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THESIS

MODELING OF THE AQUA-QUAD SOLAR POWER GENERATION SYSTEM

by

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December 2020

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MODELING OF THE AQUA-QUAD SOLAR POWER GENERATION SYSTEM

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The Aqua-Quad is a solar-powered hybrid autonomous vehicle being developed by the United States Naval Postgraduate School for surface and underwater reconnaissance. The vehicle rides on ocean currents and flies in the air to relocate. A realistic model of the Aqua-Quad's solar power generation system was developed to predict the electrical energy generated given its geographic location and charging duration. This model can be employed within a lab environment for development work or integrated into the Aqua-Quad's logic for operational use. Variables affecting solar power generation, such as geographic location and time of day and year, solar array tilt due to sea state, and degradation of the solar array efficiency were considered. Efficiencies of the solar power generation system and electrical components were also characterized through experiments and incorporated into the model to account for actual field performance. With a solar power generation model, the systematic development of the Aqua-Quad can be optimized, the cost function of the mission planning algorithm can be determined, the feasible mission envelope can be realistically evaluated, and mission execution can be made energy optimal.

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LIST OF ACRONYMS AND ABBREVIATIONS

AI	artificial intelligence
DHI	diffused horizontal irradiance
DNI	direct normal irradiance
GHI	global horizontal irradiance
GPS	Global Positioning Satellite
IMU	inertial measurement unit
KC	Kasten-Czeplak
LiPo	lithium-polymer
MPPT	maximum power point tracker
MAPE	Mean Absolute Percentage Error
NEU	North-East-Up
NPS	Naval Postgraduate School
NREL	National Renewable Energy Laboratory
PV	photovoltaic
RMSE	Root Mean Square Error
SOC	state of charge
STC	standard test conditions
UTC	Coordinated Universal Time

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I. INTRODUCTION

A. MOTIVATION

Advancements in robotics technology has led to the increased development and proliferation of unmanned and autonomous systems, both in the military and civil domains. Within the military, the employment of unmanned systems can be traced back to as early as the First World War [1] and continues to be used today across the land, sea and air battle spaces.

Unmanned systems are advantageous as a force multiplier, in reducing unnecessary risk to humans, and in increasing productivity and efficiency. However, one key constraint that continues to plague unmanned systems are its power and energy dependence, which is limited by the capacity of its battery or fuel source. This in turn limits the operational endurance and performance of the unmanned system.

In overcoming this constraint, developers of unmanned systems, especially unmanned aerial vehicles, have turned to unlimited renewable energy sources, such as solar energy. Such energy sources offer the potential to increase the endurance of these unmanned systems without adding significant mass [2]. One such system seeking to harness the use of unlimited renewable energy is the Aqua-Quad, which is a solar powered hybrid vehicle. The Aqua-Quad is being developed by the Naval Postgraduate School (NPS) of the United States Navy [3]. It can operate autonomously and is envisaged to be used for surveillance and reconnaissance of surface and underwater environments.

To be effective in performing its envisaged scope of missions, the Aqua-Quad must be energy-aware and capable of balancing its energy supply and demand. This necessitates having the capability to forecast how much solar power it can generate for its mission, so that it can be planned and executed in the most energy-optimal manner.

Previous work [3] on the Aqua-Quad assessed its solar power generation capability using a 24-hour average of solar radiation as a baseline. While this was sufficient for the conceptualization phase of the Aqua-Quad's development, a more realistic representation

of its solar power generation capability is now required to further its development. This serves as the motivation for this thesis.

B. THESIS OVERVIEW

The main thrust of this thesis was to address the energy supply aspect of the Aqua-Quad by developing a model that could forecast the solar power generation capability of the Aqua-Quad under different operating environments and conditions.

The use of average solar radiation data in previous studies [3] did not account for variables affecting solar power generation, such as weather condition, time of day and year, and effects of wave currents on the tilt of the solar array. As such, this thesis investigated the different variables affecting solar power generation for the Aqua-Quad and developed a more representative model of its solar power generation capability using theoretical relationships and experimental data.

To bound the scope of this thesis, a stationary Aqua-Quad system that is not subjected to the effects of ocean currents was considered, while local weather patterns and conditions within Monterey, California, were used as the baseline in developing the model. The developed solar power generation model was subsequently validated against data obtained through field testing of the Aqua-Quad prototype.

The development of a more realistic model of the Aqua-Quad solar power generation system offers four key benefits: (1) optimizes the systematic development of the Aqua-Quad, (2) enables the cost function of the mission planning algorithm to be determined, (3) allows for the feasible mission envelope to be realistically evaluated, and (4) achieves more energy optimal Aqua-Quad mission execution.

II. THE AQUA-QUAD CONCEPT

A. OVERVIEW OF AQUA-QUAD CONCEPT

The Aqua-Quad system is a hybrid platform capable of operating within both the air and sea domains. Its design combines a multi-rotor aerial vehicle with a buoy. As a buoy, the Aqua-Quad rides silently on ocean currents while performing persistent sensing below the thermocline. When required, the Aqua-Quad can get airborne for rapid relocation. With both air and surface mobility, the Aqua-Quad overcomes limitations faced by traditional sensor buoys, such as the lack of controlled mobility for repositioning [3-4]. Figure 1 shows the conceptual design of the Aqua-Quad.

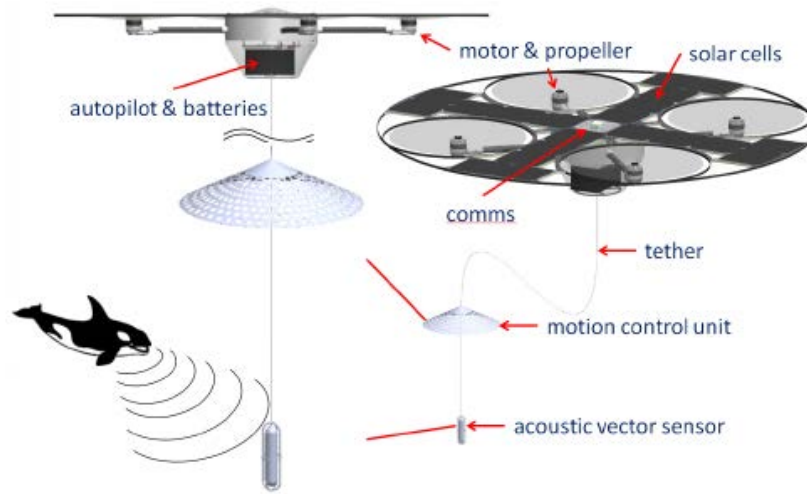


Figure 1. Aqua-Quad Conceptual Design. Source: [3].

B. ENVISAGED OPERATIONS

The Aqua-Quad can be employed in a variety of military and civilian operations, either as a single vehicle or as a network of vehicles.

With the flexibility to equip the Aqua-Quad with different types of sensors, such as metal detecting or acoustic sensors, the vehicle can be employed in a variety of military mission sets, such as mine detection, underwater surveillance or detection of submarines.

Once the target has been detected, the Aqua-Quad can transmit the enemy's location to nearby assets for target engagement.

In civilian operations, the Aqua-Quad can be used for oceanographic studies, such as the tracking of ocean currents [5]. It can also assist marine biologists in tracking the underwater behavior of marine wildlife that have been fitted with acoustic beacons, which is particularly advantageous because this area of study is currently not possible for marine wildlife that are fitted with Global Positioning Satellite (GPS) beacons [6].

Of note, the Aqua-Quad is most effective when employed as a network. For example, a swarm of Aqua-Quad vehicles can serve as a pseudo-GPS acoustic network to enable the geo-positioning of underwater assets [7]. Operating as a network of cooperative vehicles also helps overcome flight endurance limitations, as the Aqua-Quads can take turns flying and sensing, and while in flight, perform leap-frogging maneuvers to follow a moving target. Figure 2 shows a swarm of Aqua-Quads being employed as a network for underwater acoustic surveillance.

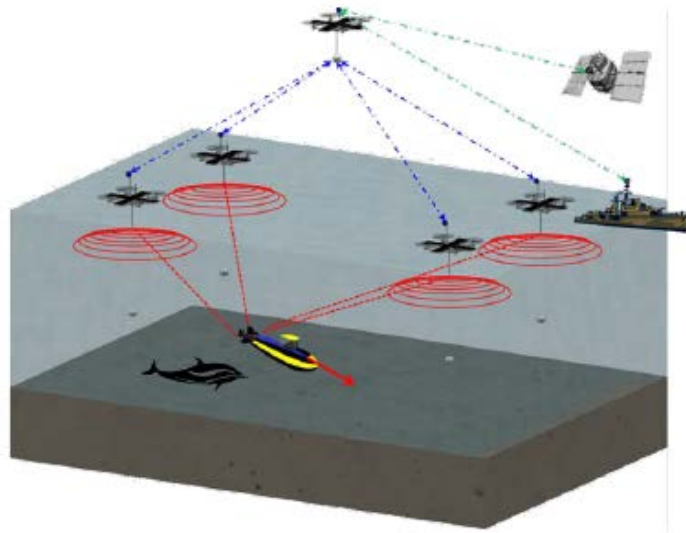


Figure 2. Aqua-Quad Distributed Sensor Network. Source: [4].

C. AQUA-QUAD VEHICLE DESIGN

The Aqua-Quad's propulsion system has a quad-rotor layout with electrically driven propellers that are installed onto a structural support frame that carries the solar array. The structural support frame will be manufactured from a foam-core composite material. Initial design assessments identified propeller diameters of 356 to 381mm to fit suitably with the solar array layout which comprises 20 pieces of photovoltaic (PV) cells. This is shown in Figure 3.

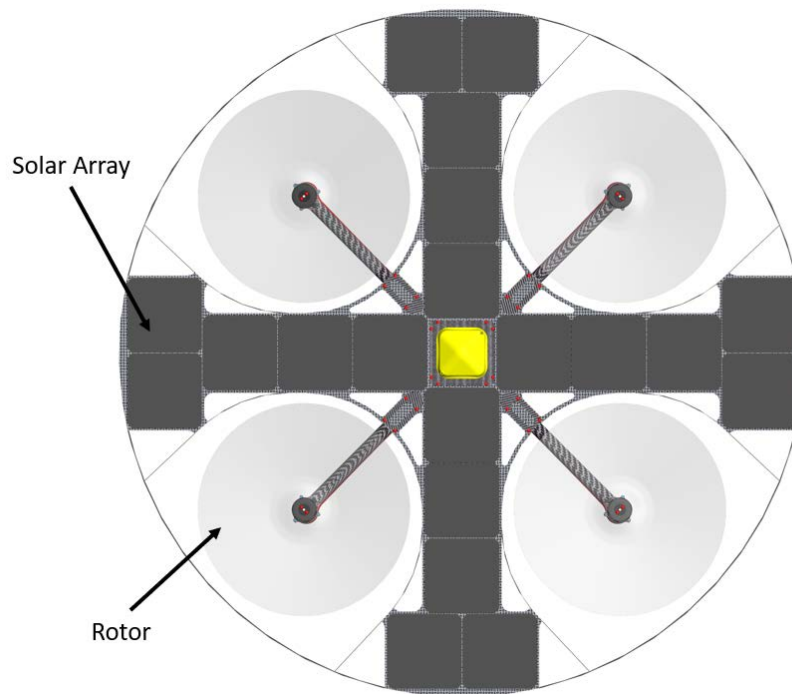


Figure 3. Solar Array Layout on the Aqua-Quad

The main body of the Aqua-Quad is attached beneath the center of the solar array as shown in Figure 4. The body functions as a buoy and houses the vehicle's onboard processor and electronics, communication equipment, as well as instrumentation for its inertial navigation system and GPS. The main body is constructed primarily from parts fabricated through the computer numerical control machining of carbon fiber and 3D printing using a mix of polycarbonate and acrylonitrile butadiene styrene print material.

These ensure optimum strength-to-weight ratio against aerodynamic loads when in flight and against the structural loads on the main body when the vehicle is subjected to strong waves during high sea state conditions.

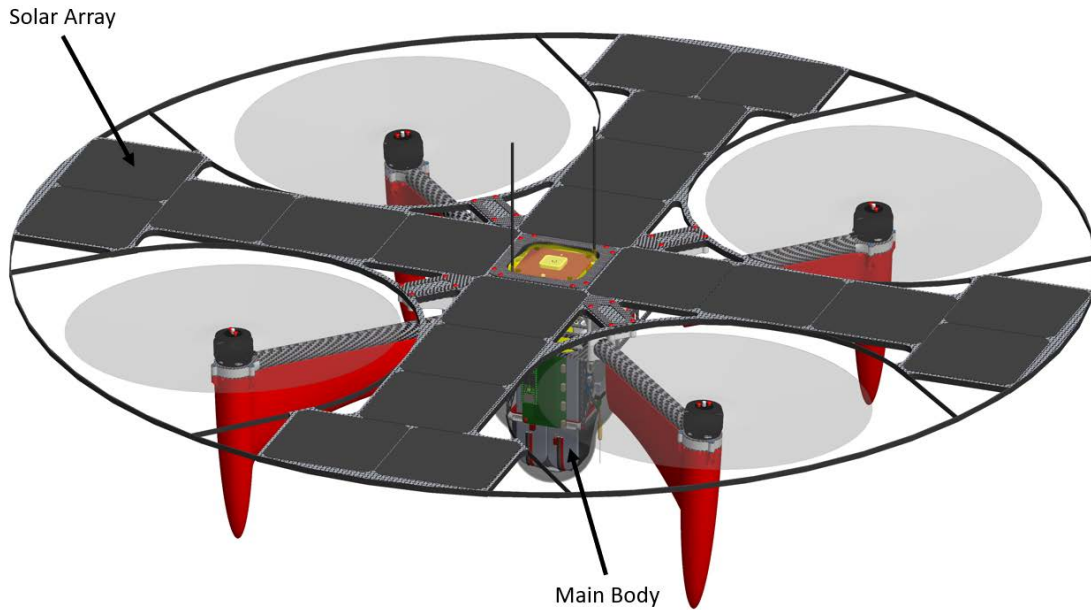


Figure 4. Aqua-Quad Complete Assembly

Initial assessment of the Aqua-Quad's performance based off this design concept was performed using a low-fidelity modeling approach [3]. The study found the Aqua-Quad's design to be feasible and identified an initial list of commercial-off-the-shelf components that can be incorporated. To aid the further development of the Aqua-Quad, higher fidelity models are being developed to characterise its flight performance, in addition to its solar power generation capability. These would aid in finalizing the Aqua-Quad's design, as well as the evaluation and selection of commercial-off-the-shelf components to maximise performance.

D. AQUA-QUAD SOLAR POWER GENERATION SYSTEM

The key components that make up the solar power generation system consists of the solar array, maximum power point tracker (MPPT), battery and other electrical wiring and hardware necessary to build-up the circuitry of the system.

As solar energy is absorbed by the solar array, electrical energy is generated and output from the array. Power extraction from the solar array is maximized through the MPPT and the electrical energy extracted is stored in the Aqua-Quad's batteries. The key components are presented in the box diagram shown in Figure 5 where E_{solar} is solar energy and $E_{electric}$ is electrical energy.

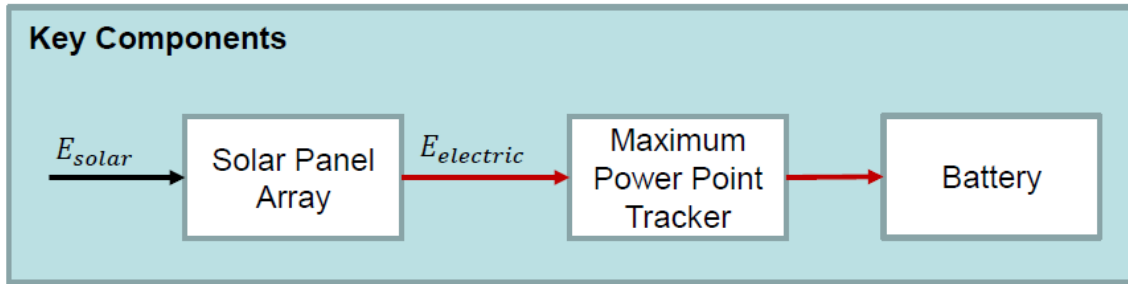


Figure 5. Key Components of Aqua-Quad Solar Power Generation System

1. Solar Array

The sole means of power generation for the Aqua-Quad are through PV cells that convert irradiating solar energy into electricity. These cells are made up of semiconductor materials, such as silicon, that transfer absorbed energy from photons of light to electrons, thereby enabling the electrons to attain a higher energy state and to flow through the material as electrical current. By combining the use of p-type and n-type semiconductors to create a p-n junction, an electric field is also formed, thereby generating a voltage through the process known commonly as the photovoltaic effect.

The Aqua-Quad's solar array comprises 20 pieces of the SunPower E60 Monocrystalline Silicon PV cell connected in series. Each cell is cut from a 166 mm diameter wafer with an advertised nominal power of approximately 3.8 Watt Peak (Wp)

and efficiency of 24.9% under standard test conditions (STC). Overall, the solar array has a theoretical nominal power of approximately 76 Wp with an array area of approximately 0.3m².

The SunPower E60 cells were chosen for the Aqua-Quad due to their affordability vis-à-vis performance, which is among the best for single crystalline silicone cells [8]. As the Aqua-Quad is designed such that its energy demands must be met by the energy it harvests, future increases in energy demands from its mission may require the adoption of more expensive but higher performing solar cells. Such cells could potentially be smaller, thereby reducing the overall weight of the system. Thin-film cells could also be explored for adoption as they would be more flexible and likely to survive better in high sea state conditions. For this thesis, the SunPower E60 cell will be used as the baseline solar cell that will be characterized and modeled.

2. Maximum Power Point Tracker

The MPPT is used in PV solar systems to maximize power extraction under all conditions, as power output from the array varies with the amount of incident irradiation and array temperature. The MPPT used for the Aqua-Quad is the STEVAL-ISV018V1 from ST Microelectronics which has an embedded controller that optimizes power output using the Perturb and Observe MPPT algorithm. The embedded controller applies repeated perturbations to the operating voltage with the goal of achieving maximum electrical power output.

The MPPT has an advertised efficiency of up to 98%, with an operating input voltage range of 6.5 to 40V and operating output voltage of up to 120V. The STEVAL-ISV018V1 board (see Figure 6) comes with three MPPT circuits, which were cut and used individually for the Aqua-Quad. Unfortunately, this MPPT board has since been discontinued and alternative solutions would be required beyond the first few prototype and proof-of-concept vehicles.

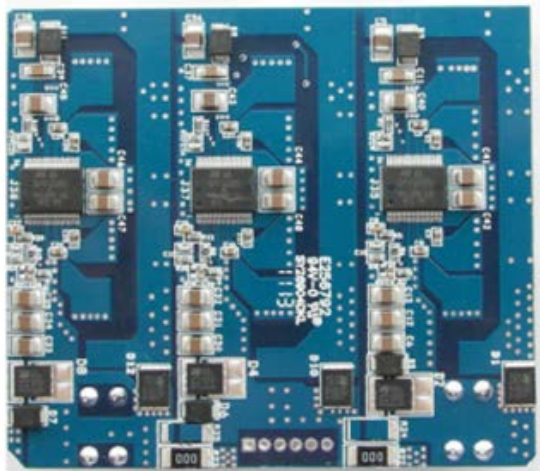


Figure 6. STEVAL-ISV018V1 MPPT Board from ST Microelectronics

3. Battery

Rechargeable lithium-polymer (LiPo) batteries are used on the Aqua-Quad to store electrical energy to support mission energy demands and provide power to baseline systems during periods of no sun. The battery used is the Thunder Power RC Prolite X TP6000-4SPX25 (see Figure 7), which is a 6000mAh 4-cell 14.8V 25C LiPo with a nominal capacity of 88.8Wh. This battery model was selected due to its optimal balance of specific energy, specific power, and mass (485g each with leads cut to length and connector installed). Two batteries connected in parallel are used for the Aqua-Quad, thereby giving the system a total nominal capacity of 12,000mAh or 177.6Wh.



Figure 7. Thunder Power RC Prolite X TP6000-4SPX25 Battery

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III. MODELING AND CHARACTERIZATION

A. OVERVIEW OF SOLAR POWER GENERATION PROCESS

Figure 8 provides an overview of the solar power generation process. This process begins with estimating the amount of solar irradiance that is available for the Aqua-Quad and is dependent on the location of the system, time of day and year, and the prevailing weather conditions. The amount of solar energy captured is then determined based on the available charging time and factors such as tilt of the solar array, as well as array shading effects. Once the amount of solar energy captured can be determined, the amount of electrical energy generated and stored can then be estimated based on known performance parameters and efficiencies of the solar array, MPPT and battery.

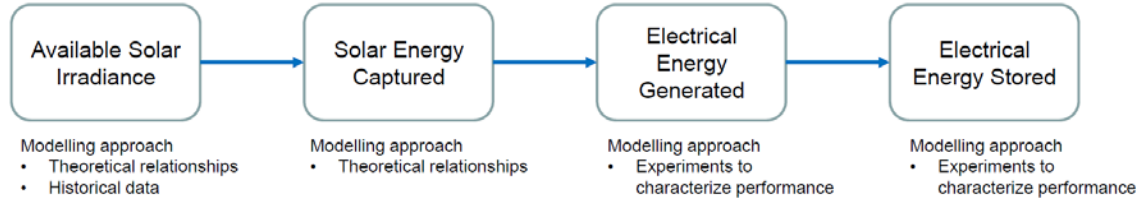


Figure 8. Solar Power Generation Process and Modeling Approach

A mix of theoretical relationships, historical data and experiments were used to model each stage of the solar power generation process. Specifically, theoretical relationships and historical data were used to estimate the amount of solar energy available and captured, while experiments were used to account for inefficiencies in the electrical components that extract and store the generated electrical energy. Details of the modeling approach taken for each stage of the process are further elaborated in this chapter.

B. ESTIMATING AVAILABLE SOLAR IRRADIANCE

Solar irradiance is the power of sunlight (W/m^2) observed and is dependent on the position of an observer on the Earth's surface relative to the sun in the sky, as well as other atmospheric and environmental conditions, such as aerosol and water vapor concentration

and surface albedo. The solar irradiance incident on the observer comprises of two key components—Direct Normal Irradiance (DNI) and Diffused Horizontal Irradiance (DHI).

DNI is the direct irradiance received when a surface is positioned perpendicular to the direction of the sun's rays [9]. DHI is the indirect irradiance received by a horizontal surface due to scattering from the atmosphere [9]. The total solar radiation on a horizontal surface (see Figure 9) is the Global Horizontal Irradiance (GHI) which is the sum of the DHI and the DNI projected onto the horizontal surface

$$GHI = DHI + [DNI \times \cos(z)] \quad (III.1)$$

where z is the Solar Zenith Angle, which is a function of geographic location on the Earth's surface (latitude/longitude) and time of day [9].

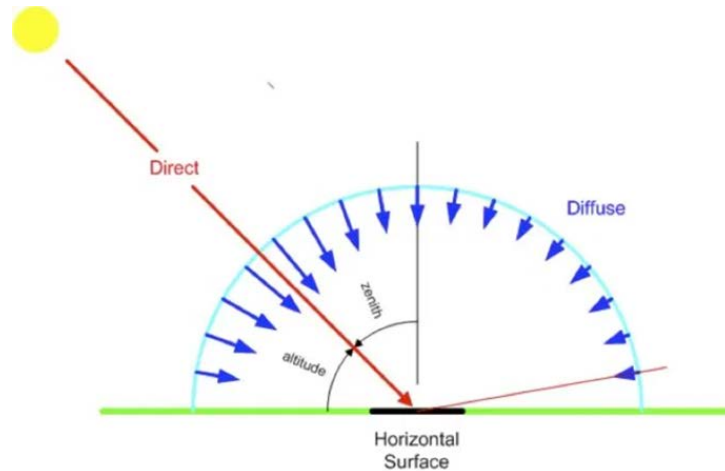


Figure 9. Irradiation of a Horizontal Surface. Source: [10].

Two approaches to estimate the available amount of solar irradiance were considered—Historical solar irradiance data and solar irradiance models.

1. Historical Solar Irradiance Data

Average historical solar irradiance data can be used to predict future available irradiance. Such solar irradiance data are measured, modeled, and collated by various

agencies around the world, such as the United States’ National Renewable Energy Laboratory (NREL) and the National Solar Repository of Singapore. While most agencies collect irradiance data within their jurisdiction, others such as the NREL offer a repository of solar data sets from other countries. The benefit of using historical data is that it accounts for seasonal weather variations, such as monsoon seasons that bring increased cloud cover resulting in lower irradiance. However, irradiance measurement sites are not always available [11], thereby requiring the use of clear sky models to estimate irradiance in lieu of measurements.

2. Solar Irradiance Models

Solar irradiance models vary in their level of complexity, ranging from very simple models that use only geometric calculations based on solar zenith angle, to more complex models that account for atmospheric conditions. This is summarized in Table 1. A more detailed analysis of different models can be found in [9].

Table 1. Comparison of Simple and Complex Solar Irradiance Models

Simple Model	Complex Model
• Single input required: ➤ Solar zenith angle • Irradiation available dependent on position of sun relative to surface • Atmospheric attenuation highly simplified as a function of zenith angle • Models are empirical correlations based on measurements • Examples include Haurwitz, Daneshyar-Paltridge-Proctor, Kasten-Czeplak	• Multiple inputs required: ➤ Solar zenith angle ➤ Measurable atmospheric parameters (air pressure, temperature, relative humidity, aerosol content, Rayleigh scattering) ➤ Ground albedo • More accurate accounting of atmospheric attenuation • Examples include Bird, MAC, Atwater, REST2

While it is desirable to adopt the use of complex solar irradiance models to improve accuracy, the choice of model is limited by the Aqua-Quad’s capability to measure the atmospheric parameters required of more complex models. In this regard, the Aqua-Quad

has the means to tell its location and time of day through its GPS sensor but is not equipped with atmospheric sensors, such as air pressure sensors. As such, simple models must be adopted instead. However, these models are limited to providing clear sky irradiance estimates based on theoretical relationships between the location of the sun relative to the Aqua-Quad through different times of the day. In addition, such models do not account for seasonal weather variations and cloud cover, which may lead to poor estimates on non-clear sky days. Hence, care must be taken in the use of such models and the suitability of the model for adoption in a particular location needs to be considered by verifying its accuracy against actual data.

An assessment was performed to compare the results output from simple solar irradiance models against the actual solar irradiance data obtained through NREL's National Solar Radiation Database. The assessment was based on three years of solar irradiation data (2017 to 2019) and the Root Mean Square Error (RMSE) was computed using the relationship

$$RMSE = \frac{\sqrt{\text{mean} \left[(GHI_{\text{estimate}} - GHI_{\text{actual}})^2 \right]}}{\text{mean}(GHI_{\text{actual}})} . \quad (\text{III.2})$$

Two locations were considered in the assessment—the Monterey Bay area near NPS in California, USA, and the area around Naval Station Pearl Harbor, Hawaii, USA. These locations were selected as they have different climates and have been identified as future test sites for the Aqua-Quad. The results are summarized in Table 2 and Table 3, wherein it can be seen that the Kasten-Czeplak (KC) model consistently achieved the lowest RMSE. Further details on the various simple solar irradiance models used can be found in Appendix A.

Table 2. Comparison of Simple Solar Irradiance Model Results against Actual Solar Irradiance Data for Location: Monterey Bay

Location: Monterey Bay (Lat: 36.61 / Long: -121.86)			
Simple Clear Sky Model	Root Mean Square Error of Model Result vs Actual		
	Year 2017	Year 2018	Year 2019
Kasten-Czeplak (KC)	0.544	0.515	0.570
Adnot-Bourges-Campana-Gicquel (ABCG)	0.565	0.531	0.593
Daneshyar-Paltridge-Proctor (DPP)	0.606	0.567	0.636
Robledo-Soler (RS)	0.655	0.612	0.689
Haurwitz	0.675	0.630	0.710

Table 3. Comparison of Simple Solar Irradiance Model Results against Actual Solar Irradiance Data for Location: Naval Station Pearl Harbor

Location: Naval Station Pearl Harbor (Lat: 21.37° / Long: -157.94°)			
Simple Clear Sky Model	Root Mean Square Error of Model Result vs Actual		
	Year 2017	Year 2018	Year 2019
Kasten-Czeplak (KC)	0.504	0.578	0.410
Adnot-Bourges-Campana-Gicquel (ABCG)	0.529	0.628	0.426
Daneshyar-Paltridge-Proctor (DPP)	0.573	0.692	0.457
Robledo-Soler (RS)	0.610	0.741	0.492
Haurwitz	0.635	0.774	0.515

3. Comparison of Both Approaches

A three-year comparison between the two approaches used to estimate available solar irradiance is shown in Table 4. In determining the RMSE, results obtained were compared against GHI data obtained from NREL for the Monterey Bay area near NPS.

Table 4. Comparison of 10-Yr Historical Average Approach vs. Kasten-Czeplak Model for Location: Monterey Bay

Location: Monterey Bay (Lat: 36.61 / Long: -121.86)			
Approach	Root Mean Square Error of Model Result vs Actual		
	Year 2017	Year 2018	Year 2019
10-Year Historical Average	0.522	0.555	0.555
Kasten-Czeplak Clear Sky Model	0.544	0.515	0.570

It can be seen that no one approach is consistently better than the other, although using a 10-year historical average tends to offer better accuracy since it would account for seasonal weather variations. The above results therefore highlight the challenges and complexity of estimating available solar irradiance, as well as the large error margin that comes with the estimated results. A case in point is shown in Figure 10 which compares the actual GHI against the estimated GHI through a 24hr period at the Monterey Bay area.

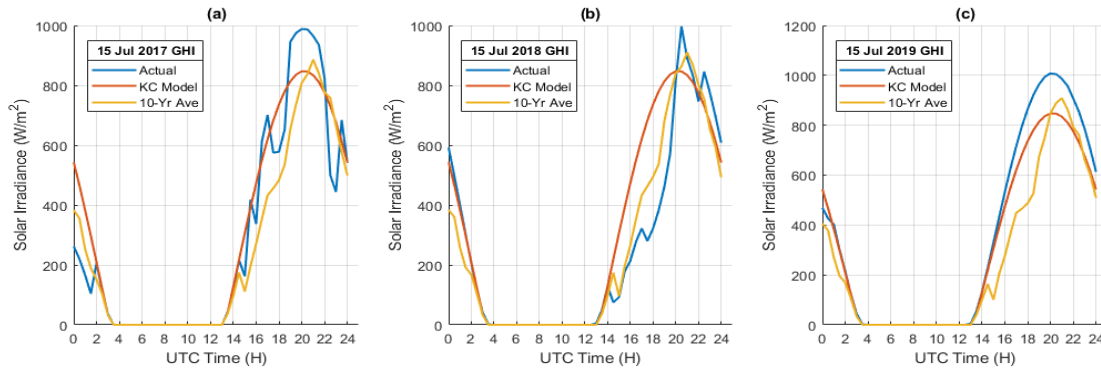


Figure 10. Comparison of Estimated GHI vs. Actual GHI on 15 July in year 2017 (a), 2018 (b), and 2019 (c) for Location: Monterey Bay

The adoption of either one of the two approaches is therefore more dependent on the deployment context of the Aqua-Quad and the availability of information required, rather than the effectiveness of the approach itself. As historical solar data will not always be available, this thesis will implement the use of the KC model to estimate the solar irradiance available to the Aqua-Quad.

Moving forward, advanced technologies such as artificial intelligence (AI) could potentially be exploited by the Aqua-Quad to more accurately predict available solar irradiation using real-time or recent information that it senses. This can be done by measuring and analyzing the changes in electrical power output from the solar array, which reflects the changes in available solar irradiation. Such an approach is also beneficial as the Aqua-Quad would be able to better sense and respond to ad-hoc and unexpected weather conditions that affect solar irradiation availability, such as sudden fog, haze due to a nearby fire, or increasing cloud cover due to an impending thunderstorm.

C. DETERMINING SOLAR ENERGY CAPTURED

The amount of solar energy captured by the Aqua-Quad is dependent on factors such as the area of its solar array, charging duration, tilt of its solar array and condition of the array. These can be described through the relationship

$$E_{captured,solar} = \left\{ \int_0^{t_{charge}} \left[GHI_{KC} \times TF \times (1 - LF_{condition}) \right] dt \right\} \times A_{array}, \quad (III.3)$$

where t_{charge} is the charging duration, GHI_{KC} is the estimated GHI using the KC clear sky model, TF is the tilt factor, $LF_{condition}$ is the loss factor and A_{array} is the area of the solar array. The solar energy captured is measured in Watt-hours (Wh).

1. Tilt Factor, TF

Tilting of the Aqua-Quad's solar array can be expected while the system is floating on the ocean due to the sea state. Depending on how the array is tilted relative to the position of the sun, the effective solar irradiance incident on the array and the amount of solar energy absorbed by the PV cells would fluctuate. The TF is therefore introduced to account for this effect.

The attitude of the solar array can be represented similar to that of an aircraft by defining a navigation axis North-East-Up (NEU) as shown in Figure 11. At neutral attitude, the solar array of the Aqua-Quad would be horizontal with the ground and its body axes aligned with NEU with the same origin. Roll is defined as the rotation about the N-axis by

angle ϕ , pitch is the rotation about the E-axis by angle θ and yaw is the rotation about the U-axis by angle ψ . The rotation matrices of the solar array are defined as

$$\text{Roll}, \mathbf{R}_3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi & \cos \phi \end{bmatrix}, \quad (\text{III.4})$$

$$\text{Pitch}, \mathbf{R}_2 = \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix}, \quad (\text{III.5})$$

$$\text{Yaw}, \mathbf{R}_1 = \begin{bmatrix} \cos \psi & \sin \psi & 0 \\ -\sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (\text{III.6})$$

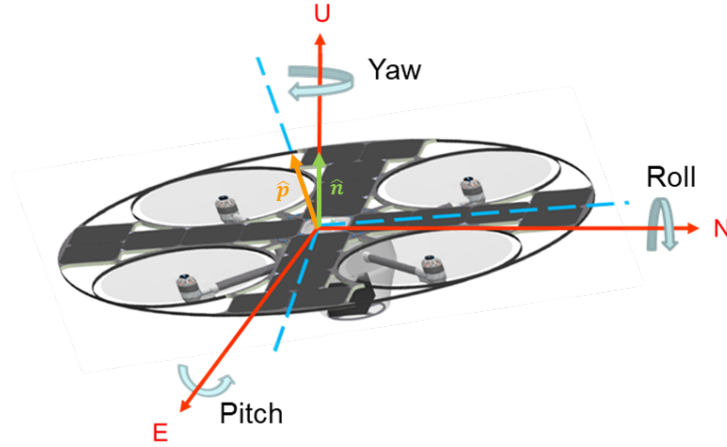


Figure 11. Aqua-Quad Tilt and Reference Axes

Since the directional vector of the GHI is normal to a horizontal surface, the GHI can be represented by a unit vector, $\hat{\mathbf{n}}$ originating from the origin of NEU along the U-axis (see Figure 11). At neutral attitude, the unit vector describing the solar array would also be $\hat{\mathbf{n}}$, since the surface of the array would be normal to the GHI. As such, the unit vector describing the solar array at any attitude would be given as

$$\hat{\mathbf{p}} = (\mathbf{R}_3 \mathbf{R}_2 \mathbf{R}_1)^T \hat{\mathbf{n}}. \quad (\text{III.7})$$

The tilt factor can therefore be computed as

$$TF = \hat{\mathbf{n}} \cdot \hat{\mathbf{p}}, \quad (\text{III.8})$$

where the scalar product of the two vectors would account for the reduction in GHI on the solar array due to its tilt from the horizontal.

In accounting for Aqua-Quad tilt, more complex time-based representations of the sea state can be incorporated into the model. Such information can be obtained from oceanographic studies that model the sea-state or tapped real-time from the inertial measurement unit (IMU) sensors of the Aqua-Quad while it is deployed out at sea.

2. **Loss Factor, $LF_{condition}$**

The amount of solar energy captured by the solar array is dependent on shading effects that would reduce its performance efficiency. Shading can be expected during operations due to soiling of the solar array from dirt, bird-droppings and sea salt build-up, as well as the accumulation of water on the array surface (see Figure 12). The impact of solar array soiling is not trivial, as seen in a research report on the performance analysis of floating PV technologies in the tropics, where it was found that the accumulation of bird droppings led to a 10% drop in its performance ratio over the course of around 10 days [12]. In the case of the Aqua-Quad, it is likely that the occasional splashing of sea water would help clear away some of the accumulated soiling on the solar array surface.



Figure 12. Soiling due to Bird Droppings. Source: [12].

In addition to shading effects, the solar array can be expected to degrade over time due to erosion of the laminate used to protect the array surface as well as corrosion of its components due to the high-salt environment the Aqua-Quad operates within. Literature on performance degradation rates from field tests suggest rates of 0.5 to 0.8% per year, depending on the material of the PV system and its operating environment [13]. However, much of these data are obtained from inland application of PV systems.

For the solar power generation model being developed in this thesis, the losses due to solar panel condition is represented by a user-defined loss factor, $LF_{condition}$ where $0 \leq LF_{condition} \leq 1$. This loss factor can be modeled as a time-dependent variable which tracks the cumulative degradation over time, starting from the time of initial deployment. It will be assumed that shading effects and degradation will account for a performance loss of approximately 1% per year, hence a $LF_{condition}$ of 0.01/year will be adopted for the model.

To have a more accurate representation of $LF_{condition}$, it is recommended that future work study the impact of Aqua-Quad solar array shading in the ocean environment, in particular the rate at which salt build-up occurs on the solar array surface, as well as the degradation of the solar array due to corrosion.

D. DETERMINING ELECTRICAL ENERGY GENERATED

The conversion of solar energy into electrical energy is achieved through the solar array, while the MPPT optimizes the maximum electrical power that can be extracted from the array. The overall performance efficiency of the system in converting solar to electrical energy is therefore dependent on the efficiencies of the solar array and the MPPT. This can be described through the following relationship

$$E_{generated,electrical} = E_{captured,solar} \times \eta_{array} \times \eta_{MPPT}, \quad (III.9)$$

where η_{array} and η_{MPPT} are the solar array and MPPT efficiency, respectively.

1. Characterizing Solar Array Efficiency

The performance efficiency of solar cells is dependent on factors such as the material used and quality of manufacturing. The build-up of solar cells into an array introduces additional efficiency losses due to the incorporation of electrical wirings, connectors, and other components. The operating temperature of the solar cell also affects its efficiency, with increasing cell temperature resulting in lower performance efficiency. This is shown in Figure 13, where although increasing temperature leads to higher current output, voltage drops more significantly with increasing temperature, resulting in a net reduction in power output. The relationship between solar cell performance and temperature varies linearly and is dependent on the Temperature Coefficient, which defines how much percentage of power is lost when the temperature increases by 1°C over STC of 25°C [14].

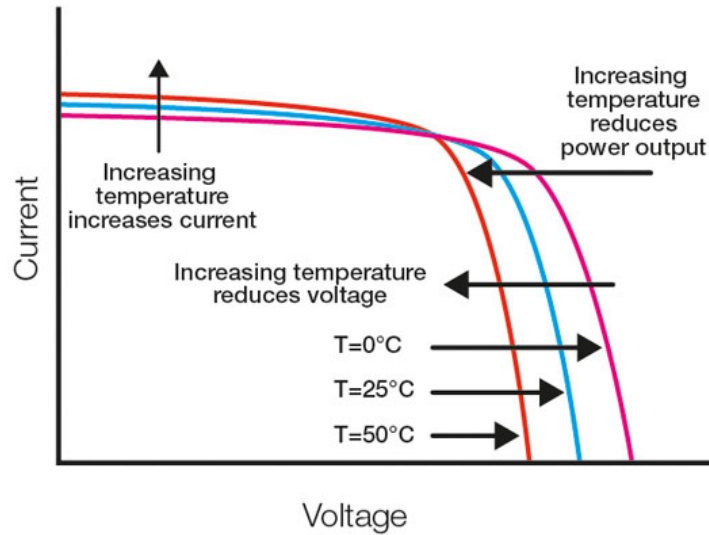


Figure 13. Effects of Temperature on the Current-Voltage Curve of a Solar Cell. Source: [15].

The SunPower E60 Monocrystalline Silicon PV cells used on the Aqua-Quad has an OEM advertised efficiency of up to 24.9% under STC. However, the overall array efficiency is expected to be lower and needs to be determined. Separately, as there was no available information from the OEM on the temperature coefficient of the E60 cells, the temperature coefficient of the Aqua-Quad solar array also needed to be characterized through experiments.

A built-up Aqua-Quad solar array was used in the conduct of experiments, with a processor connected to the array that has current and voltage sensors to log the electrical power output from the array. An irradiance meter was used to measure the amount of solar irradiance received by the solar array with readings taken at regular intervals. A temperature sensor was also placed on the surface of the solar array frame to obtain the approximate surface temperature of the solar cells. The experiment setup is shown in Figure 14.

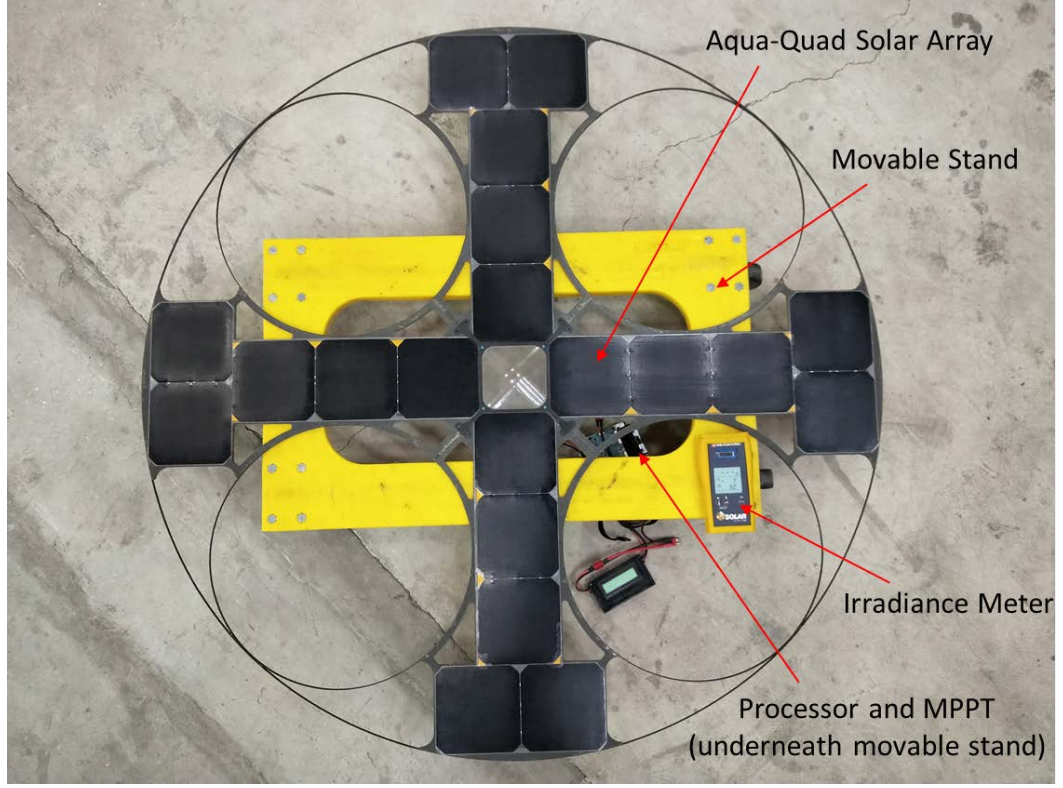


Figure 14. Aqua-Quad Solar Array Experiment Setup

Efficiency of the Aqua-Quad solar array was computed from the experimentally collected data based on the relationship

$$\eta_{array} = \frac{Power_{out,array}}{Power_{in,array}} = \frac{V_{out,array} \times I_{out,array}}{GHI_{measured} \times A_{array}}, \quad (III.10)$$

where η_{array} is the array efficiency, $V_{out,array}$ is the voltage output from the solar array, $I_{out,array}$ is the current output from the solar array and $GHI_{measured}$ is the GHI reading taken using the irradiance meter (W/m^2). The measured solar power into the solar array and electrical power output from the array for one of the experiments is shown in Figure 15, where the expected increase in electrical power output as solar irradiance increases can be observed.

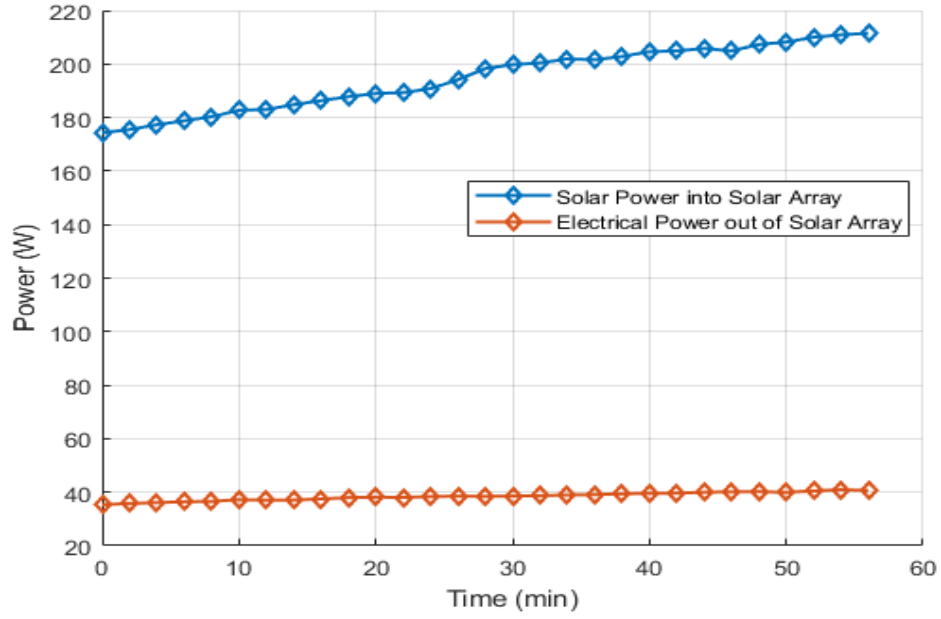


Figure 15. Solar Power into Array and Electrical Power output from Array

Experiments were performed at different times of the day to obtain efficiency data at different array operating temperatures. Figure 16 shows the efficiency of the solar array plotted against the net increase in array temperature from STC, where $\Delta T = T_{array} - 25^{\circ}C$. It can be observed that the measured η_{array} generally decreases with increasing temperature above STC, which is consistent with the expected behavior of solar cells with temperature.

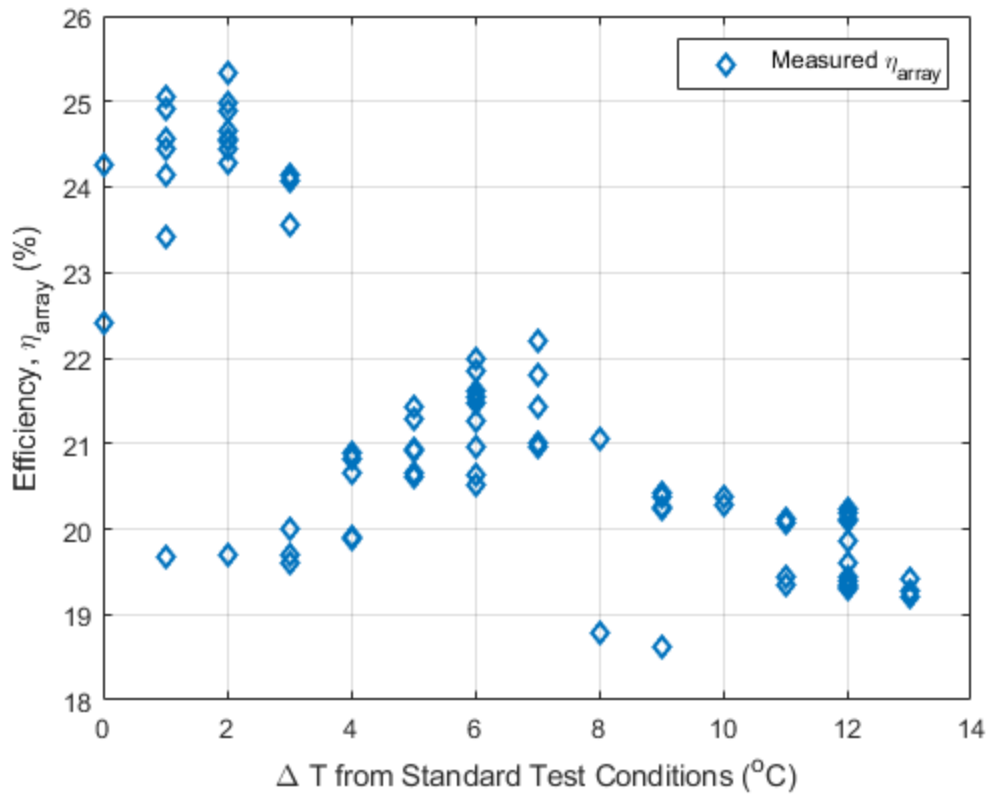


Figure 16. Solar Array Efficiency vs. Temperature Difference from STC

As efficiency is expected to vary linearly with temperature, linear regression was performed on the data to derive a temperature coefficient of $-0.35\%/^{\circ}\text{C}$. Extrapolation of the linear curve to STC also obtained an $\eta_{array,STC}$ of approximately 23.6%, which is lower than the OEM advertised efficiency of 24.9% for the E60 cell, as expected. These results are presented in Figure 17.

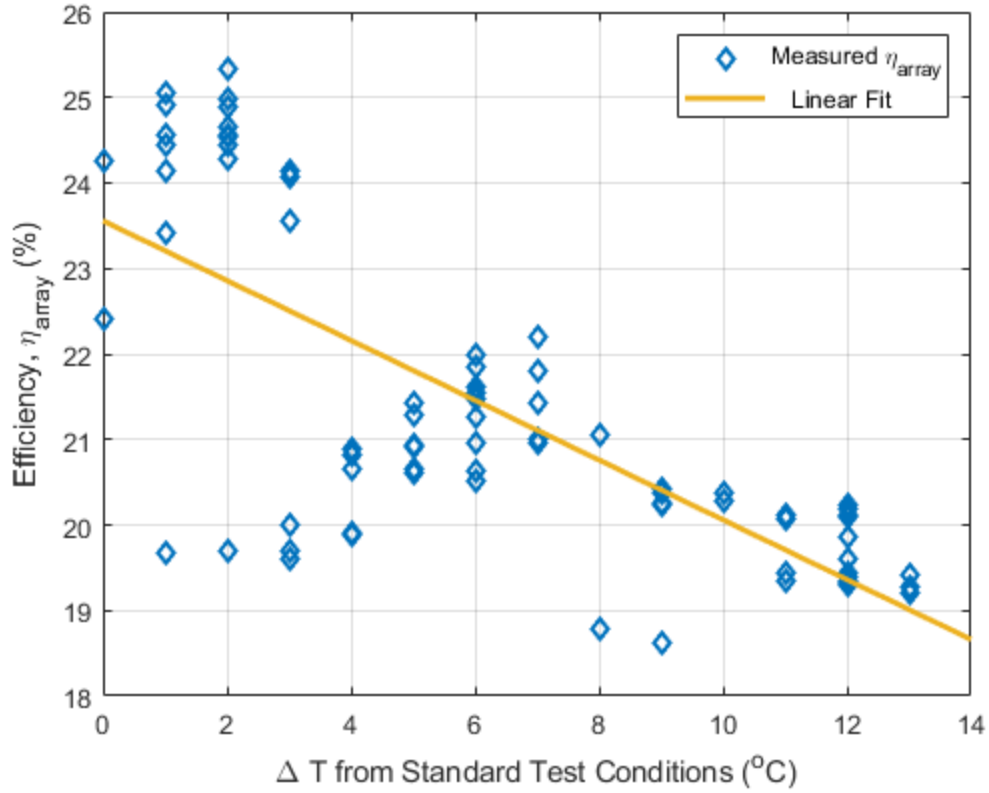


Figure 17. Linear Regression of Measured Solar Array Efficiency Data

Having defined the temperature coefficient of the solar array, the array efficiency at any point of time can be determined as

$$\eta_{array} = 23.6 + [TC_{array} \times (T_{array} - 25^{\circ}C)], \quad (III.11)$$

where TC_{array} is the temperature coefficient. The operating temperature of the array would have to be a user-input parameter into the solar power generation model, which can be given as an average operating temperature or as a time-dependent variable if the operating temperature profile over the duration of solar power generation is known.

2. Characterizing MPPT Efficiency

The efficiency of the MPPT was characterized using a similar experiment set-up shown in Figure 14 and is defined through the relationship

$$\eta_{MPPT} = \frac{Power_{out,MPPT}}{Power_{in,MPPT}} = \frac{V_{out,MPPT} \times I_{out,MPPT}}{V_{out,array} \times I_{out,array}}, \quad (III.12)$$

where the power output from the solar array is considered as the power input to the MPPT, and $V_{out,MPPT}$ and $I_{out,MPPT}$ are the measured voltage and power output from the MPPT, respectively.

Multiple experiments were computed across different times of the day to observe the relationship between the input and output power of the MPPT. Figure 18 shows the measured results for one of the experiments conducted in the late morning where the increasing power with time is reflective of the increasing solar irradiance as time progressed. The results from the chart also suggests that the STEVAL-ISV018V1 MPPT used on the Aqua-Quad has a relatively good performance efficiency.

Further analysis into the results from the experiments found the average efficiency to be at 98% (see Figure 19), which is consistent with that advertised by the OEM. However, further characterization of the MPPT efficiency through curve fitting of the measured data was not pursued as the range of power input being analyzed and the standard deviation from the mean efficiency was too small to provide a meaningful characterization of the efficiency curve. In addition, the operating range of the MPPT experienced during the experiment is likely to reflect that of actual operations. Hence, the incorporation of a 98% MPPT efficiency value for the Aqua-Quad solar power generation model would suffice.

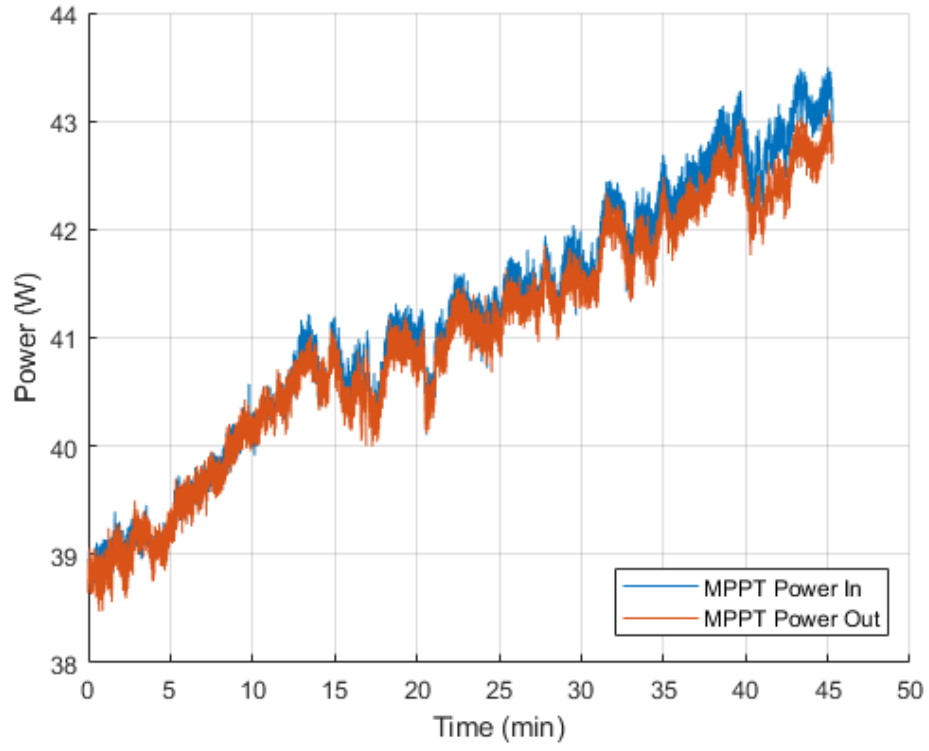


Figure 18. Measured Power into MPPT vs. Measured Power out from MPPT

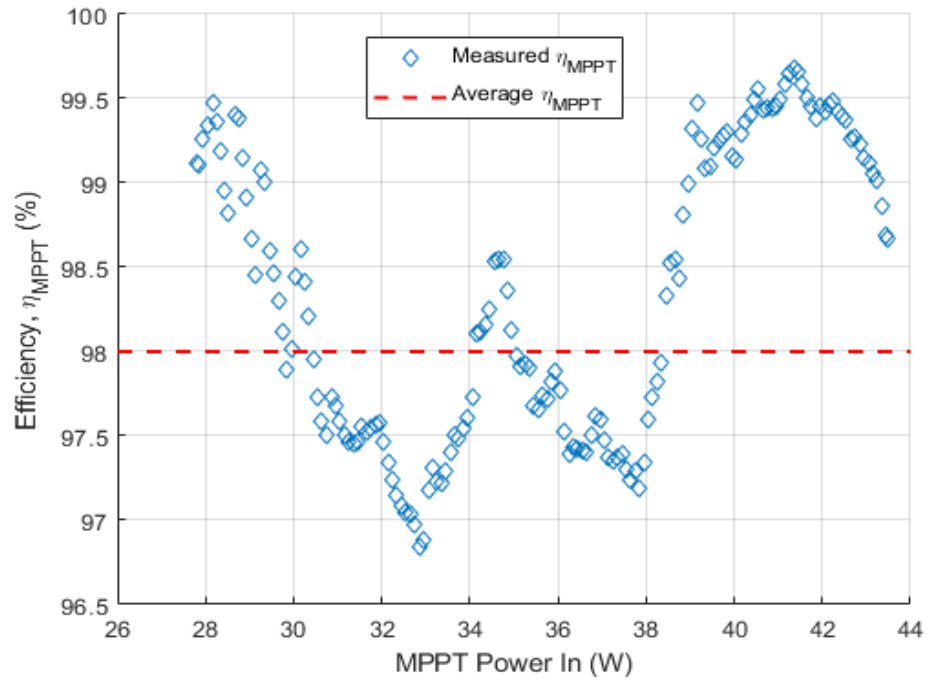


Figure 19. MPPT Efficiency vs. Power into MPPT

E. DETERMINING ELECTRICAL ENERGY STORED

Electrical energy that has been generated by the Aqua-Quad solar array and extracted through the MPPT is firstly used to meet the baseline power demands of the system while it is recharging, such as its onboard processor and sensors. Excess electrical energy is then stored within the two Thunder Power RC Prolite X TP6000-4SPX25 batteries that are connected in parallel on the Aqua-Quad. The baseline power demand of the Aqua-Quad during recharging is a user-defined input to the solar power generation model that can be changed to reflect the different payload configurations of the Aqua-Quad.

Energy losses during the battery charging process can be expected due to heat generation arising from the internal resistance of the batteries. It is therefore necessary to characterize the charging efficiency of the battery to account for such losses. The electrical energy stored can be described through the following relationship

$$E_{\text{stored,electrical}} = E_{\text{generated,electrical}} \times \eta_{\text{charging,battery}} , \quad (\text{III.13})$$

where $\eta_{\text{charging,battery}}$ is the charging efficiency of the battery.

1. Battery Charging Efficiency

Multiple battery charging experiments were performed to characterize $\eta_{\text{charging,battery}}$ for a single Thunder Power RC Prolite X TP6000-4SPX25. Charging was performed at constant charge rates of 0.8 and 1C, using the FMA CellPro Powerlab 6 battery workstation shown in Figure 20.



Figure 20. FMA CellPro Powerlab 6 Battery Workstation

Due to limitations of the charger, the variation in battery internal resistance throughout the charging cycle could not be recorded. The charger only reported an internal resistance value at the end of the charge cycle, which was assumed to represent the average internal resistance during the charge. This internal resistance value was used to determine the charging efficiency by computing the energy loss due to internal resistance and considering it as a reduction to the nominal capacity of the battery. The approach taken to compute charging efficiency is reflected in the equation

$$\eta_{\text{charging,battery}} = 1 - \left(\frac{I_{\text{charge}}^2 \times R_{\text{internal,battery}} \times t_{\text{charge}}}{\text{Capacity}_{\text{nominal,battery}}} \right), \quad (\text{III.14})$$

where I_{charge} is the charging current that is a constant during each experiment, $R_{\text{internal,battery}}$ is the average internal resistance of the battery, t_{charge} is the duration of charge, and $\text{Capacity}_{\text{nominal,battery}}$ is the nominal capacity of the battery at full charge which is 88Wh for a single Thunder Power RC Prolite X TP6000-4SPX25 battery.

The average charging efficiency of the battery was found to be approximately 99.6%, as shown in Table 5. While this charging efficiency can be expected to be lower at

higher charge rates due to increased heat generation by the battery internal resistance, field experiments on the MPPT found the actual charging rates to be less than 0.5C. Hence, the derived battery charging efficiency of 99.6% obtained was found to be sufficient for incorporation into the Aqua-Quad solar power generation model without the need for further experiments at other charge rates.

Table 5. Battery Charging Experiment Results

Charge Rate	Measured Average Battery Internal Resistance (mOhm)	Energy Loss due to Heat from Internal Resistance (Wh)	Charging Efficiency
0.8C (4.8A)	11.8	0.340	99.6%
1.0C (6.0A)	10.7	0.390	99.6%

It is necessary to note that the approach taken in characterizing the Aqua-Quad battery was based on average measured data at steady state conditions to provide an approximate of its performance efficiencies. Further efforts to model the dynamic properties of the battery, its hysteresis profile, and correlate its performance parameters with factors such as battery operating temperature, were not undertaken due to the scope of this thesis. It is therefore recommended that future work on the Aqua-Quad considers the development of a dynamic battery model which can be integrated with the solar power generation model to better reflect the chemical and electrical properties of the Aqua-Quad batteries.

2. Battery State of Charge

Additional experiments were performed to understand the discharge characteristics of the Thunder Power RC Prolite X TP6000-4SPX25 battery to estimate its state of charge (SOC). Having a knowledge of the battery's SOC is necessary to ensure that sufficient energy is available to meet mission demands and to monitor its SOC during an ongoing mission, especially while the Aqua-Quad is in flight. The experiments were performed at discharge rates of 0.17C to 3C using the West Mountain Computerized Battery Analyzer IV (see Figure 21) along with its free analyzer software. Battery voltage and current were measured, and these were used to derive the battery discharge curves shown in Figure 22.



Figure 21. West Mountain Computerized Battery Analyzer IV

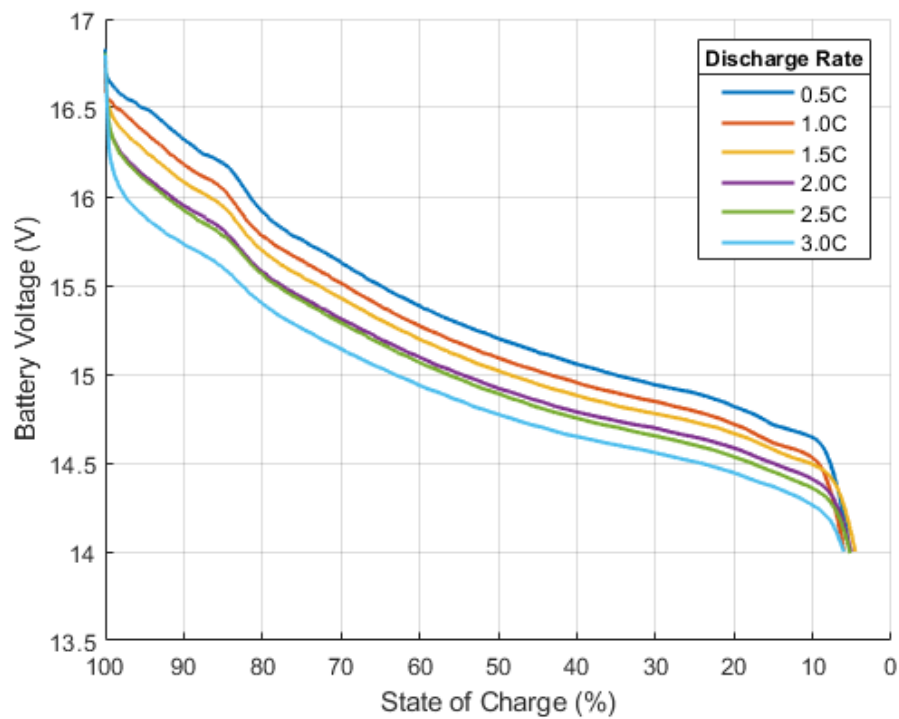


Figure 22. Aqua-Quad Battery Discharge Curves at Various Discharge Rates

The derived battery discharge curves in Figure 22 agree with the general discharge characteristics of LiPo batteries [16]. At full charge, the battery voltage is around 16.8V and it is necessary to avoid draining the battery to less than 14.8V to avoid causing damage to the battery. The derived battery discharge characteristics provide a first-level

approximation which should suffice for the ongoing developmental work on the Aqua-Quad. However, there are unknowns regarding the sensitivity of battery performance with temperature, as well as challenges in accurately measuring the battery SOC especially when the battery is under load. To determine its SOC more accurately during actual operations, future work on the Aqua-Quad could consider implementing a prediction algorithm leveraging on data obtained through the static and dynamic modeling of the battery as described in [17].

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IV. MODEL IMPLEMENTATION

A. MODEL SOFTWARE

The Aqua-Quad solar power generation model is implemented using MATLAB software. This offers the following benefits: Firstly, it allows for the model to be run in the lab for back-end system development, performance analysis and design trade-off studies. Secondly, the use of MATLAB environment across various aspects of the Aqua-Quad development allows for the subsequent ease of software integration and minimizes compatibility issues. Lastly, the MATLAB codes can be easily converted into a suitable programming language, such as PYTHON, for incorporation into the Aqua-Quad processor alongside other planning modules, such as mission planning, for use in actual operations.

B. MODEL ARCHITECTURE

An overview of the Aqua-Quad solar power generation model is shown in Figure 23. The model is driven primarily through two scripts—an initialization script and a model run script, both of which are supported by various function scripts.

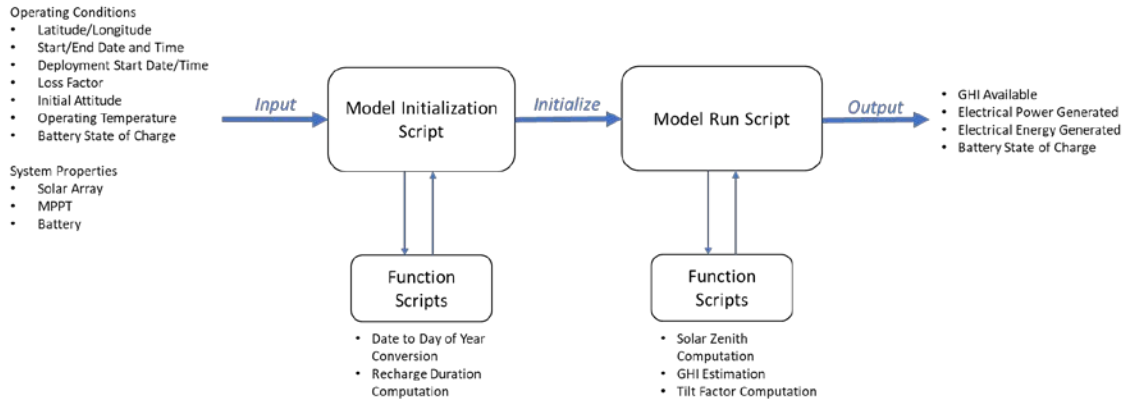


Figure 23. Overview of Aqua-Quad Solar Power Generation Model Architecture

1. Initialization Script

The initialization script “AQ_SPM_initialization” is used to initialize user-defined inputs for the operating conditions and the component properties of the Aqua-Quad solar power generation system. These are summarized in Table 6 and Table 7, respectively. The initialization script is presented in Appendix B.

Table 6. User-Defined Operating Conditions for the Aqua-Quad Solar Power Generation Model

Operating Conditions	
Parameter	Purpose
Latitude and longitude	Geographic location of Aqua-Quad used to determine solar zenith angle for GHI estimation. Latitude and longitude coordinates in degrees.
Start/end date and time	Duration available for solar power generation. Time to be input in Coordinated Universal Time (UTC).
Deployment start date/time	Date/time Aqua-Quad was first deployed. Used to account for $LF_{condition}$ due to degradation of solar array over time.
Loss Factor, $LF_{condition}$	Input expected solar array performance drop over time due to shading effects from environmental conditions and degradation of system.
Initial attitude	Defines the initial attitude of the Aqua-Quad at the start of the model run. To account for TF .
Attitude changes	Account for the change in attitude with time during the period of solar power generation. Used in determining the TF .
Operating temperature	Average operating temperature of the solar array. Used to determine array efficiency based on its temperature coefficient.
Battery state of charge	Defines the battery state of charge at the start of model run.

Table 7. Component Properties Defined for the Aqua-Quad Solar Power Generation Model

Component Properties		
Component	Specifications / Performance Parameters	Value
Solar Array	Total area	0.327m ²
	Temperature coefficient	-0.35% / °C
MPPT	Efficiency, η_{MPPT}	98%
Battery	Number of batteries	2
	Battery capacity	6Ah
	Battery charging efficiency	99.6%

2. Run Script

The “AQ_SPM_model_run” script is used to execute the model based on the initialized parameters. The codes are presented in Appendix C. The amount of electrical energy generated and stored in the Aqua-Quad batteries are computed at regular intervals for the duration of charging (t_{charge}) set by the user. This time-step execution used by the model is governed by the equation

$$E_{stored,electrical} = \left\{ \int_0^{t_{charge}} \left[GHI_{KC} \times TF \times (1 - LF_{condition}) \times \eta_{array} \times \eta_{MPPT} \times \eta_{charging,battery} \right] dt \right\} \times A_{array} \quad (IV.1)$$

A post-processing section is included in the script to display the results of the simulation through various time-based plots. These include the estimated GHI available, electrical power generated, electrical energy generated, and the battery state of charge.

3. Function Scripts

Five MATLAB function scripts are used to compute relevant results to support the initialization and run scripts during simulation. The purpose of each function script is summarized in Table 8 and the codes are presented in Appendix D.

Table 8. Function Scripts for Aqua-Quad Solar Power Generation Model

Function Script Name	Purpose
AQ_SPM_date2doy	Determines the start day of year given the start date input into the initialization script.
AQ_SPM_recharge	Computes the start time and recharge duration available for the Aqua-Quad, as well as the time since deployment, given the inputs to the initialization script.
AQ_SPM_solar_position	Computes the solar zenith in degrees at a given location, day of year and time in UTC.
AQ_SPM_GHI	Estimates the clear sky GHI from the Kasten-Czeplak solar irradiance model given the solar zenith angle in degrees.
AQ_SPM_tilt_factor	Computes the tilt factor given the attitude of the Aqua-Quad.

V. MODEL TESTING AND VERIFICATION

Testing of the developed Aqua-Quad solar power generation model was performed to verify that the outputs of the model were in line with expectations given the input conditions. Verification was then carried out to determine the model's accuracy when compared against actual data collected from physical testing of the system.

A. TESTING RESULTS

Test runs on the model was performed with varying input operating conditions, such as different time of day and operating temperatures. The results showed that the model has been set-up correctly. A summary of the test results is shown in Table 9 and the details are further elaborated in this section.

Table 9. Summary of Model Testing Results

Test No.	Scope	Results
1	Vary location	Pass
2	Vary start/end time	Pass
3	Vary deployment start date	Pass
4	Vary operating temperature	Pass

1. Test 1—Location

This test varied the location of the Aqua-Quad while keeping to the same date and time to verify that the model could correctly reflect the actual solar conditions at both locations. The input start date/time was 15 Jul 2020 0500 Coordinated Universal Time (UTC) and end date/time was 15 Jul 2020 2200 UTC. The locations selected were Monterey, California, USA (lat/long 36.59°/-121.87°) and Singapore (lat/long 1.35°/103.93°). Being 15 hours behind Singapore, the start time of the simulation would be 0400H local time in the morning for Monterey and 1900H local time in the evening for Singapore.

Figure 24 shows the comparison of results for the solar zenith angle and estimated GHI at both locations. The results agree with expectations, where daytime is dawning in Monterey, resulting in the observed changes in angle and estimated GHI, while nighttime is falling in Singapore, as reflected by the decrease in GHI.

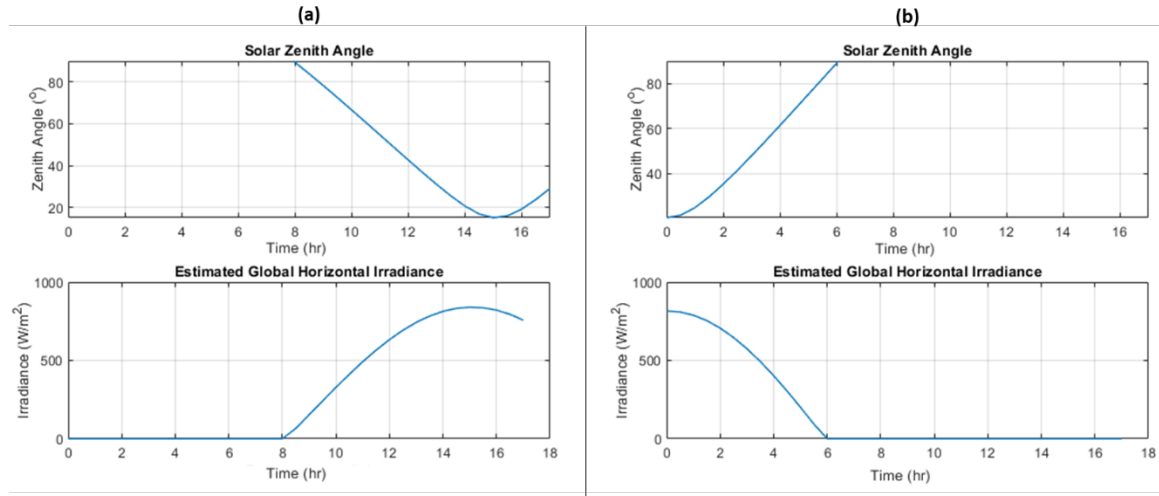


Figure 24. Comparison of Solar Zenith Angle and Estimated GHI for Monterey, California, USA (a) and Singapore (b)

2. Test 2—Start/End Time

Test 2 varied the start time of the simulation keeping to the same location and recharge duration to verify that the model could correctly reflect the solar conditions. Start times were set at 0500H local time (1200 UTC) and 1500H local time (2200 UTC) for Monterey, California with all other parameters being the same. The results agreed with expectations and are shown in Figure 25.

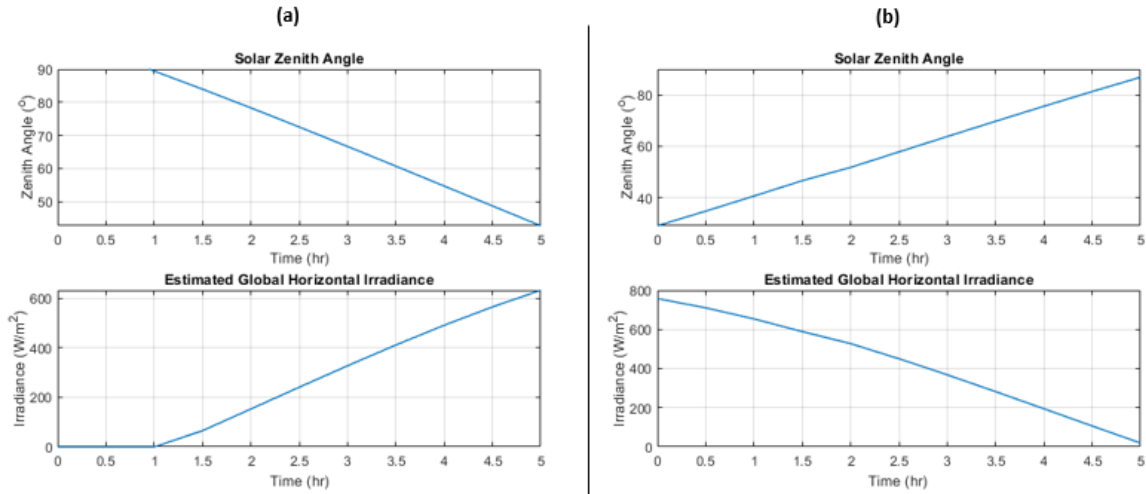


Figure 25. Comparison of Solar Zenith Angle and Estimated GHI at Monterey California with 0500H local start time (a) and 1500H local start time (b)

3. Test 3—Deployment Start Date

The deployment start date was varied to observe the drop in efficiency due to a longer period of deployment out at sea—the first being a newly deployed Aqua-Quad and the second being a system that had been deployed out at sea for one year. All other parameters were kept constant. The results are shown in Figure 26 where the system that had been deployed longer is showing a lower power generation output, which is in line with expectations. While a deployment period of one year was used in the test to verify the drop in efficiency, it is to be noted that the envisaged deployment duration for the Aqua-Quad in its operational environment is more likely to be in months rather than in years.

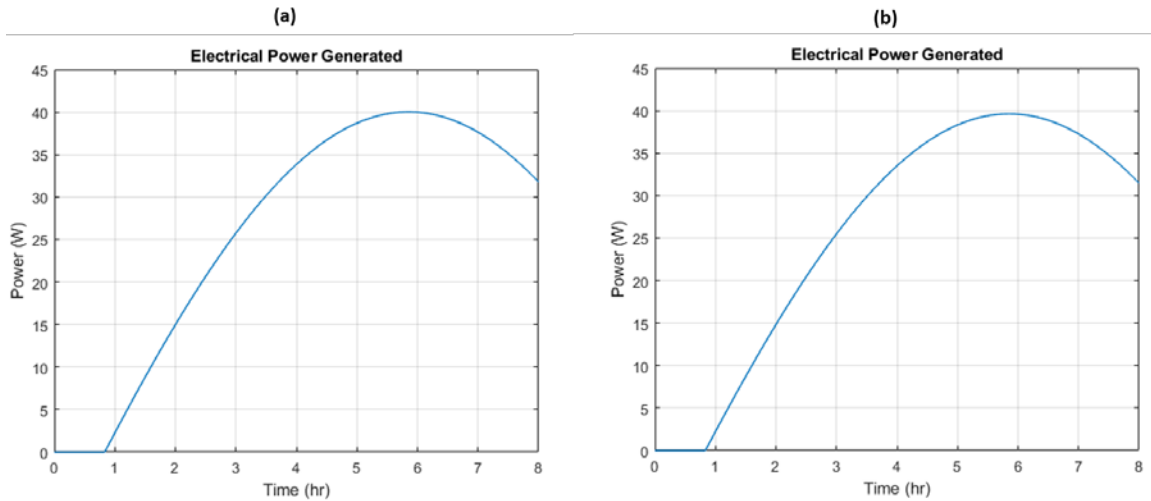


Figure 26. Comparison of Electrical Power Generated for Aqua-Quad System that Is Newly Deployed (a) and Deployed for one Year (b)

4. Test 4—Operating Temperature

This test varied the operating temperature of the Aqua-Quad solar array, with one at STC of 25°C and the other at 40°C. All other parameters were constant. The system at higher operating temperature would be expected to achieve a lower power generation output due to lower efficiency at higher operating temperatures. The results were consistent with expectations, as shown in Figure 27.

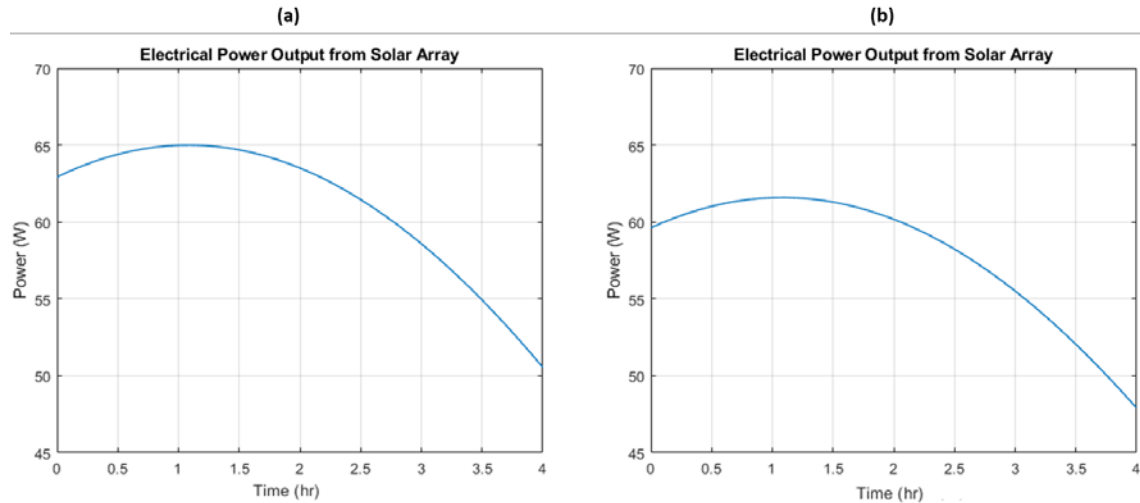


Figure 27. Comparison of Electrical Power Output for Solar Array Operating Temperature of 25°C (a) and 40°C (b)

B. VERIFICATION RESULTS

Verification tests were performed to compare the model output against measured results. Four tests were performed on different days and at different times of the day within the grounds of NPS. The tests were performed with a stationary solar array at neutral attitude, with the system considered to be newly deployed such that the $LF_{condition}$ at the start of the charging cycle is zero. The weather on the test days varied from clear skies to passing clouds. See Table 10 for a summary of the verification tests details.

Table 10. Verification Tests Details

Test No.	Location (Lat / Long)	Start Date / Time	End Date / Time	Average Array Temperature
1	36.596 / -121.876	19 Oct 2020 / 1440 PDT (19 Oct 2020 / 2140 UTC)	19 Oct 2020 / 1540 PDT (19 Oct 2020 / 2240 UTC)	29°C
2	36.596 / -121.876	29 Oct 2020 / 0944 PDT (29 Oct 2020 / 1644 UTC)	29 Oct 2020 / 1034 PDT (29 Oct 2020 / 1734 UTC)	26°C
3	36.596 / -121.876	30 Oct 2020 / 1600 PDT (30 Oct 2020 / 2300 UTC)	30 Oct 2020 / 1620 PDT (30 Oct 2020 / 2320 UTC)	25°C
4	36.596 / -121.876	03 Nov 2020 / 1110 PST (03 Nov 2020 / 1910 UTC)	03 Nov 2020 / 1150 PST (03 Nov 2020 / 1950 UTC)	24°C

The conduct of the verification test involved comparing the cumulative electrical energy generated by the solar array against the model prediction. In determining the electrical energy generated, the trapezoidal method was used to integrate the power generated by the system over the duration of charge. The power generated by the system was measured using voltage and current sensors that recorded the output from the MPPT. Measurements were taken at 0.5min intervals.

1. Findings and Analysis

Figure 28 compares the measured cumulative electrical energy generated by the solar array and the model prediction over the duration of charge for the four verification tests.

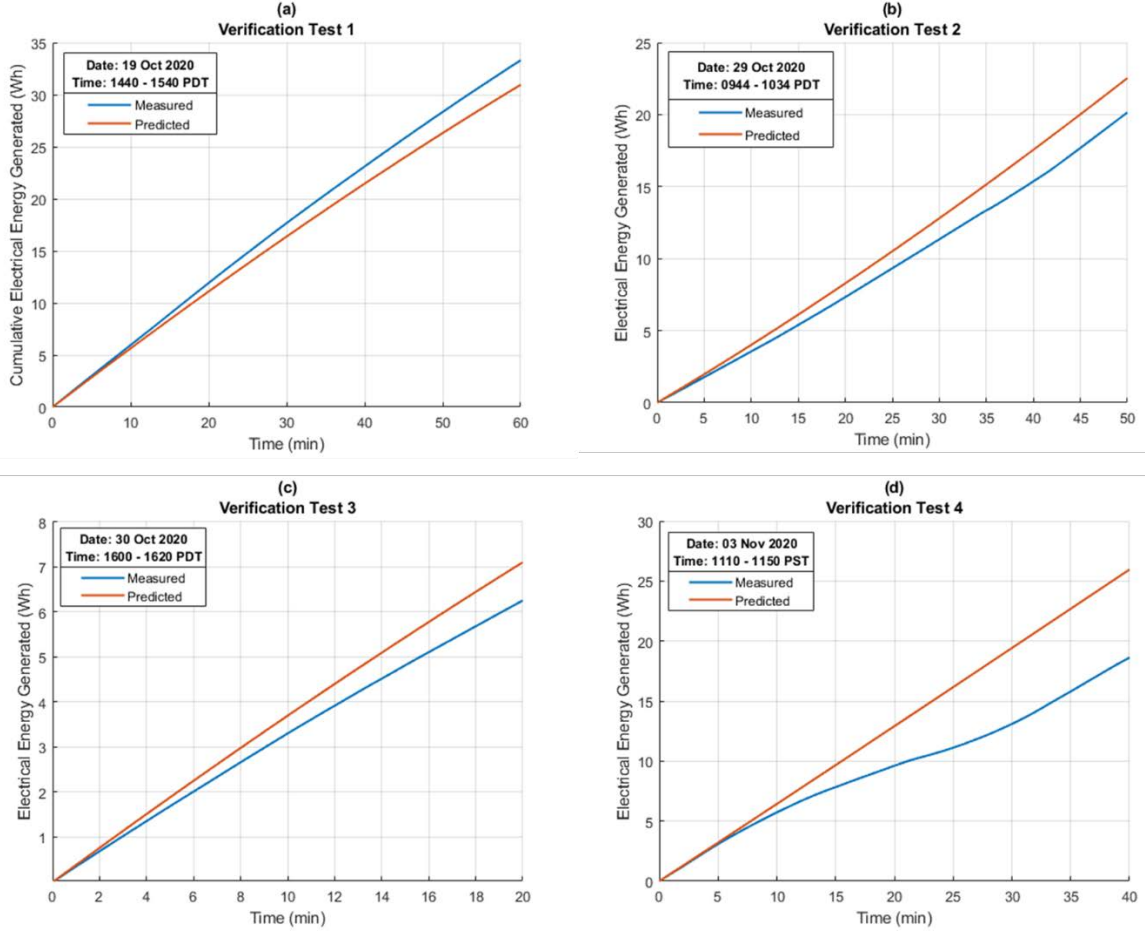


Figure 28. Measured and Predicted Cumulative Electrical Energy Generated for Verification Test 1 (a), 2 (b), 3 (c) and 4 (d)

In the comparison of results, the Mean Absolute Percentage Error (MAPE) was used to assess the accuracy of the model in predicting the actual results and to quantify the error. This is defined as

$$MAPE = \frac{100\%}{n} \sum_{i=1}^n \left| \frac{Measured - Predicted}{Measured} \right|, \quad (V.1)$$

where n is the number of data points measured.

The developed Aqua-Quad solar power generation model was found to be capable of predicting the electrical energy generated by the solar array with a MAPE of 7% to 29% as shown in Table 11. The overall MAPE across the four verification tests was $14.5\% \pm 1.3\%$ for a 95% confidence interval. Expectedly, the model performed poorer under cloudy

conditions. This is because the model is not able to account for local weather conditions affecting available GHI as discussed in Chapter III.B.2. The capability to account for local conditions affecting available GHI is therefore desired.

Table 11. Computed Mean Absolute Percentage Errors based on Measured and Predicted Cumulative Electrical Energy Generated

Verification Test	Mean Absolute Percentage Error (95% confidence interval)	Weather Condition at Test
1	6.7% $\pm$ 0.1%	Clear sky
2	12.8% $\pm$ 0.2%	Scattered clouds
3	12.2% $\pm$ 0.2%	Clear sky
4	29.4% $\pm$ 3.6%	Passing clouds

2. Other Observations

a. *The Need to Adjust Model for Accuracy*

Figure 29 shows the measured power generated against the model predication. The fluctuations in measured power are a direct reflection of the actual GHI availability influenced by local conditions. It can be observed that the predicted results lack the ability to follow and adjust for variations in measured results. This is not unexpected, since a simple solar irradiance model was used to predict the available GHI without the means to account for local conditions.

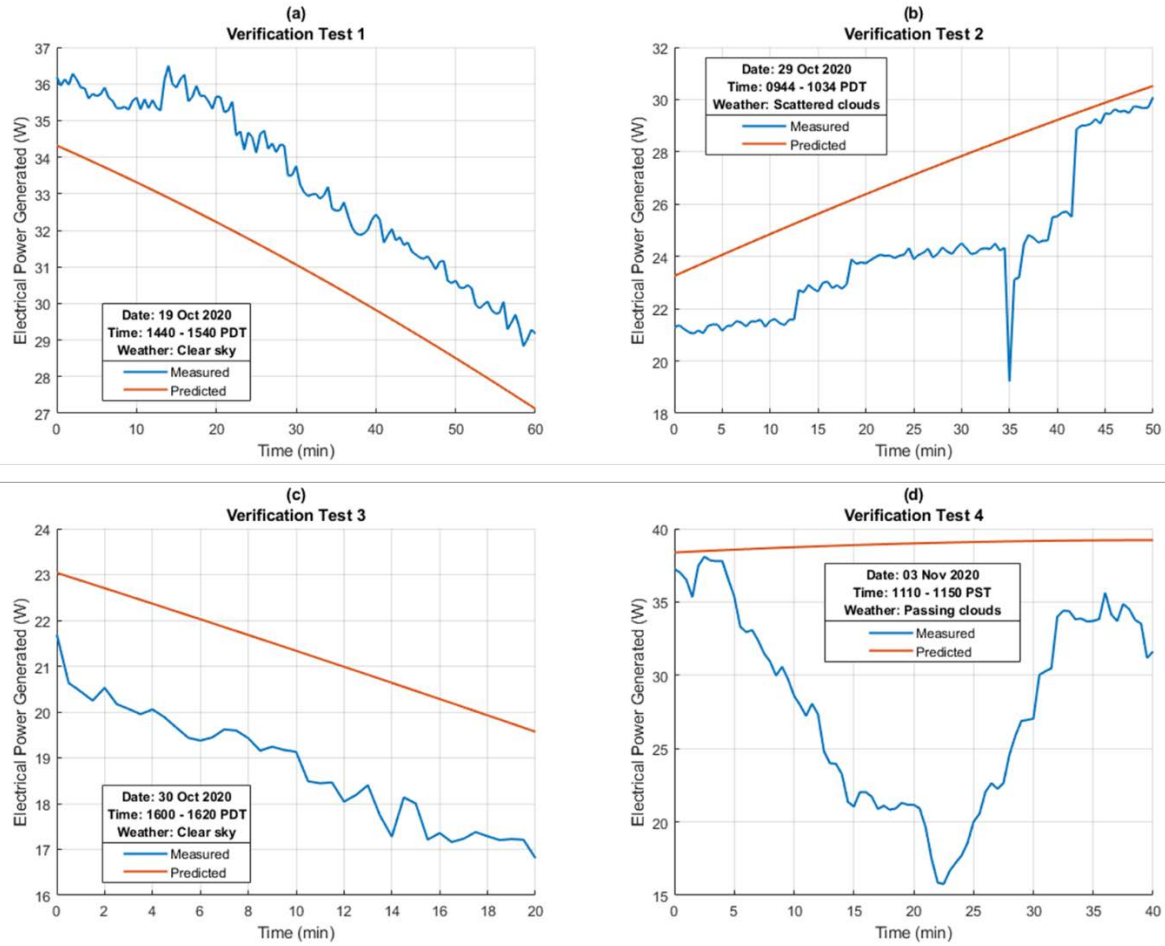


Figure 29. Measured and Predicted Electrical Power Generated for Verification Test 1 (a), 2 (b), 3 (c) and 4 (d)

Furthermore, visibly clear sky conditions may not translate to good accuracy in model predication, as shown from the MAPE for verification test 3 ($12.2\% \pm 0.2\%$), which is about 3 times larger than that of verification test 1 ($6.7\% \pm 0.1\%$) despite similar weather conditions observed. This suggests that model accuracy could either vary with time of day or that there were other atmospheric variations which could not be visibly noted. The need for the Aqua-Quad to responsively adjust its prediction by monitoring its deviation from actual values is therefore desired and this is discussed in Chapter VI.B.1.

b. Challenges in Accurate Battery SOC Estimation

The initial and final battery SOC were monitored for each of the verification tests to assess if battery SOC could be predicted using the developed Aqua-Quad solar power generation model. The battery SOC was measured using a battery checker connected to the battery while it was being charged. By adopting an energy accounting approach using the measured electrical energy generated, it was found that the battery SOC readings did not accurately reflect the actual amount of electrical energy that was charged into the battery. These are shown in Table 12 and the observations suggest that the measured initial and final battery SOC's were likely to have been erroneous.

Table 12. Initial and Final Battery State of Charge for Verification Tests

Verification Test	Measured Initial Battery SOC	Theoretical Final Battery SOC	Measured Final Battery SOC
1	75%	113%	98%
2	80%	103%	92%
3	78%	85%	81%
4	83%	104%	92%

The challenge faced in accurately monitoring the battery SOC was postulated to be due to measurement errors of the battery checker, especially since it was used to monitor battery SOC while the battery was undergoing its charge cycle. In addition, measurements were taken when the battery was under load and not at rest, resulting in voltage readings that do not accurately reflect the actual SOC of the battery.

As the Aqua-Quad's battery would constantly be under load during operations, it is therefore unlikely that an accurate battery SOC can be measured using an integrated battery checker. An alternative would be to consider an energy accounting approach with reference from a known SOC to approximate the SOC at any point in time. In this regard, a fully charged Aqua-Quad would be considered as the reference with the batteries at full capacity. The accounting process would then begin by monitoring the changes in electrical energy consumed and generated over time to compute the net amount of energy within the batteries

at a given point in time. This information is then used to estimate the battery SOC. However, it must be noted that errors in voltage and current measurement exists and these could lead to compounding errors in energy accounting over time. To minimize compounding errors, the accounting process could be reset every time the Aqua-Quad batteries attain full charge so that an accurate starting reference point will always be used.

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VI. BENEFITS, FUTURE WORK AND CONCLUSION

A. BENEFITS OF AQUA-QUAD SOLAR POWER GENERATION MODEL

1. Optimize Aqua-Quad Development Efforts

Developers can use the solar power generation model to assess the sufficiency of the Aqua-Quad's solar power generation system in meeting the energy demands of its equipment and payload during mission (see Figure 30). Towards this end, a separate project has been undertaken by the Aqua-Quad development team to model the energy demands of the Aqua-Quad in flight [18].

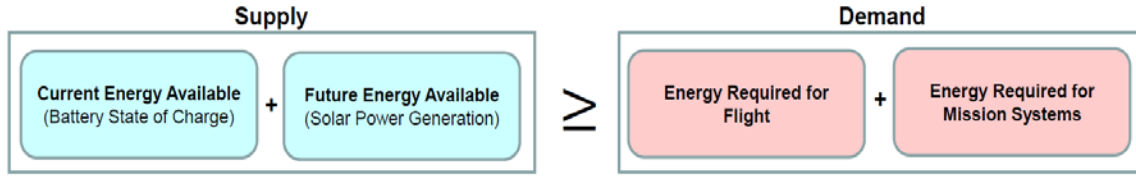


Figure 30. Energy Supply vs. Demand

By utilizing both supply and demand models, Aqua-Quad developers would now be able to perform design trade-off analyses and assess the suitability of technology enhancements by adjusting the component performance parameters of the models. This would allow for better optimization of both technology and cost in future Aqua-Quad development efforts. An example of such an analysis is in the tradespace of array size, where developers can use the developed models to analyze trade-offs between increasing power generation capability through the use of larger solar cells and its effect on weight and aerodynamics performance in flight.

2. Determine Cost Function for Mission Planning Algorithm

The process of mission planning involves ensuring the sufficiency of energy supply to meet energy demands. This is performed by a mission planning module that has been developed for the Aqua-Quad. However, the mission planning algorithm currently relies on average solar data and lacks the ability to account for specific factors affecting solar power generation, such as the sea state or operating temperature.

By leveraging on the solar power generation model, the cost function for mission planning algorithm can now be further refined. Adjustments can be made to the different operating conditions in the model to understand the impact they have on power generation. This would allow for the key cost driver affecting power generation efficiency to be identified and the mission planning algorithm to be refined to account for this. For example, if sea state was found to be the highest cost driver affecting power generation, then the mission planning algorithm can be refined to factor sea state conditions more significantly when proposing mission plans and evaluating the probability of mission success.

3. Realistic Evaluation of Feasible Mission Envelope

Performance analysis for the Aqua-Quad has thus far relied on average solar irradiance data and OEM advertised performance parameters. While this has worked well for system-level development efforts, subsequent work involving prototype development and the conduct of operational trials require higher fidelity in performance analysis.

Since the developed solar power generation model was based on field experiments that characterized the actual operating efficiencies of the Aqua-Quad solar power generation system, the model therefore offers a realistic reflection of actual system capability for performance analysis. This would enable a more realistic evaluation of the feasible mission envelope to scope the conduct of subsequent operational trials. In addition, being able to realistically evaluate the feasible mission envelope will enable mission planners to better assess the feasibility of employing the Aqua-Quad for a mission and plan for the number of Aqua-Quad systems required in swarm operations.

4. Energy Optimal Mission Execution

The MATLAB script developed for the Aqua-Quad solar power generation model can be used not just within a laboratory environment for design and development work, but also converted into an embedded programming language for implementation in the actual Aqua-Quad system. By doing so, the solar power generation model can be integrated with its path planning module to support energy supply/demand optimization in mission planning and execution. For example, the logic could be used by the Aqua-Quad to estimate charge time for mission planning or to explore the effectiveness of various mission profiles

or configurations. Combined with AI capabilities, the Aqua-Quad would be able to achieve a high level of energy-awareness that would enable it to improve its ability to self-sustain and further its endurance out at sea.

B. PROPOSED AREAS FOR FUTURE WORK

1. Artificial Intelligence for More Accurate Model Prediction

The accuracy of the Aqua-Quad solar power generation model would improve if a more accurate prediction of generated power could be achieved. However, this can be a challenge, given the performance variation of simple solar models with both time of day and time of year [10]. Since the adoption of a more complex solar irradiance model carries significant trade-offs and developmental risks to the Aqua-Quad, due to the need for additional atmospheric sensors, a more viable solution would be to leverage AI that can use feedback to adjust the solar power generation model to achieve a more accurate prediction. Such feedback could be tapped from a knowledge base of local conditions or from a new knowledge base that is being built-up as the Aqua-Quad evaluates its local operating environment.

An example is in the use of AI to form an understanding of how weather conditions are changing. This can be done by monitoring the deviation between predicted and measured results. With reference to verification test 4 (Figure 29(d)), the sudden, but fairly brief drop in measured power would prompt the AI to postulate that clouds are passing and anticipate the effect of cloud cover on subsequent predictions, such as the expected reduction in power generated or the additional time required to achieve a full charge. The appropriate courses of action can then be taken based on the AI's assessment of the outlook.

2. Modeling the Effects of the Operating Environment

Information on the actual operating conditions of the Aqua-Quad within its field environment is needed to maximize the full potential of the solar power generation model. These include sea state conditions affecting solar array tilt and the realistic characterization of the $LF_{condition}$. Towards these ends, it is proposed that the effects of the operating environment be modeled and characterized by deploying the prototype Aqua-Quad out at

sea for an extended period of time to measure actual attitude fluctuations and monitor degradation of its solar array. Sea state information obtained from oceanographic studies could also be verified against measured data to assess their suitability for incorporation as knowledge bases within the Aqua-Quad logic for solar power generation forecasting and mission planning.

The conduct of such an experiment within the actual operating environment of the Aqua-Quad also serves to support other project development efforts. For example, IMU data obtained from an Aqua-Quad out at sea can be used to build a parametric description of the wave form under different sea states to establish the operating envelope for safe take-off. Separately, understanding environmental degradation effects on the solar array will allow developers to better manage trade-offs in terms of understanding how significant the solar array contributes towards the overall survivability of the Aqua-Quad system out at sea, vis-à-vis other survivability factors such as structural damage to the main body or deterioration of the waterproof seals which would kill the onboard electronics.

C. CONCLUSION

The developed solar power generation model for the Aqua-Quad allows for the realistic forecasting of electrical power generated given its location and charging duration under different operating environments and conditions. Variables affecting solar power generation, such as geographic location and time of day and year, solar array tilt due to sea state, and degradation of the solar array were considered. Efficiencies of the solar power generation system and electrical components were also characterized through the experiments and findings were incorporated into the model to account for actual field performance. The developed model achieved a mean absolute percentage error of 7% to 29%, with larger errors attributed to the limitation of the model in accounting for the effects of local weather conditions on available global horizontal irradiance. Improvements to model accuracy is proposed through the development of an AI solution as part of future work for the Aqua-Quad. With the developed solar power generation model, the systematic development of the Aqua-Quad can be optimized, the cost function of the mission planning

algorithm can be determined, the Aqua-Quad's feasible mission envelope can be realistically evaluated, and mission execution can be made more energy optimal.

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APPENDIX A. SIMPLE SOLAR IRRADIANCE MODELS

The following simple solar irradiance models were referenced from [10] and used in this report. These models predict the available clear sky Global Horizontal Irradiance (GHI) given the Zenith angle (z) of the sun for a particular location, day of year and time of day.

Kasten-Czeplak (KC) model (1980):

$$GHI = 910 \times \cos(z) - 30 \quad (A1.1)$$

Adnot-Bourges-Campana-Gicquel (ABCG) model (1979):

$$GHI = 951.39 \times (\cos(z))^{1.15} \quad (A1.2)$$

Daneshyar-Paltridge-Proctor (DPP) model (1978):

$$DNI = 950.2(1 - \exp(-0.075(90^\circ - z))) \quad (A1.3)$$

$$DHI = 14.29 + 21.04 \left(\frac{\pi}{2} - z \frac{\pi}{180} \right) \quad (A1.4)$$

$$GHI = DNI \times \cos(z) + DHI \quad (A1.5)$$

Robledo-Soler (RS) model (2000):

$$GHI = 1159.24 \times (\cos(z))^{1.179} \times \exp(-0.0019 \times (90^\circ - z)) \quad (A1.6)$$

Haurwitz model (1945):

$$GHI = 1098 \times \cos(z) \times \exp\left(\frac{-0.057}{\cos(z)}\right) \quad (\text{A1.7})$$

APPENDIX B. AQUA-QUAD SOLAR POWER GENERATION MODEL INITIALIZATION SCRIPT

This script is used for initializing the parameters of the Aqua-Quad solar power generation system which is to be modeled using the AQ_SPM_model_run.m script. Functions that will be called in this script are: AQ_SPM_date2doy.m and AQ_SPM_recharge.m

```
clear all; close all; clc;
```

Input Parameters - Solar Irradiance Computation

```
% Aqua-Quad Location
% This is the current location of the Aqua-Quad and is used to determine
% the solar irradiation available at that location. Latitude is positive
% for north of equator, negative for south of equator. Longitude is
% positive for east of prime meridian, negative for west of prime meridian.

lat      = 36.596;    % Latitude coordinate in degrees;
long     = -121.876;  % Longitude coordinate in degrees;

% Start/End Date/Time of Solar Power Charging
% This is the charging period of the Aqua-Quad, which is also time period
% in which the solar power generation capability is being analysed.
% All time parameters are to be input in UTC.

start.UTC = '03-Nov-2020 19:10'; % UTC start; 'DD-MMM-YYYY HH:MM' string format
end.UTC   = '03-Nov-2020 19:50'; % UTC end; 'DD-MMM-YYYY HH:MM' string format

% Aqua-Quad Deployment Start Date
% This is the date/time Aqua-Quad was first deployed in the area of
% operation and is used to account for the degradation of solar power
% generation capability over time. This can be set to the start.UTC if
% the deploy.UTC is unknown.

deploy.UTC = '03-Nov-2020 19:10'; % UTC deployed date/time; 'DD-MMM-YYYY HH:MM' string
format
```

Input Parameters - Operating Conditions

```
% Aqua-Quad Solar Panel Operating Temperature
% Difference in operating temperature from the nominal of 25 degrees C
% affects the efficiency of solar panel performance. Input can be
% operating temperatures over the period of recharge or as an average
% operating temperature throughout the period of recharge.

temp_op = 24; % Average operating temperature of solar panel in degrees C.
```

```

% Aqua-Quad Initial Attitude
%   This defines the initial attitude of the Aqua-Quad solar panels in
%   [roll, pitch, yaw] format in degrees. For [0 0 0], body axes of
%   Aqua-Quad is aligned with North-East-Up (NEU) with same origin, and
%   solar panels are horizontal with the surface.

att_ini      = [0 0 0]; % Default is [0 0 0].

% Aqua-Quad Attitude Changes
%   Changes in attitude affect the amount of solar radiation incident on
%   the solar panels.

att_change = [0 0 0]; % Change in [roll pitch yaw] attitude.

% Loss Factor
%   This factor reduces the amount of irradiance received by the solar
%   cells due to soiling on the solar panels from salt deposits, bird
%   droppings, as well as from degradation of the solar array over time.

LF          = 0.01;      % Percentage yearly performance reduction (e.g. -1%/year = 0.01)

% Battery Initial SOC
%   This defines the battery state of charge at the start of the charging
%   cycle.

batt.SOC_ini      = 75;      % Initial battery state of charge (%)

```

Solar Panel Properties

```

% Single Solar Cell Parameters
PV.cell.area      = 0.01635; % Area of one SunPower E60 cell (w/ nipped corners)
in m2

% Solar Array Parameters
PV.array.cells     = 20;      % No. of cells in solar array
PV.array.area      = PV.array.cells*PV.cell.area; % Area of array in m2
PV.array.eff       = 0.236;   % Experimentally determined array performance
efficiency (%)
PV.array.temp_coeff = -0.0035; % Performance efficiency drop with every 1 deg C
increase in temperature (-0.35%/degC)
PV.array.temp_norm  = 25;     % Nominal temperature in deg C for PV array

```

MPPT Properties

```

MPPT_eff          = 0.98;    % MPPT efficiency

```

Battery Properties

```

batt.num_parallel      = 2;          % Number of batteries in parallel
batt.amp_cap_single    = 6;          % Capacity of one battery (Ah)
batt.volt_norm_single  = 14.8;       % Nominal voltage of one battery (V)
batt.charge_eff        = 0.996;     % Charging efficiency (99.6% = 0.996)

batt.cap               =
batt.num_parallel*batt.amp_cap_single*batt.volt_norm_single;    % Total battery capacity
(Wh)

```

Baseline Power Consumption

```

AQ_pwr_consume        = 1.3;        % Baseline power consumption by AQ systems during
recharging (W)

```

Compute the Start Day of Year in which Recharge Begins

```

start_doy=AQ_SPM_date2doy(start.UTC);    % Start day of year in which recharge begins.

```

Compute the Day of Year Start Time, Recharge Duration Available and Time since Deployment

```

[t_start, t_charge, t_deploy]=AQ_SPM_recharge(start_doy, start.UTC, end.UTC, deploy.UTC);

```

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APPENDIX C. AQUA-QUAD SOLAR POWER GENERATION MODEL RUN SCRIPT

This script is used to determine the amount of power generated by the Aqua-Quad solar power generation system. Initialization of parameters is to be performed using the following script: AQ_SPM_initiatlization.m. Functions that will be called in this script are: AQ_SPM_solar_position.m, AQ_SPM_clearsky_GHI.m and AQ_SPM_tilt_factor.m

```
close all
```

Solar Power Generation Model

```
t_div = 0:0.5/60:t_charge; % Define intervals for computation. Estimated GHI will be  
computed at every 0.5/60 hr interval from t=0 to t=t_charge.  
  
for i=1:1:length(t_div)
```

Irradiation Available

```
% Determine day of year and UTC time  
doy = floor(t_start+t_div(i)/24); % Determine the current doy without zero-  
wrapping  
t_UTC = ((t_start+t_div(i)/24)-doy)*24; % Determine the current UTC time in decimal  
format (e.g. 1830H = 18.5)  
  
if doy>365  
    doy = doy-365*floor(doy/365); % Zero-wrapping of doy to keep within 1 to 365  
days in a year  
end  
  
% Determine zeta angle and azimuth of sun  
[zeta, az] =AQ_SPM_solar_position(doy, t_UTC, lat, long); % (degrees)  
  
% Estimate clear sky GHI  
[clear_GHI] = AQ_SPM_GHI(zeta); % (W/m2)  
  
% Determine effect of solar panel tilt to GHI  
attitude = att_ini + att_change;  
  
[tilt_f] = AQ_SPM_tilt_factor(attitude);  
  
% Determine effect of loss factor to GHI absorbed  
LF_GHI = 1-((t_deploy+t_div(i))/(24*365)*LF); % Percentage of GHI absorbed due  
to loss factor over time
```

```

% Compute the estimated GHI
est_GHI      = clear_GHI*tilt_f*LF_GHI; % (W/m2)

PV_pwr_in    = PV.array.area*est_GHI;   % Solar power absorbed by array

```

Power Generated

```

PV_temp_eff = PV.array.eff+((temp_op-PV.array.temp_norm)*PV.array.temp_coeff); % PV
array efficiency due operating temperature

PV_pwr_out  = PV_pwr_in*PV_temp_eff; % Power output by PV array (W)

PV_pwr_gen  = PV_pwr_out*MPPT_eff; % Power generated by solar power system

```

Power Stored

```

PV_pwr_store = batt.charge_eff*(PV_pwr_gen-AQ_pwr_consume); % Power stored by
battery

```

Save output data

```

output.t_charge(i)    = t_div(i);
output.doy(i)         = doy;
output.t.UTC(i)       = t.UTC;
output.zeta(i)        = zeta;
output.clear_GHI(i)   = clear_GHI;
output.tilt_f(i)      = tilt_f;
output.est_GHI(i)     = est_GHI;
output.PV_temp_eff(i) = PV_temp_eff;
output.PV_pwr_in(i)   = PV_pwr_in;
output.PV_pwr_out(i)  = PV_pwr_out;
output.MPPT_eff(i)    = MPPT_eff;
output.PV_pwr_gen(i)  = PV_pwr_gen;
output.PV_pwr_store(i) = PV_pwr_store;

```

Cumulative Watt Hour Generated

```

if (i==1)
    output.Wh(i)    = 0;

else
    output.Wh(i)    = trapz([output.t_charge(i-1)
output.t_charge(i)], [output.PV_pwr_gen(i-1) output.PV_pwr_gen(i)]); % Compute increment
in Wh generated

end

```

```
output.cum_Wh      = cumsum(output.Wh); % Cumulative Wh generated
```

Battery State of Charge

```
if (i==1)
    output.Wh_store(i)    = 0;

else
    output.Wh_store(i)    = trapz([output.t_charge(i-1)
output.t_charge(i)], [output.PV_pwr_store(i-1) output.PV_pwr_store(i)]); % Compute
increment in Wh generated

end

output.cum_Wh_store      = cumsum(output.Wh_store); % Cumulative Watt Hour to
battery

output.SOC               = batt.SOC_ini+(output.cum_Wh_store/batt.cap)*100; % Battery
state of charge

output.SOC(output.SOC >= 100) = 100;

end

save('sim_output.mat', 'output');
```

Plot Irradiation Parameters

```
figure ('Name', 'Irradiation Parameters')
subplot(2,1,1)
plot(output.t_charge*60, output.zeta, 'LineWidth', 1);
title('Solar Zenith Angle')
xlabel('Time (min)')
ylabel('Zenith Angle (^{o})')
ylim([-inf 90])
grid on

subplot(2,1,2)
plot(output.t_charge*60, output.est_GHI, 'LineWidth', 1);
title('Estimated Available Global Horizontal Irradiance')
xlabel('Time (min)')
ylabel('Irradiance (W/m^{2})')
grid on
```

Plot Power Generation Parameters

```
figure ('Name', 'Elecrcial Power Generation Parameters')
subplot(2,1,1)
```

```

plot(output.t_charge*60,output.PV_pwr_out,'LineWidth',1);
title('Electrical Power Generated')
xlabel('Time (min)')
ylabel('Power (W)')
grid on

subplot(2,1,2)
plot(output.t_charge*60,output.cum_wh,'LineWidth',1);
title('Cumulative Electrical Energy Generated')
xlabel('Time (min)')
ylabel('Cumulative Energy (Wh)')
grid on

```

Plot Battery Charging Parameter

```

figure ('Name','Battery Charging Parameters')

plot(output.t_charge*60,output.SOC,'LineWidth',1);
title('Battery State of Charge');
xlabel('Time (min)')
ylabel('State of Charge (%)')
grid on
ylim([-inf 100])

```

APPENDIX D. AQUA-QUAD SOLAR POWER GENERATION MODEL FUNCTION SCRIPTS

A. AQ_SPM_DATE2DOY

```
function start_doy=AQ_SPM_date2doy(start.UTC)
% AQ_SPM_date2doy determines day of year from year, month of year, and day of month
%
% Syntax
%   doy=AQ_SPM_date2doy(month, day)
%
% Description
%   Calculate the day of the year given the year, month of year, and day of
%   month in the Gregorian calendar. Does not account for leap year. In a
%   leap year, 29 February is considered as 28 February.
%
% Inputs:
%   year - scalar or vector of years (e.g. 1990). Year(i) corresponding
%   to Month(i) and Day(i).
%   month - scalar or vector of month numbers (1-12). Month must be >=1 and <13
%   Month must be of the same length as Year.
%   day - scalar or vector of day of month numbers. Must be of same
%   length as Year. Day must be >=1 and <32.
%
% Outputs:
%   doy - A column vector of the day of year as a floating point number from 1 to
%   366.999...
%   If any of the input values are NaN, the corresponding output value will be NaN.
%
% Note that while Day must be >=1 and <32. The calculation does NOT check
% to ensure that the day of month is valid for a given month. Thus
% AQ_SPM_date2doy(2012, 4, 31) = AQ_SPM_date2doy(2012, 5, 1).
%
% Sources:
%
% [1] Sandia National Library 2014, https://pvpmc.sandia.gov/PVLIB\_Matlab\_Help/

mth = month(datetime(start.UTC));
dy = day(datetime(start.UTC));

if mth==2
    if dy==29
        dy=28;
    end
end

month_offset = [1;2;0;1;1;2;2;3;4;4;5;5]; %Offset from (n-1)*30
```

```

month_start = ((mth - 1) .* 30) + month_offset(mth);

start_doy=month_start + (dy - 1);

end

```

B. AQ_SPM_RECHARGE

```

function [t_start, t_charge, t_deploy]=AQ_SPM_recharge(start_doy, start.UTC, end.UTC,
deploy.UTC)
% AQ_SPM_recharge computes the start time and recharge duration
% available for the Aqua-Quad, as well as the time since deployment.
%
% Syntax
% [start_t, t_charge, t_deploy]=AQ_SPM_recharge(start_doy, start.UTC, end.UTC,
deploy.UTC)
%
% Description
% Calculate the recharge duration available for the Aqua-Quad based on
% its start date/time and end date/time. The recharge duration is given
% in hours. This function also calculates the time since deployment in
% hours to factor for degradation of the solar panel performance.
%
% Inputs:
% start_doy - this is the the day of the year given the year, month
% of year, and day of month in the Gregorian calendar. Does not
% account for leap year. In a leap year, 29 February is considered as
% 28 February.
%
% start.UTC - UTC start time in 'DD-MMM-YYYY HH:MM' string format.
%
% end.UTC - UTC end time in 'DD-MMM-YYYY HH:MM' string format.
%
% deploy.UTC - UTC deployment date/time in 'DD-MMM-YYYY HH:MM'
% string format.
%
% Outputs:
% t_start - scalar value of the day of year start time in decimal
% notation (e.g. 15-Jul 15:00H is given as 196.625).
%
% t_charge - scalar value of the recharge duration in hours.
%
% t_deploy - scalar value of the time since deployment in hours.

t_start = start_doy+(hour(datetime(start.UTC))+minute(datetime(start.UTC))/60)/24; %
Start time in terms of doy

t_charge = hours(datetime(end.UTC)-datetime(start.UTC)); % Recharge duration in terms of

```

```
hours
```

```
t_deploy = hours(datetime(start.UTC)-datetime(deploy.UTC)); % Duration since start of  
deployment in terms of hours
```

```
end
```

C. AQ_SPM_SOLAR_POSITION

```
function [zeta, az] =AQ_SPM_solar_position(doy, t.UTC, lat, long)
```

```
% AQ_SPM_solar_position computes the solar zenith and azimuth.
```

```
%
```

```
% Syntax:
```

```
% zeta =AQ_SPM_solar_zenith(doy, t.UTC, lat, long)
```

```
%
```

```
% Description:
```

```
% Calculate the solar zenith and azimuth in degrees at a given location,  
% day of year and time in UTC.
```

```
%
```

```
% Inputs:
```

```
% doy - Day of year as an integer from 1 to 365. Computed using the  
% AQ_SPM_date2doy function. Does not account for leap year - 29 Feb  
% during leap year is considered as 28 Feb.
```

```
%
```

```
% t.UTC - The current time of day in UTC. Time is in decimal format.  
% (e.g. 18:30H is input as 18.5).
```

```
%
```

```
% lat - Latitude coordinate of Aqua-Quad location in degrees. Positive  
% for north of equator, negative for south of equator.
```

```
%
```

```
% long - Longitude coordinate of Aqua-Quad location in degrees. Positive  
% for east of prime meridian, negative for west of prime meridian.
```

```
%
```

```
% Outputs:
```

```
% zeta - Solar zenith angle in degrees. This is the angle between the  
% zenith and the center of the sun's disc.
```

```
%
```

```
% az - Solar azimuth angle in degrees. This is the angle of the sun's  
% rays measured in the horizontal plane from due north in a clockwise  
% positive direction. Sun is due north if az=0 deg and due south if sun  
% is due south.
```

```
%
```

```
% Reference: www.pveducation.org
```

Equation of Time

```
B=(360/365)*(doy-81);
EoT=9.87*sind(2*B)-7.53*cosd(B)-1.5*sind(B);
```

Local Standard Time Meridian

This accounts for the difference (del.UTC) between the local time from UTC

```
% Using UTC:
LSTM=0; %Considers use of UTC
```

Local Solar Time

This computes the local solar time given the starting local UTC time (t.UTC)

```
% Using UTC:
LST=t.UTC+(1/60)*(4*(long-LSTM)+EoT);
```

Hour Angle, h (in degrees)

```
h=15*(LST-12);
```

Declination Angle, delta (in degrees)

```
delta=-23.45*cosd((360/365)*(doy+10));
```

Solar Altitude Angle, alpha (in degrees)

```
alpha=asind(sind(delta)*sind(lat)+cosd(delta)*cosd(lat)*cosd(h));
```

Solar Zenith Angle, zeta (in degrees)

```
zeta=90-alpha;
```

Solar Azimuth Angle, az (in degrees)

```
az=acosd((sind(delta)*cosd(lat)-cosd(delta)*sind(lat)*cosd(h))/cosd(alpha));
```

```
end
```

D. AQ_SPM_GHI

```
function clear_GHI = AQ_SPM_GHI(zeta)
% AQ_SPM_GHI estimates the clear sky GHI from the Kasten-Czeplak
% (1980) model
%
% Description
%   Implements the Kasten-Czeplak clear sky model for global horizontal
%   irradiance (GHI) as presented in [1,2].
%
% Input Parameters:
%   Zenith - The sun zenith angle in degrees.
%
% Output:
%   ClearSkyGHI - the modeled global horizontal irradiance in W/m^2 provided
%   by the Kasten-Czeplak clear-sky model.
%
% Sources:
%
% [1] F. Kasten and G. Czeplak, "Solar and terrestrial radiation dependent
%     on the amount and type of cloud," Solar Energy, vol. 24, pp. 177-189,
%     1980.
%
% [2] M. Reno, C. Hansen, and J. Stein, "Global Horizontal Irradiance Clear
%     Sky Models: Implementation and Analysis", Sandia National
%     Laboratories, SAND2012-2389, 2012.
%

clear_GHI = 910*cosd(zeta)-30;
clear_GHI(clear_GHI<0)=0;
```

E. AQ_SPM_TILT_FACTOR

```
function [tilt_f] = AQ_SPM_tilt_factor(attitude)

% Syntax:
%   [tilt_f] = tilt_factor(attitude)
%
% Description:
%   This function computes the fraction of GHI on a tilted Aqua-Quad solar
%   panel. A North-East-Up (NEU) coordinate system is considered.
%
% Inputs:
%   attitude - Defines the initial attitude of the Aqua-Quad solar panels
%   in [roll, pitch, yaw] format in degrees. For [0 0 0], body axes of
%   Aqua-Quad is aligned with NEU with same origin and solar panel is
```

```
% considered horizontal with surface.
%
% Output:
% tilt_f - Fraction of the GHI for a solar panel that is horizontal with
% the surface. Value of 1 means that the solar panel is horizontal with
% the surface. Value of 0 means that the solar panel is tilted 90 degrees
% perpendicular to the surface.
%
% Source:
% [1] Adapted from "PV_model3.m". Authored by Dan Edwards, US Naval
% Research Laboratory, 2015; dan.edwards@nrl.navy.mil; 202.404.7623
```

Define the Initial Attitude of Aqua-Quad

For [0 0 0] attitude, body axes of Aqua-Quad is aligned with NEU with same origin.

```
phi = attitude(1); % Roll. Rotation of Aqua-Quad about the N-axis;...
                    ...tilt angle from the horizontal surface in degrees,...
                    ...facing due north,roll to right is positive.
theta = attitude(2); % Pitch. Rotation of Aqua-Quad about the E-axis;...
                    ...tilt angle from the horizontal surface in degrees,...
                    ...pitch upwards is positive.
sai = attitude(3); % Yaw. Rotation of Aqua-Quad about the U-axis;...
                    ...angle is clockwise positive in degrees
```

Find Unit Vector from NEU Origin to the Sun Rays

```
sun_v = [0 0 1]; % since we are using GHI in the model, component of...
                 ...sun rays onto a horizontally placed solar panel is...
                 ... considered and this is normal to the horizontal...
                 ...solar panel.
```

Find Unit Vector from NEU that is along the Normal to Solar Panel Surface

```
R1 = [cosd(sai) sind(sai) 0; -sind(sai) cosd(sai) 0; 0 0 1]; % Rotation around U-axis
R2 = [cosd(theta) 0 sind(theta); 0 1 0; -sind(theta) 0 cosd(theta)]; % Rotation around E-
axis
R3 = [1 0 0; 0 cosd(phi) -sind(phi); 0 sind(phi) cosd(phi)]; %Rotation around N-axis

R = transpose(R3*R2*R1);

n_v = R*[0; 0; 1];
```

Compute tilt_f

```
tilt_f = dot(sun_v,n_v);
```

```
end
```

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