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# Optimization of the Standalone Hybrid Energy Storage System in The All-Electric Seabus Power System Based on Pulsed Propulsion Load Prediction

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***Abstract*— In marine applications, the energy storage system (ESS) functions as the primary energy supply for fully electric propulsion vessels. During variable operation conditions involving pulsed propulsion load, the ESS employing monotype topologies are often oversized and can damage the cells. This study proposes a hybrid energy storage system (HESS) for an all-electric Seabus with a 10-year operational lifespan, with the objective of optimizing the storage system size to ensure longer operation than 72 minutes at a speed of 30 knots under variable conditions. The impact of the HESS system on installation cost and weight was thoroughly investigated. Some HESS configurations are presented, utilizing Lithium Iron Phosphate (LFP) as the high-energy (HE) cell and supercapacitors, Lithium-Ion Capacitor (LIC), and Lithium Titanium Oxide (LTO) as three alternatives of the high-power (HP) cell. The HESS design predates a parallel full-active configuration for both ESS types. The optimization method is based on the rule-based energy management method that utilizes cut-off power between HE and HP cells. In this specific case, the LFP-LTO configuration is the optimal HESS design rather than the LFP-SC and LFP-LIC configurations, meeting all established optimization criteria and weight limitations. The study demonstrates that the HESS configuration can achieve 120 minutes of operation under variable conditions, which is 67% longer than the operation time of previous Seabus operations.**

*Keywords*— Batteries, Electric ship, Hybrid storages, Pulsed load, Supercapacitors

## I. INTRODUCTION

Lately, the maritime industry worldwide has been preoccupied with some hot issues related to environmental pollution resulting from maritime activities on the ocean and around port environments [1]. As a result, developing new ship propulsion concepts, such as the all-electric ship (AES) concept, is an important thing to implement [2]. However, the AES concept still produces some exhaust gas emissions from diesel-fueled generators. Therefore, another concept was invented using an onboard energy storage system or ESS with a standalone configuration as the main energy source rather than the use of diesel-fueled generators [3].

As the main energy source, ESS will provide the required electrical energy needed for electric propulsion and other supporting needs. The amount of energy storage depends on several factors, such as the size of the ship and the type of electric propulsion used. Therefore, the implementation of the ESS for big-size ships needs to be considered in order to address various issues such as heat management, high initial installation costs, the safety of the storage system in the face of unpredictable sea conditions, limitations in ship machinery space, limited energy density and power of the energy storage, limitations in operating distance, and electrical capability from the ESS itself like discharge and charge current capacity [4].

In its application, the ESS can be divided into two different topologies, which are a high-power (HP) density cell type and a high-energy (HE) density cell type, each represented by, for example, lithium-ion batteries and supercapacitors [5]. During ship operations, each ship has different propulsion characteristics caused by the various surrounding ocean conditions and often enters into emergency operations requiring more power [6][7]. That variable condition will affect the size and characteristics of the ESS installed on the ship. Maximizing energy storage potential in terms of a HE type will be larger and result in a higher initial investment value [8][9]. This has given rise to a new configuration for energy storage systems where an energy storage system will have both characteristics called a hybrid energy storage system (HESS). This configuration can solve size problems, increase the lifecycle of an energy storage system, and reduce the initial investment value [10]. However, the implementation of HESS on a ship will require several adjustments and requirements that must be met, such as the location and length of the ship's route, the ship's service speed and acceleration, the port schedule, and the maximum time of ship operation [11].

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HESS configuration is widely used or implemented in many applications such as electric vehicles (EVs), renewable energy, and also marine. In EVs, HESS has been used to solve the problem of sudden power surges that lead to the deterioration of EV batteries. Zhou et al. [12] have investigated related to hybrid storage systems for EVs consisting of Lithium Titanium Oxide (LTO) and Nickel Manganese Cobalt (NMC) batteries. The resulting energy efficiency increases to 1.6% - 2.5%, and the lifetime of the HESS also increases to 159% - 203%.

Andika et al. [13] have conducted research in energy management systems using cascade fuzzy logic controller (FLC) for Li-Ion batteries and supercapacitors in EVs. The results show that the proposed FLC prevents the batteries from being overloaded, and the EV can operate longer lifetime.

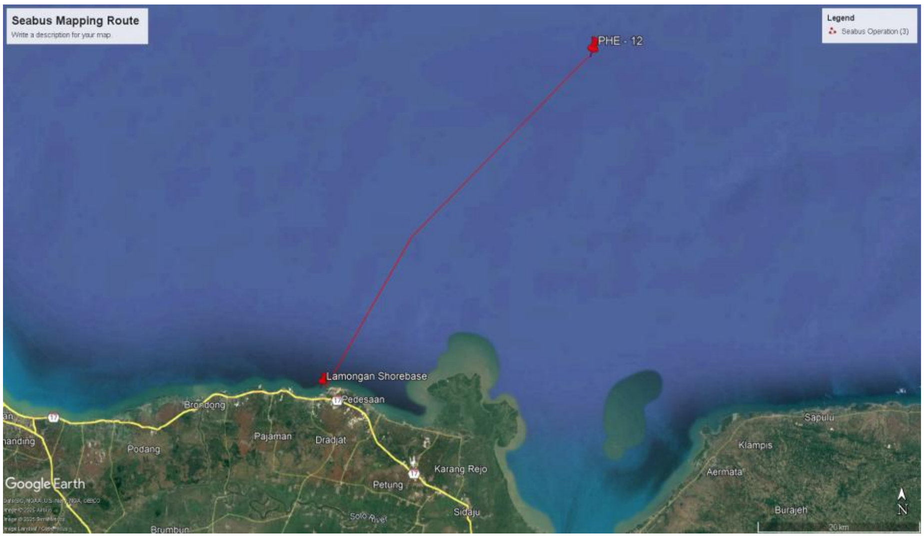


**Figure. 1.** Satellite image of the Seabus operation route in the PHE-WMO area

For renewable energy purposes, Saputra et al. [14] have investigated the use of low-pass filter frequency for energy management between Li-Ion batteries and supercapacitors in solar energy. The simulations indicate that optimization can achieve a cost-effective and sustainable HESS during its intermittent nature.

In marine applications, Wang et al. [15] also optimized the AES optimal power management for a combination of diesel generators and a HESS consisting of Li-Ion batteries and supercapacitors. The calculations show that the participation of a hybrid storage system can reduce the operating cost by 85%, reduce the Energy Efficiency Operational Indicator (EEOI) factor by 5%, and the output power of the hybrid storage system can meet the optimal power allocation for ship operation. Using a standalone system, Balsamo et al. [16] have investigated both the HESS optimal design and energy management consisting of Li-Ion batteries and supercapacitors using the Ritz Method for inland waterways ships. The experimental results have shown a reduction of 40% in battery peak current value and 15% in battery root mean square (RMS) current value that can increase HESS efficiency and durability.

After reviewing some previous research, it can be concluded that using the HESS configuration is one of the optimistic solutions as the main energy source and also to solve the ESS sizing and characteristics problem on ships, which is often encountered when implementing a standalone system during variable conditions. Previous studies discuss the electrification of an 11-meter Seabus with electric propulsion connected to a monotype ESS [17], [18], [19]. Therefore, this study proposes a transition to a HESS consisting of Lithium Iron Phosphate (LFP) cells as HE cells and supercapacitors, Lithium-Ion Capacitor (LIC), and LTO as HP cells is expected to improve the efficiency of the ship's operation and the energy storage system. The factors studied include the optimal size of the HESS, considering the characteristics of the propulsion load prediction, the availability of space on board the ship, and an energy management strategy that will optimize the switching between the two types of ESS.

In this paper, section 2 elaborates on the research methodology, detailing the initial data acquisition, pulsed propulsion load simulation procedures, and HESS optimization iteration process. Section 3 presents the propulsion load prediction and offers an analysis of the HESS sizing optimization based on the prediction load profile and given HESS configuration. Finally, section 4 synthesizes the study's results and proposes directions for future studies.

## II. METHOD

The subsequent section delineates the procedures to be carried out in order to ascertain the optimal sizing of a hybrid energy storage system (HESS) on a parallel full-active configuration for the all-electric Seabus. Initially, the stage encompasses the identification of the Seabus from a preceding study (in section A) and mapping its operation (in section B). Collecting general Seabus data and modelling a 3D hull model (in section C) represent the preliminary processes that must be completed before conducting a ship resistance simulation. During the simulation, two conditions are simulated using Maxsurf Resistance for calm-water conditions (in section D) and

Motion software for variable conditions (in section E) to create a propulsion load prediction (in section F). Subsequently, a model of energy storage lifetime is created (in section G) to determine the storage capacity during 10 years of Seabus operation. An optimization objective is established to obtain the optimal sizing of the HESS, along with the relevant criteria and limitations (in section H) to be followed during the power-sharing iteration process using a rule-based method (in section I). Finally, the HESS is represented in the Seabus general arrangement drawing (in section J) to visualize the final configuration using the optimal HESS size value.

### *A. Problem Identification*

The problem raised in this study is the electrification process of an 11-meter Seabus with Azipod electric propulsion. It is known that the Seabus has two operating modes assuming calm water conditions, which are a maximum speed of 30 knots for 72 minutes and a constant speed mode for 2 hours at a constant speed of 16 knots. However, variable conditions are not considered beforehand. Therefore, the problem addressed in this study is the HESS sizing for Seabus operation considering pulsed propulsion load coming from the surrounding environment conditions with a speed of 30 knots for 2 hours.

The studied Seabus operates for approximately within 10-years with an average annual operation day of 200 days. It is assumed that on an operation day, the Seabus operates 3 trips with a route from the land facility to the offshore facility.

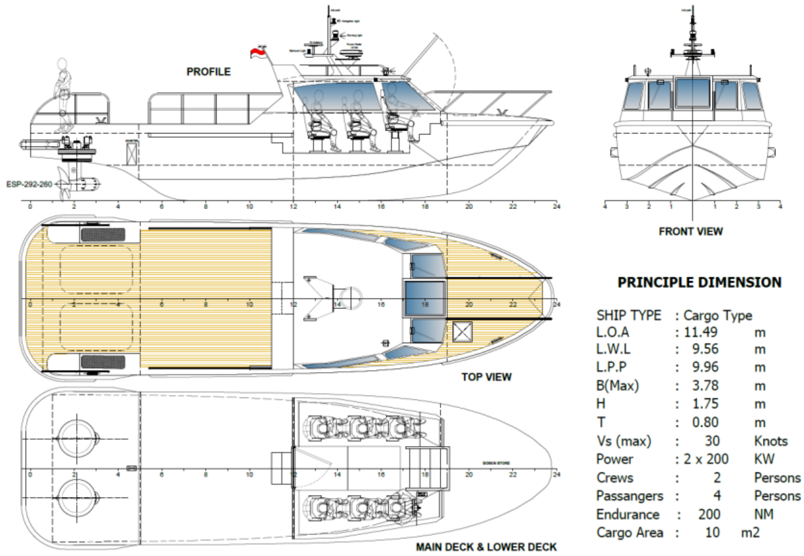


**Figure. 2.** General arrangement of Seabus 11-meter

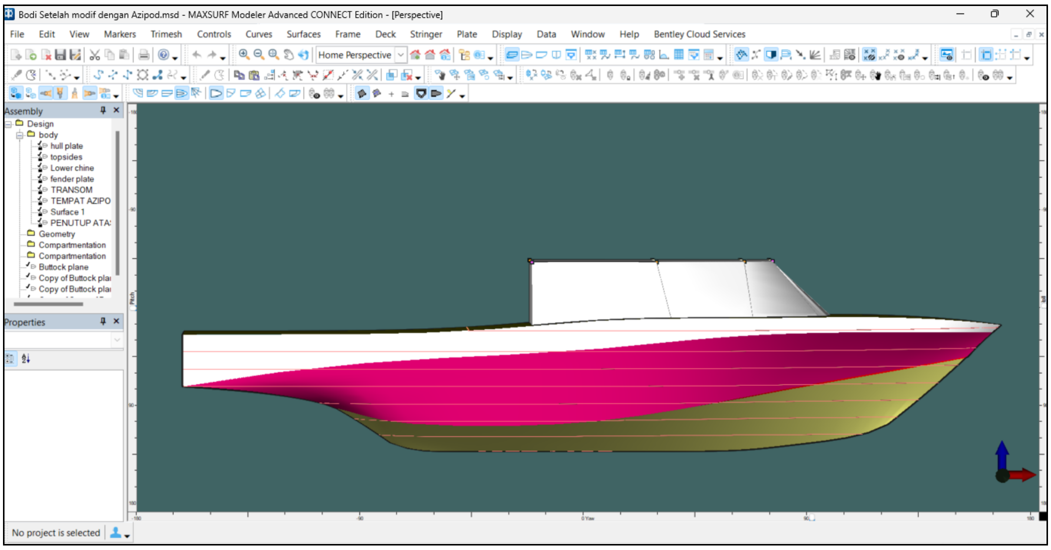


**Figure. 3.** 3D hull form of Seabus 11-meter in Maxsurf Modeller

### *B. Mapping of Ship Operating Routes*

Mapping is required to collect wave data along a predetermined operational route. The route used in this study is the west Madura – Lamongan shore-based route, specifically in the Pertamina Upstream Energy West Madura Offshore (PHE WMO) area. This area is one of the oil and gas fields owned by Pertamina company and where PHE-12 support facilities are located. The studied Seabus transports offshore platform workers and their supplies back to onshore facilities.

Using ship operating routes mapping as shown in **Figure 1.**, average wave height and direction data along with the direction of wind blowing in the operation area are collected and then used as input data for Seabus ship resistance simulation. As explained in the previous subchapter, there is an additional resistance value due to the variable environmental conditions of the operating waters. The collected data covers the ocean wave conditions in 24 hours, as the Seabus operation is not limited to day and night.

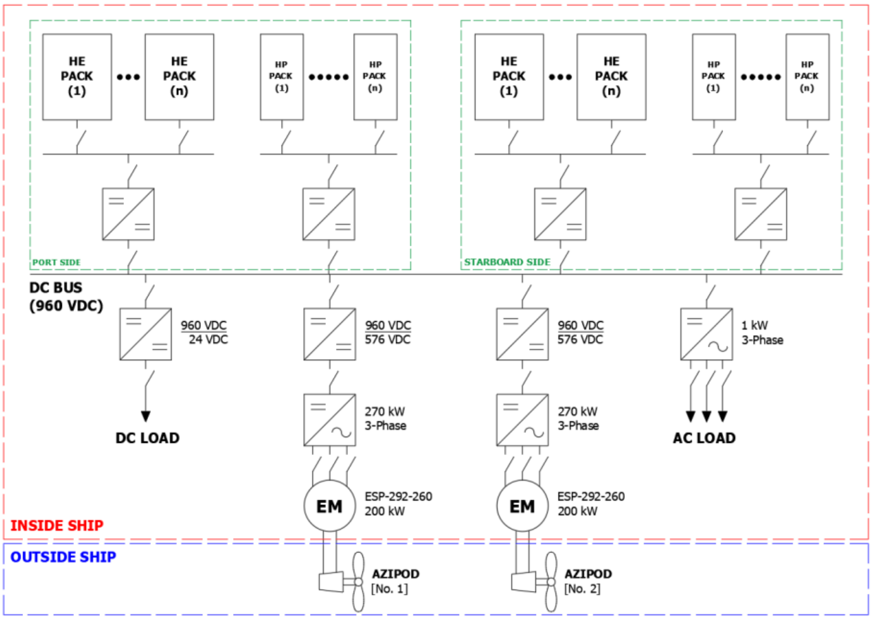


**Figure. 4.** Single line diagram of Seabus 11-meter power system

*C. Seabus Data Collection and 3D Hull Modelling*

The ship data to be used in this study is cargo-type Seabus data. Vessel data from previous research includes the following main dimensions.

| | |
|---|---|
| L.O.A. | = 11.49 meter |
| L.W.L. | = 09.56 meter |
| L.P.P. | = 09.96 meter |
| B (Max.) | = 03.78 meter |
| H | = 01.75 meter |
| T | = 00.80 meter |

After obtaining the main dimension, the drawing data in the form of a general plan of the Seabus can be modelled with Autocad software, as shown in **Figure 2.** The modelling process continues with the 3-dimensional modelling of the hull, which is used as input for the calm and additional resistance simulation. The 3D hull model is created using the Maxsurf Modeller software, as shown in **Figure 3.**

In addition, the Seabus electrical power system is obtained from previous research. After propulsion system conversion, the main power system consists of several shiploads such as navigation load, lighting load, auxiliary engine load, and Azipod electrical engine load supplied by a HESS parallel full-active configuration. The Seabus power system uses 960 Volt DC on the main bus. The detailed single-line diagram of the Seabus power system is shown in **Figure 4**.

*D. Ship Resistance Simulation during Calm Water Condition*

The resistance generated by the Seabus can be calculated manually using various formulas or a software simulation process. The software used is Maxsurf, which includes Maxsurf Modeller and Maxsurf Resistance. The 3D model obtained is linked as input to Maxsurf Resistance. In calm water conditions, additional resistance values are not considered, so using Maxsurf Resistance is more adequate in the calm resistance simulation process. It is known that there are two operation conditions which are simulated separately so that at the end of this process, calm water resistance results are obtained, which are then added to the additional resistance simulated with different simulation software.

The calm water resistance simulation is performed using speed values of 30 knots in the 2-hour condition based on the simulation results in the previous study. According to the following formula, the simulation output can be the required resistance and effective power.

$$P_{eff}\ (kW) = R_T(kN) \times v_s(kn) \qquad (1)$$

Where $(P_{eff})$ is the required effective propulsion power in kilo-watts to move the ship with calculated ship resistance $(R_T)$ in kilo-newton and service speed $(v_s)$ in knot.

*E. Additional Ship Resistance Simulation*

Additional resistance is required to calculate the effect of the variable operating condition on the performance of the Seabus. It is known that the additional resistance depends on several environmental ocean factors. However, only the wave height and the wave direction can influence the additional resistance value. The data on the wave height and the wave direction were obtained while mapping the operating area. Unlike the previous modelling and simulation, the additional resistance due to environmental conditions is simulated using Maxsurf Motion, which predicts the total additional drag, considering the predetermined factors.

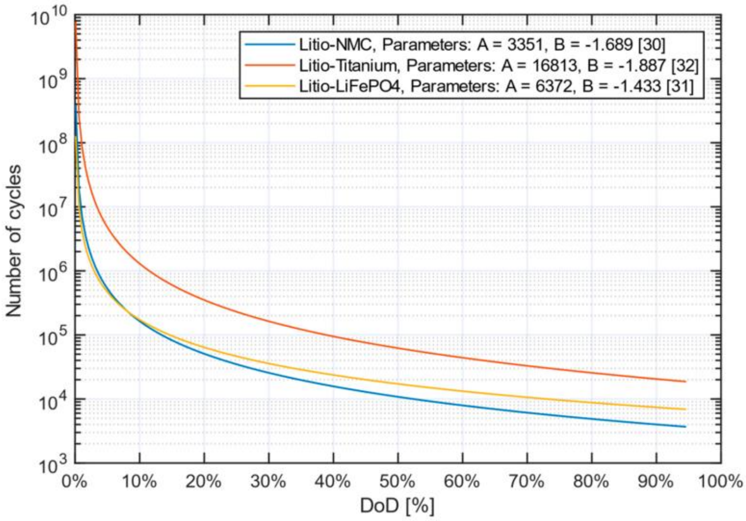


**Figure. 5.** Three concurrent illustrating the relationship between the DoD and the number of battery cycle for various Litio battery [22]

*F. Propulsion Load Profile Modelling*

The propulsion load profile is formed by calculating propulsion power in calm water conditions and additional power. In the previous explanation, the value of propulsion power has been obtained by knowing the existing resistance value. The propulsion power for the propulsion system of a Seabus fluctuates during ship operation. These fluctuations create several pulsed propulsion powers determined based on predicted environmental conditions during different Seabus operation scenarios. The pulsed power is calculated according to collected average wave height and direction data along with the direction of wind blowing in the Seabus operation area.

In this study, only a propulsion load profile depicts an operating cycle. The load profile graph includes the operating time on the X-axis with a time step of every 1 second and the total propulsion power required from calm and variable conditions on the Y-axis. The output of this propulsion graph will be used as a basis in the energy management system optimization process to achieve the problem objectives carried out in this study.

*G. Batteries Lifetime Determination*

The lifetime of energy storage is important in energy storage applications, as it predicts the reduction of battery capacity, which is then used in ESS size optimization. The pure-lifetime models can be realized using two different methods which are throughput counting and cycle counting. This study considers the cycle counting approach in which Depth of Discharge (DoD) represents the stress factor on battery lifetime. The number of cycles ($N_C$) that the battery can operate before reaching the end of life (EOL) is represented on the relation curve between DoD and a number of battery cycles. **Figure 5.** visualizes three different concurrent curves illustrating the relationship between the DoD and the number of battery cycles for three lithium-ion battery technologies, which are the LFP cell in a yellow curve, the NMC cell in a blue curve, and the LTO cell in a red curve. The selected DoD of the HESS during Seabus operation influences the $N_C$ value.

*H. Supercapacitor & Other High-Power Cell Lifetime Determination*

The lifetime of a supercapacitor is determined by using both a mathematical model and an experimental method conducted by a supercapacitor manufacturer. Inside each supercapacitor product specification, the estimated lifetime is often mentioned in units of cycles. The chosen supercapacitor manufacturer in this study is LS Materials [20] using a supercapacitor at a normal discharge voltage of 2.7V and an ambient temperature of approximately 25 degrees Celsius will result in 1,000,000 cycles over 10 years of supercapacitor use. This is also considered when determining the loss of charge, the value of which in this study is a function of the optimization limit for sizing energy storage on ships.

Other HP cells like LIC and LTO have different lifetimes compared to the supercapacitors. For LIC, CDA [21] one of LIC manufacturers, stated that a normal discharge voltage of 3.8V to 1/2 rated voltage and an ambient temperature of approximately 25 degrees Celsius would result in 500,000 cycles over 10 years. For LTO, it is similar to the previous battery lifetime determination using the curve in **Figure 5.** that relates to determined DoD.

*I. Formulation of Optimization Objectives and Limitations Functions*

In the optimization process, the objective and constraint functions are two related things. The objective function must be achieved with optimization results that satisfy all the requirements of the constraint function. In this study, the optimization objective function considered comes from an economic perspective, considering feasible technical conditions. From a technical point of view, the ship's endurance is an important consideration since the ship in this study must be able to operate at a speed of at least 30 knots for 2 hours. The objective function represents the investment cost of installing a HESS for the Seabus. The following is the mathematical formulation of the economic objective function in this study.

$$C_{HESS} = E_{ins,HE} \times C_{HE} + E_{ins,HP} \times C_{HP} + C_{CONV} \quad (4)$$

Where ($E_{ins,HE}$) and ($E_{ins,HP}$) are the energy storage installed on the Seabus in kilo-watt hours or kWh. ($C_{HE}$) and ($C_{HP}$) are the investment value for the HESS installed on the Seabus in dollars. In addition to energy storage, the investment value for DC-DC and AC-DC converter equipment are also calculated in the mathematical formulation as ($C_{CONV}$) in dollars.

In addition, there is consideration for the HESS about 80% of the State of Health (SoH) with 20% of the ($C_{loss}$) that represents the ratio of the number of energy storage usage cycles on the design side and the number of energy storage usage cycles on the technical side of each type of energy storage. With an assumption that the energy storage degradation is the same every time, the $C_{loss}$ can be calculated as follows.

$$C_{loss} = \left(\frac{N_{design\,life}}{N_C}\right) \times 20\% \quad (5)$$

Where ($N_{design\,life}$) is the total or number of energy storage operation cycles to perform during the design life. ($N_C$) is the total or number of energy storage operation cycles that can endure before reaching the EOL.

$N_{design\,life}$ is determined from the mentioned annual Seabus operation. As mentioned earlier, Seabus operates approximately 600 operating cycles annually and 6000 cycles in 10 years of design life. $N_C$ is determined by using the curve between the DoD and the number of battery cycl

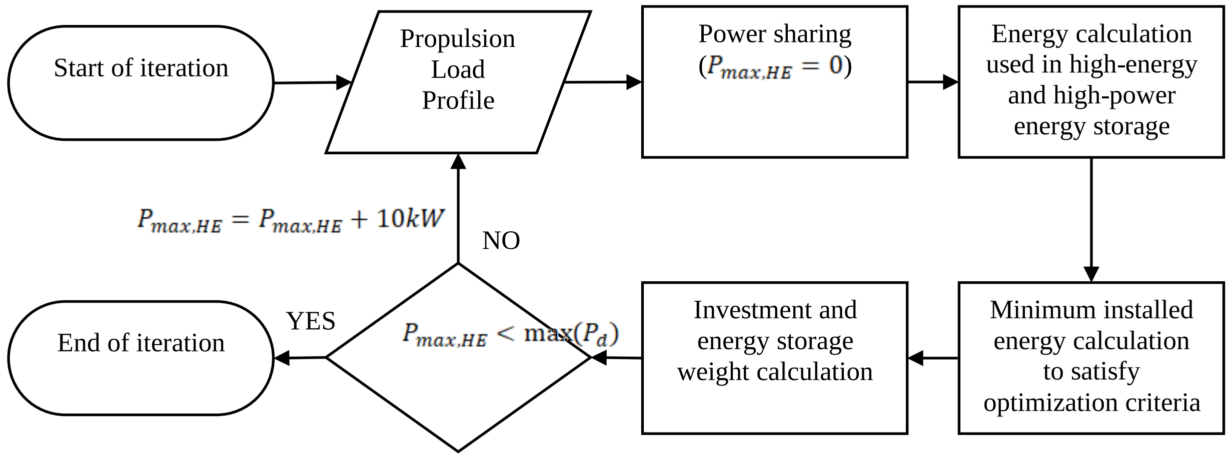


**Figure. 6.** Flowchart of rule-based iteration for HESS power-sharing [7]

The amount of energy storage installed must satisfy the criteria or constraint functions specified at the beginning of the study. There are several criteria to be considered in this study, as follows.

(1) The HESS must provide 10 years of operation before reaching the cell lifecycle with a maximum of 20% $C_{loss}$ represented by ($E_{ins,1}$).
(2) The HESS must ensure that the amount of usable energy is within the range of 10-90% of the battery state of charge (SoC) during the operating period represented by ($E_{ins,2}$).
(3) The HESS must ensure that the discharge current does not exceed the normal charge current of the battery and supercapacitor cells represented by ($E_{ins,3}$).
(4) The HESS capacity to be installed while meeting all the above criteria represented by ($E_{ins}$).

Besides all the given criteria, a limitation must be followed while optimizing the HESS installation, considering the installation weight. In the Seabus operation, weight becomes an important factor to be considered carefully. An overloaded Seabus can lead to unsafe conditions or operations. One of the ship parameters that regulate loading weight is freeboard rules. Freeboard becomes a parameter that represents the loading condition on a ship. In this study, the freeboard value is 0.7 meters with a normal draught of 0.8 meters. Considering the weight of ship constructions, electric engine installations with inverters, and some crews onboard, the weight reserves can be calculated. The studied Seabus has a displacement of about 8700 kg with weight reserves of approximately 5300 kg. This value becomes a limitation in the optimization process, considering the total weight of the HESS installation.

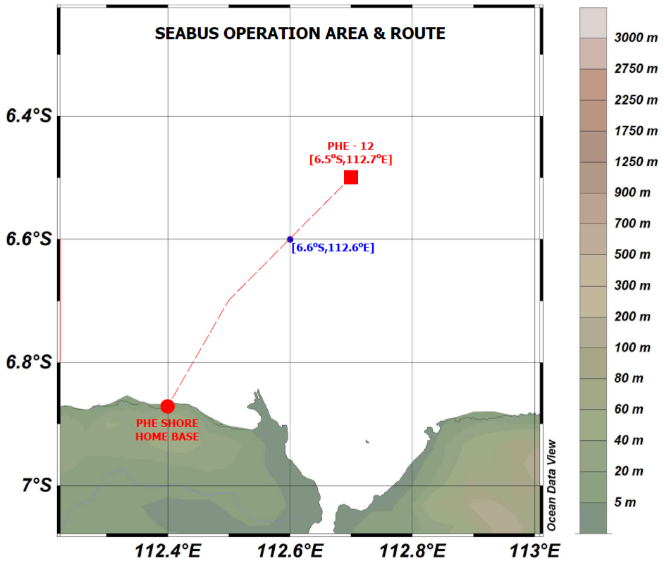


**Figure. 7.** Mapping of Seabus Operation Area and Route

### *J. Rule-Based Iteration Process Power-Sharing*

The power-sharing in HESS is a critical issue to consider because the algorithm will obtain the optimal size of the installed HESS on the Seabus. In this study, the HESS power-sharing algorithm between the two cell types uses a rule-based algorithm for three different HESS configurations, which are LFP-SC, LFP-LIC, and LFP-LTO to find the most suitable configuration that meets the objective function, criteria, and limitation. The flowchart shown in **Figure 6** describes the sizing iteration process used in this study for each proposed configuration.

($P_{max,HE}$) is defined as the maximum power supplied by the HE cells, and the value varies from 0 to the maximum demanded power ($P_d$) in the pulsed propulsion load profile. As long as the Seabus propulsion power is less than ($P_{max,HE}$), the supplied power only comes from the HE cells. Besides that, the HP cell supplies the additional power when the ($P_d$) exceeds ($P_{max,HE}$). From the given flow chart, the amount of installed energy and the investment cost of the HESS are calculated from ($P_{max,HE} = 0$) represents the initial state where the power is supplied only by the HP cell until the maximum ($P_d$) repeatedly at 10 kW. The iteration will stop when the value. $P_{max,HE} = \max\ (P_d)$ becomes the final state where all power can only be output from the HE cells. This iteration process uses a script in the MATLAB program.

### *K. Installation of Energy Storage on Seabus*

The number of installed energy storage has been determined in the previous iteration process. The next step is to check the arrangement of the batteries and supercapacitors on the Seabus. Due to the limited space on the lower deck and in the engine room, the energy storage must be placed as optimally as possible so that the results obtained in the previous process do not have to be repeated. The location of the HESS is shown in the Seabus general arrangement drawing.

## III. RESULTS AND DISCUSSION

This chapter presents all the results from pulsed propulsion load modelling and simulation, the iteration process for optimizing HESS size with some configuration, and the HESS installation on the Seabus.

### *A. Wave Data Collection*

At the beginning of this study, the wave and wind data are collected for the initial simulation process of Seabus operations. The amount of data collected has a period of 1 year, and the large value used in the following simulation is the average value of all data within this period. The data collection process is carried out through a database collected with the help of buoyant at several points distributed around the Seabus operating area.

All the data are collected using a model developed by the European Center for Medium-Range Weather Forecasts (ECMWF). That model is one of the most advanced numerical weather prediction models that utilizes complex algorithms and high-resolution data assimilation techniques to generate accurate forecasts globally. This ensemble approach helps capture the range of possible weather scenarios and improves forecast reliability. This study used the ERA5 data model as the basis for initial simulation data, which collects data over the past 8 decades. ERA5 provides hourly data for many atmospheric, ocean-wave, and land-surface data. All the data provided have been formed into a regular latitude-longitude grid of 0.25 degrees for the reanalysis and 0.5 degrees for the uncertainty's estimates, such as for ocean waves.

It is known that the Seabus operation area is located at the coordinates (112°24'-112°42'E;6°30'-6°51'S), as seen in **Figure 7.** From the given coordinates, there is only a single point Buoyant due to the extent of buoyant point distribution that provides many types of environmental data. However, this study only considers their different data, which mean wave direction (mwd) in degree, mean wave period (mwp) in seconds, and significant wave height (swh) in meters. The mean wave direction is the mean direction of ocean surface waves, which consist of a combination of waves with different heights, lengths, and directions. The mean wave period is the average time for two consecutive wave crests on the ocean's surface to pass through a fixed point. This parameter also consists of a combination of waves with different heights, lengths, and directions. The significant wave height is the average height of the highest third of surface ocean waves associated with either the first or the second swell partition. This parameter represents the vertical distance between the wave crest and the trough. Before going into a simulation of the Seabus operation, the average value of all wave data collected over one year is calculated and then used as baseline data to create several Seabus operating scenarios.

### *B. Determination of Sea Conditions or Scenarios*

In Seabus operations, environmental conditions will always change and be influenced by several wave parameters mentioned above. In addition, Seabus operations are also influenced by other shipping operations because they operate close to the northern shipping lane of Java, which is quite busy with several national and international shipping lanes. Therefore, the Seabus operation scenario is made with several actual conditions that are expected to occur. The modeling of the operational scenario is based on the three parameters of mean wave direction, mean wave period and significant wave height. Changes in the scenarios or conditions are indicated by changes in the three parameters, either increasing or decreasing. These scenarios are divided into several periods during the Seabus operating period. It is known that the Seabus operation takes 9000 seconds or 150 minutes, with a departure and return time of 60 minutes each and 30 minutes for cargo and crew transfers.

TABLE I.
SEABUS OPERATION SCENARIO BASED ON WAVE PARAMETERS

| Sea Condition / Scenario | Time Range | | Wave Data | | | | Added Res. | | Added Power | |
|---|---|---|---|---|---|---|---|---|---|---|
| | From (s) | To (s) | Period (s) | Direc. (Deg.) | Hs (m) | Hm (m) | +Rt (kN) | -Rt (kN) | +Pp (kW) | -Pp (kW) |
| Departure Maneuvering Condition | 0 | 300 | 4.408 | 290 | 0.300 | 0.381 | 0.26 | -0.26 | Vary | Vary |
| Normal Condition | 300 | 900 | 4.408 | 290 | 0.453 | 0.575 | 0.60 | -0.60 | 11.57 | -11.57 |
| Big Ship Crossing | 900 | 1200 | 4.408 | 290 | 0.829 | 1.053 | 2.00 | -2.00 | 38.55 | -38.55 |
| Normal Condition | 1200 | 1500 | 4.408 | 290 | 0.606 | 0.770 | 1.07 | -1.07 | 20.70 | -20.70 |
| Normal Condition | 1500 | 2100 | 4.408 | 290 | 0.760 | 1.064 | 2.05 | -2.05 | 39.51 | -39.51 |
| Longer Big Ship Crossing | 2100 | 2700 | 4.408 | 290 | 1.213 | 1.698 | 5.22 | -5.22 | 100.62 | -100.62 |
| Normal Condition | 2700 | 3300 | 4.408 | 290 | 1.066 | 1.492 | 4.03 | -4.03 | 77.68 | -77.68 |
| Arrival Maneuvering Condition | 3300 | 3600 | 4.408 | 290 | 1.219 | 1.707 | 5.29 | -5.29 | Vary | Vary |
| Passenger & Supplies Loading | 3600 | 5400 | 4.397 | 290 | - | - | - | - | - | - |
| Departure Maneuvering Condition | 5400 | 5700 | 4.397 | 290 | 1.202 | 1.683 | 5.29 | -5.29 | Vary | Vary |
| Normal Condition | 5700 | 6300 | 4.397 | 290 | 1.043 | 1.460 | 3.86 | -3.86 | 74.42 | -74.42 |
| Big Ship Crossing | 6300 | 6600 | 4.397 | 290 | 1.214 | 1.700 | 5.24 | -5.24 | 100.96 | -100.96 |
| Normal Condition | 6600 | 7200 | 4.397 | 290 | 0.805 | 1.127 | 2.30 | -2.30 | 44.39 | -44.39 |
| Longer Big Ship Crossing | 7200 | 7800 | 4.380 | 290 | 0.897 | 1.255 | 2.85 | -2.85 | 55.01 | -55.01 |
| Normal Condition | 7800 | 8400 | 4.380 | 290 | 0.488 | 0.620 | 0.70 | -0.70 | 13.43 | -13.43 |
| Big Ship Crossing | 8400 | 8700 | 4.380 | 290 | 0.608 | 0.772 | 0.95 | -0.95 | 18.21 | -18.21 |
| Arrival Maneuvering Condition | 8700 | 9000 | 4.380 | 290 | 0.250 | 0.318 | 0.18 | -0.18 | Vary | Vary |

As mentioned earlier, the propulsion load is calculated from ship resistance in calm water and additional ship resistance based on the wave characteristics. From **Equations 1** and **2**, The propulsion power load is calculated with an 80% efficiency assumption at various speed variations from 0-30 knots in maneuvering conditions and a constant speed of 30 knots in sailing conditions. Details of the Seabus operation scenario are shown in **Table 1.**

Each sea condition or scenario is created based on several parameters: time range, wave data consisting of wave period, wave direction, significant wave height (Hs), and estimated maximum wave height (Hm). The parameter time range describes the time allocation for its scenario. The wave period and direction were important parameters obtained from ERA5 hourly data. **Table 1.** shows that there are normal conditions, big ship crossings, and longer big ship crossings, which are determined based on the time range to classify the big or longer big ship crossing. On the other hand, the normal conditions and big ship crossing are classified based on Hs and Hm. When there is a big ship crossing condition, those values are higher than the normal conditions. For determining the expected values, the initial values are used, then added by 0.4 meters based on simulation using Maxsurf Motion software. All the scenario results are formed as 9000 data with a time step of 1 second .

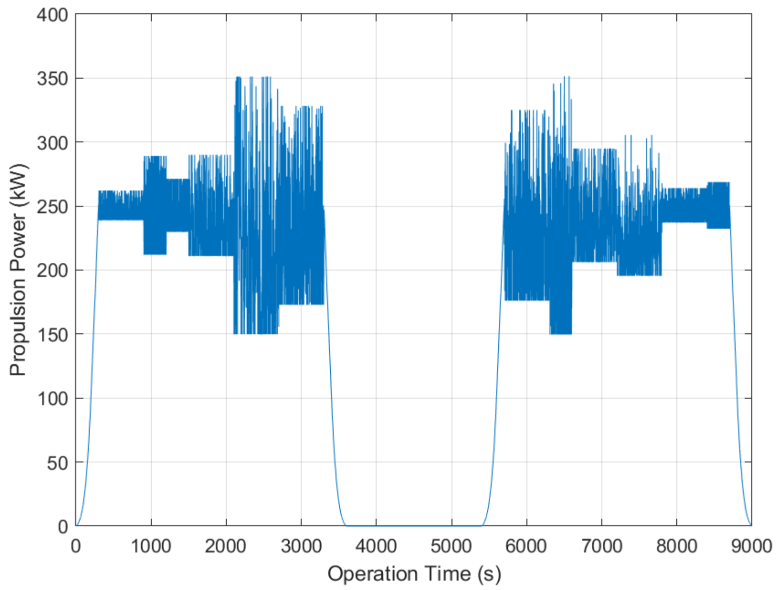


**Figure. 8.** Seabus propulsion load profile in a cycle operation

*C. Propulsion Load Profile Modelling*

The Seabus load profile modelling process is based on input data from the previously obtained calm water and added power. Calculating the propulsion power formula in **Equations 1** and **3**, the total propulsion load representing the required propulsion power can be determined according to different Seabus operation scenarios with variable conditions. Therefore, these variable conditions are modelled with two statistical parameters: mean reversion and volatility. Mean reversion represents the propulsion load data deviation, and the higher the data moving amplitude represents the variable conditions of Sea bus operation. Volatility also represents variability in terms of data width.

Each scenario has different statistical parameters to represent various operation conditions. Then, both statistical values get higher when the Seabus operated far from the land. Those increasing or decreasing values are used to know that the Seabus operation is getting worse or better based on several wave parameters that have already been mentioned previously. The mean reversion parameter varies from 0 to 0.15, and the volatility parameter varies from 1 to 12 depending on the already created scenario. The biggest parameter value represents the worsened condition and big ship crossing scenarios, as seen in **Table 1.**

In order to create a more varied pulsed propulsion load, the MATLAB code is used to create randomized fluctuations of propulsion loads based on mean reversion and volatility parameters. The average value is taken from the calm water propulsion power, and the positive-negative amplitude is taken from the added propulsion power from **Table 1.** The result of propulsion load profile modelling is seen in **Figure 8.**

*D. Determination of Energy Storage Module Specifications*

Before doing the optimization process for sizing Seabus HESS, several parameter values from the storage specification need to be determined first. Every storage cell has different parameters that represent its storage characteristics. The main specifications of both the HE and HP cells are summarized in **Table 2.**

*E. Optimization Process Initialization*

At the beginning of the optimization process, the initial problem formulation must be determined first, including the Seabus operation scheme, the selected value of equipment specifications, the energy storage sizing method, the determination of optimization criteria, and limitations. The Seabus has a design life of 10 years with 6000 operating cycles and consumes a HE and HP energy storage cycle in a single round trip. In order to calculate the optimal size of the HESS, which considers the minimum installation cost, the rules-based iteration method is used to find the optimal energy storage system sharing between the HE and the HP cells. Based on the basic principles of energy conservation, the power required by the Seabus during operation is as follows:

$$P_{HE}(t) + P_{HP}(t) = P_d(t) \quad (6)$$

Where $P_{HE}(t)$ and $P_{HP}(t)$ are the propulsion power supplied by both the HE and HP storages in kW and

$P_d(t)$ represents the required propulsion power generated by the electric propulsion unit onboard in kW. This study considers the power values are always positive during the discharge of HESS due to the charging process not being considered. Then, the discharged HESS energy ($E_{dis}$ in kWh) can be calculated using the following formula.

$$E_{dis} = \int P_{dis}(t)\,.dt \quad (7)$$

$P_{dis}(t)$ is the discharge power of the HESS in kW, and $t$ is the time step that values at 1 second. Using the required HESS and the installed HESS, the DoD can be calculated using the following formula.

$$DoD = \frac{E_{dis}}{E_{ins}} \quad (8)$$

Where $DoD$ is the HESS depth of discharge in percent, $E_{dis}$ is the discharged HESS energy in kWh, and $E_{ins}$ is the rated installed HESS energy in kWh. Using the calculated DoD, the lifetime model in the previous section can be estimated.

TABLE 2.
SPESIFICATIONS OF BOTH HIGH ENERGY AND HIGH-POWER ENERGY STORAGE

| Parameter | Value | | | |
|---|---|---|---|---|
| Cell-Type | LFP (HE Cell) [23] | SC (HP Cell) [20] | LIC (HP Cell) [21] | LTO (HP Cell) [24] |
| Capacity | 105 Ah | 3400 F | 250 F | 100 Ah |
| Nominal Voltage | 12.8 V | 3.0 V | 3.8 V | 12.8 V |
| Standard Discharge Current | 55 A | 270 A | 10 A | 400 A |
| Energy Density | 10 kg / kWh | 122.35 kg / kWh | 16 kg / kWh | 14.17 kg / kWh |
| Weight | 12 kg | 520 g | 250 g | 17 kg |
| Internal Resistance | 30 mΩ | 0.12 mΩ | 50 mΩ | 1.1 mΩ |
| Storage Energy Cost | $ 521 / kWh | $ 8500 / kWh | $ 6000 / kWh | $ 1058 / kWh |
| Storage Power Cost [25] | $ 1446 / kW | $ 835 / kW | $ 1000 / kW | $ 1200 / kW |
| DC / DC Converter Cost [7] | $ 100 / kW | | | |
| AC / DC Converter Cost [7] | $ 240 / kW | | | |

## F. *Determination of Optimization Criteria*

As mentioned previously, the supplied power separation from the HESS was determined through rule-based energy management. Considering some design requirements, four criteria are created while iterating the required installed HESS together with the formulation based on [7].

(1) The HESS must provide 10 years of operation before reaching the cell lifecycles and ensures $C_{loss} \leq 20\%$.

$$\left(\frac{N_{design\ life}}{N_C}\right) \times 20\% \leq 20\% \quad (9)$$

$$\frac{N_{design\ life}}{N_C} \leq 1 \quad (10)$$

$$N_{design\ life} \leq N_C \quad (11)$$

$$6000\ cycles \leq N_C \quad (12)$$

Where $N_{design\ life}$ is the total HESS lifetime in cycles, $N_C$ is the number of cycles before the end of life. Using the desired cycle value, the required DoD of the HESS is calculated based on the battery lifetime modelling with the cycling counting method, as seen in **Figure 6**. The required HESS DoD value that ensures a minimum of 6000 operating cycles during 10 years of operation is 0.90. Then, the minimum installed energy for the first criterion can be calculated as follows.

$$E_{ins,1} = \frac{E_{dis}}{0.90} \quad (13)$$

Where $E_{ins,1}$ is the minimum installed energy based on the first criteria in kWh and $E_{dis}$ is the discharged HESS energy from the Seabus load profile in kWh.

(2) The HESS must ensure the amount of usable energy is within 10-90% of the storage SoC. Then, the minimum installed energy for the second criterion can be calculated as follows.

$$80\% \times E_{ins,2} = E_{dis} \quad (14)$$

$$E_{ins,2} = \frac{E_{dis}}{0.80} \quad (15)$$

Where $E_{ins,2}$ is the minimum installed energy based on the second criterion in kWh and $E_{dis}$ is the discharged HESS energy from the Seabus load profile in kWh.

(3) The HESS must ensure the discharge current does not exceed the nominal discharge current defined in the specifications. These criteria ensure that the HESS's current output during the discharging process does not exceed the nominal value. Each type of energy storage cell has its formula based on the cell characteristics. For lithium ion-based cells assuming that battery cells voltage is constant, the required installed storage can be written as follows.

$$E_{ins,3} = \frac{Ah_{capacity} \times V_{bus} \times I_{disch}}{I_{cell}} \quad (16)$$

$$E_{ins,3} = \frac{P_{disch,max} \times Ah_{capacity}}{I_{cell}} \quad (17)$$

Where $E_{ins,3}$ is the minimum installed energy based on the third criterion in kWh, $P_{disch,max}$ is the maximum discharge power required for supplying the electric propulsion unit in kW, $Ah_{capacity}$ is the HE storage capacity in Ampere-hour, $V_{bus}$ is the Seabus main bus voltage in VDC, $I_{disch}$ is the electric propulsion discharge current in Ampere, and $I_{cell}$ is the HE cell nominal discharging current in Ampere. For supercapacitor-based cells assuming that supercapacitor cell's voltage is also constant, the required installed storage can be written as follows.

$$E_{ins,3} = \frac{3}{8} \times \frac{C_{cell} \times V_{cell} \times V_{bus} \times I_{disch}}{I_{cell}} \quad (18)$$

$$E_{ins,3} = \frac{3}{8} \times \frac{C_{cell} \times V_{cell} \times P_{disch,max}}{I_{cell}} \quad (19)$$

$C_{cell}$ is the cell capacitance in Farad, $V_{cell}$ is the supercapacitors cells voltage in Volt, $V_{bus}$ is the Seabus main bus voltage in VDC, $P_{disch,max}$ is the maximum discharge power in kW, $I_{disch}$ is the electric propulsion discharge current in Ampere, and $I_{cell}$ is the HP cells nominal discharging current in Ampere.

(4) The capacity to be installed for the HESS to satisfy all the above criteria can be determined as follows.

$$E_{ins} = \max(E_{ins,1}, E_{ins,2}, E_{ins,3}) \quad (20)$$

Where $E_{ins}$ is the HESS capacity to be installed, $E_{ins,1}$, $E_{ins,2}$, and $E_{ins,3}$ are the minimum installed energy for all the above criteria.

### *G. Iteration Process of LFP-SC Configuration*

This section presents the results of LFP and the supercapacitors configuration sizing, cost, and weight analysis. **Figures 9(a)** and **9(b)** show the installed energies based on all the criteria in terms of maximum power supplied by HE storage or $P_{\max,HE}$ in kW. As $P_{\max,HE}$ increases, the installed LFP battery for HE storage also increases. On the other hand, the installed supercapacitors are decreasing as $P_{\max,HE}$ increases. The largest energy installed comes from the 2nd criterion in the range ($P_{\max,HE}$ < 310 kW) and the 3rd criterion in the range ($P_{\max,HE}$ > 310 kW) for LFP. Regarding the supercapacitors as HP storage, the largest energies installed come from the same criteria. But with different separation points at ($P_{\max,HE}$ < 130 kW).

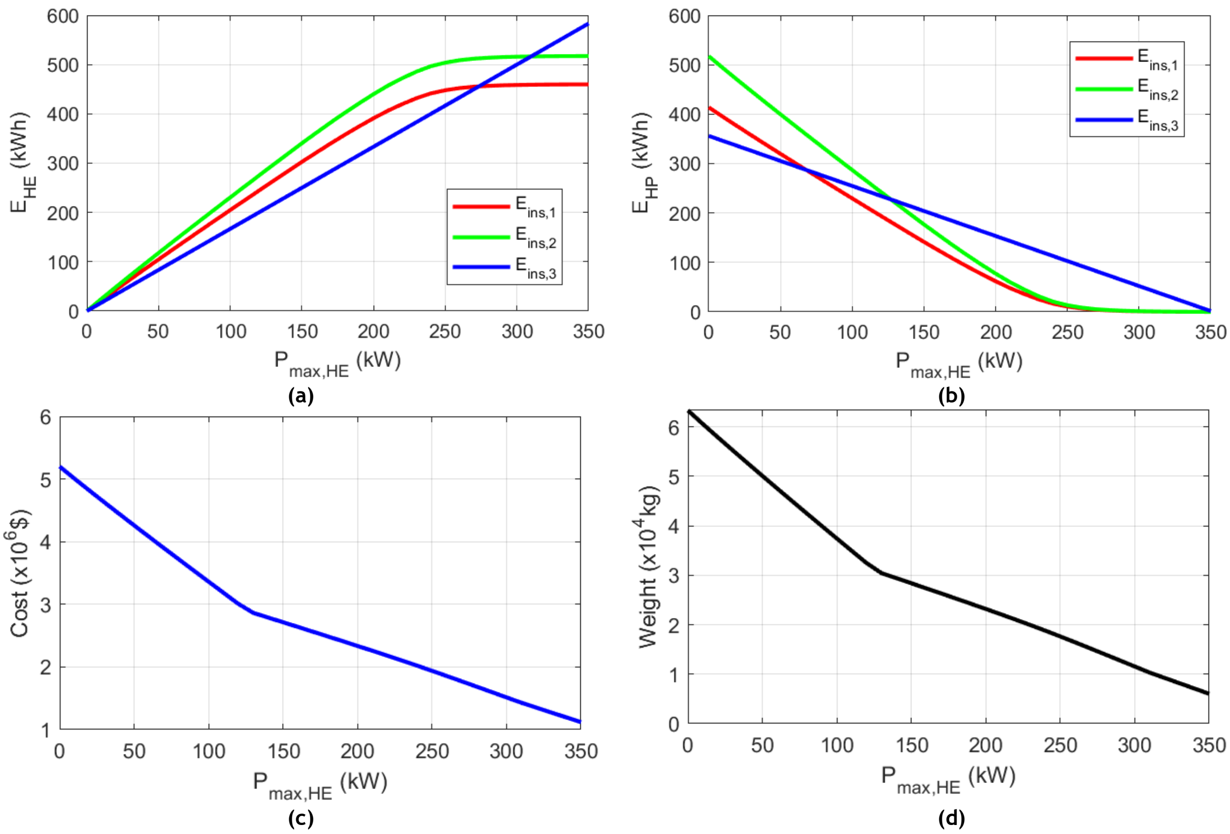


**Figure. 9.** HESS installed energy based on different design criteria for LFP (a), for SC (b), installation cost (c), and installation weight (d)

**Figure 9(c)** represents the installation cost, including the cost for converters in terms of $P_{\max,HE}$. It can be observed that the minimum cost is achieved for the HESS at $P_{\max,HE}$ = 350 kW, with an installation cost of about $ 1,118,920. Currently, the required installed HESS is only LFP with an energy of about 583 kWh. No supercapacitors is installed, or it can be stated as monotype topology. This could happen due to relative cost differences between the LFP and supercapacitors.

**Figure 9(d)** represents the installation weight for HESS calculated based on the cells weight data in **Table**

**2**. It is known that the weight reserve for energy storage onboard is only 5300 kg. The HESS weight at ($P_{\mathbf{max,HE}}$ = 350 kW) is 6023 kg, which is already above the energy storage weight limit. . Therefore, this configuration between LFP and supercapacitors cannot be applied on the Seabus due to cost and weight constraints.

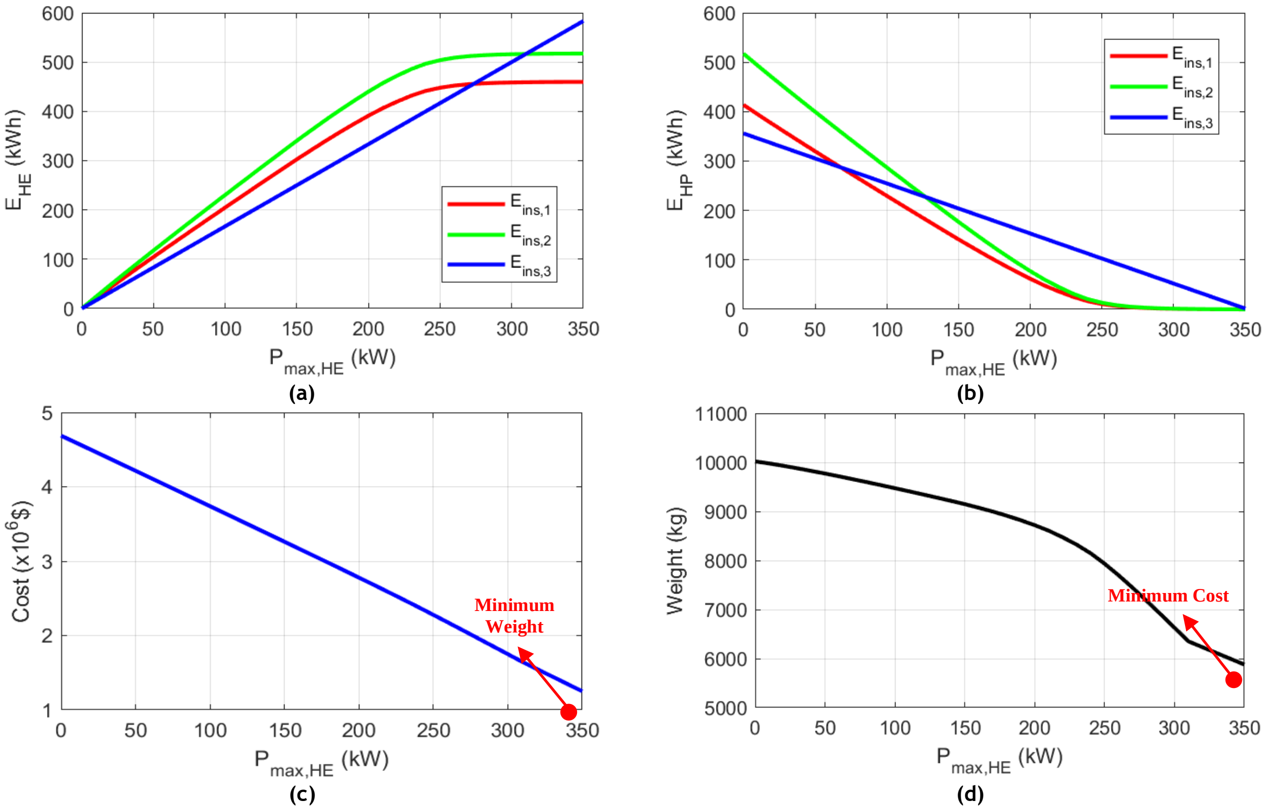


**Figure. 10.** HESS installed energy based on different design criteria for LFP (a), for LIC (b), installation cost (c), and installation weight (d)

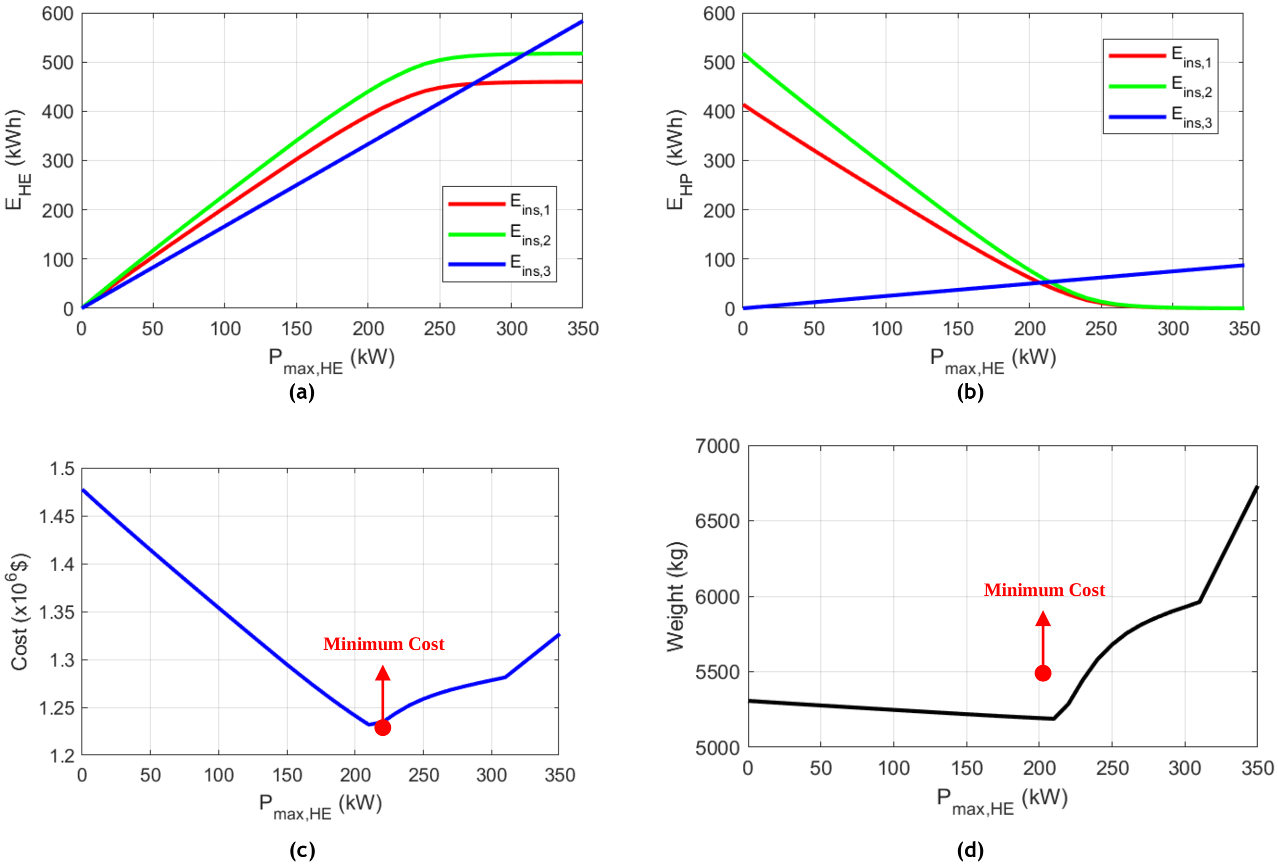


**Figure. 11.** HESS installed energy based on different design criteria for LFP (a), for LTO (b), installation cost (c), and installation weight (d)

*H. Iteration process of LFP-LIC Configuration*

This section presents another HESS configuration between the LFP and the LIC. As with the previous configuration, the HESS size, cost, and weight will be analyzed. **Figure 10(a)** and **Figure 10(b)** show the installed energies based on all the given criteria in terms of $P_{\max,\mathrm{HE}}$ in kW. As $P_{\max,\mathrm{HE}}$ increases, the installed LFP battery for HE cells also increases. On the other hand, the installed LIC is decreasing over $P_{\max,\mathrm{HE}}$. The largest energies installed come from the 2$^{nd}$ criterion in the range ($P_{\max,\mathrm{HE}}$ < 310 kW) and 3$^{rd}$ criterion in the range ($P_{\max,\mathrm{HE}}$ > 310 kW) for LFP. Regarding the LIC as the HP cells, the largest energies installed come from only the 3$^{rd}$ criterion along the $P_{\max,\mathrm{HE}}$ value iteration.

**Figure 10(c)** represents the installation cost of $P_{\max,\mathrm{HE}}$ in this second HESS configuration. It can be observed that the minimum cost is also achieved for the HESS at $P_{\max,\mathrm{HE}}$ = 350 kW, with an installation cost of about $ 1,250,420. Currently, the required installed HESS is only LFP with the same energy as the LFP-SC configuration. **Figure 10(d)** represents the installation weight for HESS calculated based on the cell weight data in **Table 2** which at $P_{\max,\mathrm{HE}}$ = 350 kW is 5877 kg, and this value is already achieving the energy storage weight limit. Therefore, this configuration also cannot be applied to the Seabus due to cost and weight constraints.

*I. Iteration process of LFP-LTO Configuration*

This section presents another HESS configuration between the LFP and the LTO. The HESS size, cost, and weight will be analyzed for this configuration capability. **Figure 11(a)** and **Figure 11 (b)** show the installed energies based on all the given criteria in terms of $P_{\max,\mathrm{HE}}$ in kW. The installed LFP is creating the same results as the previous configuration. On the other hand, the installed LTO is decreasing and increasing over $P_{\max,\mathrm{HE}}$. The largest energies installed for LTO come from the 2nd criterion in the range ($P_{\max,\mathrm{HE}}$ < 210 kW) and the 3$^{rd}$ criterion in the range ($P_{\max,\mathrm{HE}}$ > 210 kW).

**Figure 11 (c)** represents the installation cost of $P_{\max,\mathrm{HE}}$ in this third HESS configuration. It can be observed that the minimum cost is achieved for the HESS at $P_{\max,\mathrm{HE}}$ = 210 kW, with an installation cost about $ 1,231,910. Currently, the required installed HESS consists of 457 kWh LFP and 60 kWh LTO. **Figure 11(d)** represents the installation weight for HESS calculated based on the cells weight data in **Table 2** which at $P_{\max,\mathrm{HE}}$ = 210 kW is 5188 kg, representing the lightest point. Therefore, this configuration becomes the optimal sizing solution for the HESS and applies to the Seabus after considering the installation cost and weight constraints

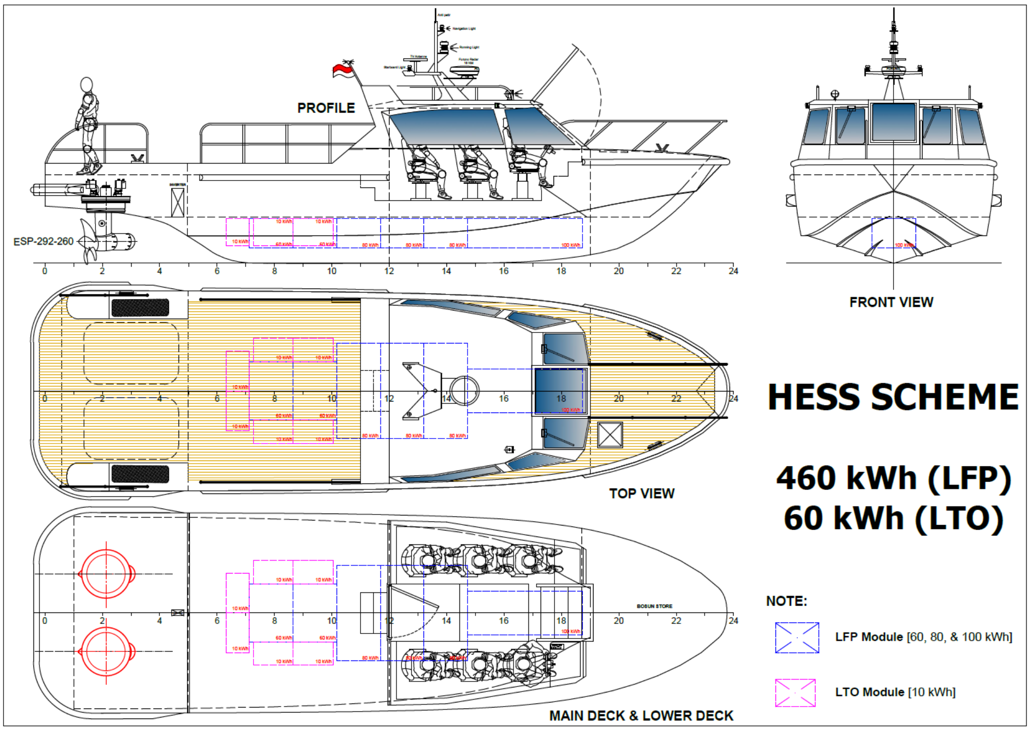


**Figure. 12.** HESS consists of LFP and LTO visualization onboard Seabus

*F. Visualization of Hybrid Energy Storage Installations*

After knowing the HESS installed energies for both LFP and LTO, the visualization of HESS arrangement onboard the Seabus is required to determine the distribution placement of the HESS modules. This visualization is important for further studies about ship stability and other ship motion analyses to ensure the safety of Seabus operation. The HESS visualization is presented on the Seabus general arrangement, as seen in Figure 12.

## IV. CONCLUSION

This study investigated the effect of energy storage hybridization based on the installation cost and weight for an all-electric Seabus equipped with an electric propulsion system. The proposed HESS configurations were LFP-SC, LFP-LIC, and LFP-LTO to find the best configuration for fulfilling a 10-year Seabus operation with pulsed propulsion load consideration. Using a rule-based optimization method, optimal sizing for HESS configuration was achieved using an LFP-LTO configuration that meets all the given criteria and weight limitations with an installation cost of about $1,231,910 and a weight of about 5188 kg. Therefore, an optimized HESS could provide enoughenergy to operate the Seabus with a speed of 30 knots for 2 hours under variable conditions, which is 67% longer than the operation time in the previous study. For further research, additional ship stability analysis and overall operational cost for the Seabus operation could be conducted.

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