated fuel. The model uses a 9-kilogram tank to fill 2 UxVs that each have a 5-kilogram tank. To compress the hydrogen for the tank, the model uses 1.35 kilowatts per kilogram. The UxV activities part of the model is directly related to the EABO activities of the UxVs that are conducting a mission. Initially the model defines the UxV creation time, quantity of UxVs created, fuel type, tank size, and burn-rate from the user inputs. The UxVs then transit and perform mission activities. The model uses the mission activities to determine the UxV need for additional fuel and facilitates the refueling process.

A preliminary design of experiments was performed using the ExtendSim model. The preliminary analysis was conducted to identify combinations of power type, burn rate, UxV number, and number of generation devices that could achieve a queue time of near zero for a complete day. Assessment of that model suggested that the UxV number had the largest impact on queue times. Additionally, across all model runs, the solar power type performed the best and yielded the lowest queue times.

Building on the preliminary analysis, more detailed analysis of the model was completed using JMP software with nine input variables and over 60,000 runs. The inputs varied during the test were number of UxV, tank size, burn rate, mission time, travel-to, travel-from, mean time to refuel, power type, and number of devices. Model analysis was conducted using a multivariate, least squares fit, and a decision-tree. The outputs used for the tests were the number of UxVs refueled and the average queue time at the hydrogen refueling. The regression analysis identified that Power Type, Number of Electrical Generation Devices, UxV burn rate, mission time (mean), and Number of UxVs had a statistically significant impact on results. Statistical analyses performed showed that the most impactful factor was power type followed by number of devices. Note that the level of technology may influence the performance of each power type. For our project, the highest performing power type was always solar across all model simulations. The number of devices needed to improve operational performance varied depending on whether number of UxVs refueled or average refuel time was the desired output metric. For the number of UxVs refueled, the number of devices needed to impact performance varied from 14 to 21 (high performance systems associated with the lower number of devices and vice versa). For the UxV average wait times, the number of devices was around 10 to 11 for all four power types.

This capstone project sought to determine the performance of a hydrogen fuel system in an EABO environment where logistics is limited which was achieved via a discrete-event model simulation. The model was developed in ExtendSim and was the basis for a Design of Experiments analysis where eight system factors were varied over a range of values, and the corresponding system performance was measured. The analysis identified that a hydrogen system is capable of being established in an EABO scenario and

additionally identified the significant factors that will impact operational performance. Overall, a hydrogen generation system may address the logistics concern in the EABO environment. However, operational performance will be dependent on several system factors that are provided by the analysis.

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I. INTRODUCTION

A. BACKGROUND

Several recent documents and concepts define the future of U.S. Navy and Marine Corps operations. Navy and Marine Corps planners developed the Expeditionary Advance Base Operations (EABO) concept of operations to provide maritime commanders with more options for future sea-control operations (USMC 2021). Related to EABO, Littoral Operations in a Contested Environment (LOCE) emphasizes the importance of logistical support across multiple sites as the United States Marine Core (USMC) matures the EABO concept (Department of the Navy and United States Marine Corps 2017). Finally, Navigation Plan (NAVPLAN) 2021 and the Tri-Service Maritime Strategy detail the importance of unmanned systems capabilities to future warfighting (Chief of Naval Operations and M Gilday 2021; Berger, Gilday, and Schultz 2020). The future combat environment 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 will assess hydrogen as a fuel in order to inform the development of a capability evolution plan for EABO (Beery 2021).

B. PROJECT OBJECTIVE

Unmanned undersea and aerial systems currently in development may use alternative energy sources, including hydrogen, to maximize operational reach and persistence. EABO processes are heavily reliant on logistics and depleting petroleum sources. This capstone project will analyze the potential use of hydrogen fuel generated via a mobile, independent system to address logistics and fuel depletion concerns for EABO.

The project will investigate future hydrogen-as-a-fuel requirements in an EABO environment, with the ultimate outcome of making recommendations to inform development of a capability evolution plan. Specifically, the capstone team will determine the short-term (5 years), mid-term (10 years), and long-term (20 years) system requirements within the areas of facility, generation, and storage.

C. TAILORED SYSTEMS ENGINEERING

This capstone project utilizes the waterfall method as in the *Systems Engineering and Analysis*, 5th edition (Blanchard and Fabrycky 2014, 36). Figure 1 shows the different phases of the waterfall method. The capstone will primarily focus on the Requirements Analysis and Specifications phases, colored in blue.

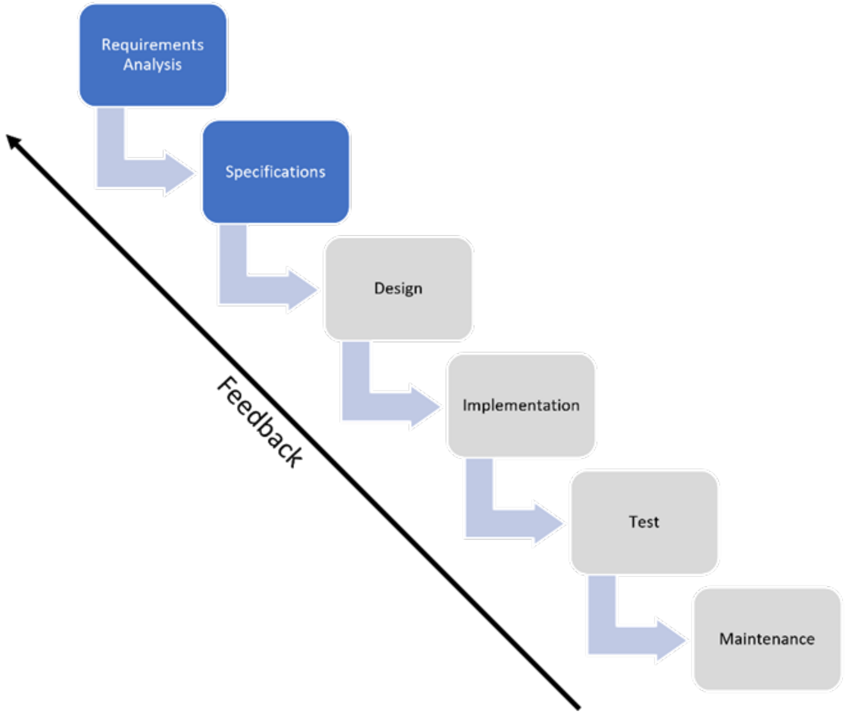

Figure 1. Waterfall Method

D. REPORT ORGANIZATION

The sections in this report discuss the approach and results of this capstone project. The initial project phase involved background research regarding the topic of hydrogen fuel generation in an EABO environment. A literature review was performed, and the effort is summarized within the second chapter of this report. Following the literature review chapter is Chapter III: Project Analysis. This portion of the report describes the Systems Engineering (SE) activities performed to define the problem space, analyze the stakeholder needs, and identify the major requirements and functions of the hydrogen generation system. The remainder of the report focuses on the ExtendSim model that was built and used to provide results and inform recommendations for the EABO hydrogen generation system. In Chapter IV: Model Description, an overview of the modeling approach is discussed along with the model inputs, outputs, assumptions, and limitations. The next chapter presents the results of the model simulations that were run and includes statistical analysis of outputs. The report concludes with recommendations for the path forward with the modeled hydrogen generation system in an EABO environment.

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II. LITERATURE REVIEW

This chapter is organized into four sections. The first reviews the EABO environment, with specific focus on the role of unmanned systems. The second reviews alternative methods for electricity generation, a primary enabler of hydrogen fueling for unmanned systems. The third and fourth sections review methods of hydrogen generation and hydrogen storage, respectively.

A. EABO ENVIRONMENT

A major consideration for the use of hydrogen as a fuel source for the USMC is the EABO environment. According to the 2021 *Tentative Manual for Expeditionary Advanced Base Operations* put out by the USMC, a definition for EABO is "a form of expeditionary warfare that involves the employment of mobile, low-signature, persistent, and relatively easy to maintain and sustain naval expeditionary forces from a series of austere, temporary locations ashore or inshore within a contested or potentially contested maritime area in order to conduct sea denial, support sea control, or enable fleet sustainment" (1-3). This EABO manual explains that an expeditionary advanced base is characterized by being temporary and able to change location relatively quickly. In addition, an expeditionary advanced base is located within the "Weapons Engagement Zone" (WEZ) of an adversary (USMC, 1–6). Central to EABO is the littoral environment where the operations take place. The EABO concept is a supporting idea to the USMC and Navy's concept of Littoral Operations in a Contested Environment (LOCE) which is described in a 2017 document by the Navy and USMC (Department of the Navy and United States Marine Corps 2017). The USMC and Navy's description of LOCE identifies a need for the littorals to be treated "as a singular integrated battlespace" (Department of the Navy and United States Marine Corps 2017, 4). The EABO definition and description of the littorals form the picture of an environment with multiple, mobile sites across small island chains that are within reach of adversarial weapons. One of the aspects of EABO is the use of unmanned vehicles which promote the desired mobile and low-signature forces. Unmanned undersea vehicles (UUV), unmanned surface vessels (USV), and unmanned aerial vehicles (UAV) would be used across a network of EABO sites with the potential for unmanned vehicles to travel between sites and offshore ships (Duchynski et al. n.d.).

One of the major challenges facing EABO is logistics and sustainment (Blivas 2020). To preserve the desired mobility and low signature operations, minimizing the required external logistics support is important. However, the characteristics of an EABO environment add to the challenge of providing the needed logistics. There are multiple factors about the EABO environment that impact providing logistics support. Not addressing the logistics concerns is a risk and could even result in “preventable casualties” (Panicacci 2021, 65). One of the factors that affects the needed logistics support in an EABO environment is the surrounding countries in the environment. While host nation logistics support would be possible, the nations that surround littoral regions include a “continuum of cooperation” (Duchynski et al. n.d., 35). The “continuum” includes countries that are unlikely to support USMC and Navy EABO (Duchynski et al. n.d., 35). A 2021 article in the *Marine Corps Gazette*, “How to do Logistics in EABO,” lays out additional logistics concerns in EABO which include: transportation support, ship-to-shore, water production, and bulk fuel (Panicacci 2021). This capstone project is focused on the concern of fuel in an EABO environment.

EABO being performed on small island chains may result in limited availability of resources, such as fuel. To support the mobility and desired capabilities of the manned and unmanned systems at EABO sites, alternative energy sources are needed. An article from the Center for International Maritime Security (Eyer and McJessy 2019) discusses the risk involved in the current refueling process, in which combat ships require regular refueling from oilers. The same article points out that the availability of these oilers is limited, and risk is compounded by the lack of “stealth” of oilers when operating (13). The hydrogen generation system of this capstone project looks at using hydrogen gas to fuel the USVs, UUVs, UAVs, and additional systems that are integrated for the EABO concept. One of the goals of deploying a hydrogen generation system in this environment is to de-couple from the fuel supply chain and the depleting petroleum sources. Hydrogen fuel can be generated from a renewable and abundant resource: seawater. Seawater does not require logistics support as with other fuels. The EABO environment will have influence on various aspects of the hydrogen system as the distance between islands and covertness will directly impact size and storage requirements. Additionally, the number of unmanned vehicles used in the EABO environment will result in greater hydrogen generation and refueling demands from the system.

B. ELECTRICITY GENERATION

Electricity generation typically comes from the following types of sources: coal, natural gas, solar photovoltaic, concentrated solar panels, geothermal, hydroelectric, biomass, tidal, wave, wind, and nuclear. Other experimental methods for electricity generation exist (e.g., benthic microbial fuel cells) but those will not fall into the scope of this project.

While there are a range of options for electricity generation in an unconstrainted environment, the EABO environment places constraints that limit the potential options for hydrogen generation. The important factors for selecting/narrowing the type of electricity generation utilized are as follows:

1. Ability to decouple from logistics chain
2. Size and transportability
3. Startup/shut down times (includes any assembling or disassembling)
4. Location of raw energy resource

Incorporating these factors in the selection process will allow the system to be independent from external refueling and ensure easy transportability. Some of the types of electricity generation are dependent on the location of the energy resource and the system may not have freedom to be placed freely. Table 1 provides an evaluation of the factors for various sources of electrical generation.

Table 1. Electricity Generation Factors

Energy Source	**Logistics Dependence**	**Size**	**Start Up/ Shut Down Speed?**	**Dependent on the Location of Resource?**	**Viable for Hydrogen System**
Coal	Yes	Viable	Viable	Not dependent	No
Natural Gas	Yes	Viable	Viable	Not dependent	No
Solar Photovoltaic (Conventional Solar Panels)	No	Viable	Viable	Not dependent	Yes
Concentrated Solar Panel (a.k.a. Solar Thermal)	No	Viable	Too Slow	Dependent**	No
Geothermal	No	Viable	Viable	Dependent	No
Hydroelectric	No	Too Large	Too Slow	Dependent	No
Biomass	Yes	Viable	Viable	Not dependent	No
Tidal	No	Viable	Viable	Not dependent*	Yes
Wave	No	Viable	Viable	Not dependent*	Yes
Wind	No	Viable	Viable	Not dependent	Yes
Nuclear	No	Viable	Too Slow	No	No

* Some forms of this power generation type are location dependent

** This form of power generation needs consistent sunlight in order to function

The evaluation has identified that solar, tidal/wave, and wind are the most promising candidates for the hydrogen fuel system. It is important to note that the model and simulation will make the following assumptions about the systems using these electrical sources:

- no loss of performance after extended use,
- no critical errors will be encountered during operation,
- assembling and disassembling can be accomplished within an 8-hour timeframe with the users at an EABO site,
- preventative maintenance will not impact performance or availability (i.e., performed when the device is not needed),
- transportable in a 45-ft cube standard shipping container (Hemisphere Freight Services LTD 2018).

Additionally, it is important to note that cost is typically a major factor for any system but will not be a consideration for the system.

(1) Solar Power

A typical solar power system generates between 250 to 400 watts per panel (Aggarwal 2018). The project will assume that there will be 6 hours of sunlight per day in the EABO environment; the 6 hours of sunlight was estimated by taking a 12-hour day (average amount of sunlight during the spring and fall equinox) and reducing the sunlight amount by 50% in order to account for cloud cover and inadvertent shade caused by the surrounding environment. For the simulation, the analysis will use values provided by the OGK-1 solar kit (12-panels) which yields approximately 25.8 kilowatt-hours (kWh) per day with 6 hours of sunlight (ShopSolarKits.com 2022). Note that sunlight may differ depending on the location.

(2) Tidal Power

Tidal power may utilize different types of technologies to extract power and may also vary greatly in size. The EABO environment will limit the types of technologies suitable for the project and, thusly, any technology that requires a permanent structure or is too large to be easily transported will be deemed out-of-scope for the project. The model will use a power-absorber buoy as the tidal power source. More specifically, the performance of the Ocean Power Technologies (OPT) PB3 Power-Absorber Buoy which is expected to produce approximately 8.4kWh per day (Ocean Power Technologies 2022).

(3) Wind Turbines

Wind turbines may vary in sizes and can produce significantly different amounts of energy depending on turbine size, turbine efficiency, and wind conditions. For the purposes of transportability, a wind turbine approximately ten feet in height will be deemed appropriate for the project. The following performance values will be utilized: Aeolos-1kW wind turbine i.e., 1 kW of power for 22.3 mph sustained winds (Aeolos Wind Turbine Company 2022); the average wind speed of New Zealand, 12 mph (Weather Atlas 2022); and 6 hours of continuous, sustained winds per day. Using these values, the estimated energy obtained is approximately 3.229kWh per day. Note that these energy values may fluctuate daily based on weather and location climate.

(4) Power Generation Setup

The power generation setup will consist of an electrical generator, an electrical controller, and batteries. The device is responsible for generating the electricity; the electrical controller will determine where the electrical energy should be routed (i.e., generator to battery, battery to system, or generator to system); the batteries will be used for storing electrical energy. In the system model, the power generation will be represented as a “generator” component and reservoir of “available power” component will represent the storage and controller.

C. HYDROGEN GENERATION

Hydrogen is not normally found in the environment in large amounts; accordingly, there are several methods that can be used to produce hydrogen. One of the major ways is to apply energy to hydrogen containing compounds. Hydrogen can be produced via methods such as solar, photocatalytic, photoelectrochemical, thermochemical, and biohydrogen generation methods. Most of the hydrogen produced today is created through utilizing fossil fuels such as natural gas and coal. It is currently the most economical way to produce hydrogen in a large scale. Below are different methods of hydrogen generation:

(1) Hydrocarbons

Hydrocarbons often contain a high amount of hydrogen content. Hydrocarbons refer to compounds that contain hydrogen and carbon atoms. A good example of a hydrocarbon rich fossil fuel is natural gas. A major component of natural gas is Methane (CH_4). Hydrogen accounts for 25 percent of methane's mass content. On the other hand, hydrogen accounts for 18 percent of propane's mass content. Hydrogen is generated by breaking the C-H bond. Most of the hydrogen is currently made from reforming fossil fuels by heating them to high temperatures.

There are several methods to obtain hydrogen from hydrocarbons. Steam Methane Reforming (SMR) of natural gas is affected by pressure, temperature, and catalyst used. "Methane steam reformers have been built over a large range of sizes and types, including conventional, compact 'fuel cell type,' plate-type, and membrane reactors" (Zhang 2014). Partial oxidation method is based on thermo-chemistry for hydrogen generation. SMR utilizes water for steam reforming while partial oxidation uses oxygen gas. Coal gasification is another way hydrocarbons can be used to produce hydrogen, but this method has a high financial cost and uses an endothermic reaction to form gas that is treated with steam and produces hydrogen. Some other methods of obtaining hydrogen from hydrocarbons include glycerol ($C_3H_8O_3$) reforming, and thermos-decomposition of ammonia/methane.

(2) Biohydrogen Generation

Biohydrogen can be produced from bio-renewable sources via "chemical, thermochemical, biological, biochemical, and bio-photolytical methods" (Zhang 2014). Bio-photolysis exposes light on biological systems that results in the formation of molecular hydrogen and oxygen. This process is known as bioconversion and utilizes microorganisms to produce hydrogen. Zhang states that "Hydrogen can be produced by anaerobic bacteria, grown in the dark on carbohydrate-rich substrates. Dark fermentation of carbohydrate-rich substrates as biomass presents a promising route of biological hydrogen production, compared with photosynthetic routes. Anaerobic hydrogen fermenting bacteria can produce hydrogen continuously without the need for photoenergy"

(Zhang 2014). Biohydrogen can also be generated by heating decomposable biological material and combusting plants matter to create thermal energy for electrolytic production of hydrogen.

(3) Solar Hydrogen Generation: Photocatalytic and Electrolysis Methods

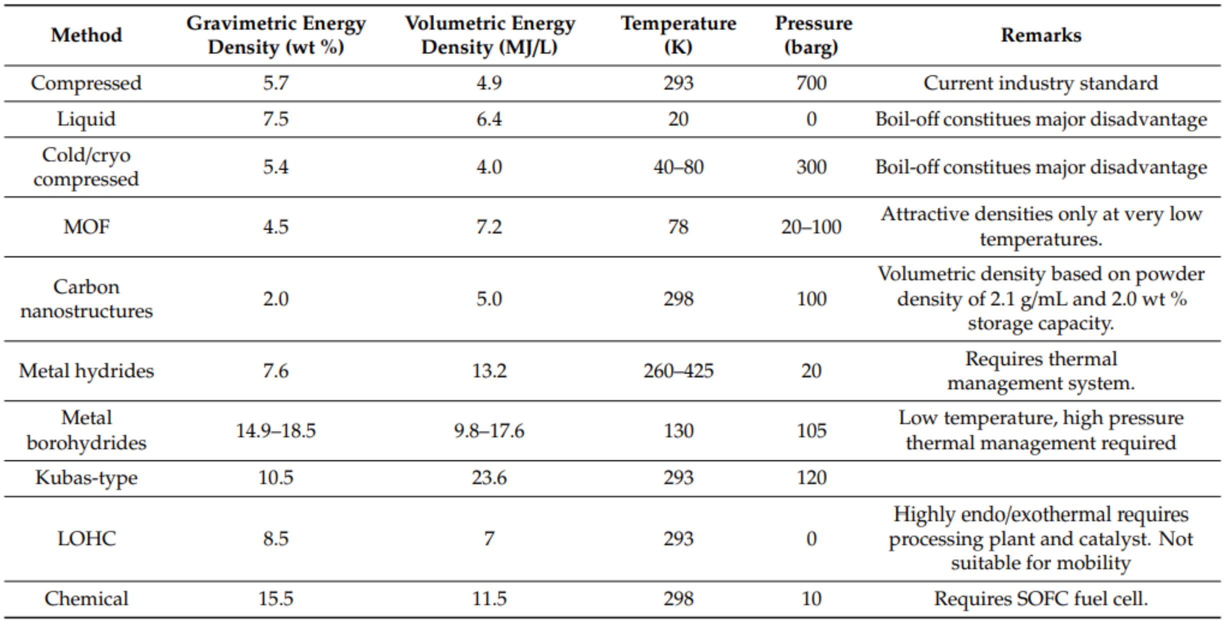
Solar Hydrogen Generation utilizes the process that splits water into hydrogen and oxygen. “The common industrial electrolyzer with platinum as catalyst can achieve a hydrogen production efficiency of around 70%” (Zhang 2014). This efficiency was achieved by conducting this process with highly filtered water. In 2019, Stanford University published an article (Garcia de Jesus 2019) where researchers generated hydrogen via the use of electrodes, solar power and saltwater sourced from the San Francisco Bay. The 2019 Stanford University article stated “Theoretically, to power cities and cars, you need so much hydrogen it is not conceivable to use purified water” (Garcia de Jesus 2019). In this proof-of-concept demonstration, the researchers coated the nickel-foam core anode with nickel-iron hydroxide on nickel sulfide to decrease corrosion caused by negatively charged chloride in seawater salt. This coating allowed the electrode to have a lifespan over one thousand hours and conduct more electricity through the researcher’s device. As a result, the Stanford researchers were able to generate hydrogen faster. Although the researchers were using salt water for electrolysis, the researchers were able to operate at electrical currents that match technologies that rely on purified water. The ability to use salt water and not rely on purified water is greatly beneficial. Existing electrolysis systems could be retrofitted with the new anode coating techniques and yield high results using salt water instead of purified water.

Based on assessment of technological maturity and discussion with USMC researchers, the electrolysis-based hydrogen generation method was chosen to be analyzed. The team chose to explore wind, solar, and wave sources as options to generate electricity used to conduct the electrolysis. The integration of this into the model will be discussed more in depth in the model description section of this document.

D. HYDROGEN STORAGE/DISTRIBUTION

Hydrogen has a challenge of being easily stored in its natural state. At room temperature and standard atmosphere, hydrogen is a gas, very light, and combustible. The key challenges for storage are weight, volume, efficiency, durability, refueling time, cost, codes, standards, life-cycle, and efficiency analysis (Jin Zhong Zhang, Jinghong Li, Yat Li, and Yiping Zhao, 2014). Compared to battery systems, hydrogen fuel storage is heavier at lower range and lighter after a certain point. In one comparison for a small vehicle, the cross point is at a distance of 150 miles. The following subsections present the considerations for storing hydrogen as a gas, liquid, and in solid material and discuss the viability of each approach for this capstone project. After comparing the different hydrogen storage options, gas was chosen for the current model due to availability.

Table 2. Storage Methods Overview



Method	Gravimetric Energy Density (wt %)	Volumetric Energy Density (MJ/L)	Temperature (K)	Pressure (barg)	Remarks
Compressed	5.7	4.9	293	700	Current industry standard
Liquid	7.5	6.4	20	0	Boil-off constitues major disadvantage
Cold/cryo compressed	5.4	4.0	40–80	300	Boil-off constitues major disadvantage
MOF	4.5	7.2	78	20–100	Attractive densities only at very low temperatures.
Carbon nanostructures	2.0	5.0	298	100	Volumetric density based on powder density of 2.1 g/mL and 2.0 wt % storage capacity.
Metal hydrides	7.6	13.2	260–425	20	Requires thermal management system.
Metal borohydrides	14.9–18.5	9.8–17.6	130	105	Low temperature, high pressure thermal management required
Kubas-type	10.5	23.6	293	120	
LOHC	8.5	7	293	0	Highly endo/exothermal requires processing plant and catalyst. Not suitable for mobility
Chemical	15.5	11.5	298	10	Requires SOFC fuel cell.

1. Storage as a Gas

Hydrogen is most commonly available in gas form. Storage of hydrogen as a gas typically requires high-pressure tanks (350–700 bar or 5,000–10,000 psi). The energy cost for 350 bar is 2.2 kWh/kg and the energy cost for 700 bar is 3.2 kWh/kg(U.S. Department of Energy 2009). Hydrogen gas storage can come in 20’ or 40’ tanks used for transport which may be ideal for onsite storage(U.S. Department of Energy 2015). The types of compressors are reciprocating, rotary, ionic, and centrifugal. Smaller tanks are available from many companies such as Steelhead industries. Figure 2 is an example of 4 tanks that will hold 8kg of hydrogen at 350 bar. The size of each tank is about 90L. Gas storage is ideal for providing a solution within 5 years.

Figure 2. Steelhead 8kg Hydrogen solution. Adapted from Steelhead Composites (2022.

2. Storage as a Liquid

Currently, liquefying hydrogen takes 12kWh of power per kilo of hydrogen, equivalent to about 25% of the energy that hydrogen would release in a fuel cell (U.S. Department of Energy 2009). The target is for liquid hydrogen to bring the power requirement below 6kWh (U.S. Department of Energy 2009). To create liquid hydrogen, the temperature of the gas must by brought below its boiling point of −252.8°C at one atmosphere pressure is (U.S. Department of Energy 2009). Hydrogen can be stored as a hybrid of gas and liquid which requires the low temperature and the high insulation tanks

(U.S. Department of Energy 2015). To compare with gas form, a liquid storage for 8kg would be 22 liters. Liquid hydrogen technology may be a more viable solution in 10 years.

3. Storage in Material

Metal hydride materials are a technology that uses adsorption which allows hydrogen to stick on the outside of the material (Zhang, Li, Li, and Zhao 2014). This can increase the density of hydrogen up to 150 kgm^{-3}(Zhang, Li, Li, and Zhao 2014). In comparison, chemical hydrogen storage uses absorption to hold the hydrogen inside of the material or liquid(Zhang, Li, Li, and Zhao 2014). Absorption can be through chemical or physical methods. One such physical method is using metal-organic frameworks such as crystal structures or carbon nanofibers(Zhang, Li, Li, and Zhao 2014). Chemical absorption (2-3 eV) has a much higher bonding energy compared to physical absorption (0.1 eV) (Zhang, Li, Li, and Zhao 2014). Even though the physical method is more energy efficient, the chemical method is more dense(Zhang, Li, Li, and Zhao 2014). Material storage is triggered by temperature variation and is more efficient at temperatures as low as 77K (Rivard, Trudeau, and Zaghib 2019). The hydrogen storage in 20 years could use this technology.

4. Future Storage

Beyond the traditional approaches of storage as a gas, liquid, or in a hybrid solid material, there are a few options there are additional options for hydrogen storage that may become viable in the future. Some options include: liquid organic hydrogen carriers, Kubas-type hydrogen, metal borohydrides, metal hydrides, and carbon nanostructures (Rivard, Trudeau, and Zaghib 2019). Thermal management is required for most of these technologies and therefore are not considered for this project.

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III. PROJECT ANALYSIS

A. OPERATIONAL AREA AND EXTERNAL SYSTEMS IDENTIFICATION

Future USN and USMC operations in an EABO environment require innovative approaches to handling logistics support. A major logistics concern in this arena is supplying fuel to support unmanned systems capabilities. The future warfighter in an EABO environment needs to minimize dependence on traditional fuel sources, such as petroleum. Renewable and abundant resources within an EABO environment provide the means to generate hydrogen fuel from seawater, which can be used by USN and USMC systems. A hydrogen fuel generation system needs to be developed that is capable of sustaining the refueling needs of multiple unmanned systems while being mobile and low-signature. The hydrogen system must be able to support the USN/USMC operations in a contested environment. This EABO environment is displayed in the Major Operational Activities Diagram in Figure 3. Multiple EABO sites are deployed across an island chain and are supported by USVs, UUVs, and UAVs. The hydrogen generation system serves as the refueling station for these unmanned vehicles. As is visible in the diagram, offshore forces are present but detached from the EABO sites.

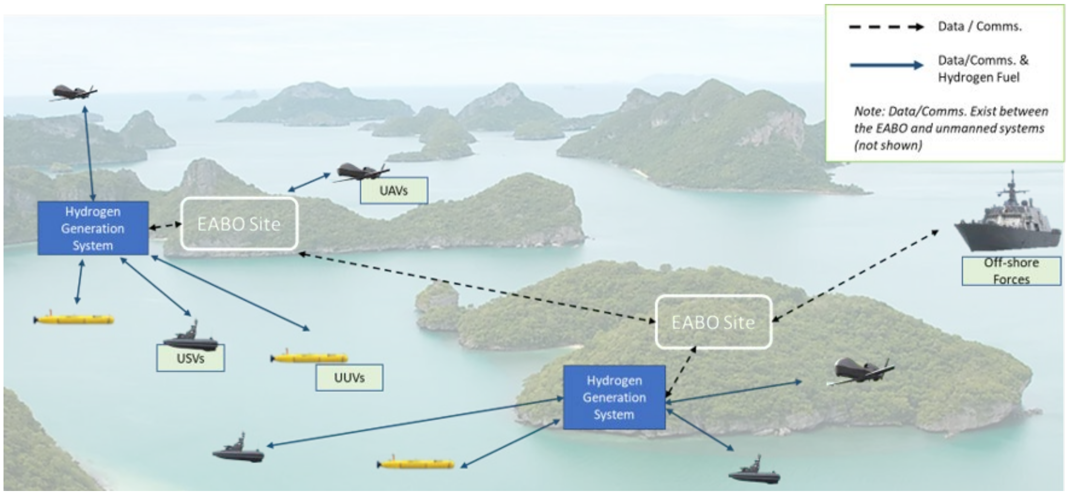

Figure 3. The Major Operational Activities Diagram for a Hydrogen Generation System in an EABO Environment. Adapted from World Atlas (2018).

In order to sufficiently meet the needs of the stakeholder, the hydrogen generation system cannot require external resources to operate. The hydrogen system will need to include the capability to generate the electricity to power the electrolysis of seawater into hydrogen. The electricity generation portion of the system is also constrained to using renewable and abundant resources in the EABO environment. As indicated above, mobility is a key factor for this system in an EABO environment. The CH-53 helicopter is assumed to be the primary mode of transporting this hydrogen capability across EABO sites. Therefore, the system is constrained by the size and weight limitations of what the CH-53 can carry.

A mobile generation system is needed to produce and dispense hydrogen fuel from seawater to unmanned systems operating in an EABO environment. This low-signature system needs to transportable by a CH-53 helicopter and require only the surrounding seawater and renewable, abundant resources to perform the hydrogen fuel process. As a result of this needs analysis, the external system interfaces were identified. The Figure 4 contains a diagram of the hydrogen generation system external interfaces. The diagram is organized such that input-related interfaces on the left side and output-related interfaces on the right side of the hydrogen system block.

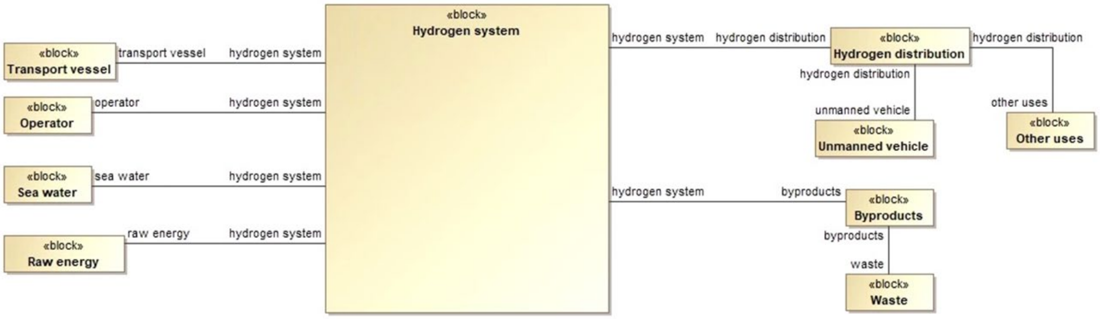

Figure 4. External Interface Diagram for the Hydrogen Generation System.

B. REQUIREMENTS ANALYSIS

The stakeholder needs and desired operational activities for the hydrogen generation system are used to develop initial requirements for the system. The table below summarizes the most important stakeholder needs discussed in the preceding section.

Table 3. List of Stakeholder Needs that Will Inform Requirements.

Major Stakeholder Needs	
I.	Decouple from logistics supply chain and petroleum fuel resources.
II.	Mobility of equipment in EABO environment.
III.	Support EABO and LOCE.

Initial requirements are translated from each of the stakeholder needs and begin to describe the desired capabilities of the hydrogen generation system. The initial system requirements are captured in Table 4.

Table 4. Initial Requirements for the Hydrogen Generation System.

Need	Requirement	
I	1.0	The system shall generate hydrogen fuel using seawater available at EABO sites
I	2.0	The system shall only require electricity that can be generated with renewable resources
II	3.0	The system shall be able to be transported within the weight limitations of a CH-53 helicopter.
III	4.0	The system shall interface with unmanned systems for refueling purposes

Along with the identified external interfaces, the system requirements outline more specifically what the hydrogen generation must be capable of in order to meet the stakeholder needs. The next step in developing system requirements is taking these high-level requirements and decomposing them into further detail. For the scope of this project, system requirements will remain at this high-level because the focus is to inform the development of a capability evolution plan. The next step is to take the identified needs and requirements and determine the necessary functions of the system. The system functions will then be used to inform the potential physical architecture of the hydrogen generation system. The system functions and architecture are discussed in the following section.

C. FUNCTIONAL ANALYSIS

The needed functions of the hydrogen generation system are developed from assessing the stakeholder needs and requirements and determining what the hydrogen system must do. For this capstone project, a majority of the system functions are directly tied to the activities involved in taking water and synthesizing hydrogen fuel.

The desired output from this hydrogen system is hydrogen fuel that can be used to refuel unmanned vehicles in an EABO environment. The key inputs to this process are the source of hydrogen, which is seawater, and the electricity required to operate the system. The system functions detail the actions to take these inputs and yield the desired output. The highest-level functions are identified in the Figure 5.

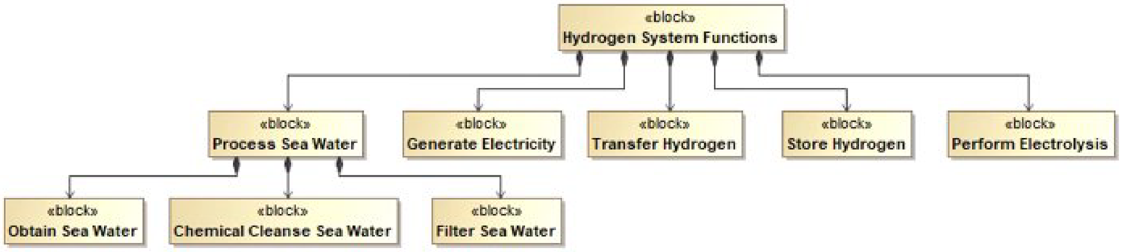

Figure 5. Top-level Function Block Diagram of the Hydrogen Generation System

A functional analysis of the hydrogen system follows a similar process to the requirements analysis: high-level functions are identified and then decomposed into further detail. This functional block diagram is used to build the functional block diagram, which factors in the inputs, outputs, mechanisms, and controls that are present. Figure 6 contains the functional flow of the hydrogen system; this diagram organizes the functions in the order that the system operates.

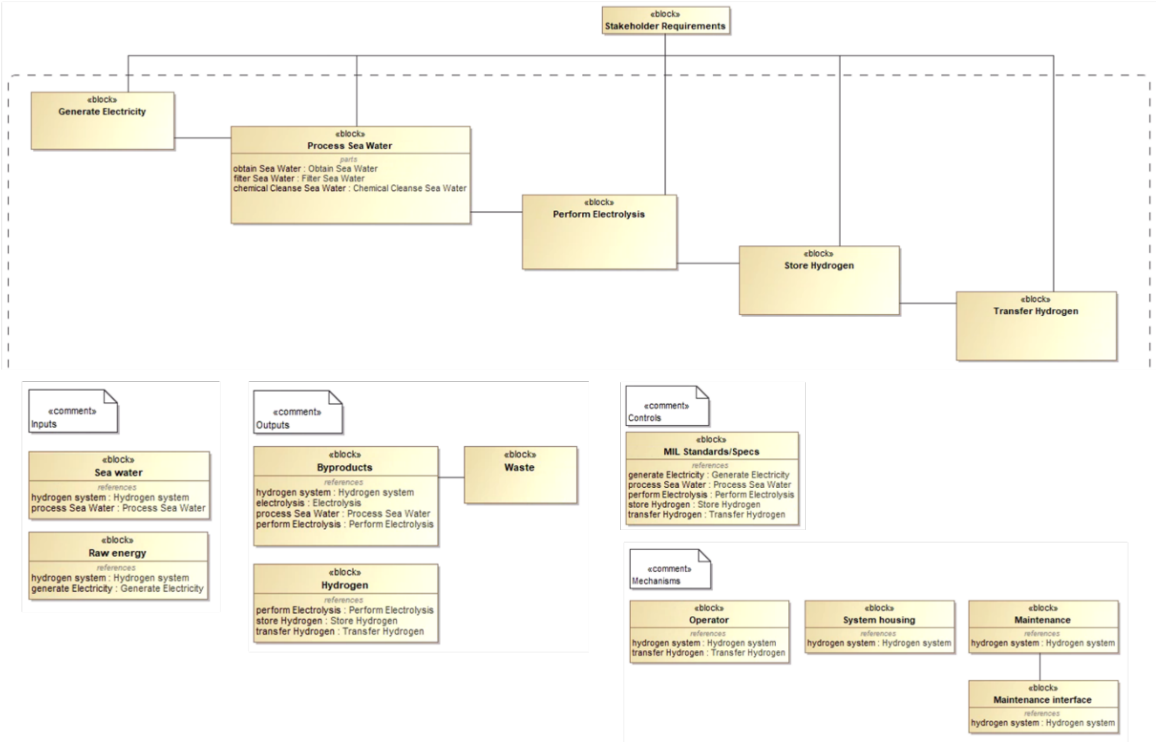

Figure 6. Top-level Functional Block Diagram for the Hydrogen Generation System

Each of the functions included in Figure 6 were broken down into the necessary lower-level functions of the hydrogen system creating additional lower-level functional flow block diagrams. Understanding the system functions at multiple levels provides insights into the type of architecture needed to perform the outlined functions.

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IV. MODEL DESCRIPTION

A. SUMMARY

To facilitate operational analysis the functions defined in Chapter III are implemented in a discrete-event simulation software program called ExtendSim. ExtendSim was chosen due to its ability to use variable data, set inputs, and then calculate several different results over many runs. The ExtendSim model is separated into three main functions. The functions are:

1. electricity generation and electrolysis.
2. hydrogen generation, storage, and transfer.
3. UxV activities.

Processing functions, such as Process Sea Water, will be assumed to have been performed and thusly not an activity block in the model

Figure 7 provides the framework view of the model.

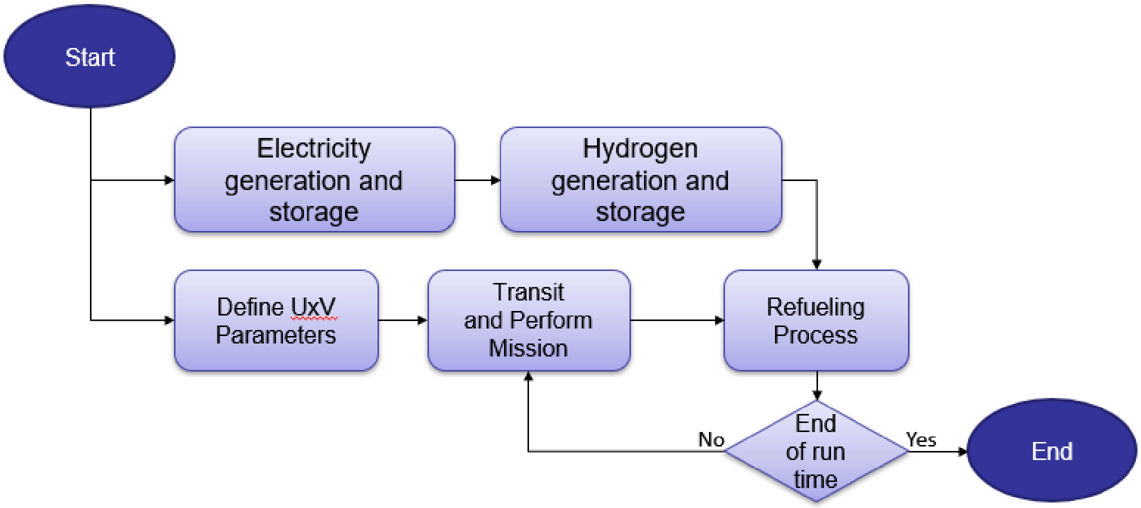


Figure 7. Model Framework

The subsequent sections will cover user inputs and model outputs, further detail about each of the model's functional areas, and the assumptions/limitations used for the model.

B. MODEL INPUTS AND OUTPUTS

1. User Inputs

To facilitate large scale input and output of data, the model allows the user to change various aspects of the model via the "Unmanned Vehicle" database. Within this database there are two tables that the user may input data: any input data pertaining to UxVs is stored in the "UxVParameters" table while all other data (e.g., mission times, refueling rate, power generation type) is stored in the "MissionParameters" table. Table 5 provides a list of inputs for the UxVParameters table and Table 6 provides the list of inputs for the MissionParameters Table.

a. UxV Parameters

Table 5. List of Input Parameters and Descriptions Pertaining to the UxVParameters Table

UxVParameters Table Description: This table contains data pertaining to UxV data.	
Item	Description
_CreateTime	This parameter specifies at what Scenario time a UxV should be created. UxVs will not be created if the _CreateTime value exceeds total simulation runtime. Units = minutes
_Item Quantity	This parameter specifies how many UxVs are created at _CreateTime. It is recommended that the user inputs a numerical value larger than 0. Units = integer

UxVParameters Table Description: This table contains data pertaining to UxV data.	
_Item Priority	This field is included so that this table and the Start activity block share the same parameters. The Start activity block is responsible for creating the UxVs. This parameter does not impact the model, and it is recommended that the user sets this parameter to one. Units = Integer
SumOperTime	This parameter is used only for debugging. It is recommended that the user sets this parameter to zero. Units = integer
FuelAmount	This parameter defines the UxV's starting fuel amount. It is recommended that the user sets this value equal to or less than TankSize parameter. Note that the model will not stop the user if inconsistent values are entered. Units = grams
TankSize	This parameter defines the size of UxV hydrogen tank. It is recommended that the user sets this value equal to or more than the FuelAmount parameter. Note that the model will not stop the user if inconsistent values are entered. Units = grams
BurnRate	This parameter defines the number of grams of hydrogen that is used per minute by the UxV while it is travelling or on a mission (i.e., UxV item is at either the "Vehicle Travel to Mission," "Vehicle on Mission" or "Vehicle return from Mission" activity blocks). Units = grams per minute

An example of the UxVParameters table is provided in Figure 7. For all runs, the example UxVParameters will generate the following UxVs:

- One UxV at time = 0 minutes that has 5000g hydrogen tank, 5000g of hydrogen fuel, and 3g/min burn rate;
- Two UxVs at time = 30 minutes that has 4500g hydrogen tank, 4000g of hydrogen fuel, and a 2.67g/min burn rate;

- One UxV at time = 60 minutes that has a 6000g hydrogen tank, 5780.65g of hydrogen fuel, and 3g/min burn rate.

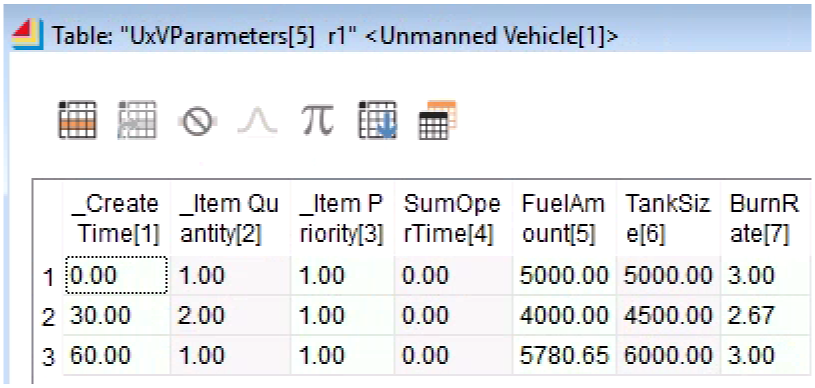


Table: "UxVParameters[5] r1" <Unmanned Vehicle[1]>

	_Create Time[1]	_Item Quantity[2]	_Item Priority[3]	SumOperTime[4]	FuelAmount[5]	TankSize[6]	BurnRate[7]
1	0.00	1.00	1.00	0.00	5000.00	5000.00	3.00
2	30.00	2.00	1.00	0.00	4000.00	4500.00	2.67
3	60.00	1.00	1.00	0.00	5780.65	6000.00	3.00

Figure 8. Example of User Input for UxVParameter Table

b. Mission and System Parameters

The Mission and System Parameters are defined in the MissionParameters table. Note that the number of records in this table must be equal to or greater than the number of runs set in the simulation (see Section IV.B.1.d for setting the number of runs). It is recommended that the user provide values for all the table records up to the number of runs being performed.

Table 6. List of Input Parameters and Descriptions Pertaining to the UxVParameters Table

Mission Parameters Table Description: This table contains data pertaining to Mission or the hydrogen system.	
Item	Description
Travel to Mission (Mean)	(Normal Distribution Parameter) This parameter defines the mean time the UxV will spend at "Vehicle Travel to Mission" activity block. Units: Minutes

Mission Parameters Table Description: This table contains data pertaining to Mission or the hydrogen system.	
Travel to Mission (STD)	(Normal Distribution Parameter) This parameter defines the Standard Deviation about the mean time that the UxV will spend at “Vehicle Travel to Mission” activity block. Units = minutes
Mission Time (Mean)	(Normal Distribution Parameter) This parameter defines the mean time the UxV will spend at “Vehicle on Mission” activity block. Units: Minutes
Mission Time (STD)	(Normal Distribution Parameter) This parameter defines the Standard Deviation about the mean time that the UxV will spend at “Vehicle on Mission” activity block. Units = minutes
Travel From Mission Time (Mean)	(Normal Distribution Parameter) This parameter defines the mean time the UxV will spend at “Vehicle Return from Mission” activity block. Units: Minutes
Travel From Mission Time (STD)	(Normal Distribution Parameter) This parameter defines the Standard Deviation about the mean time that the UxV will spend at “Vehicle on Mission” activity block. Units = minutes
Refuel Time (Mean)	(Normal Distribution Parameter) This parameter defines the mean amount of time that the system can transfer a gram of hydrogen. Note: that the total refuel time is also dependent on the amount of fuel needed to be transferred to the UxV. Units = minutes per gram.
Refuel Time (STD)	(Normal Distribution Parameter) This parameter defines the standard deviation about the mean time that the system can transfer a gram of hydrogen. Note: that the total refuel time is also dependent on the amount of fuel needed to be transferred to the UxV. Units = minutes per gram.
Power Type	This parameter defines the type of electrical generator to be used. Model currently holds four different electrical generators. The user should enter one of the following integer values.

Mission Parameters Table Description: This table contains data pertaining to Mission or the hydrogen system.	
	1 = Solar 2 = Wind (Rated 1kW) 3 = Wind (3kW) 4 = Wave/Tidal Note that the model will not stop the user from entering bad values and Power Types cannot be mixed.
Number of Devices	This parameter defines the number of electrical generators used. Units = Positive Integer

An example of user input of the MissionParameters table is provided below. Note that the values at each record number will be used with the corresponding simulation run (e.g., Record 2 values is applied to Run 2). The example will provide the following

- Run 1: UxVs will spend 60 ± 10 min traveling to the mission, 600 ± 60 minutes on the mission, and 60 ± 10 min returning back from the mission. The UxV will be refueled at a rate of 0.01 ± 0.001 g / min (ExtendSim will hold the small value but will only display two digits). The system will use three devices of Power Type = 1 (Solar).

- Run 2: UxVs will spend 60 ± 10 min traveling to the mission, 600 ± 60 min on the mission, and 60 ± 10 min returning back from the mission. The UxV will be refueled at a rate of 0.02 ± 0.001 g/min (ExtendSim will hold the small value but will only display two digits). The system will use four devices of Power Type = 2 (Wind).

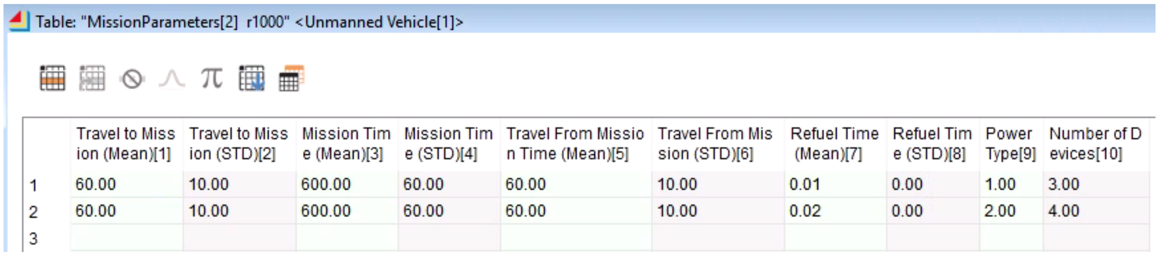


Table: "MissionParameters[2] r1000" <Unmanned Vehicle[1]>

	Travel to Mission (Mean)[1]	Travel to Mission (STD)[2]	Mission Time (Mean)[3]	Mission Time (STD)[4]	Travel From Mission Time (Mean)[5]	Travel From Mission (STD)[6]	Refuel Time (Mean)[7]	Refuel Time (STD)[8]	Power Type[9]	Number of Devices[10]
1	60.00	10.00	600.00	60.00	60.00	10.00	0.01	0.00	1.00	3.00
2	60.00	10.00	600.00	60.00	60.00	10.00	0.02	0.00	2.00	4.00
3										

Figure 9. Example of User Input for MissionParameters Table

c. *Direct Model User Input*

There are a few inputs the user may change but must be performed by changing model elements vice user input databases. The three inputs are: weather influence on travel times (multiplicative factor), initial value for hydrogen storage amount, and initial value for the system’s stored electrical power.

The user may change the weather factor by navigating to the bottom left of the model and double clicking the random number block marked “Weather.” The current values set for the weather is a normal distribution with a mean of one and standard deviation of 0.05.

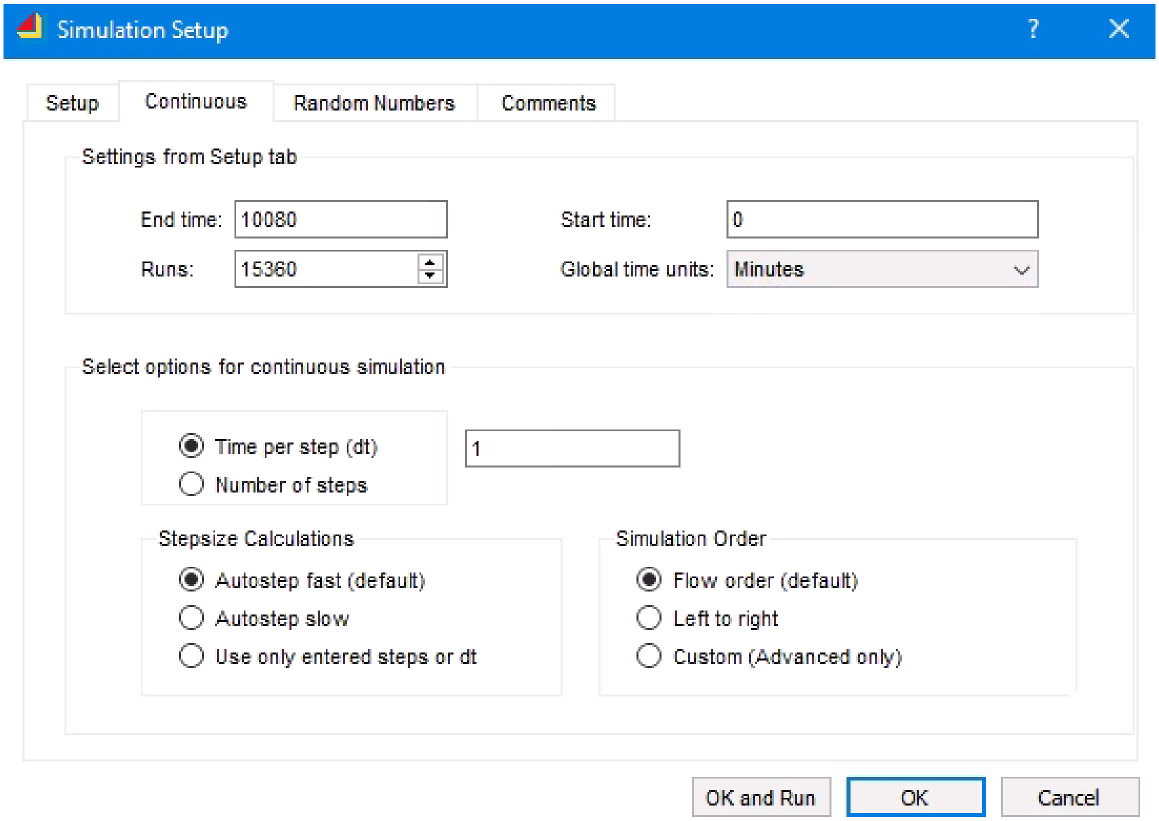
The user may set the initial values for the hydrogen storage amount and system stored electricity. Table 7 provides a description of the inputs. Note that these values will change throughout the run and if more that the initial conditions set will only apply to the first run. All subsequent runs will use the last values of the previous run as the initial conditions.

Table 7. List of Input Parameters and Descriptions Pertaining to the Refueling Values Table

<table>
<tr><td colspan="2">Refueling values Table
Description: This table contains the current amount of hydrogen stored in the system as well as the stored electrical power in the systems battery</td></tr>
<tr><td>Item</td><td>Description</td></tr>
<tr><td>Hydrogen amount</td><td>This parameter defines the current level of hydrogen in the system. Note that a storage limit of 9000g is imposed via the hydrogen generation elements in the model. Units = grams</td></tr>
<tr><td>Battery</td><td>This parameter defines the current power stored in the system’s battery. Note that a storage limit of 200kWh is imposed via the electrical generation elements in the model. Units = kWh</td></tr>
</table>

d. Scenario Parameters

The user may define the scenario start time (units = minutes), scenario end time (units = minutes), and the number of runs for the simulation by going to the top pulldown bar and selecting Run > Simulation Setup. It is recommended that the user does not alter the other values in the Simulation Setup dialog box. Figure 10 provides an example of a Simulation that starts at time = 0 minutes, ends at time = 10080 minutes (i.e., seven full days), and performs five runs.



Settings from Setup tab

End time: 10080

Start time: 0

Runs: 15360

Global time units: Minutes

Select options for continuous simulation

● Time per step (dt) 1
○ Number of steps

Stepsize Calculations

● Autostep fast (default)
○ Autostep slow
○ Use only entered steps or dt

Simulation Order

● Flow order (default)
○ Left to right
○ Custom (Advanced only)

Figure 10. Example of Simulation Setup Dialog Box

2. Outputs

After a simulation run is performed, all recorded data is stored into the Output Table in the UxV Parameters database. The model currently records the following outputs for every run performed in the simulation.

- Number of UxVs refueled
- Total Hydrogen Generated
- Total Electricity Generated
- UxV Average Queue Times (i.e., UxV's average wait time for refueling)

The user is also provided graphing blocks which will show the user the amount of hydrogen stored with the hydrogen system as well as total electricity available in the system battery. Note that these output graphs will only show the values with one simulation run and the values will be overwritten if another run is performed during the simulation.

If further outputs are desired, the model will need to be updated with additional recording elements.

C. ELECTRICAL GENERATION

Our system includes electricity generation and storage activities in order to decouple from the logistics chain. The model design and scenario incorporate these activities as described in Figure 11. The electricity generation and storage activities are executed in parallel with the EABO activities and is a precursor for the Hydrogen Generation and Storage Activities.

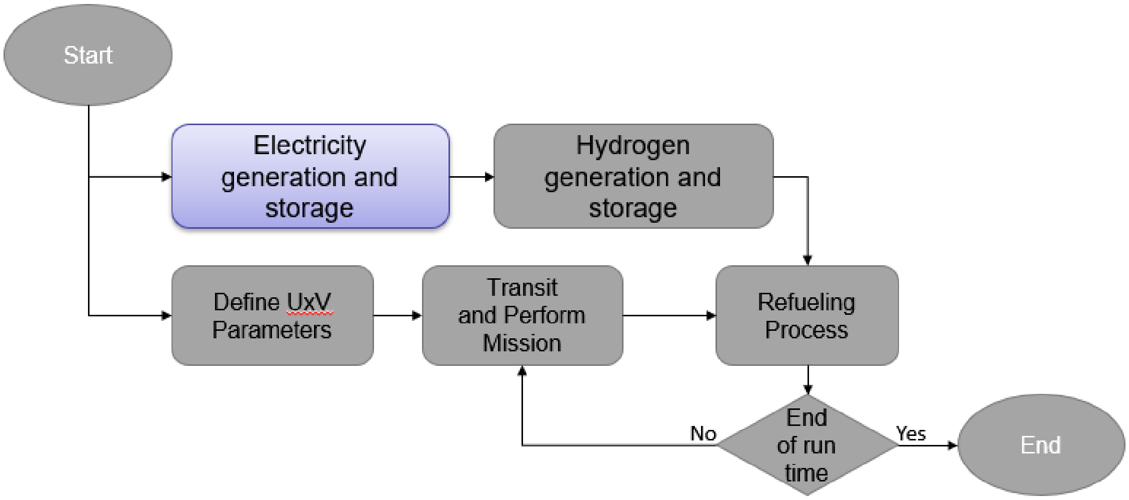


Figure 11. Electricity Generation and Storage Activities in the Model Design Process

The Electricity generation and storage activities can be broken further down into the following three functions

1. electricity generation via a renewable power source,
2. electrical power storage, and
3. electrolysis function.

These three functions are illustrated as the first three items in Figure 12, going from left-to-right, and further described in subsequent sections.

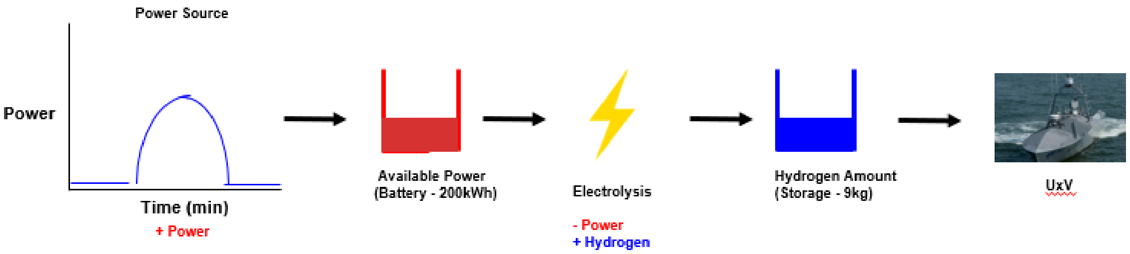


Figure 12. Model Design for Generating Electrical Power, Performing Electrolysis, and Transferring Hydrogen to the UxV

1. Electrical Generation via a Renewable Power Source

The first part of the Electrical Generation and Storage activities is to select a power source. The model contains 4 different electricity methods available to select from:

1. Solar
2. Wind (rated 1kW)
3. Wind (rated 3kW)
4. Wave/Tidal

Each of these electrical generators was modeled off pre-existing devices which is further detailed in Section II.B. The user is able to select one type of electrical generation as well as the number of devices.

a. Solar Power Implementation

The solar power type was implemented into the model via the positive values of a sine wave, as depicted in Figure 13. Any negative values of the sine wave were set to zero.

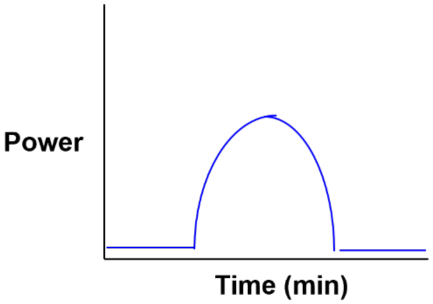


Figure 13. Modeling a Solar Power Source via the Positive Values of a Sine Wave

The generic form of the sine wave can be defined as follows. The proceeding subsections detail how each parameter was calculated

$$f(x) = A * \sin(B * X + C) + D$$

(1) Amplitude (Parameter A)

The amplitude was obtained by solving for parameters B, C, D of the generic sine equation first and then setting the integral of the generic sine equation to the average daily power. Then a calculator was used to solve for A. Using the WolframAlpha calculator, the parameter was found to be

$$A = 0.0562869$$

(2) Period (Parameter B)

The period of the sine wave was selected such that the period would equal 1,440 minutes (1 day). This will result in the waveform repeating every 1,440 minutes. The period can be obtained by utilizing the generic sine wave equation above and the equation

$$\text{period} = \frac{2 * \pi}{|B|}$$

The equation can be re-written to solve for B and then solved for with the period set to 1,440 minutes

$$\mathrm{B} = \frac{2 * \pi}{1440\mathrm{min}}$$

ExtendSim already has a global variable for pi and that was used in lieu of fully calculating the exact value for B. The final value used by ExtendSim is as follows

$$\mathrm{B} = \frac{\pi}{720\mathrm{min}}$$

(3) Phase (Parameter C)

The phase of the sine wave will dictate when positive values occur (e.g., when sunlight will occur). A phase shift can be introduced by subtracting the amount of right-shifting desired from the time variable. Time of 06:00 has been selected as the start of the day and thusly the sine wave is shifted by 360 minutes which will result in

$$C = -360\mathrm{min}$$

(4) Duty Cycle (Parameter D)

The y-intercept of the generic sine equation will dictate how much of the waveform will be positive/negative. One of the model assumptions is that there will be an equal amount of daylight (i.e., 12 hours) and equal amount of no daylight (e.g., 12 hours). This will result in a duty cycle of 50% and is achievable with the D Parameter set to 0.

Using the parameters defined above, the solar power waveform used for the model is as follows.

$$f_{\mathrm{solar}}(time) = A * \sin\left(\frac{\pi}{720\mathrm{min}} * time - 360\mathrm{min}\right) + 0$$

b. *Wind Power Implementation*

The Wind Power type was implemented into the model via a random number with a uniform distribution that is added to power storage every scenario time interval. Figure 14 provides a visual depiction of the power distribution provided to the system battery.

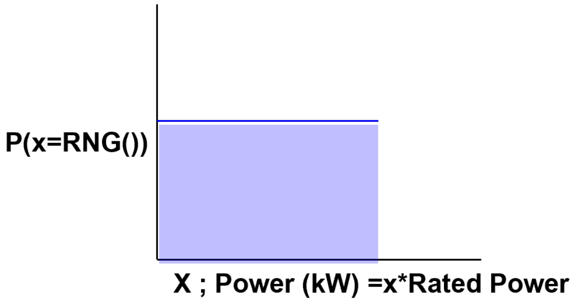


Figure 14. Wind Output Power Distribution

The amount of power added at each time interval was calculated by getting the average daily power of a wind turbine (see Section II.B.3 for the average daily power for the wind turbines selected), adjusting the average daily power to obtain the average power in 1 minute, and multiplying the average power in 1 minute by a random number ranging from 0 to 1. Since the expected value for the random number will converge to 0.5, the equation was multiplied by 2. This power can be expressed by the following equation.

$$f_{\mathrm{wind}}(time) = \frac{\mathrm{Power}_{\mathrm{daily}}}{24\mathrm{hours} * 60\mathrm{minutes}} * RNG_{\mathrm{uniform}}(0,1) * 2$$

c. *Wave/Tidal Power Implementation*

The Wave/Tidal power was implemented by adding a consistent static amount of power at each time interval. Figure 15 provides a visual depiction of the power provided to the system battery.

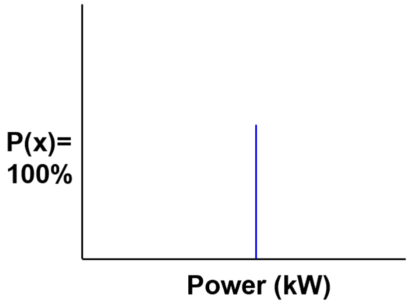


Figure 15. Wave/Tidal Output Power Distribution

The power value added at each time interval was obtained by taking the average daily power and adjusting the amount to obtain the average power in 1 minute. This power can be expressed by the following equation:

$$f_{\text{wave-tidal}}(time) = \frac{\text{Power}_{\text{daily}}}{24\text{hours} * 60\text{minutes}}$$

2. Electrical Power Storage

The electrical power storage of the system is where the electrical generator will deposit electrical power. The value for power storage was set to 200kWh limit which amount to approximately two Tesla car batteries. The model factors in losses due to electrical storage by removing 0.001% of the power at each time interval.

3. Electrolysis Function

The final function of the Electricity Generation Activities is the Electrolysis function. This function is performed only if there is enough electricity to perform electrolysis for 1 full minute. This restriction is based on the scenario time interval being set to minutes. Section IV.D provides further details on the values used for electrolysis and hydrogen storage.

D. HYDROGEN GENERATION AND STORAGE

The hydrogen generated is dependent on the electricity generated as well as the hydrogen reserves. This model tries to fill the reserves as fast as possible in an effort to fill the UxV as it needs to.

Hydrogen in the model is created using electrolysis as a baseline. The model creates 6.94 grams per minute for a maximum of 9.99 kilograms a day. The power demand in the model is 0.273 kilowatts per minute for a total of 393 kilowatts per day. The power demand is 39.3 kWh per kilogram of hydrogen created. This demand may be much higher depending on the electrolyzer and typically is 52.5 kWh (Blain 2022). The storage limit of the hydrogen created is much easier than creating the hydrogen. The model uses a 9-kilogram tank to fill 2 UxV that each have a 5-kilogram tank. To compress the hydrogen for the tank, the model uses 1.35 kilowatts per kilogram.

E. EABO ACTIVITIES

The ExtendSim model includes the following EABO activities: The UxV Parameters are defined in the beginning portion of the model. Then the transit and perform mission parameters are defined. Factors such as weather are taken into consideration. Following that, the refueling process is also modeled in ExtendSim Figure 16 outlines the sections of the model discussed in this portion.

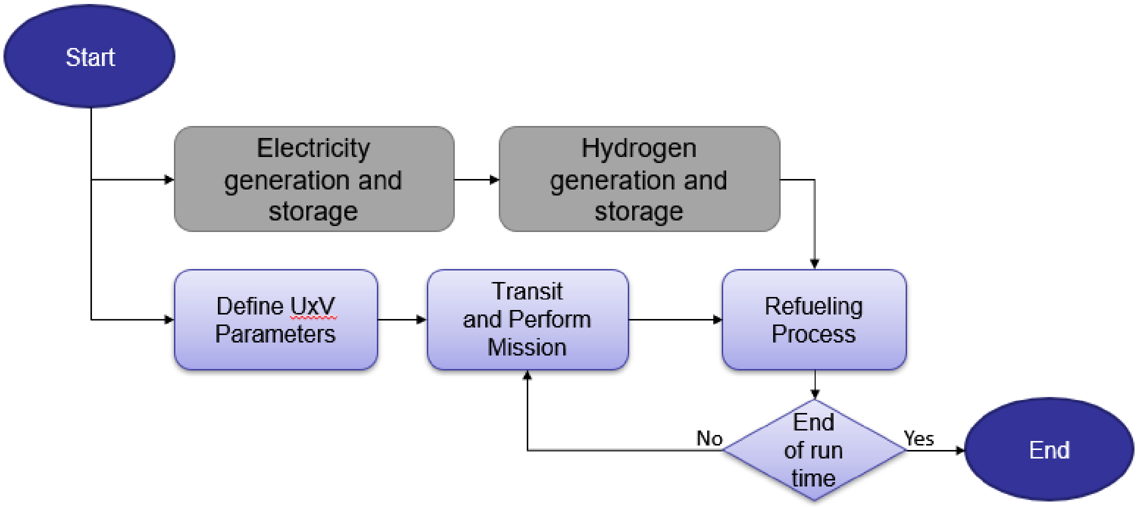


Figure 16. EABO Activities Summary

There are several UxV build parameters that can be changed by the user. The user can modify the UxV creation time, quantity of UxVs created, fuel type, tank size, and burn-rate. For this project model, these attributes can be defined in the "UxVParameter" database.

1. Transit and Perform Mission Activities

After being created with user defined "UxVParameters," the UxVs continue in the ExtendSim to the "Transit and Perform Mission" activities portion of the model. This is depicted in Figure 17. The duration of each activity is randomized using normal distributions where the mean and standard deviation are read into the model from the Mission Parameters database table. Note that weather is a factor, and it is incorporated into the ExtendSim model as a multiplying factor that extends the duration of each activity. These mission parameter functions can be viewed in Figure 18. Weather affects "travel mission time" and "Travel from mission" variables. The user can define these values in the "MissionParameters" database.

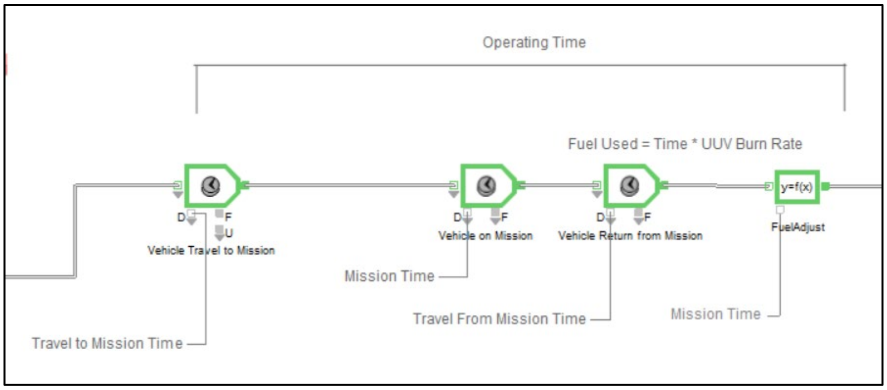


Figure 17. UxV on Mission

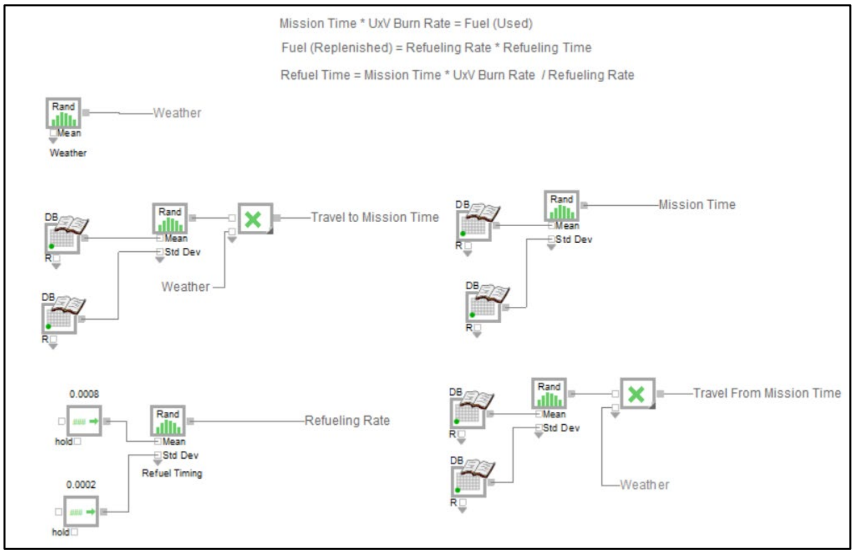


Figure 18. Defining UxV Mission Parameters

After returning from the mission, the UxVs enter the refueling process. This process is based on Refueling Rate (how fast Hydrogen can be transferred) and how much fuel is needed to supply the UxVs. It is assumed that the UxVs are being refueled to 100% of the tank capacity. When there is not enough hydrogen available in hydrogen reserves, the UxVs are put into a block labeled “EABO Queue.” Once there is a sufficient supply of hydrogen to refuel the UxV, it progresses to the refueling activity block. The refuel amount is calculated within the model. The quantity of hydrogen is subtracted from the reserves, and the UxV is sent back out on a mission. UxVs loop through the model until end of mission

F. MODEL ASSUMPTIONS AND LIMITATIONS

The model was built with assumptions and limitations incorporated and is as follows.

1. EABO Environment Activities

- Mission time starts at midnight (i.e., 00:00)
- 12 hours of daylight, not factoring in seasons or geographical location
- Missions will be 24 hours a day (non-stop)
- Payload helicopter can make multiple trips to deliver electricity generation devices
- User will ensure total weight of the system is within limits of transport
- Each time interval will be one minute

2. Unmanned Vehicle (UxV)

- UxVs need to be refueled to 100% fuel tank capacity
- UxVs do not undergo maintenance (either corrective or preventive)
- UxV burn rate will factor in items that influence how fast fuel will be consumed (e.g., drag, UxV shape, payload weight)
- UxV burn rate will not change over time

3. Electricity Generation and Storage

- No power losses between connections and/or interfaces
- Electrical generator types cannot be mixed (e.g., 1 Solar, 1 Wind Turbine)
- Electricity does not experience cycling losses.
- Electricity losses are experienced from storage.

- Losses from storage will remain constant percentage.

4. Hydrogen Generation and Storage

- Fuel provided to the UxVs will be consistent (e.g., impurities in the fuel will present with all batches of fuel)
- Single compressor will be used
- Hydrogen storage does not leak
- Hydrogen generation will match hydrogen transfer rate
- Standby mode does not use power
- Power is drawn/applied to hydrogen instantaneously. Hydrogen generation is created instantaneously
- UxV in queue does not burn up hydrogen

5. Base Units

- Battery will use kilowatt-hours (kWh),
- Power Generator will use kilowatts (kW),
- Hydrogen Fuel Amounts (Fuel Tank and Storage Tank) will be in grams.

There is a block in the diagram that can be used to employ probability of UxV breakdown. This feature is not currently utilized, but in the future, it could be implemented. In addition, preventative maintenance efforts have not been incorporated into the model.

V. MODEL RESULTS

A. INTRODUCTION

This chapter is organized into two distinct analyses. The first manually alters the system configuration to highlight the impact of UxV quantity and UxV burn rate. The second implements a formal experimental design approach as described in MacCalman, Beery, and Paulo (2016) to determine the operational and design decisions that have the largest impact on performance. The limits for the design of experiments were selected to be realistic and modelled on pre-existing technologies and values if available.

B. PRELIMINARY DESIGN OF EXPERIMENTS

For the initial EABO experiments, the model started with using 2 UxVs and a single power source to create hydrogen. The goal of the experiment was to have a queue time of near zero for a model run for a complete day. At the start of the experiment, the hydrogen and battery amount are set to zero. The experiments also compared the number of UxVs with those values being 1 and 2. The test was then run with the burn rate being reduced to to 2.5g/min from a baseline value of 3g/min. Each power generator was run at 3 different ratings and repeated 5 times. The three solar ratings for the day are 77.4 kW, 103 kW, and 129 kW. The three 1kW wind ratings for the day are 70.4 kW, 80 kW, and 86.4 kW. The three 3kW wind ratings for the day are 72 kW, 81 kW, and 90 kW. The three wave ratings for the day are 67.2 kW, 75.6 kW, and 84 kW. Figures 19–22 present the results of those experiments, focused on the impact that changes to electricity generation type has on UxV queue time.

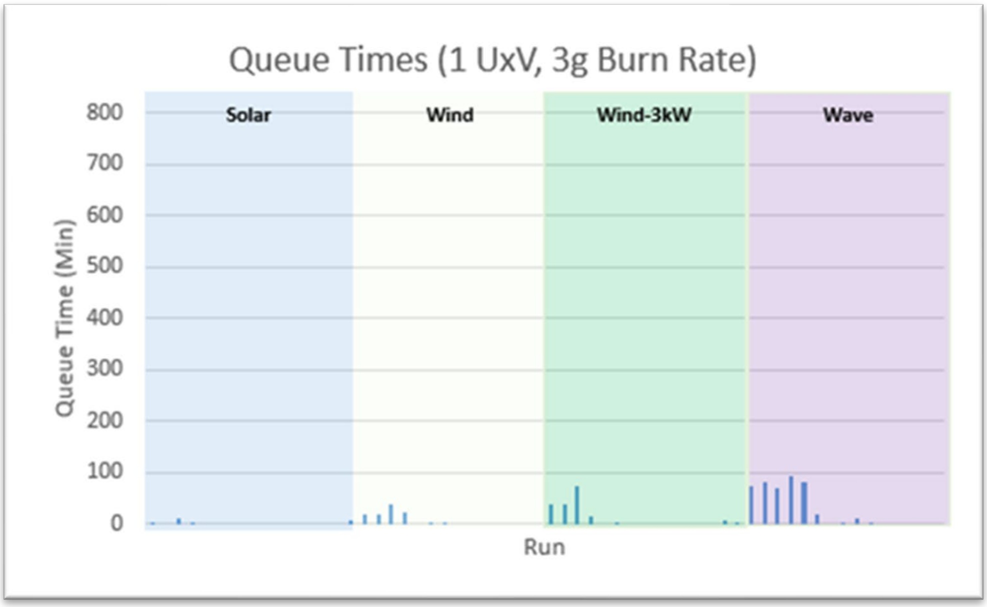


Figure 19. 1UxV at 3g/min

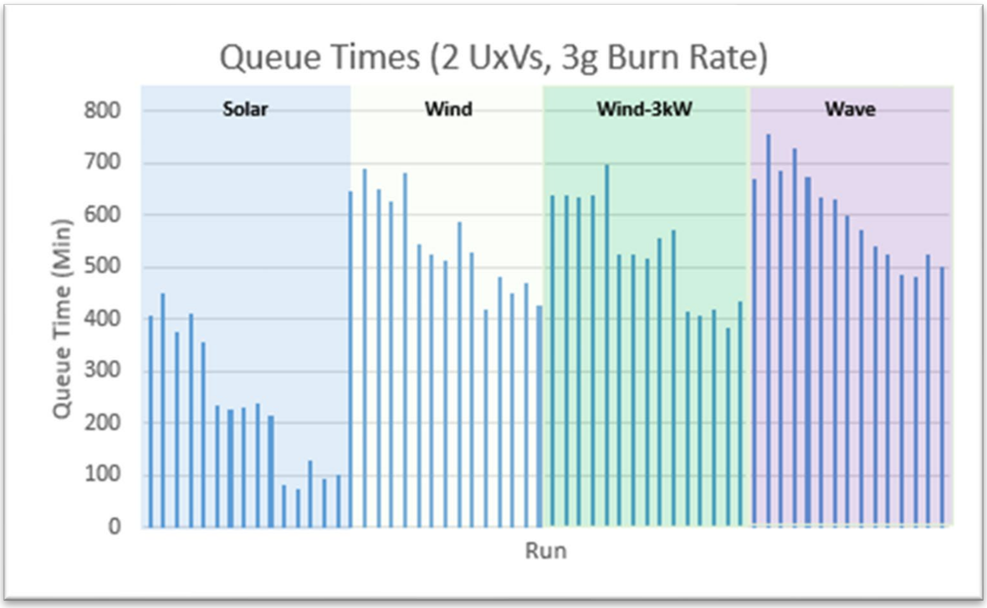


Figure 20. 2UxV at 3g/min

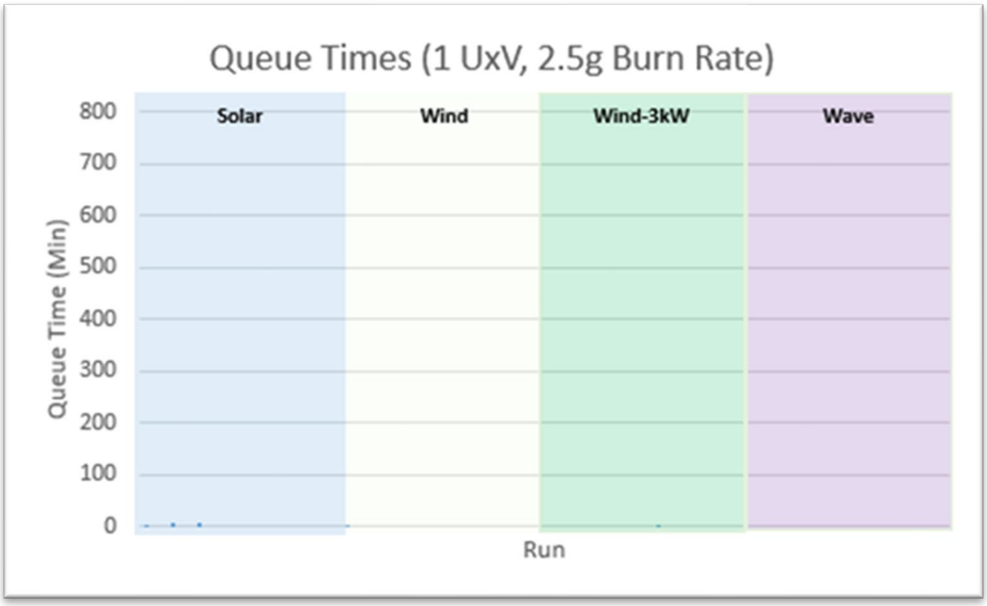


Figure 21. 1UxV at 2.5g/min

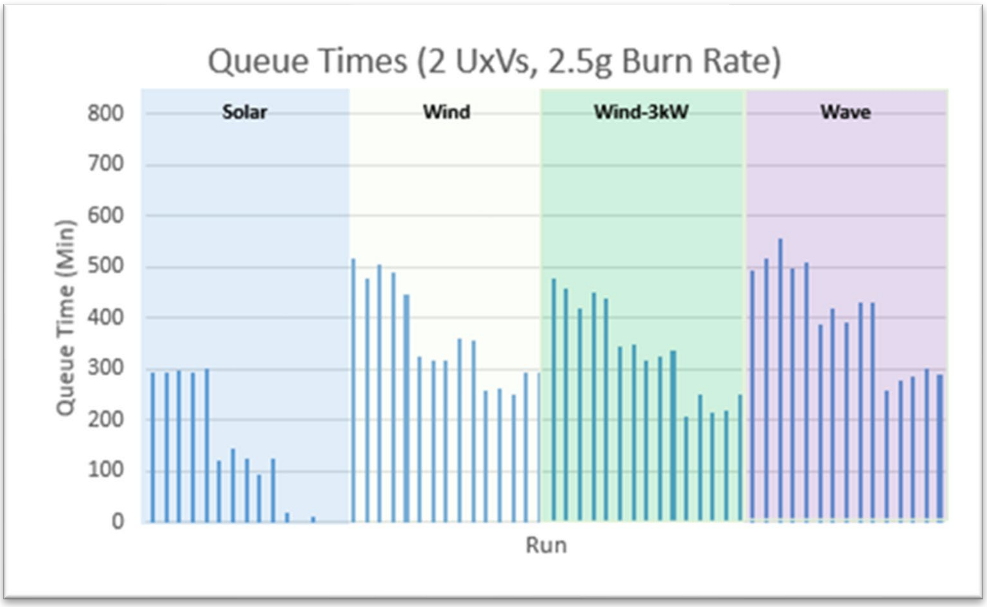


Figure 22. 2UxV at 2.5 g/min

The power type and number of devices was selected such that the overall power amounts were relatively close to each other. Each configuration was simulated 5 times. Figure 19 and Figure 20 depict the queue time when comparing one UxV vs. two UxVs with the burn rate set to 3g/min. It can be seen that the queue time drastically increases by adding an additional UxV. Each of these figures includes values for the four different electricity generation sources: solar, wind, wind-3kW, and wave. Notice that with one UxV, the queue time is less than 100 minutes in all cases. Once an additional unit is added, the queue time for each of the energy source type increases.

Figure 21 and Figure 22 depict UxV Queue Time with a lower burn-rate of 2.5g/min. The queue time for one UxV is very low and barely appears on the graphs. When adding an additional UxV unit, the queue time increases for all the energy sources, but the systems perform better than with the higher burn rate. Overall, increasing the UxV number made the most impact while burn rate, power type, and number of devices had a less but still substantial impact.

C. DETAILED DESIGN OF EXPERIMENTS

To conduct a more in-depth assessment of the drivers of overall operational effectiveness a formal design of experiments approach was employed to systematically vary the characteristics of the hydrogen generation system. The detailed design of experiments is composed of a multi-variate analysis and a least-fit-squares analysis. The design of the experiment starts with adjusting input variables and measuring the output response (i.e., Number of UxVs refueled). The inputs that were adjusted for the design of experiment is as follows:

- The number of UxVs from 1 to 4
- The tank size for the UxVs in grams of hydrogen from 4000 to 6000
- The burn rate for the UxVs in grams per minute from 2.5 to 3.5
- The mean travel to and from mission time in minutes from 40 to 80 (note that standard deviation for these travel times remained the same)
- The mean mission time in minutes from 500 to 700 (note that standard deviation for the mission time remained the same)

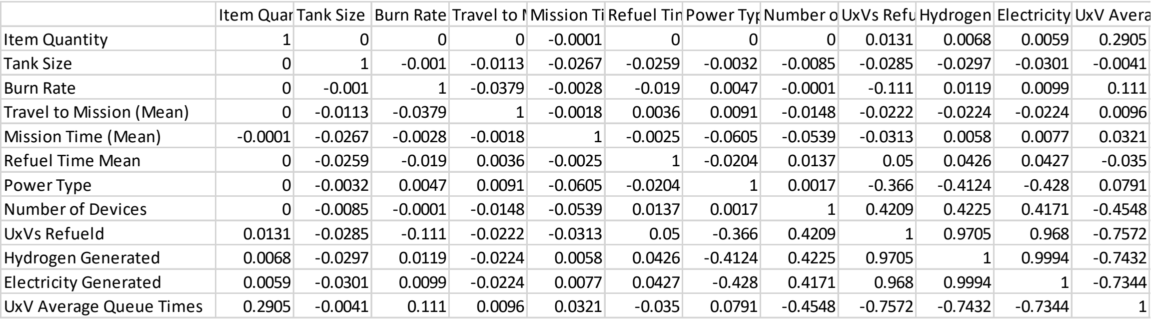
- The mean time to refuel per gram of hydrogen from 0.0005 to 0.001
- The power type of the electricity generator defined as solar, wind-1kW, wind-3kW, and tidal. These are designated with the numbers 1, 2, 3, and 4, respectively
- The number of generators of the defined power type from 5 to 30.

The outputs collected for each run are: hydrogen generated, electricity generated, Number of UxVs refueled, and the average queue times to refuel a UxV. This analysis focuses on the Number of UxVs refueled output. A nearly orthogonal/nearly balanced experimental design with 512 design points was generated using (Vieira 2012). The full design was repeated for each of the electricity generation alternatives, resulting in a total of 2,048 design points. To capture model variability each design point was replicated 30 times, for a total of 61,440 simulation runs.

1. Multivariate Analysis

The first analysis performed was a multi-variate analysis, and the intention was to find the correlation between the different inputs and outputs which is provided in Table 8.

Table 8. Correlation of Inputs and Outputs



	Item Quar	Tank Size	Burn Rate	Travel to	Mission Ti	Refuel Ti	Power Typ	Number o	UxVs Refu	Hydrogen	Electricity	UxV Avera
Item Quantity	1	0	0	0	-0.0001	0	0	0	0.0131	0.0068	0.0059	0.2905
Tank Size	0	1	-0.001	-0.0113	-0.0267	-0.0259	-0.0032	-0.0085	-0.0285	-0.0297	-0.0301	-0.0041
Burn Rate	0	-0.001	1	-0.0379	-0.0028	-0.019	0.0047	-0.0001	-0.111	0.0119	0.0099	0.111
Travel to Mission (Mean)	0	-0.0113	-0.0379	1	-0.0018	0.0036	0.0091	-0.0148	-0.0222	-0.0224	-0.0224	0.0096
Mission Time (Mean)	-0.0001	-0.0267	-0.0028	-0.0018	1	-0.0025	-0.0605	-0.0539	-0.0313	0.0058	0.0077	0.0321
Refuel Time Mean	0	-0.0259	-0.019	0.0036	-0.0025	1	-0.0204	0.0137	0.05	0.0426	0.0427	-0.035
Power Type	0	-0.0032	0.0047	0.0091	-0.0605	-0.0204	1	0.0017	-0.366	-0.4124	-0.428	0.0791
Number of Devices	0	-0.0085	-0.0001	-0.0148	-0.0539	0.0137	0.0017	1	0.4209	0.4225	0.4171	-0.4548
UxVs Refueld	0.0131	-0.0285	-0.111	-0.0222	-0.0313	0.05	-0.366	0.4209	1	0.9705	0.968	-0.7572
Hydrogen Generated	0.0068	-0.0297	0.0119	-0.0224	0.0058	0.0426	-0.4124	0.4225	0.9705	1	0.9994	-0.7432
Electricity Generated	0.0059	-0.0301	0.0099	-0.0224	0.0077	0.0427	-0.428	0.4171	0.968	0.9994	1	-0.7344
UxV Average Queue Times	0.2905	-0.0041	0.111	0.0096	0.0321	-0.035	0.0791	-0.4548	-0.7572	-0.7432	-0.7344	1

The results presented in Table 8 are also shown graphically in Figure 23, which displays the scatterplot results of the multi-variate analysis. The red square in Figure 23 highlights the inputs while the blue square highlights the outputs. The inputs are independent from each other (i.e., a low correlation value). There are two important takeaways from Table 8 and Figure 23. First, there is near zero correlation between the input variables, which demonstrates that the experimental design is appropriate. Second, there is correlation between the output variables that establishes validity of the model. Notice that electricity generation is strongly correlated with hydrogen generation, establishing that the connection between model subsections for electricity and hydrogen generation are working properly. Additionally, notice that hydrogen generation is positively correlated to the Number of UxVs refueled and negatively correlated to the UxV Queue Time, indicating that production of hydrogen within the model is successfully fueling UxVs and, as a result, decreasing fueling wait time. Figure 23 shows an interesting limitation to solar power. This is due to the power only being created during the day and completely filling the 200kW battery. This prevents the hydrogen generation to reach it's max of 9.99 kg.

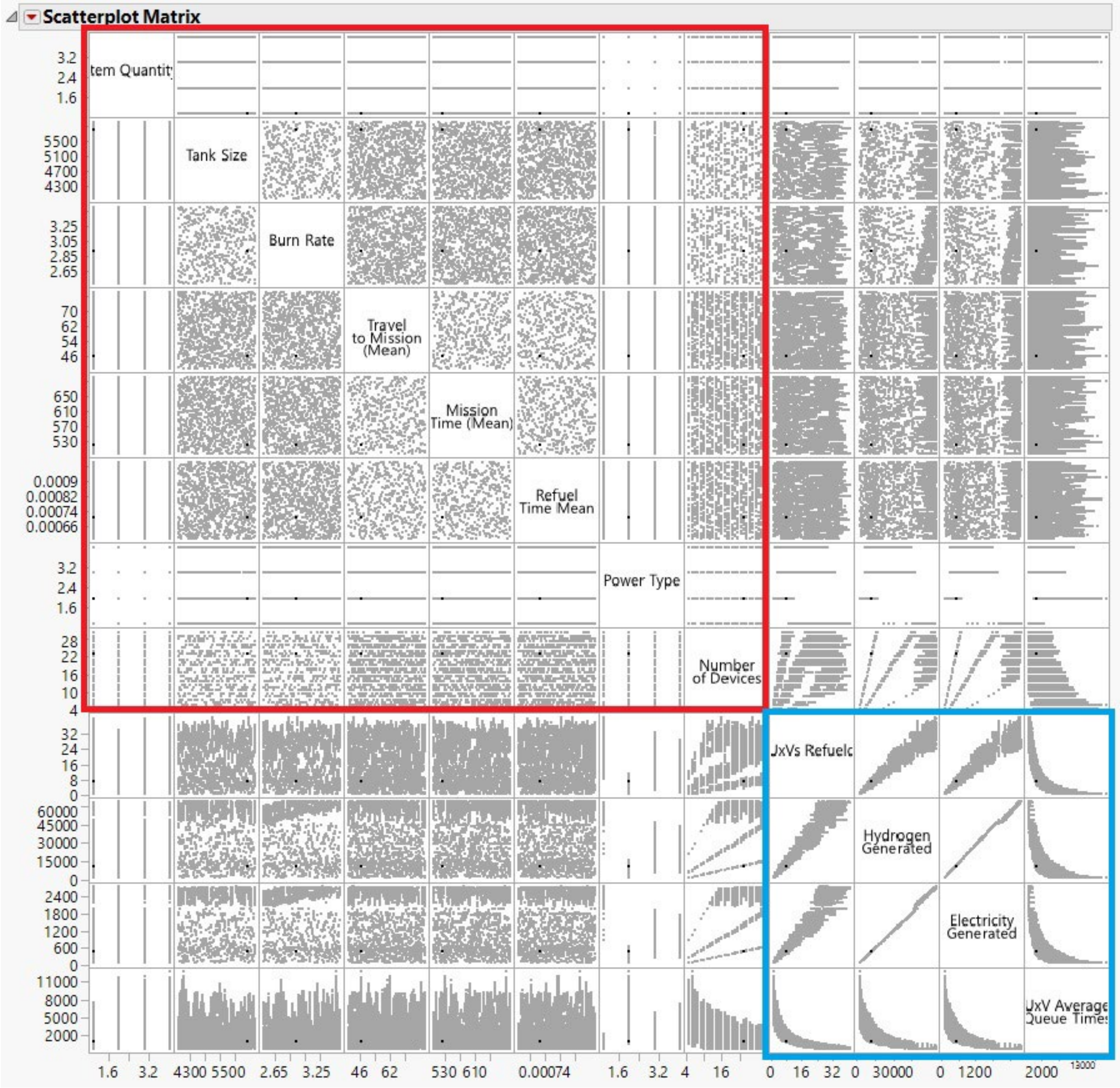
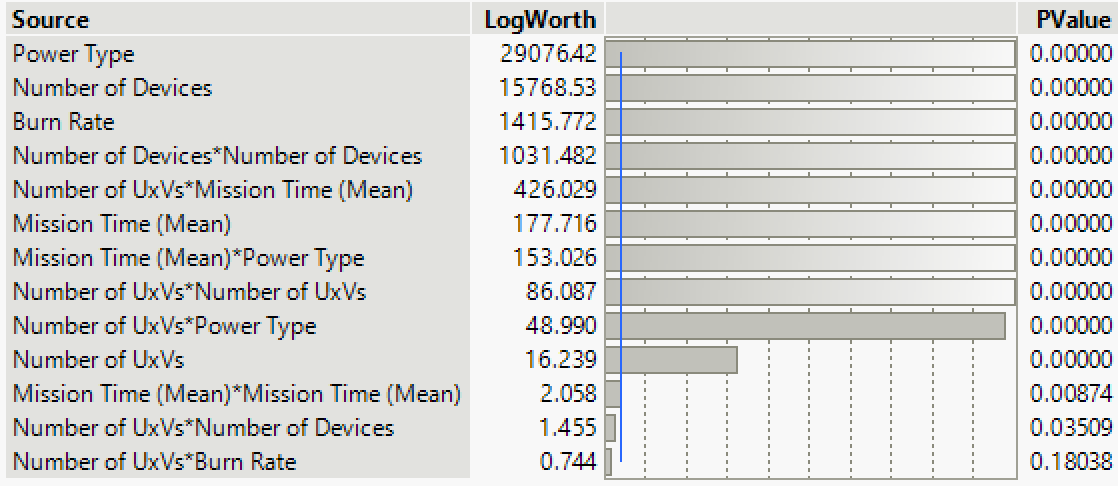


Figure 23. Multivariate Scatterplot with Inputs Highlighted in Red and Outputs in Blue

2. Least-Fit-Squares Analysis

A least-fit-squares analysis was conducted with the provided list of inputs and the UxVs Refueled output was measured. This analysis showed that Power Type, Number of Devices, Burn Rate, Mission Time (Mean), and Number of UxVs had a statistically significant impact on the output results; Figure 24 provides the full list of inputs and their impact.



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 24. Regression Analysis Inputs Sorted from Most Impactful to Least Impactful. Not All Inputs Are Shown

Because several interactions were identified as statistically significant in Figure 24, an interaction profiler was generated. Figure 25 provides a map of the interactions between input variables that impact the Number of UxVs Refueled.

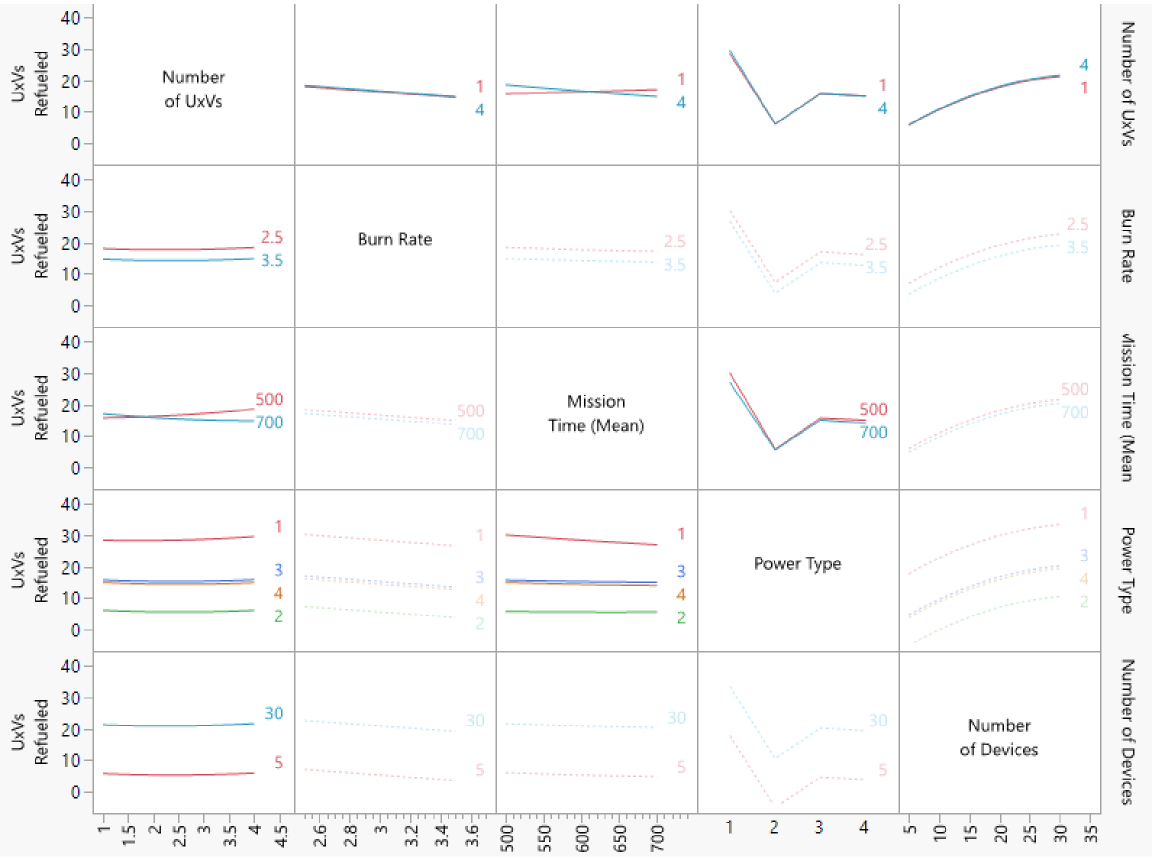


Figure 25. Interaction Profile for Impactful Inputs and UxVs Refueled Output

While there are several interactions that are identified as statistically significant, assessment of Figure 25 suggests that there are no operationally significant interactions that need to be discussed. The only interaction that has any noticeable impact on performance is the interaction between the Number of UxVs and the Mission Time, where an increase to Mission Time increases the Number of UxVs refueled when only a single UxV is employed and decreases the Number of UxVs refueled when four UxVs are employed. Alternatively stated, if you expect mission time to be very low, you would want to have more UxVs. If you have a very high mission time, then it is less important to have a large amount of UxVs.

3. Decision-Tree Analysis

Decision-Tree analysis was performed to provide a hierarchical list of the most impactful factors in the model. The outcomes used to determine the list was the Number of UxVs Refueled and the average UxV refueled Queue Time. Figure 26 shows a graphical representation of the decision-tree analysis while Figure 27 presents the results of the decision-tree analysis as a hierarchy chart. The first decision tree analysis was conducted using the Number of UxVs refueled as the performance metric. The variable that had the largest impact on the Number of UxVs refueled was the selection of Power Type 1 (rather than Power Types 2, 3, or 4). Examining the right side of Figure 27 shows that Power Type 1 (solar) results in an average of approximately 27 UxVs refueled. Continuing on that branch of the decision tree shows that the variable that has the largest impact on performance, contingent on the use of Power Type 1 (solar) is the Number of Devices. Having greater than 10 solar devices increases the Number of UxVs refueled to approximately 30, compared to an average of 15 UxVs refueled when there are fewer than 10 solar devices. Examining the left side of Figure 27 shows the variables that have the largest impact when Power Type 1 (solar) is not utilized. In this case, Power Type 2 (1 kW wind turbine) is less effective than either Power Type 3 or 4. Use of Power Type 2 (the 1 kW wind turbine) results in an average of approximately 5 UxVs refueled and an increase to 21 total devices only increases the total Number of UxVs refueled to approximately 7.5. The 3-kW wind turbine and the tidal/wave (Power Types 3 and 4) had an overall average of approximately 14 UxVs refueled, which can be increased to approximately 20 UxVs refueled when the Number of Devices is increased to 19.

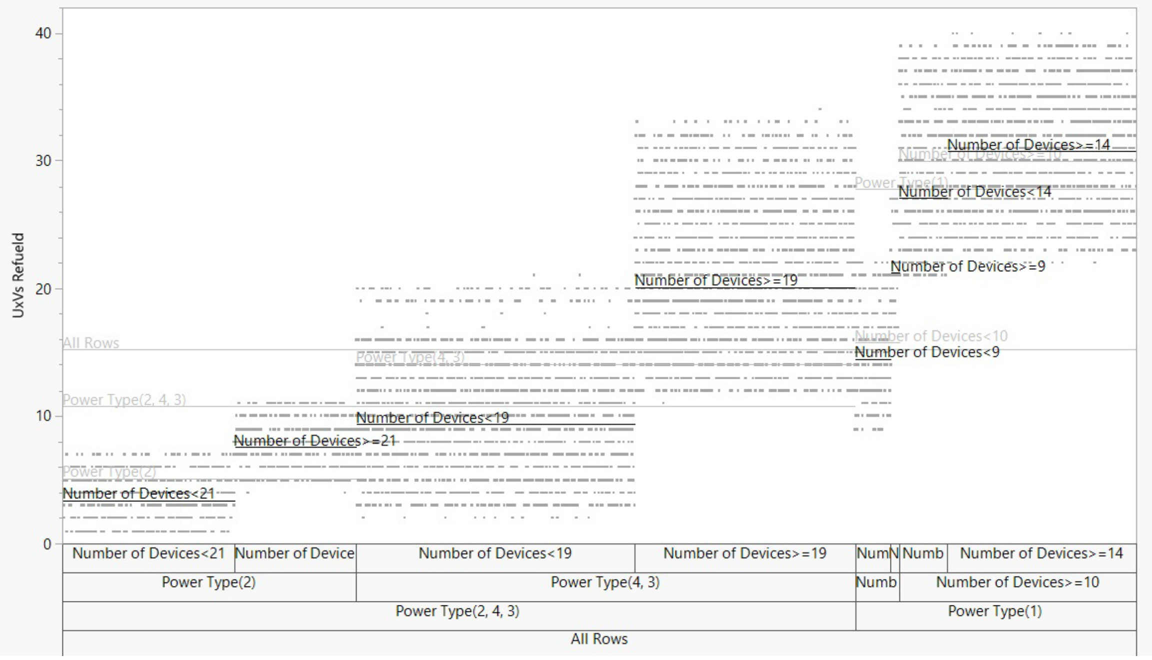
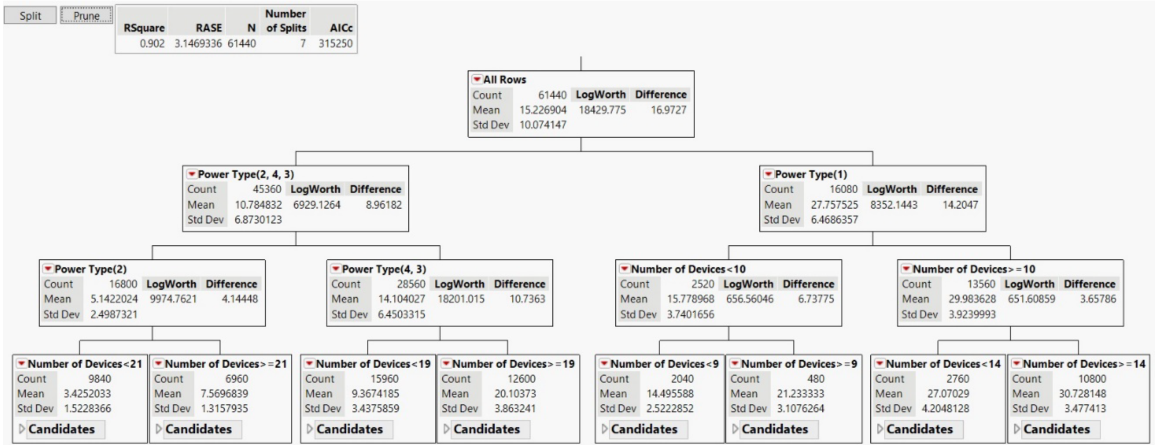


Figure 26. Decision Tree Chart for UxVs Refueled



RSquare	RASE	N	Number of Splits	AICc
0.902	3.1469336	61440	7	315250

All Rows
Count 61440 LogWorth 18429.775 Difference 16.9727
Mean 15.226904
Std Dev 10.074147

Power Type(2, 4, 3)
Count 45360 LogWorth 6929.1264 Difference 8.96182
Mean 10.784832
Std Dev 6.8730123

Power Type(1)
Count 16080 LogWorth 8352.1443 Difference 14.2047
Mean 27.757525
Std Dev 6.4686357

Power Type(2)
Count 16800 LogWorth 9974.7621 Difference 4.14448
Mean 5.1422024
Std Dev 2.4987321

Power Type(4, 3)
Count 28560 LogWorth 18201.015 Difference 10.7363
Mean 14.104027
Std Dev 6.4503315

Number of Devices<10
Count 2520 LogWorth 656.56046 Difference 6.73775
Mean 15.778968
Std Dev 3.7401656

Number of Devices>=10
Count 13560 LogWorth 651.60859 Difference 3.65786
Mean 29.983628
Std Dev 3.9239993

Number of Devices<21
Count 9840
Mean 3.4252033
Std Dev 1.5228366
Candidates

Number of Devices>=21
Count 6960
Mean 7.5696839
Std Dev 1.3157935
Candidates

Number of Devices<19
Count 15960
Mean 9.3674185
Std Dev 3.4375859
Candidates

Number of Devices>=19
Count 12600
Mean 20.10373
Std Dev 3.863241
Candidates

Number of Devices<9
Count 2040
Mean 14.495588
Std Dev 2.5222852
Candidates

Number of Devices>=9
Count 480
Mean 21.233333
Std Dev 3.1076264
Candidates

Number of Devices<14
Count 2760
Mean 27.07029
Std Dev 4.2048128
Candidates

Number of Devices>=14
Count 10800
Mean 30.728148
Std Dev 3.477413
Candidates

Figure 27. Hierarchy Chart for UxVs Refueled

Another decision-tree analysis was performed using the UxV Queue Time as the performance metric (lower queue times are better). Figure 28 shows a graphical representation of the decision-tree analysis while Figure 29 presents the results of the decision-tree analysis as a hierarchy chart. The analysis showed that choosing Power Type 1, 3, or 4 vice Power Type 2 has the most impact on results. The Number of Devices is the next most impactful factor, with 10 devices being the dividing point that has the largest impact. Notice that regardless of whether greater than or less than 10 devices are utilized, the next decision that has the largest impact on reduction to Queue Time is the use of Power Type 1 (solar).

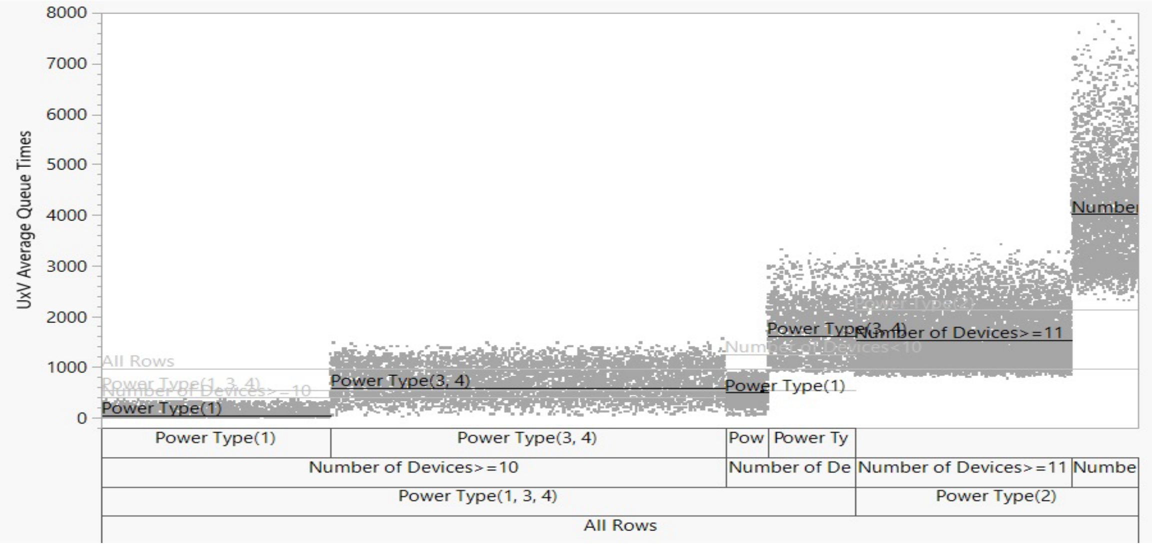
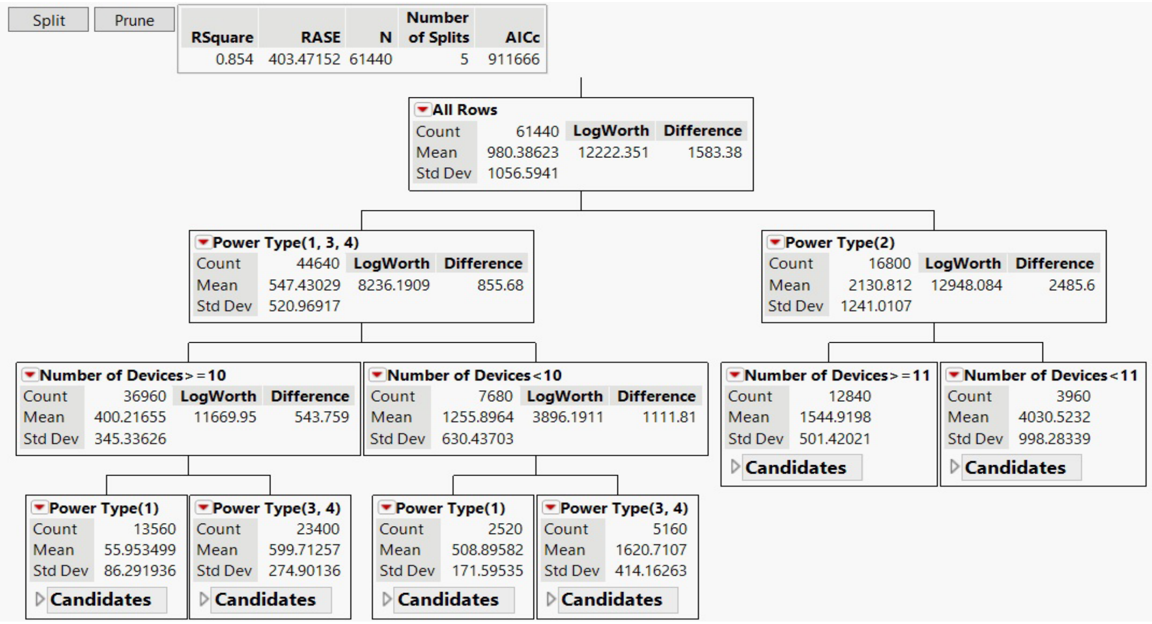


Figure 28. Decision Tree Chart for UxV Queue Times



RSquare	RASE	N	Number of Splits	AICc
0.854	403.47152	61440	5	911666

All Rows

		LogWorth	Difference
Count	61440		
Mean	980.38623	12222.351	1583.38
Std Dev	1056.5941		

Power Type(1, 3, 4)

		LogWorth	Difference
Count	44640		
Mean	547.43029	8236.1909	855.68
Std Dev	520.96917		

Power Type(2)

		LogWorth	Difference
Count	16800		
Mean	2130.812	12948.084	2485.6
Std Dev	1241.0107		

Number of Devices>=10

		LogWorth	Difference
Count	36960		
Mean	400.21655	11669.95	543.759
Std Dev	345.33626		

Number of Devices<10

		LogWorth	Difference
Count	7680		
Mean	1255.8964	3896.1911	1111.81
Std Dev	630.43703		

Number of Devices>=11

Count	12840
Mean	1544.9198
Std Dev	501.42021

Number of Devices<11

Count	3960
Mean	4030.5232
Std Dev	998.28339

Power Type(1)

Count	13560
Mean	55.953499
Std Dev	86.291936

Power Type(3, 4)

Count	23400
Mean	599.71257
Std Dev	274.90136

Power Type(1)

Count	2520
Mean	508.89582
Std Dev	171.59535

Power Type(3, 4)

Count	5160
Mean	1620.7107
Std Dev	414.16263

Figure 29. Hierarchy Chart for UxV Queue Times

While each of the previous analyses focused inputs that a system designer may practically control, it is also useful to highlight the electricity that needs to be generated in order to achieve certain performance levels. While the amount of electricity generated may not be practically controllable, it facilitates definition of measures of performance that may be useful to inform system development. Figure 30 and Figure 31 show another decision-tree analysis which focuses on the impacts to UxV average Queue Time and Number of UxVs by varying the amount of electricity generated. As expected, more electricity results in lower refueling Queue Time as well as a higher amount of UxVs refueled.

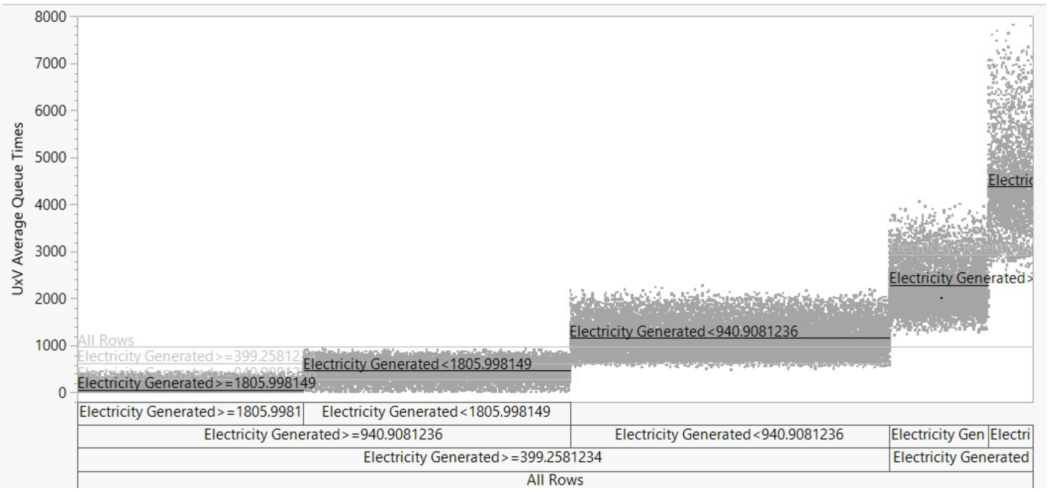


Figure 30. Decision Tree Chart for Queue Times with Electricity Generated

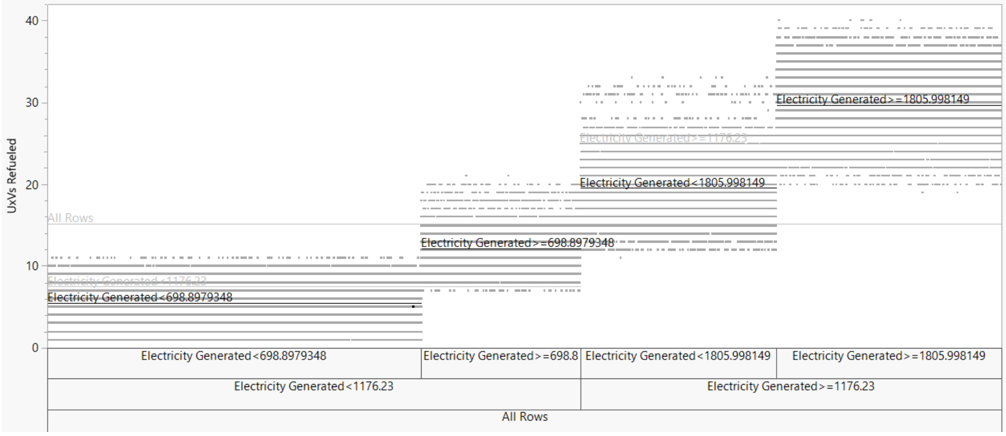


Figure 31. Decision Tree Chart for UxVs Refueled with Electricity Generated

There are a few major takeaways from this analysis. For both output metrics of interest (i.e., UxVs Refueled and UxV Queue Time) the use of solar for electricity generation is a statistically significant preferred choice. For both output metrics of interest (i.e., UxVs Refueled and UxV Queue Time), the use of a 1 kW wind turbine is a statistically significant underperformer when compared to the other alternatives.

VI. CONCLUSION / PATH FORWARD

The purpose of this capstone project was to analyze the potential use of hydrogen fuel generated via a mobile, independent system to address logistics and fuel depletion concerns for an EABO environment. To conduct that analysis, an ExtendSim discrete-event model was created to estimate the performance of a hydrogen fuel system in an EABO environment. The model was set up to generate hydrogen using electrolysis via renewable power sources. The power sources selected for the model was solar (Power Type 1), wind-rated for 1kW (Power Type 2), wind-rated for 3kW (Power Type 3), and tidal/wave (Power Type 4). Of these power types, solar has the highest-rated performance, wind-3kW and tidal/wave has medium performance, and wind-1kW has the lowest performance. Note that each power type has a different approach of generating electricity in the model (e.g., solar must account for day and night while wind is treated as a random variable).

The model incorporates UxV and EABO characteristics, allowing the user to change the EABO scenario. Specifically, the model allows for variance in the number of UxVs used and their characteristics (e.g., tank size and burn rate). The EABO environment consists of traveling times, mission times, and weather impacts. Limitations for all aspects of the model are provided in Section IV.F.

Using the model, various design of experiments and analysis were conducted. The following outputs were recorded: Number of UxVs refueled, total electricity generated, total hydrogen generated, average Queue Time for a UxV to get refueled.

A preliminary design of experiments was conducted to observe the impact to UxV refuel Queue Times when the Number of UxVs is varied between 1 and 2; Burn Rate varied between 2.5 and 3g; Power Types varied between 1 through 4; and Number of Devices varied between low, medium, and high amounts. The Power Type and Number of Devices was selected such that the overall power amounts were relatively close to each other. Each configuration was simulated 5 times. Overall, increasing the Number of UxVs had the largest impact while Burn Rate, Power Type, and Number of Devices had a less but still noticeable impact.

A more detailed design of experiments was conducted after the preliminary design of experiments. In this more detailed analysis, the Number of UxVs refueled was used as the desired performance metric. The inputs varied for this design of experiments were the Number of UxVs (1 to 4), UxV Tank Size (4000 to 6000 minutes), UxV Burn Rate (2.5 to 3.5 kilograms per hour), Travel to and from Mission Times (40 to 80 minutes), Mission Time (500 to 700 minutes), Refueling Rate of one gram of hydrogen (0.0005 to 0.001 grams), Power Type (1 to 4), and the Number of Electrical Devices (5 to 30). A regression analysis was conducted and identified that Power Type, Number of Electrical Devices, UxV Burn rate, Mission Time (mean), and Number of UxVs had a statistically significant impact on results. An interaction plot was generated, and it identified that while there are some statistically significant interactions, none of these interactions were operationally significant.

Lastly, a decision-tree analysis was also performed in order to identify a hierarchical list of the most impactful factors in the model when looking at Number of UxVs refueled and average refueling Queue Times. The most impactful factor was Power Type followed by the Number of Devices. Of the Power Types assessed, the highest performance was always seen with solar. The specific number of devices required to increase operational effectiveness is sensitive to the output metric (Number of UxVs refueled or UxV Queue Time). For the Number of UxVs refueled, the Number of Devices needed varied from 14 to 21 (high performance systems are paired with the lower number of devices and vice versa). For the UxV average wait times, the Number of Devices was around 10 to 11 for all four Power Types.

For future tests, there are several viable options that can be added. For example, options to the power type and size of generator such as having a 50-kW wind turbine (around 9000lbs) can be added. A list can be created that only includes models that the EABO sites can support due to transport size and install times. In addition, a list of known hydrogen generators with their power requirements and size can be created. Location selection should also be considered. The location will adjust factors such as the potential wind and solar availability for a region. This availability can be impacted by annual values. A specific location may lower solar energy in response to cloudy weather or from mountain ranges. Furthermore, seasonal changes would cause energy output to differ depending on the location selected. Wind energy can be updated to have random power on a daily basis and not per minute.

To improve the function of the system, some key aspects of subsystems could be improved. As technology regarding solar, battery, hydrogen generation, and hydrogen storage continue to improve, these subsystems will need to be updated. Having a selection of different subsystem options will assist in estimates and will provide adequate resources to meet the higher power demands to support additional unmanned vehicles. Furthermore, the storage options could have the ability to set starting values in the test. As technology progresses, a reassessment of viable subsystem component options will need to be made in the future.

To improve the fidelity of the model, the limitations and assumptions provided in Chapter IV.F should be addressed and/or expanded upon to allow more flexibility or additional detail.

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