Endurance Driven Energy Management System for All-Electric Marine Autonomous Surface Vehicle

Taimur Zaman[1], Mazheruddin Syed[1], Graeme Burt[1], Ali Wahoud[2], Gianfranco Gobbo[2], Garry Millard[2], and Stefano Malagodi[2]

[1] Institute for Energy and Environment, University of Strathclyde, Glasgow, United Kingdom
[2] Innovo Engineering & Construction Ltd., Aberdeen, United Kingdom
Email: {taimur.zaman, mazheruddin.syed, graeme.burt}@strath.ac.uk
{awahoud, ggobbo, gmillard}@innovoteam.com

***Abstract*—An autonomous eco-robotic Surface Vessel (ASV) is designed to operate in extreme weather conditions with an autonomy of several days. This research work aims to present a process for on-board power management between the vessel's power sources, while maximizing the use of Renewable Energy Sources (RES) and taking into consideration onboard sensor, navigation and control and data transfer power requirements. A detailed architecture for a DC network integrating Photovoltaic (PV) panels, Fuel Cells (FCs), hydro generator and energy storage systems is developed. An efficient and flexible Energy Management System (EMS) is developed for managing power sources and maximising endurance using only clean energy. To assess the performance of EMS in meeting the energy demands of the Ocean drone's equipment and propulsion systems, a simulation-based analysis is carried out for realistic missions and scenarios. The developed EMS strategy intends to harvest the energy from PV and hydrogenerator while maintaining the Battery Energy Storage Systems (BESS) as charged as possible. The developed power supply system architecture and EMS can jointly accommodate the need for efficient and long-lasting operation of the vessel with CO2-emission free energy sources.**

***Index Terms*—Energy Management, Control System, Fuel Cells, Photovoltaic**

I. Introduction

Autonomous Surface Vehicle (ASVs) refers to the emerging marine industry vehicles operated autonomously without any crew on board. The ASVs origin belongs back to several decades but has evolved back in the past years with the recent developments in fueling and control system that has enabled the enhanced autonomous operation of these vehicles for different operations. The different operations include the exploration of oceans for wide range of scientific studies, natural resources, defense, and surveillance. The projection of requirements varies in accordance with the mission and geographical profiling (e.g. weather forecast, mission endurance, maximum stability in accordance to payload types, and fueling system, etc.), which are essentially important to meet for the successful endeavoring of the mission [1].

The ASVs pave a path for marine industry with lower operational cost, high endurance, better flexibility and maneuverability. However, the objective to achieve maximum endurance and stability which are the prolific outsources of an efficient Energy Managmenet System (EMS) has been greatly challenged with the transition of fueling system to non-conventional power sources [2].

The non-conventional power sources are stochastic in nature and so their integration, control, and energy management is a challenging issue. These power sources are the constituents of power electronics-based converters and feedback control which increases the overall system complexity [3]. Therefore, the EMS is an upholding requirement for marine based ASV's to support system dynamics in the presence of disturbance and balance the demand and supply with effort to enhance the overall system efficiency, achieve maximum endurance and stability [4].

Several methods are proposed to address the principal challenge of integrating RE sources and especially the slow dynamics based emerging FCs with wind and PV to achieve decarbonization in marine industry. All these sources are used in different formations in efforts to reduce environmental pollution. Generally, the storage system is proposed in a hybrid format with diesel generators to supply power in high peak times. This helps in deducing the emissions and enhancing the overall efficiency [5]. Further, a hybrid system based on a diesel engine, super-capacitors, and BESS is proposed for docking and casting-off of the ship to mitigate the pollution and enhance fuel consumption [6]. Similarly, the hybrid system of PVs and BESS with diesel engines can be considered to enhance the fuel consumption, however, require an energy management system based on intelligent and dynamic control.

Apart from the integration of non-conventional power sources in marine applications, several efforts have been reported to control and manage the power using EMS. In persuasion of the All-Electric-Ships (AES) concept, a hybrid energy storage system is proposed in [7]. The concept is realized using model predictive control (MPC) and the results show effectiveness in tracking the reference trajectories. Similarly, a PV system is proposed for a large-scale ship where its MPPT is modeled as global optimization on large scale in [8]. However, no information on EMS is provided. A hybrid method with

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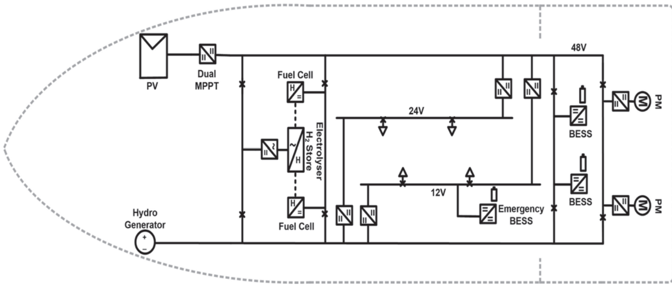


Fig. 1: Power architecture of the ASV

a diesel engine using a two-step multi-objective EMS is reported in [9], where the diesel generators regulate the system energy in the first step and active power is distributed proportionally in the second step to optimize the equal battery utilization. In [10], a PI controller is used to regulate voltage across the Bus connecting PV and BESS only. The approach is more focused on regulating Bus voltage and doesn't consider the EMS plan to ensure endurance. Similarly, the authors in [11] discuss the EMS for onboard ship microgrid. The EMS manages power in both grid connected and islanded mode by balancing and sharing proportionate power using hierarchical droop control, however, does not consider the FCs integration. Similarly, the authors in [12] discuss the same context but don't consider the integration of FCs and the electrolyser system. An effort to regulate the DC bus using a nonlinear controller is proposed in [13]. However, such type of control mechanism leads to conduction and switching losses which deteriorates the enhanced performance of the overall system. Most of these methods focus on the DC bus regulation rather than providing explicit information on EMS in-connection with enhanced mission endurance.

Very limited literature is available on all Electric-Vehicle inspired marine system that takes advantage of PV with BESS and Fuel Cells (FCs) to evaluate the performance of EMS for ASVs while considering the realistic mission profiles and ASVs dynamics. In addition, PV and FC as primary source of energy with battery system in hybrid formation has not been evaluated before for ensuring long term mission endurance. The concept is realized through EMS plan which manages the power balance in the system, ensures regulated power supply and achieve lowest fuel consumption rate per actual geographical area. The BESS is only provided to support the system stability for transients and step load changes.

The rest of the paper is organized as follows: Section II presents the details of the system architecture and its modeling, followed by the proposed EMS in Section III. The methodology for the performance evaluation of the EMS and the results are discussed in Section IV while Section V concludes the paper.

II. ASV Network Architecture and Modeling

The electrical power system architecture of the ASV is presented in Fig. 1. It comprises a mix of generation sources, storage and loads. The generation sources include two PV systems (horizontally and vertically inclined), a modular FC system (two fuel cells incorporated with one electrolyser and a hydrogen storage tank) and a hydrogenator. Storage includes three BESSs (one for emergency) and a hydrogen tank. To obtain the effective results, each power source is modeled in MATLAB/Simulink with realistic data obtained from the manufacturers datasheets and considering the associated losses.

A. PV Model

The ASV incorporates two PV systems, one horizontally mounted on the hull of the ASV and another vertically on its sail. To replicate the I-V and P-V curves of a photo-cell, the single diode based model with series and shunt resistance is considered [14]. The photo current of the cell can be mathematically presented as:

$$I_{ph} = \frac{I_R}{1000}[(T-298)\alpha + I_{sc}] \tag{1}$$

where, I_R is the radiance in (W/m^2), T is the operating temperature of cell in Kelvin and α is the temperature coefficient $(0.0017A/^oC)$. The reverse saturation current can be calculated as

$$I_{res} = I_{sc}\left[\frac{1}{e^{\frac{v_{oc}Q}{TAkN_s}} - 1}\right] \tag{2}$$

where, $Q = 1.6 \times 10^{-19}$ C is the Coulombs charge, $k = 1.3805 \times 10^{-23}$ J/K is Boltzman constant , v_{oc} and A refer to the open circuit voltage of cell and ideal factor of silicon diode respectively, while N_s refers to the number of cells connected in series. The diode current can be written as:

$$I_d = e^{\left[\frac{Qe_V}{kA}\left(\frac{T_{ref}-T}{T_{ref}T}\right)\right]} \tag{3}$$

The terms e_V and T_{ref} refer to the bandgap value of silicon (1.1 ev) and the reference operating temperature, respectively. The output current can be computed as:

$$I_o = N_p I_{ph} - N_p I_d \times \left[e^{\left(\frac{Qv_{pv}+I_s}{Tk\alpha N_s}\right)} - 1\right] \tag{4}$$

Here, N_p refers to the number of parallel connected cells in a module while v_{pv} denotes overall module voltage.

The PV system is interfaced to the 48 V bus through a DC/DC converter employing Perturb and Observe (P&O) MPPT algorithm to extract maximum available power from the PV panels as shown in Fig 2. Since the azimuth angle and radiance have direct impact on the output of PV panels, Dual-MPPTs is designed for horizontal and vertical surfaces to ensure maximum extraction of power.

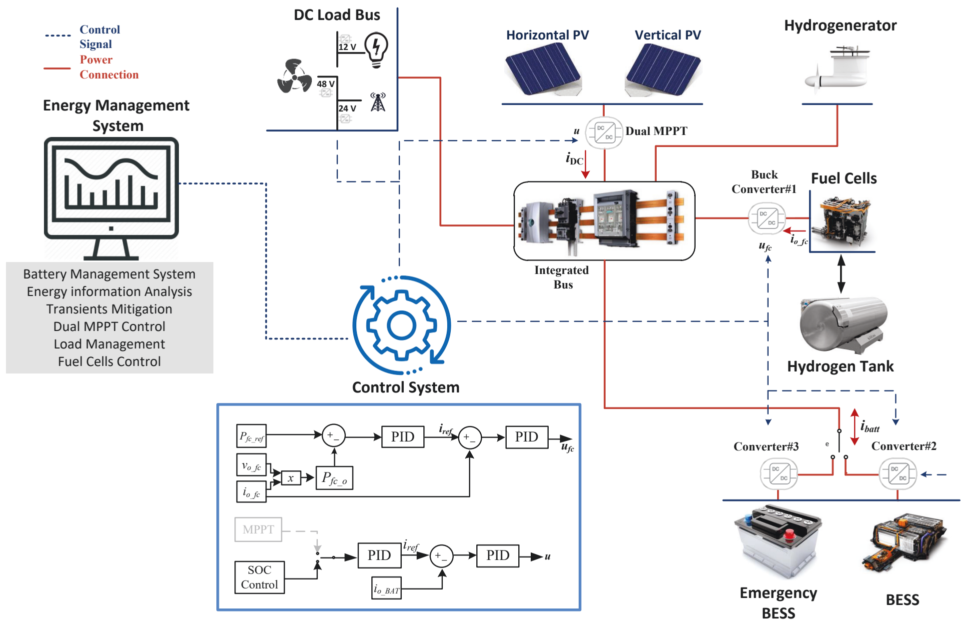


Fig. 2: Schematic of power architecture integrated with EMS and control system

B. Fuel Cells Model

A proton exchange membrane fuel cell (PEMFC) is chosen for its high-power density and efficiency [15]. The mathematical representation of output voltage for a single cell ($v_{o,fc}$) in PFMC type FC can be written as

$$v_{o,fc} = v_{oc} - v_{act,fc} - v_{\Omega,fc} \tag{5}$$

Where $v_{act,fc}$, $v_{\Omega,fc}$ are the activation and ohmic voltage drops respectively. v_{oc} is the open circuit voltage derived as

$$\begin{aligned} v_{oc} = G_C &\left[\frac{R_{gas} T_{fc}}{zf} \left(0.5 ln Po_2 + ln P_{H_2}\right) \right] \\ &- 44.43 \frac{1}{zf} \left(T_{fc} - 298\right) + E^o \end{aligned} \tag{6}$$

$$V_{act,fc} = \frac{1}{\tau s + 1} \left(T_{fc} - 298\right) \tag{7}$$

$$v_{o,fc} = R_{FC} I_{FC} \tag{8}$$

The terms T_{fc} refers to the operating temperature of the fuel cells, R_{FC} and I_{FC} refer to the internal resistance and current of cell stack, respectively. Whereas the constants R_{gas} and G_c refer to the gas constant, output voltage constant and electrons transfer number, respectively. The gas pressures for hydrogen and oxygen are denoted by Po_2 and P_{H2}, whereas τ denotes the time delay in output voltage of cell stack for a step change in current. Fig. 2 shows the detail schematic of FC connecting hydrogen and power converter to the main Bus.

C. Battery Model

The accurate model and type of batteries play an important role in supporting the system for transients and disturbances. Therefore, Li-ion battery is used and is represented as a variable voltage source having finite internal series impedance. This can be written as:

$$V_{batt} = V_{oc,batt} - Z_{batt} I_{batt} \tag{9}$$

The state of charge (SOC) is an essential factor to be considered while modeling and controlling BESS. This can be computed as:

$$SoC = SoC_{int} + 100 \left[\frac{1}{Q_{bat}} \int I_{bat}\left(t\right) dt \right] \tag{10}$$

Where SoC_{int} , Q_{bat} refers to initial SoC and maximum charging capacity of battery, respectively. To achieve high endurance and maximum efficiency for fuel rate consumption, the definition of battery efficiency is explicitly important. It is directly related to its open circuit voltage ($V_{oc,batt}$) and internal impedance (Z_{batt}), charging and discharging rates, and is given by:

$$\eta_{batt} = \begin{cases} \eta_{chg} = & 2 \left[\frac{1}{\left(1 + \sqrt{1 - \frac{4 Z_{chg.} P_{batt}}{V_{batt}{}^2}}\right)} \right] \\ \eta_{dischg.} = & \frac{1}{2} \left[1 + \sqrt{1 - \frac{4 Z_{dischg.} P_{batt}}{V_{batt}{}^2}} \right] \end{cases} \tag{11}$$

The boundary limits for charging and discharging with respect to input impedance can be written as:

$$Z_{batt} = \begin{cases} Z_{chg.}, & x_1 \left(SOC, I_{bat}\right), I_{bat} \geq 0; \\ Z_{discchg.}, & x_2 \left(SOC, I_{bat}\right), I_{bat} \leq 0; \end{cases} \tag{12}$$

III. Energy Management System

The ASV in consideration is intended for environmental monitoring, expected to leave the shore with a fully charged BESS and a full hydrogen tank and return to shore after a successful mission. The EMS is expected to maximise

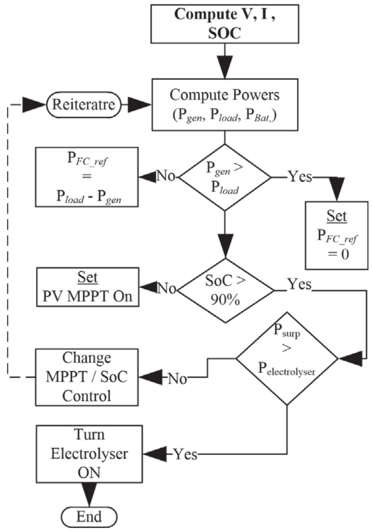


Fig. 3: Flow chart of Energy Management System

the endurance, i.e., the duration of the missions. To realize the objective, EMS coordinates all the generation sources integrated via closed loop power converters to meet the demand on buses (12V, 24V, 48V) connecting propulsion, surveillance and actuating systems. High level schematic of the power architecture integrated with EMS and control system is presented in Fig. 2. As can be observed from Fig. 2, the MPPT and SoC control of the PV system and the power regulation of FC are integrated within the EMS. The EMS has total observability of the sources and loads within the network. Fig. 3 shows the flowchart of the EMS for balancing the power supply and demand while prioritizing the maximum power extraction and utilization from PV, FCs and hydrogenerator. The EMS calculates the total demand and supply in iterative process and initiates the charging process for the batteries when there is surplus power. The BESS SoC are continuously monitored to avoid any potential damage. If the batteries are fully charged, the electrolysers turn on to generate hydrogen for storage. In addition, the operation point of FC is adjusted to balance the demand and supply when the power from the PV

TABLE I: Parameters of Power System Resources

Power Sources	Value
PV Panels	5.2 kW
Fuel Cells	12 kW
Hydrogen Tank Capacity	33 kWh/kg
Hydrogenerator	30 W
Battery System	5 kW
Emergency Storage System	5 kW

and hydrogenerator does not meet the demand. The reference for the FC can be computed from the power flow equations as:

$$P_{gen} = P_{pv} + P_{Hydro} \tag{13}$$

$$P_{load} = P_{24v} + P_{12v} + P_{Bat} \tag{14}$$

$$P_{fc_{ref}} = P_{load} - P_{gen} \tag{15}$$

Although the charging and discharging of the BESS is controlled by the EMS, the BESS is responsible to maintain the voltage of the 48 V ring bus. This ensures any dynamic steps in load are catered for by the BESS, reducing the impact of the dynamic and transient response on the other sources within the network.

IV. Performance Evaluation

The EMS is designed to maximise the endurance of the ASV, minimising consumption rate, and ensuring stability. The objective of the studies undertaken in this section are two fold: (i) to evaluate the endurance realized under different operating conditions and (ii) to assess the dynamic responses and transients mitigation subject to step loads.

A. Scenario Setting

In this section, the vessels specification, the load profiles and the mission profiles for the evaluation of the EMS are presented.

1) Vessel Specification: The network architecture of the ASV remains as in Fig. 1, the power ratings of the sources and the capacity of the hydrogen storage is summarized in Table I.

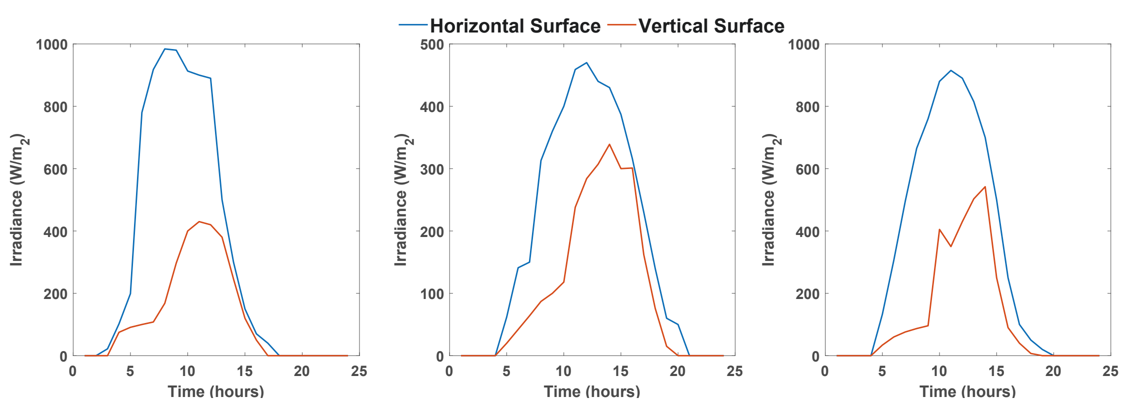
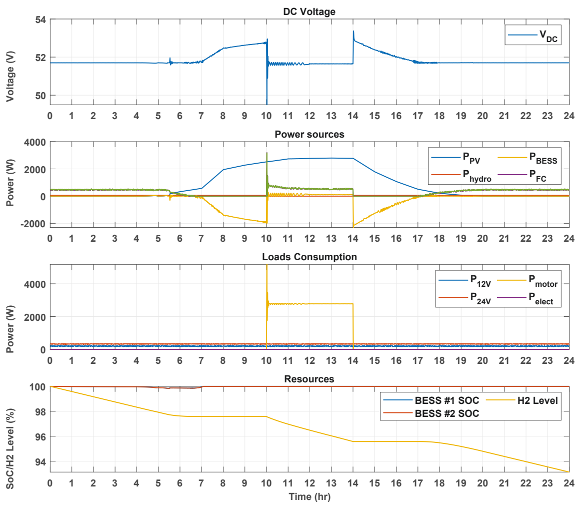
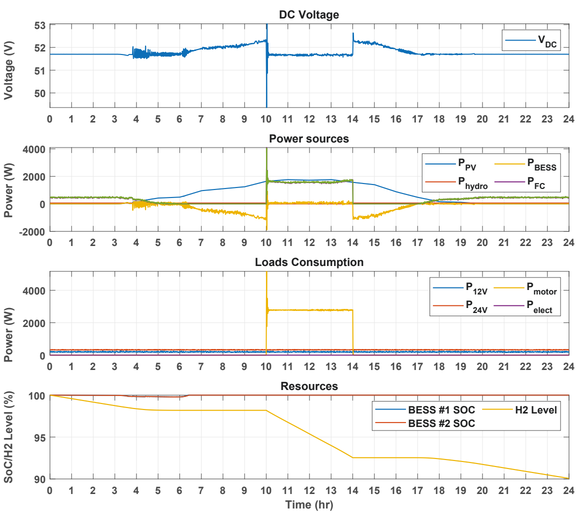


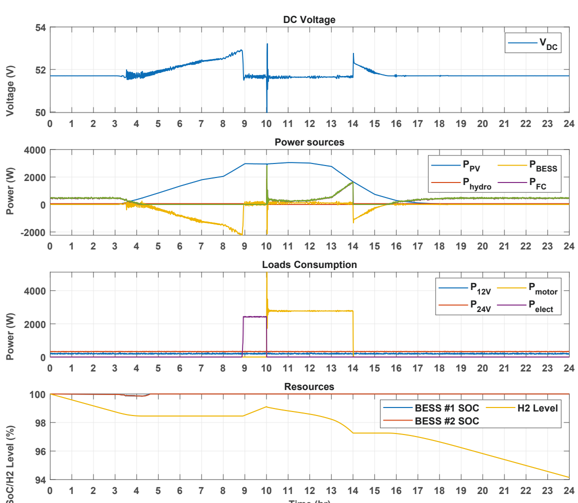
Fig. 4: **(A)** Arabian sea at 25.93^o latitude and 56.28^o longitude **(B)** North sea at 55.995^o latitude and -3.239^o longitude **(C)** Sicilian channel at 36.769^o latitude and 12.039^o longitude



(a) Performance in the Arabian Sea



(b) Performance in the North Sea



(c) Performance in the Sicilian Channel

Fig. 5: Performance evaluation of EMS

2) Mission Profiles: To evaluate the effectiveness of the proposed EMS, three real-world mission profiles are developed, demonstrating the ASV's operation in (i) the Arabian Sea, (ii) the North Sea and (iii) the Sicilian Channel. The temperature and irradiance profiles for the three chosen geographically distinct locations is utilized as input for the PV panels. Two season (Summer high and winter low) profiles are considered, with the high season profile illustrated in Fig. 4. The losses due to salt deposits on the panels is considered to be uniform for the three scenarios. For a comparative analysis, same load profile is utilized for the three scenarios as detailed in the following sub-section.

3) Load Profiles: The loads on the ASV can be broadly classified into four: (i) instrumentation and control loads, (ii) propulsion load comprising motors that allow maneuvering (iii) actuating loads and (iv) an electrolyser serving as a load when producing hydrogen. Fig. 6 shows the 24 hours dynamic load profile of the ASV considered for performance evaluation. The load on the ASV is minimal for a major proportion of the time (less than 500 W), but presents a peak of around 3 kW when the propulsion load is turned on. The turning on of the motor presents a step load that can introduce transients that need to be effectively mitigated by the control and energy management system. The electrolyser as a load is not represented within the profile in Fig. 6 as it is activated by the EMS when surplus energy is available.

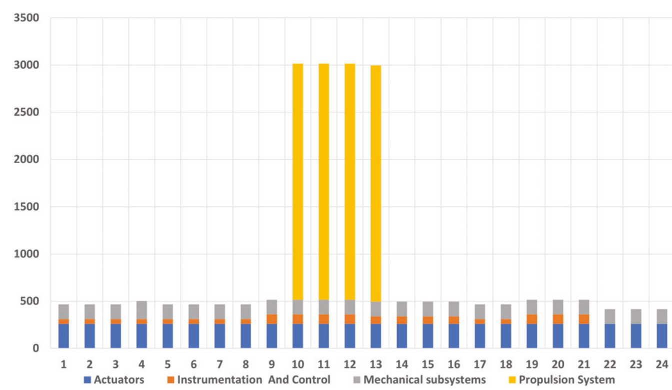


Fig. 6: 24 Hours Load Profile

B. *Results and Discussion*

The results of the performance evaluation of the EMS under three different operating conditions are presented in Fig. 5. For each scenario in consideration, the bus voltage, the power output of the generation sources, the load consumption and the storage utilization is presented (top to bottom, respectively).

Fig. 5 (a) illustrates the performance of EMS in the Arabian sea where the PV production starts from 4:00 and ends at 19:00 during high summer season. Similarly, the power production from PV changes with the alternate geographical region and the subsequent changes in EMS performance for energy production and load consumption can be seen in Fig. 5(b) and Fig. 5(c) for the North sea and the Sicilian channel, respectively. The electrolyser is only activated in

TABLE II: Summary of mission profiles for three different operating conditions

Energy Sources	**Summary of Energy Production and Consumption per 24hrs Mission**					
	North Sea		Arabian Sea		Sicilian Channel	
	High Season	Low Season	High Season	Low Season	High Season	Low Season
Sum of Energy Produced by RES	17 kWhr	3.77 kWhr	23.54 kWhr	16.96 kWhr	23.93 kWhr	11.23 kWhr
Sum of Energy Consumed by Loads	25.48 kWhr	25.48 kWhr	25.48 kWhr	25.48 kWhr	25.48 kWhr	25.48 kWhr
BESS SOC at start of Mission	100%	100%	100%	100%	100%	100%
BESS SOC at end of Mission	100%	100%	100%	100%	100%	100%
H2 Tank Level at Start of Mission	7.5 kg	7.5 kg	7.5 kg	7.5 kg	7.5 kg	7.5 kg
H2 Tank Level at End of Mission	6.76kg	6.454 kg	6.98 kg	6.83kg	6.06 kg	6.5 kg
Mission Endurance	10.1 days	6.62 days	14.6 days	11.2 days	17.1 days	7.51 days

the Sicilian Channel due to high irradiance leading to excess PV production as observed in from 5(C). The electrolyser remains activated for 60 minutes to effectively harness the surplus energy available when undertaking a mission in the Sicilian channel. In all the cases, the PV system is prioritized to provide power to the loads. The fuel cells provide power to meet the difference between PV power produced and total demand when necessitated. The batteries provide power only when both the sources are not able to balance the demand. In addition, the dynamics within the network are adequately handled by the developed control and EMS.

Table II presents the detailed comparison of EMS performance for all three regions in both high (summer) and low (winter) seasons. The total energy produced is the highest in the Sicilian Channel during the summer, followed by production in the Arabian Sea and the North Sea. The energy production in the Arabian Sea surpasses that in of the Sicilian Channel in the low season. For a 24 hour mission, the BESS maintains a 100% SoC in all three scenarios considered. This is due to the fact that the use of hydrogen through FC is prioritised. Table II further presents the a projection of the endurance of the ASV if the mission continued beyond the initial assessment period of 24 hours (last row of the table, presented as mission endurance). In high season, the ASV is capable of autonomous operation for 17.1 days in the Sicilian Channel, 14.6 days in the Arabian Sea and only 6.62 days in the North Sea. The endurance of the ASV is significantly reduces in the Sicilian Channel during the low season, down from 17.1 days to 7.51 days while there is not a significant difference in endurance when the ASV undertakes missions in the North sea.

V. Conclusions

This work presents a power architecture for an all-electric marine autonomous surface vessel and proposes an EMS to effectively coordinate its constituent resources to enhance endurance. The ASV comprises of low carbon generation sources only, with the PV system, hydrogenerator, FC and BESS integrated to a common bus. EMS is developed to prioritize the renewable power sources to balance the generation and load demand. The EMS strategically consumes power from PV and FC to keep the BESS for dynamic response mitigation or in cases of emergency. The performance of the EMS is evaluated in wide operating conditions, representive of the ASV undertaking missions in the Arabian Sea, the North Sea and the Sicilian Channel. Analytical approach is used to determine the maximum mission endurance, consumed SOC, and available hydrogen at the end of each mission.

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