Journal of Ship Production and Design, Vol. 00, No. 00, Month 2023, pp. 1–31
http://dx.doi.org/10.5957/JSPD.07230016

Modeling Shipboard Power Systems for Endurance and Annual Fuel Calculations

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Endurance fuel calculations are used to determine the required volume of fuel tanks; annual fuel calculations are used to estimate the fuel consumed during a year of ship operations, primarily to estimate the projected cost of fuel as part of the life cycle cost estimate. These calculations depend on the fuel rates (kg/h) for different electrical and propulsion system configurations. The fuel rates in turn depend on factors, such as equipment efficiency, prime mover-specific fuel consumption curves, electrical loads, ambient temperature, propulsion loads, and the manner in which the power and propulsion systems, are operated. This paper details how to perform endurance fuel and annual fuel calculations, provides guidance for modeling system components based on data typically provided in data sheets, and provides guidance on the manner in which the power and propulsion systems are operated. Four examples are provided to illustrate the methods using the Smart Ship System Design modeling and simulation tool along with supporting spreadsheets.

Keywords: Marine design for ships and offshore structures; endurance; fuel efficiency; electrical efficiency; electrical system; performance prediction

1. Introduction

Two important activities in the design of a ship are performing calculations to determine the minimum required amount of fuel that should be stored in its fuel tanks (endurance fuel calculations), and performing calculations to estimate how much fuel will be consumed during a year of operations (annual fuel calculations).

Endurance fuel and annual fuel calculations are important to the design of both commercial and naval ships. These calculations are often used to compare the performance of different concepts under consideration in the early stages of design. Performing these calculations accurately is important to ensure the best concept is chosen for further development. This is particularly important when concepts feature power and propulsion systems that differ significantly from each other. Examples include a mechanical drive ship, a hybrid electric drive ship, and a full-integrated power system ship.

For U.S. Navy ships the process for conducting endurance fuel calculations is defined in NAVSEA DDS 200-1 Rev 1 which is often referred to as DPC 200-1. The process for conducting annual fuel calculations is defined in NAVSEA DDS 200-2. Since the processes for commercial ships are similar (Woud and Stapersma 2015), this paper will concentrate on the processes defined in NAVSEA DDS 200-1 Rev 1 and NAVSEA DDS 200-2, specifically on the method for determining fuel rates for specific operational conditions, ambient conditions, and ship speeds; as well as how to convert these fuel rates into required fuel tank volume and into annual fuel usage estimates. In particular, this paper highlights methods for predicting losses when equipment is operated at part load.

Newer revisions of NAVSEA DDS 200-1 Rev 1 and NAVSEA DDS 200-2 were issued in 2023 during the production of this paper. Because these newer revisions have limited distribution, this paper is based on the previously approved for public release revisions. Individuals working on U.S. Navy programs and having the proper access should review the newer revisions of NAVSEA DDS 200-1 Rev 1 and NAVSEA DDS 200-2 for changes to the procedures described in this paper. The process for modeling components and systems remains unchanged.

Fuel rates depend on the electrical load estimated for the operational condition and ambient condition, the propulsion power

Manuscript received by JSPD Committee July 26, 2023; accepted October 13, 2023.
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required to achieve the stated ship speed, the planned manner in which the electrical system and propulsion system are to be operated (system concept of operations), the power losses (efficiency) within power system apparatus, and the fuel consumption properties (specific fuel consumption [sfc]) of the prime mover.

A variety of tools may be used to implement the calculations. For this paper, Smart Ships System Design (S3D) along with supporting spreadsheets is used in four examples. The methods described in this paper are applicable to implementations using many different software analysis tools.

This paper is structured as follows:

Section 2 discusses endurance fuel and annual fuel calculations, details the analysis process, and lists study requirements.

Section 3 relates efficiencies to the loss mechanisms within electrical equipment and recommends ways to extrapolate efficiency curves and loss curves based on the relatively few data points typically provided in equipment data sheets. For alternating current (ac) systems, directly using loss curves instead of efficiencies eliminates the dependency on power factor.

Section 4 discusses using the fuel rate to extrapolate data instead of extrapolating data using sfc.

Section 5 describes the modeling implications of different methods for sharing real and reactive power among paralleled sources.

Section 6 provides an overview of software needed to perform the calculations, and includes an introduction to S3D.

Section 7 provides specific guidance for modeling the various components of a shipboard power system: prime movers, reduction gears, propellers and shafting, electrical azimuth thrusters, generators, generator sets, transformers, rectifiers, inverters, propulsion motor drives, propulsion motors, multiport power-conversion equipment, energy storage, and ship service loads.

Section 8 describes the contents and use of an electrical power system concept of operations and of a propulsion system concept of operations.

Section 9 provides guidance on implementing the component models within an integrated system model.

Section 10 describes using a run matrix as a means of organizing the use of the system modeling tool and recording the fuel rate results.

Section 11 describes how to calculate the endurance fuel requirements and annual fuel usage based on the previously calculated fuel rates.

Section 12 provides two examples each of endurance fuel and annual fuel calculations. The examples differ in the assumptions used to create the system concepts of operations.

2. Background

2.1. Fuel calculations

Fuel calculations are performed to determine the required amount of fuel storage tank volume as well as to estimate the annual usage of fuel. The process for both sets of calculations is similar in that fuel rates are calculated for specific operational conditions, ship speeds, and ambient conditions.

NAVSEA DDS 200-1 Rev 1 defines the following types of endurance fuel requirements:

- Surge to theater distance: "minimum distance (nautical miles) which a ship can sail without replenishment and using all of its burnable fuel (excluding cargo and aviation fuel), at sustained speed, deep water, and full load displacement, with a ship service operating condition corresponding to a cruise with self defense capability."
- Economical transit distance: "minimum distance (nautical miles) which a ship can sail without replenishment and using all of its burnable fuel (excluding cargo and aviation fuel), at a specified endurance speed, deep water, and full load displacement, with a ship service operating condition corresponding to a cruise with self defense capability."
- Operational Presence Time: "minimum time in hours that a ship can conduct specified missions with a given speed-time profile, with a ship service operating condition corresponding to the specified missions, without replenishment, and using all of its burnable fuel (excluding cargo and aviation fuel)."

The ship's requirements may specify one or more of these requirements. The burnable fuel must be capable of fulfilling all of the specified requirements.

The fuel calculations determine the required mass (kg) of burnable fuel. This weight is converted to a volume by dividing by the fuel mass density. The fuel mass density is a function of temperature and the chemical makeup of the fuel. For the U.S. Navy, the standard fuel is F76 which has a representative mass density of .84 kg/L (NAVSEA DDS 200-2).

As detailed in NAVSEA DDS 200-1 Rev 1, the required fuel tank volume is equal to the burnable fuel volume divided by a tailpipe allowance and multiplied by a factor of 1.05. The tailpipe allowance accounts for the fuel that is below the fuel system suction and cannot be used. The tailpipe allowance should ideally be calculated based on tank geometry. If calculating the tailpipe allowance is not practical, it may be estimated as .95 if the tanks are broad and shallow, or .98 if narrow and deep. The factor of 1.05 is to account for the expansion of fuel due to temperature changes. The fuel tank volume should also be adjusted to account for structural elements within the tank; these structural elements are typically about 2% of the tank volume.

NAVSEA DDS 200-2 details how to estimate the annual usage of fuel. This process depends on the development of an operational profile which "describes the number of hours a ship operates for each year within the ship's design service life in each of its operational modes and with a corresponding speed-percent time profile." Examples of operational modes include

- Maintenance and Modernization
- Predeployment Training
- Deployment
- Major Combat Operations (MCO).

These operational modes are then related to ship states via a ship state participation table (Table 1) that indicates for each operational mode the fraction of time spent in each ship state. Ship states are usually aligned with electric power load analysis (EPLA) operational conditions for the endurance conditions. Examples of ship states include

- Inport—shore
- Underway—Economical Transit
- Underway—Surge to Theater
- Underway—Mission.

The fuel rates for each ship state are calculated in the same manner as for the endurance fuel calculations.

Table 1 Ship state participation table (NAVSEA DDS 200-2)

	Inport—shore	Underway—economical transit	Underway—surge to theater	Underway—mission
Maintenance and modernization	.90	.05	.00	.05
Predeployment training	.60	.20	.00	.20
Deployment	.10	.20	.00	.70
MCO	.05	.15	.05	.75

MCO, major combat operations.

2.2. Analysis process

The steps to complete an endurance fuel or annual fuel estimate are

a) Establish analysis requirements
   1) Identify the operational conditions/ship states and ambient conditions.
   2) For annual fuel usage, define the operational modes, operational profile, and ship state participation table.
   3) Identify the ship's speeds required by the analysis.
b) Define the design and develop component models
   1) Define the power and propulsion architecture.
   2) Define the electrical loads for the operational conditions and ambient conditions.
   3) Define the propulsion loads for the ship's speeds previously identified.
   4) Define efficiency and sfc curves for all power system and propulsion system components.
c) Develop system model
   1) Define electrical system and propulsion system concepts of operations.
   2) Develop an analysis model for calculating a combined fuel rate for a given set of system parameters, ship speed, operational condition, and ambient condition.
d) Perform analysis
   1) Develop a "run matrix" with rows holding configuration data for the analysis model for every desired combination of system parameters, ship speed, operational condition, and ambient condition.
   2) Execute each row of the run matrix and record the fuel rates of the prime movers and the total fuel rate.
   3) Post process the fuel rates to determine the required size of fuel tanks or the estimated annual fuel usage.

The large number of steps and data elements needed to complete the process calls for these studies to be deliberately planned. Developing a study guide as described in Doerry (2014) is strongly encouraged.

2.3. Study requirements

The following items are needed to conduct an endurance fuel calculation or annual fuel usage calculation:

1) Endurance fuel requirements (if applicable)
2) Operational conditions/ship states
3) Ambient Conditions
4) Speed time profiles
5) Ship State Participation Table and operational profile (annual fuel only)
6) Electrical power and propulsion systems architectures
7) Electrical loads
8) Propulsion speed power curves
9) Component property data
10) Concepts of Operations
11) Analysis tool
12) Analysis model
13) Run matrix
14) Post processing tool

The study guide should identify which elements are completely defined at the beginning of the study; and for those that are not completely defined, the remaining work needed to mature them sufficiently for use in the study.

3. Modeling efficiency

The efficiency of a power conversion device is defined as the power out divided by the power in. The losses are defined as the power in minus the power out. Losses and efficiency data may be provided in a number of different ways in equipment data sheets. Often the efficiency or losses at only a few points are provided. Simulations or calculations usually require extrapolation of this data for a given operating point of the system. The following discussion will detail how to perform extrapolation and interpolation based on the actual loss mechanisms of the components.

For many types of electrical equipment, the losses (P_{Loss}) can be modeled as

$$P_{\text{Loss}} = P_{\text{noLoadLoss}} + R_{\text{loss}} I_{\text{out}}^2, \tag{1}$$

$P_{\text{noLoadLoss}}$ is the power at the input when there is no power supplied at the output. $R_{\text{loss}} I_{\text{out}}{}^2$ reflects the effective resistive losses in the equipment. Although there are other loss mechanisms, this simplified model has been shown to be sufficient for many power conversion components.

The efficiency is thus

$$\eta = \frac{P_{\text{out}}}{P_{\text{out}} + P_{\text{noLoadLoss}} + R_{\text{loss}} I_{\text{out}}^2}, \tag{2}$$

For direct current (dc) systems, P_{out} and I_{out} are related by

$$P_{\text{out}} = V_{\text{out}} I_{\text{out}}, \tag{3}$$

For three phase ac power

$$P_{\text{out}} = \sqrt{3} V_{\text{out}} I_{\text{out}} (\text{PF}), \tag{4}$$

where (PF) is the displacement power factor (often simply called power factor) and V_{out} is measured line to line. V_{out} and I_{out} are root mean square (rms) quantities. The displacement power factor is the cosine of the difference in phase angles of the phase (line to neutral) voltage and phase current waveforms. A detailed derivation of equation (4) is provided in Doerry (2017).

For dc systems, the efficiency can be restated as

$$\eta = \frac{P_{\text{out}}}{R_{\text{loss}} \left(\frac{P_{\text{out}}}{V_{\text{out}}}\right)^2 + P_{\text{out}} + P_{\text{noLoadLoss}}}, \tag{5}$$

This equation can be normalized by dividing the numerator and denominator by the rated power.

$$\eta = \frac{\frac{P_{\text{out}}}{P_{\text{rated}}}}{\frac{P_{\text{rated}}R_{\text{loss}}}{V_{\text{out}}^2}\left(\frac{P_{\text{out}}}{P_{\text{rated}}}\right)^2 + \frac{P_{\text{out}}}{P_{\text{rated}}} + \frac{P_{\text{noLoadLoss}}}{P_{\text{rated}}}}, \tag{6}$$

This form is convenient since the no load losses are often provided on data sheets as a percentage of the rated load. The efficiency at full load is also often provided. Restating again to calculate the coefficient of the power squared term in the denominator

$$\frac{P_{\text{rated}}R_{\text{loss}}}{V_{\text{out}}^2} = \frac{1}{\eta_{\text{RatedPower}}} - \left(1 + \frac{P_{\text{noLoadLoss}}}{P_{\text{rated}}}\right), \tag{7}$$

With this solution and the assumption that the output voltage level is relatively constant, the efficiency can be estimated at any output power level.

In some cases, the efficiency will be provided for several output power levels (as a fraction of rated power) but the no-load losses may not be provided. If we assume that the output voltage is relatively constant (as is desired), then $\frac{P_{\text{rated}}R_{\text{loss}}}{V_{\text{out}}^2}$ and $\frac{P_{\text{noloadLoss}}}{P_{\text{rated}}}$ can be estimated by curve fitting to

$$\frac{P_{\text{rated}}R_{\text{loss}}}{V_{\text{out}}^2}\left(\frac{P_{\text{out}}}{P_{\text{rated}}}\right)^2 + \frac{P_{\text{noLoadLoss}}}{P_{\text{rated}}} = \frac{P_{\text{out}}}{P_{\text{rated}}}\left(\frac{1}{\eta} - 1\right), \tag{8}$$

A curve fit of the data can be accomplished by assembling the following matrices where each row of A and B corresponds to a given pair $\left(\frac{P_{\text{out}}}{P_{\text{rated}}}, \eta\right)$

$$x = \begin{vmatrix} \left(\frac{P_{\text{rated}}R_{\text{loss}}}{V_{\text{out}}^2}\right) \\ \left(\frac{P_{\text{noLoadLoss}}}{P_{\text{rated}}}\right) \end{vmatrix}, \tag{9}$$

$$A = \begin{vmatrix} \left(\frac{P_{\text{out}}}{P_{\text{rated}}}\right)^2_1 & 1 \\ \left(\frac{P_{\text{out}}}{P_{\text{rated}}}\right)^2_2 & 1 \\ \left(\frac{P_{\text{out}}}{P_{\text{rated}}}\right)^2_3 & 1 \\ \left(\frac{P_{\text{out}}}{P_{\text{rated}}}\right)^2_4 & 1 \\ \cdots & \cdots \\ \left(\frac{P_{\text{out}}}{P_{\text{rated}}}\right)^2_n & 1 \end{vmatrix}, \tag{10}$$

$$B = \begin{vmatrix} \frac{P_{\text{out}}}{P_{\text{rated}}}\left(\frac{1}{\eta} - 1\right)_1 \\ \frac{P_{\text{out}}}{P_{\text{rated}}}\left(\frac{1}{\eta} - 1\right)_2 \\ \frac{P_{\text{out}}}{P_{\text{rated}}}\left(\frac{1}{\eta} - 1\right)_3 \\ \frac{P_{\text{out}}}{P_{\text{rated}}}\left(\frac{1}{\eta} - 1\right)_4 \\ \cdots \\ \frac{P_{\text{out}}}{P_{\text{rated}}}\left(\frac{1}{\eta} - 1\right)_n \end{vmatrix}, \tag{11}$$

The matrices form an equation

$$Ax = B, \tag{12}$$

The pseudo-inverse may be used to solve for x

$$x = (A^T A)^{-1} A^T B, \tag{13}$$

The original data points should be recreated using the elements of x as coefficients for the curve. If the results are not sufficiently close, then an alternate estimating method should be pursued.

For three phase ac systems, the efficiency can be restated

$$\eta = \frac{P_{\text{out}}}{\frac{R_{\text{loss}}}{3}\left(\frac{P_{\text{out}}}{V_{\text{out}}(\text{PF})}\right)^2 + P_{\text{out}} + P_{\text{noLoadLoss}}}, \tag{14}$$

The rated output apparent power S_{rated} is often used instead of the rated output real power for ac apparatus.

$$\eta = \frac{\frac{P_{\text{out}}}{S_{\text{rated}}}}{\frac{S_{\text{rated}}R_{\text{loss}}}{3V_{\text{out}}^2}\left(\frac{1}{(\text{PF})}\right)^2\left(\frac{P_{\text{out}}}{S_{\text{rated}}}\right)^2 + \frac{P_{\text{out}}}{S_{\text{rated}}} + \frac{P_{\text{noLoadLoss}}}{S_{\text{rated}}}}, \tag{15}$$

In this formulation, if we assume that the output voltage is relatively constant, then the efficiency is a function of the output power as a fraction of the rated apparent power and of the power factor. The power factor can be dealt with by calculating the curve for 3 power factors $\{.8, .9, \text{and } 1.0\}$ and then using the curve closest to the actual power factor. Figure 1 depicts an example of efficiency curves plotted for multiple power factors.

One drawback to using efficiency is that with a nonzero no-load loss, the efficiency will always be zero at zero output power; efficiency cannot be used directly to determine the losses at no load. Another drawback is that if an interpolation method is applied to estimate the efficiency between provided data points, one must check to ensure that the estimated efficiency is not negative and no greater than 1.0. If one directly calculates the losses, the loss at zero output power is easily calculated. Furthermore, since the loss curve has relatively simple curvature, interpolating between points on the loss curve is less likely to result in significant errors. For these reasons, it is usually better to directly calculate the losses. For dc this translates to

$$\frac{P_{\text{Loss}}}{P_{\text{rated}}} = \frac{P_{\text{noLoadLoss}}}{P_{\text{rated}}} + \frac{P_{\text{rated}}R_{\text{loss}}}{V_{\text{out}}^2}\left(\frac{P_{\text{out}}}{P_{\text{rated}}}\right)^2, \tag{16}$$

The input power is then made equal to the output power plus the losses.

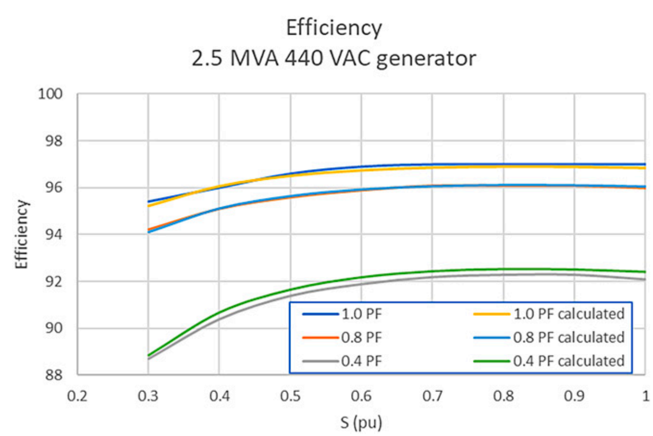

Fig. 1 Example efficiency curve for a three phase ac generator

Similarly, for ac systems

$$\frac{P_{\text{Loss}}}{S_{\text{rated}}} = \frac{P_{\text{noLoadLoss}}}{S_{\text{rated}}} + \frac{S_{\text{rated}} R_{\text{loss}}}{3V_{\text{out}}^2} \left(\frac{1}{(\text{PF})}\right)^2 \left(\frac{P_{\text{out}}}{S_{\text{rated}}}\right)^2, \tag{17a}$$

or

$$\frac{P_{\text{Loss}}}{S_{\text{rated}}} = \frac{P_{\text{noLoadLoss}}}{S_{\text{rated}}} + \frac{S_{\text{rated}} R_{\text{loss}}}{3V_{\text{out}}^2} \left(\frac{S_{\text{out}}}{S_{\text{rated}}}\right)^2, \tag{17b}$$

equation (17b) is useful in that unlike efficiency, the losses can be estimated based on only the apparent output power; the power factor is not explicitly required. Unfortunately, most simulation programs use an efficiency curve that does depend explicitly on the power factor as shown in equation (15).

For ac, the equation and matrices for calculating the pseudo-inverse are

$$\frac{S_{\text{rated}} R_{\text{loss}}}{3V_{\text{out}}^2} \left(\frac{S_{\text{out}}}{S_{\text{rated}}}\right)^2 + \frac{P_{\text{noLoadLoss}}}{S_{\text{rated}}} = \frac{P_{\text{out}}}{S_{\text{rated}}} \left(\frac{1}{\eta} - 1\right), \tag{18}$$

$$x = \begin{vmatrix} \left(\frac{S_{\text{rated}} R_{\text{loss}}}{3V_{\text{out}}^2}\right) \\ \left(\frac{P_{\text{noLoadLoss}}}{S_{\text{rated}}}\right) \end{vmatrix}, \tag{19}$$

$$A = \begin{vmatrix} \left(\frac{S_{\text{out}}}{S_{\text{rated}}}\right)^2_1 & 1 \\ \left(\frac{S_{\text{out}}}{S_{\text{rated}}}\right)^2_2 & 1 \\ \left(\frac{S_{\text{out}}}{S_{\text{rated}}}\right)^2_3 & 1 \\ \left(\frac{S_{\text{out}}}{S_{\text{rated}}}\right)^2_4 & 1 \\ \cdots & \cdots \\ \left(\frac{S_{\text{out}}}{S_{\text{rated}}}\right)^2_n & 1 \end{vmatrix}, \tag{20}$$

$$B = \begin{vmatrix} \frac{P_{\text{out}}}{S_{\text{rated}}} \left(\frac{1}{\eta} - 1\right)_1 \\ \frac{P_{\text{out}}}{S_{\text{rated}}} \left(\frac{1}{\eta} - 1\right)_2 \\ \frac{P_{\text{out}}}{S_{\text{rated}}} \left(\frac{1}{\eta} - 1\right)_3 \\ \frac{P_{\text{out}}}{S_{\text{rated}}} \left(\frac{1}{\eta} - 1\right)_4 \\ \cdots \\ \frac{P_{\text{out}}}{S_{\text{rated}}} \left(\frac{1}{\eta} - 1\right)_n \end{vmatrix}, \tag{21}$$

The magnitude of the real input power is equal to the magnitude of the output real power plus the losses. The relationship of the input and output reactive power is determined by the design of the ac apparatus.

Figure 1 displays the efficiency curves for a representative 2.5 MVA 440 VAC 60 Hz generator (ABB 2011). Efficiency curves are displayed as depicted from the data sheet as well as the associated efficiencies calculated from the elements of x using the pseudo-inverse method described above (equation 22). Figure 1 clearly demonstrates the ability of the two-parameter elements of x to accurately estimate the losses and efficiency of the generator over a broad range of power and power factor. The slight differences are likely due to loss mechanisms that are not represented in the simplified loss model.

$$x = \begin{vmatrix} \left(\frac{S_{\text{rated}} R_{\text{loss}}}{3V_{\text{out}}^2}\right) \\ \left(\frac{P_{\text{noLoadLoss}}}{S_{\text{rated}}}\right) \end{vmatrix} = \begin{vmatrix} 0.01947 \\ 0.01331 \end{vmatrix}, \tag{22}$$

4. Modeling fuel rates

SFC is typically used to calculate the amount of fuel required to provide a given power output for prime movers (such as diesel engines and gas turbines) as well as generator sets. For prime movers, the output power is the mechanical power at the shaft. For generator sets, the output power is the electrical power provided to the power system.

$$\text{FuelRate} = \text{sfc} \times P_{\text{out}}, \tag{23}$$

When working with this equation, ensuring the units of all the variables are consistent is critical. The *sfc* is often expressed in units of kg/kW-h, and the power is expressed in kW. The resulting fuel rate is thus kg/h. A fuel rate in kg/h can be converted to kg/s by dividing by 3600.

As with efficiency, one of the challenges with using sfc directly is that at zero output power, the sfc must be infinite for a nonzero FuelRate. In general, gas turbines and diesel engines have an idle fuel rate corresponding to zero output power. Doerry (2022) recommends modeling the fuel rate directly as a cubic curve instead of interpolating sfcs to calculate the fuel rate:

$$\text{FuelRate} = r_3 P_{\text{out}}^3 + r_2 P_{\text{out}}^2 + r_1 P_{\text{out}} + r_0, \tag{24}$$

The coefficients $\{r_0, r_1, r_2, \text{and } r_3\}$ may be estimated from fuel rates calculated from provided sfc data using the pseudo-inverse method as described in the previous section or other curve-fitting techniques. The r_0 coefficient is the idle fuel rate. If a cubic equation does not sufficiently fit the data, then additional terms may be added, or the use of orthogonal functions series (such as Legendre polynomials or Chebyshev polynomials) may be employed (Doerry 1991).

For virtually all gas turbines and diesel engines, the fuel rate will always be positive and have a positive slope with respect to power. In other words, more fuel is required for more power. This can be easily checked by ensuring the derivative of FuelRate with respect to P_{out} is not zero for P_{out} between 0 and P_{rated}, and that r_0 and r_1 are positive.

The modeling and simulation tool chosen to perform the analysis may limit one to using fuel rate or sfc curves. If given a choice, fuel rate curves should be used. In any case, interpolation and extrapolation of component datasheet values should be based on fuel rate and not sfc.

5. Power sharing

When the outputs of multiple power sources, such as generators, inverters, and rectifiers, are connected together, the algorithm for allocating the load power among these sources should be described in the appropriate system concept of operations.

The simplest approach is to specify the output real power, and for ac sources, reactive power for all but one of the paralleled sources. The remaining source acts as a "Swing" source which makes up the difference in the total real and reactive power required by loads and the total real and reactive power provided by the other sources. While this is easy to model, it is not reflective of the way sources typically operate onboard ship.

Typically, sources share real and reactive power in proportion to their rating. The sharing is implemented either through control signals, or via droop.

For dc sources using droop, the power provided by a source is a function of the voltage. Typically, this function is a line characterized by a no-load voltage and a percentage of the rated voltage; the output voltage drops from the no-load voltage at full load. For ac sources using droop, the real power provided by a source is a function of the frequency and the reactive power provided by a source is a function of the voltage. See Doerry (2017) for more details.

Although sharing power in proportion to generator rating is typically implemented onboard ship, Doerry (2022) demonstrates this may not be the most fuel-efficient way.

The swing source approach may be used to manually implement a power-sharing scheme by manually calculating the power each source should provide for a given total load. Once the total load is determined, either by manual calculations or an initial simulation, the appropriate power levels are assigned to all but the "swing" generator. The value predetermined for the "swing" generator should be close to the value calculated through the simulation.

6. Modeling and simulation software

6.1. Overview

This paper describes methods to mathematically model the components of a power system and to document how these components are intended to be configured for a specific analysis. The details of the implementation of these mathematical models, their interconnection to form a system, and the analysis of the systems depends on the chosen analysis software. Modeling simple systems in a spreadsheet tool, such as Microsoft Excel, are feasible and often done. More complex systems may call for modeling and simulation-based tools, such MATLAB or S3D. The choice of modeling and simulation tool should be documented in the study guide. Although S3D is used for the examples in this paper, the modeling methods presented are widely applicable to many different tools.

One of the functions of the modeling and simulation software is to generate mathematical equations that link the various component mathematical models. These network equations, along with the constitutive equations of the component mathematical models, form an overall set of system equations. The modeling and simulation software includes a system solver to provide a consistent solution for the set of system equations (Doerry 1991).

6.2. Smart ships system design

S3D is a multidiscipline, systems modeling, and simulation software tool integrated with the U.S. Navy's concept-stage ship design software applications using the leading edge architecture for prototyping systems (LEAPS) product model. S3D is developed jointly by the Naval Surface Warfare Center Carderock Division and the University of South Carolina's Electrical Engineering Department.

Like many modeling and simulation tools, S3D allows the user different options for setting up the network equations and for the system solver. The ac load flow solver provides the complete solution of the real and reactive (imaginary) components of ac voltages, currents, and powers. The dc load flow solver ignores the reactive (imaginary) components of voltages and currents in ac systems; all results are expressed in terms of real numbers. In many systems, the impact of reactive power on fuel rates is small and can be ignored for endurance fuel and annual fuel calculations. The dc load flow solver allows for a simpler system model, faster run time, and guaranteed convergence.

S3D is currently capable of performing the steady-state analysis of integrated electrical, mechanical, and fluid systems. This capability is ideally matched to the analytical needs for performing endurance fuel calculations and annual fuel calculations.

7. Modeling components

7.1. Introduction

The following subsections describe how to model prime movers, reduction gears, propellers and shafting, electrical azimuth thrusters, generators, generator sets, transformers, rectifiers, inverters, propulsion motor drives, propulsion motors, multiport power-conversion equipment, energy storage, and ship service loads.

Component models are generally defined in terms of ports, properties, and constitutive equations. Ports are associated with connection variables that interact with other component ports through a network defined on a diagram. Ports are therefore also associated with a type of diagram. These diagrams are the basis for the network equations and are the way that component models are integrated into system models; the manner in which this is done depends on the chosen modeling and simulation tool (Doerry 1991).

For example, the networks as defined in S3D diagrams represent different types of power and energy flow. Other networks may represent the flow of monitoring and control signals. The S3D diagrams that apply to endurance and annual fuel calculations are the piping diagram, the mechanical diagram, and the electrical diagram. Other modeling and simulation software may define these networks in a related but different way.

Constitutive equations define relationships among connection variables based on the component and port properties.

7.2. Prime movers

Prime movers generally have two modeling ports of interest: a fuel port and a rotating mechanical port.

The fuel port is associated with a pressure and a mass flow rate of the fuel. The fuel port is modeled as part of a piping diagram.

The rotating mechanical port is associated with a power and a rotational speed (rpm). The torque can be calculated from the power and rotational speed. The rotating mechanical port is generally modeled as part of a mechanical diagram.

Normally the prime mover model constitutive equations are used to calculate the mass flow rate of the fuel port and the rotational speed of the rotating mechanical port. A system solver determines the fuel port pressure and the rotating mechanical port power based on the appropriate network diagram.

For fuel rate calculations, both gas turbines and diesel engines may be modeled using the following properties:

Online: {true or false} indicates whether the prime mover is consuming fuel. If the prime mover has Online = true and is not providing any output power, then the fuel rate is equal to the idle fuel rate. If Online = false, the fuel rate is 0.

Specific Fuel Consumption Curve: The sfc curve is typically defined as a set of coordinates with the x-values corresponding to output power (kW or MW) and the y-values the corresponding sfc (kg/kW-h). As indicated previously, this sfc curve should be converted to a Fuel Rate Curve defined as either a set of coordinates, or as a set of coefficients for a formula to calculate the fuel rate.

Rated Power: The rated power is used to ensure the prime mover is not overloaded at the rotating mechanical port. Typically in units of kW or MW.

For diesels and gas turbines, the sfc curve is specific to a given speed-power curve and is extracted from a sfc map as depicted in Fig. 2. SFC maps plot iso-sfc curves as a function of rpm (*x*-axis) and power (*y*-axis). SFC maps also depict the power limits for a given shaft speed (rpm), and the maximum and minimum rated shaft speeds (rpm).

Models of mechanical drive applications typically assume the power is proportional to the rpm cubed. The shaft speed at the rated power is plotted on the sfc map and the cubic curve drawn from that point. Different propulsion configurations may result in different sfc curves. For example, the curve for one engine online on a single shaft will be different than if two engines are online on the same shaft.

Electrical power generation applications for ac distribution systems will operate at a constant rpm corresponding to the largest submultiple of 3600 rpm (for 60 Hz operation) that is below the maximum rated speed. The prime mover power rating should be derated to the maximum power limit for this speed as depicted on the sfc curve. For the diesel engine depicted in Fig. 2, the engine

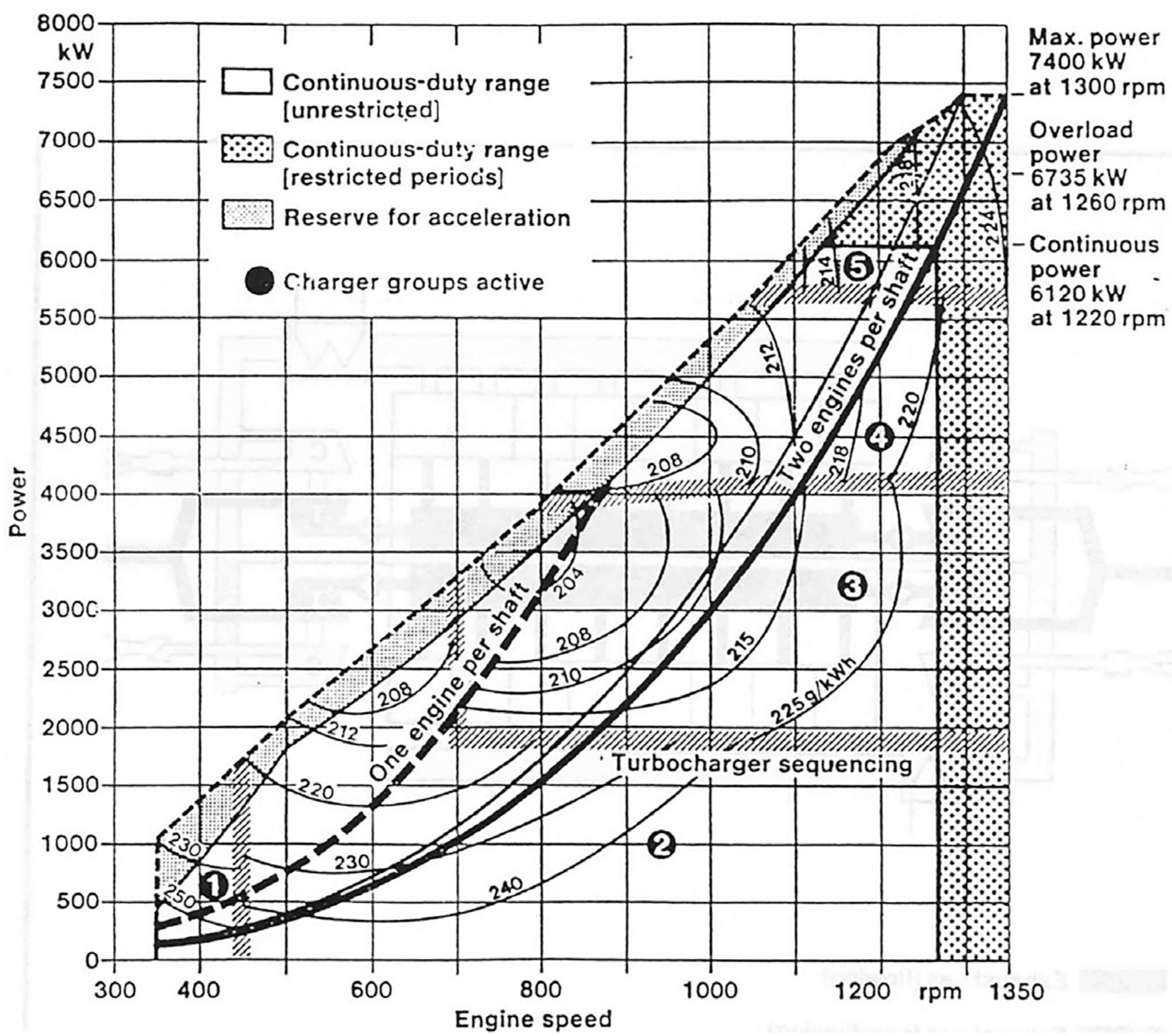

Fig. 2 Diesel sfc map (Guenther 1989)

would operate at 1200 rpm (1/3 of 3600 rpm). At this speed, the continuous power rating of 6120 kW could still be used. If the engine operates at 900 rpm (1/4 of 3600 rpm), the engine would be derated to roughly 4250 kW. While operating at the lower speed results in a substantial loss of maximum power, the fuel efficiency is improved as indicated by the lower sfc contours along the constant 900 rpm line as comparted to the constant 1200 rpm line.

Electrical power generation applications for dc distribution systems would be expected to operate at the speed corresponding to the lowest sfc for a given power level. Although this results in variable frequency output power, the rectifier can be designed to handle the expected range of frequencies. Because of variable speed operation, the engine need not be derated. If the ship is anticipated to have large power transients, the sfc curve may be adjusted away from the power limit for a given shaft speed. This improves the ability of the engine to respond to transient power needs at the cost of increased fuel consumption.

As depicted in Fig. 3, gas turbines have similar sfc maps. The difference in sfc values for mechanical drive, fixed frequency ac power generation, and variable speed for dc power generation are not as great as for diesel engines.

7.3. Reduction gears

Reduction gears generally have two types of modeling ports of interest: input rotating mechanical ports and output rotating mechanical ports. A reduction gear may have one or more input

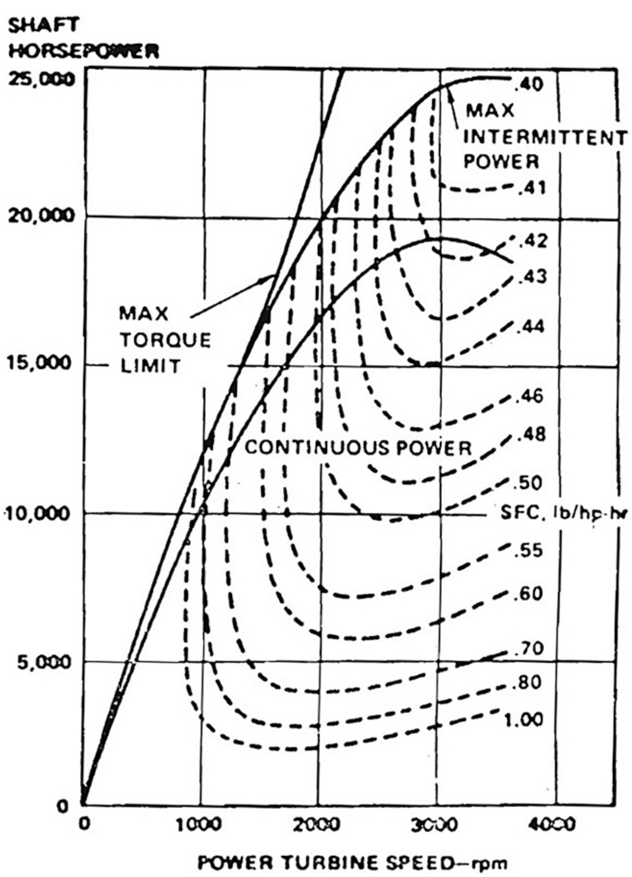

Fig. 3 Gas turbine sfc map (USNA 1979)

rotating mechanical ports and may have one or more output rotating mechanical ports. In certain special cases, such as in some hybrid electric drives, a rotating mechanical port may be bidirectional. Reduction gears with one input port and two output ports are splitting gears, while reduction gears with two input ports and one output port are combining gears. Combining gears are commonly used in mechanical drive applications. Some ships use a combination of combining and splitting gears.

The rotating mechanical port is characterized by a power and a rotational speed (rpm). The torque can be calculated from the power and rotational speed.

Normally, the reduction gear model specifies the relationship between the input and output port rotational speeds and the relationships of the powers on the input ports with the power on the output ports. A system solver determines the rotating mechanical port power of all but one of the ports and the rotational speed of the other port.

Reduction gears may be modeled using the following properties:

Input port Rated Speed and Output port Rated Speed. These properties are used to determine the gear ratios between the input and output ports.

Efficiency curve. The efficiency curve is typically defined as a set of coordinates with the x-values corresponding to output power as a fraction of the rated output power and the y-values corresponding to the efficiency. As indicated previously, this efficiency curve should be converted to a loss curve defined as either a set of coordinates, or as a set of coefficients for a formula to calculate the fuel rate.

Rated power. The rated power at the output port. Used to ensure the reduction gear is not overloaded.

A simplified model of the losses in a reduction gear uses two coefficients (k_n and k_P)

$$\frac{P_{\text{Loss}}}{P_{\text{outRated}}} = k_n \frac{n_{\text{out}}}{n_{\text{outRated}}} + k_P \frac{P_{\text{out}}}{P_{\text{outRated}}}, \tag{25}$$

$$\eta = \frac{P_{\text{out}}}{P_{\text{out}} + P_{\text{Loss}}}, \tag{26}$$

$$\frac{P_{\text{Loss}}}{P_{\text{outRated}}} = \frac{P_{\text{out}}}{P_{\text{outRated}}} \left(\frac{1}{\eta} - 1 \right), \tag{27}$$

Although the no-load losses are modeled as a proportional constant with respect to output shaft speed, the actual loss mechanisms are more complex (Michaelis et al. 2011). The assumed relationship generally results in loss estimates with acceptable levels of accuracy. For mechanical drive applications, the output power can be assumed to be proportional to the cube of the output shaft speed. In this case, the losses can be approximated by

$$\frac{P_{\text{Loss}}}{P_{\text{outRated}}} = k_n \left(\frac{P_{\text{out}}}{P_{\text{outRated}}} \right)^{\frac{1}{3}} + k_P \frac{P_{\text{out}}}{P_{\text{outRated}}}, \tag{28}$$

For reduction gears with multiple input ports, the losses are calculated based on the power on the output ports and must be apportioned to the input ports. Normally, the losses are apportioned based on the power provided by the input ports; the losses provided by an input port divided by the total power provided by the input port is a constant for all the input ports. In many cases, it may be adequate to equally apportion the losses to all input ports with an online prime mover.

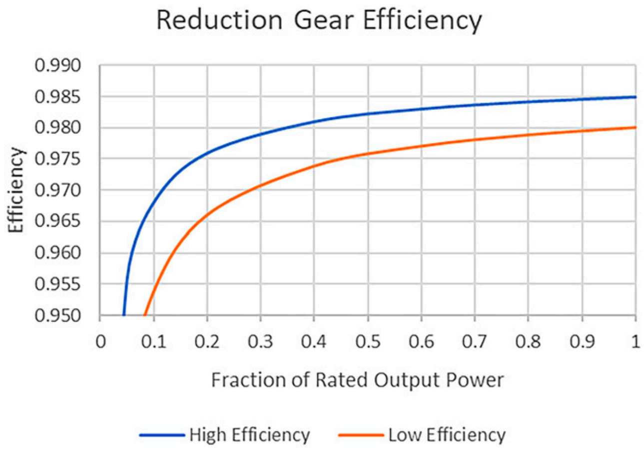

Fig. 4 Reduction gear efficiency

During some configurations, such as when only a single shaft is powered and the other trailed, the relationship between shaft speed and output power should be separately determined and the more general equation employed. The more general equations should also be used for applications employing controllable pitch propellers.

Based on data provided by Mowers (1992), the range of losses for a marine double reduction gear can be approximated by

High efficiency: $k_n = .004866$ $k_P = .01036$
Low efficiency: $k_n = .007686$ $k_P = .01272$

Figures 4 and 5 present the efficiency and losses as a fraction of output power for these coefficients. The graphs assume that the power is proportional to the cube of the shaft speed.

The losses for a single reduction gear would be roughly half that for a double reduction gear.

Radzevich (2012) states the range of efficiency for each stage of double helical gears is from 97% to 99.5%, which generally agrees with the data from Mowers (1992) used to generate Figs. 4 and 5.

7.4. Propellers and shafting

Propellers and shafting are typically modeled using a shaft port associated with a mechanical diagram and a property for specifying the ship's speed.

Fig. 5 Reduction gear losses

Propellers and shafting are modeled as a ship speed—power curve and a shaft speed—power curve. These curves estimate power and shaft speed at the output shaft of reduction gears and propulsion motors. These curves depend on the hull resistance characteristics, appendage resistance characteristics, propeller characteristics, propeller—hull interaction characteristics, powering margin, shaft bearing losses, shaft seal losses, thrust bearing losses, and the propulsion system concept of operations. Different operational conditions may result in different curves if the proportion of propulsion power provided by each shaft changes. For example, some operational conditions may specify that at low speeds only one shaft be powered and other shafts freewheel in what is known as trail-shaft operation. Other operational conditions may specify that all shafts provide power in equal proportion to their rated power.

The shaft speed—power curve is used in mechanical drive configurations to extract the specific fuel consumption curve from the prime mover sfc map. This curve is used in electric drive configurations to ensure the propulsion motor has the capability to operate over the curve.

Losses due to shaft bearings, shaft seals, and thrust bearings depend on the design details and for large ships can at maximum shaft speed be in the range of 10 to 100 s of kW (Komar et al. 2013). The losses at less than maximum shaft speed are generally less, but the relationship is complex and depends on design details not often available to the modeler. Many times, the impact of these losses is neglected and assumed to be within the margin of error of the ship's speed power curve.

In very early studies where a ship's hull has not even been defined yet, a shaft power is estimated for a given ship speed based on analogy to another ship design. The powers at other ship speeds are estimated assuming the power is proportional to the cube of the ship speed. Similarly, the shaft rpm at a given ship speed is estimated, and the shaft speeds at other ship speeds are estimated assuming the shaft speed is proportional to the ship speed.

7.5. Electrical azimuth thrusters (Pods)

Electrical azimuth thrusters are modeled using an electrical port and a property for specifying the ship's speed. The model incorporates the same subcomponents as for propeller and shafting, but also includes the motor and motor drive. Hence, the power in the ship speed—power curve is the electrical power at the electrical port. This electrical port is connected to the ship's distribution system and is typically a constant frequency (60 Hz). The power at the electrical port includes the losses of the propeller, shafting, motor, and motor drive.

As with the propellers and shafting, different operational conditions may result in different ship speed—power curves.

7.6. Generators

Many times, generators are modeled together with the prime mover as part of a generator set. In some cases, it may be desirable to model the generator separately

1) Data are available for the prime mover and generator separately.
2) The generator is not part of a traditional generator set, such as a power take off generator on a reduction gear.
3) Multiple generators are connected to the same prime mover.

Table 2 Transformer losses

Power rating (MVA)	Power rating (MW) at .8 PF	Efficiency category	No-load losses (kW)	Losses due to load (kW)	$\left(\frac{S_{rated}R_{loss}}{3V_{out}^2}\right)$	$\left(\frac{P_{noLoadLoss}}{S_{rated}}\right)$
1.0	.8	B	.94	9.0	.009000	.000940
1.6	1.3	B	1.45	14.0	.008750	.000906
2.0	1.6	B	1.80	18.0	.009000	.000900
2.5	2.0	B	2.15	22.0	.008800	.000860
1.0	.8	A	.77	7.6	.007600	.000770
1.6	1.3	A	1.20	12.0	.007500	.000750
2.0	1.6	A	1.45	15.0	.007500	.000725
2.5	2.0	A	1.75	18.5	.007400	.000700

A generator generally has two modeling ports of interest: a mechanical port connected to the prime mover, and an electrical output port providing ac power to connected components. A generator can be modeled by the following properties.

Rated apparent power: the rated apparent power of the output port.

Rated power: the rated power at the output port. The rated power is equal to the rated apparent power times the rated power factor. For most generators connected to an ac distribution system, the rated power factor is typically .80.

Efficiency curve: expressed as a percentage (0–100) as a function of percentage of rated apparent power. Should be converted to losses as a function of percentage (0–100) of rated apparent power. The losses are added to the real power at the output port to calculate the power at the mechanical port.

Rated mechanical speed (rpm): used to ensure a match between the prime mover and the generator. For constant frequency operation, the rated mechanical speed is typically the same as the operating speed and is a submultiple of 3600 rpm for 60 Hz operation and a submultiple of 3000 rpm for 50 Hz operation. If the output of the generator is intended to be immediately rectified, then the rated speed is not limited and the operating speed may be less than the rated speed.

Rated frequency (Hz): the rated frequency is used to ensure a match between the generator output port and load equipment. For ac distribution systems, the rated frequency is typically 60 Hz (or 50 Hz). If the output of a generator is intended to be immediately rectified, the rated frequency is not limited.

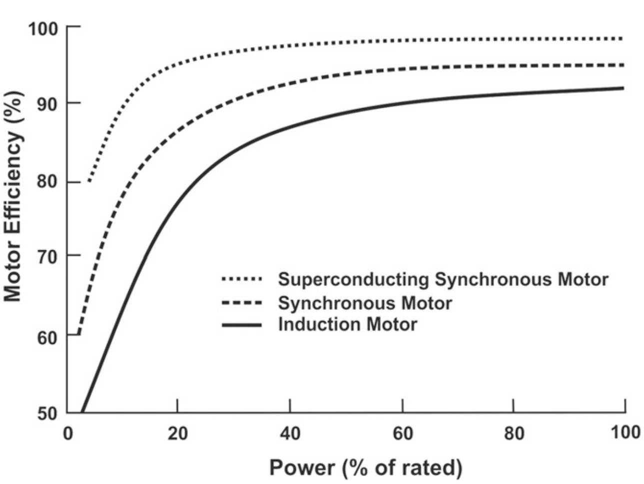

Fig. 6 Comparison of motor efficiencies (adapted from Patel 2012)

Rated voltage (V): the rated voltage is used to ensure the generator output port voltage matches that of the distribution system and load equipment.

Load sharing parameters: a generator model will require one or more parameters to implement the desired load-sharing approach.

For multimegawatt generators operating at rated voltages between 1 and 15 kV, the efficiencies at full load typically fall within the range of 96% and 98%. The respective no-load losses are 1.3% and 1% of rated apparent power. These parameters translate to the following range of properties for these generators:

$$x = \left| \begin{matrix} \left(\frac{S_{rated}R_{loss}}{3V_{out}^2}\right) \\ \left(\frac{P_{noLoadLoss}}{S_{rated}}\right) \end{matrix} \right| = \left| \begin{matrix} 0.0287 \\ 0.013 \end{matrix} \right| \text{ to } \left| \begin{matrix} 0.0104 \\ 0.010 \end{matrix} \right|, \qquad (29)$$

7.7. Generator sets

Generator sets for ac distribution consist of a prime mover (usually either gas turbine or diesel, but could be a steam turbine) and a generator. Generator sets for dc distribution may also include the rectifier or the rectifier may be modeled separately. The real power rating of an ac generator set can be no greater than the power rating of the prime mover multiplied by the efficiency of the generator at that input power level. The real power rating of a dc generator set should also include the efficiency of the rectifier.

Although the sfc curve for a prime mover is defined with respect to the output mechanical power, the sfc curve for a generator set is defined with respect to the output electrical power.

7.8. Transformers

High power transformers that link primary distribution systems (typically with a nominal system voltage greater than 1000 V) to low voltage distribution systems (typically with a nominal system voltage between 400 and 1000 V) are normally modeled in fuel calculations because the losses they incur can be significant.

Smaller distribution transformers that transform the low voltage distribution system to even lower voltage secondary distribution (typically with a nominal system voltage below 400 V) are normally not directly modeled. Instead, these distribution transformers and all the loads they service are lumped together into a single proxy load.

Table 3 Generator set schedule without energy storage example

	Rating (MW)	Generator set 1A 20	Generator set 1B 5	Generator set 2A 20	Generator set 2B 5
Total load	up to 9.5	Offline	Share	Offline	Share
	9.5–23.75	Share	Offline	Offline	Share
	23.75–28.5	Share	Share	Offline	Share
	28.5–38	Share	Offline	Share	Offline
	38–42.75	Share	Share	Share	Offline
	42.75–50	Share	Share	Share	Share

Table 4 Generator set schedule with energy storage example

	Rating (MW)	Generator set 1A 20	Generator set 1B 5	Generator set 2A 20	Generator set 2B 5
Total load	up to 5	Offline	Online	Offline	Offline
	5–10	Offline	Share	Offline	Share
	10–20	Online	Offline	Offline	Offline
	20–25	Share	Offline	Offline	Share
	25–30	Share	Share	Offline	Share
	30–40	Share	Offline	Share	Offline
	40–45	Share	Share	Share	Offline
	45–50	Share	Share	Share	Share

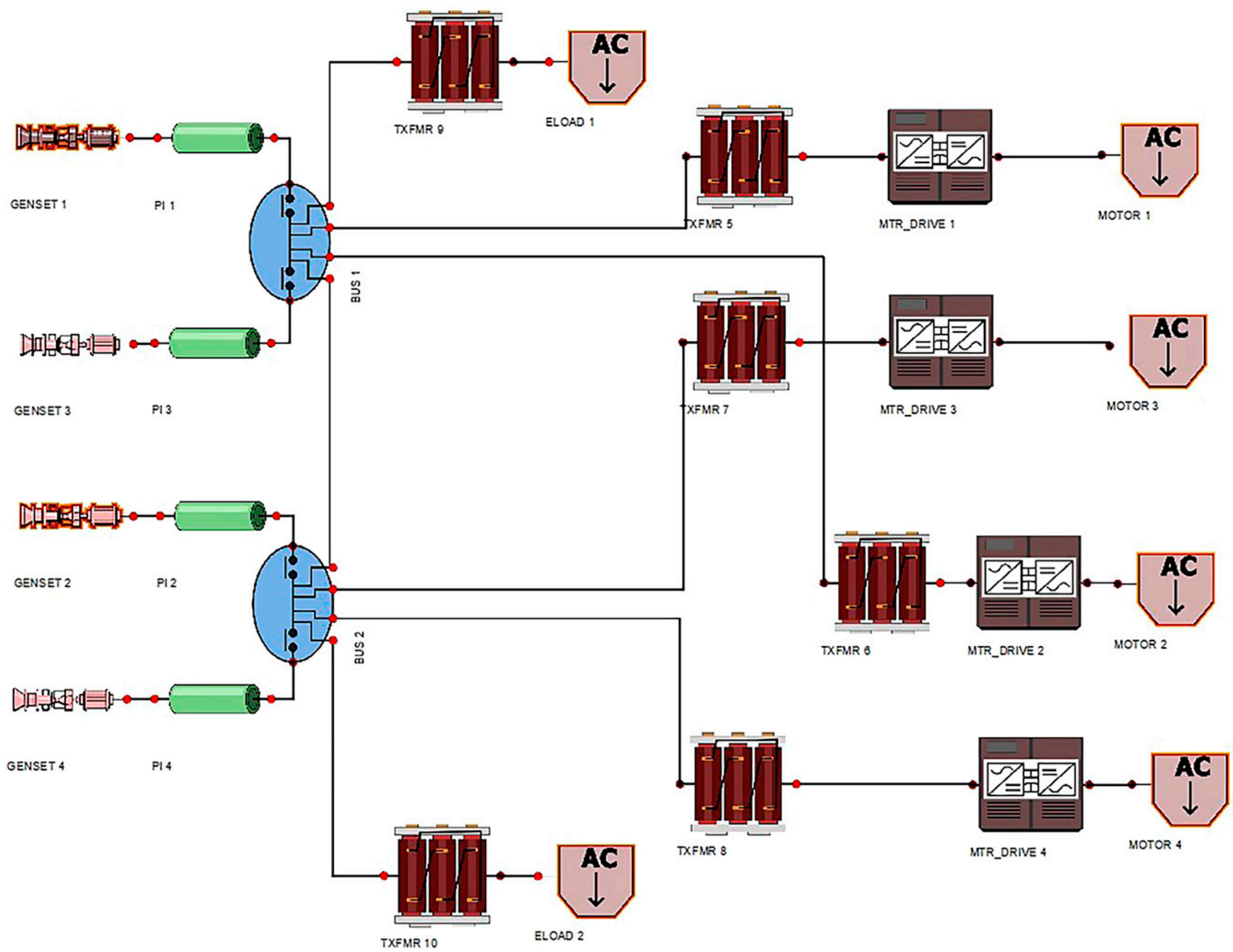

Fig. 7 Example electrical system model

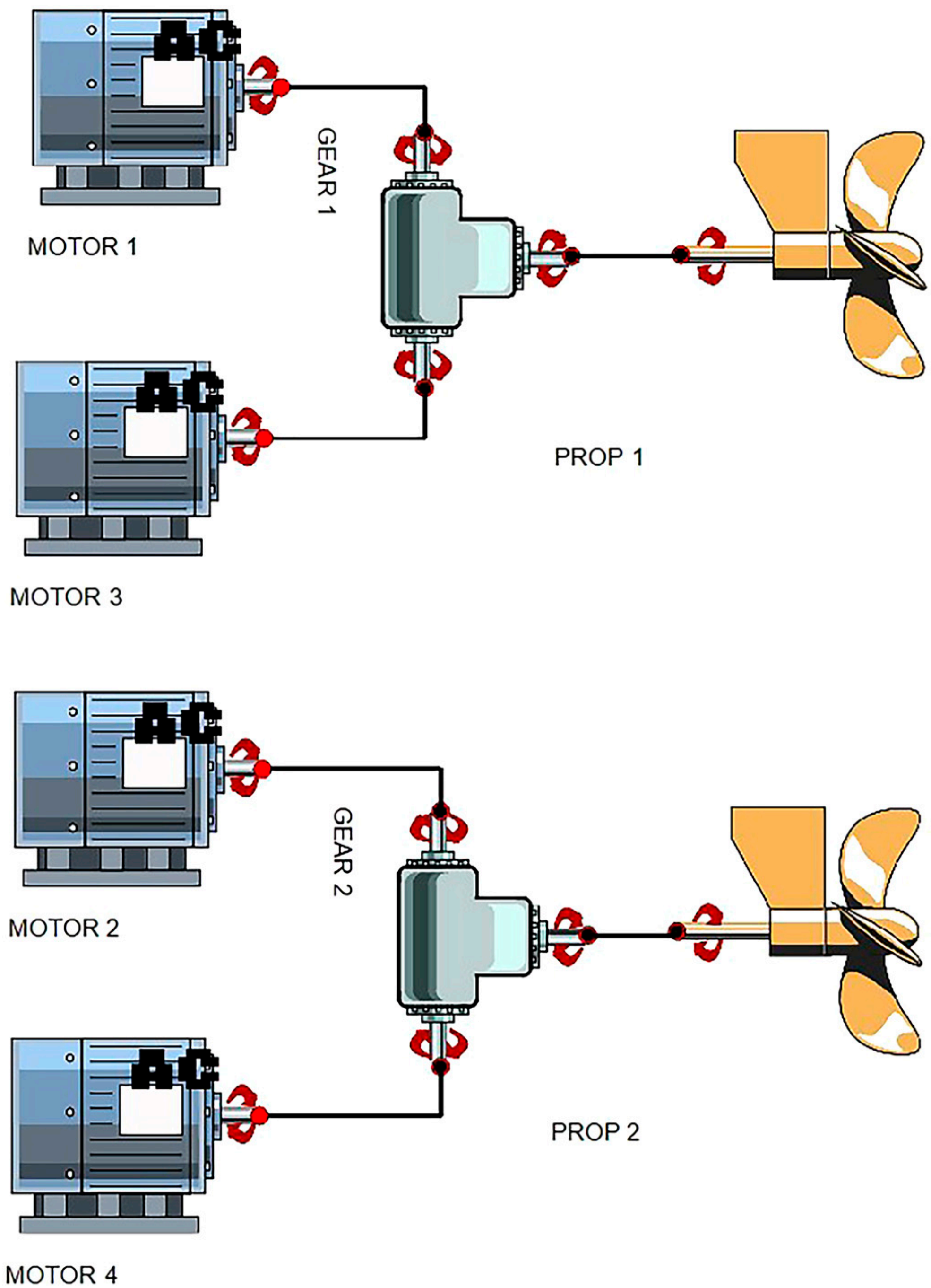

Fig. 8 Example propulsion system model

For the purposes of fuel calculations, transformers are usually modeled as an efficiency curve and two ports: an electrical primary port and an electrical secondary port. Losses in the transformer should be calculated based on the apparent power delivered to the load via the secondary port. These losses are added to the real power on the primary port. The reactive power on the primary port is usually set equal in magnitude to the reactive power on the secondary port; the impact of the transformer on the reactive power is typically not modeled in early stages of design.

If the losses of the transformer being modeled are known, then the known data should be used in parameterizing the transformer model. If details on the transformer design are not known, then the performance can be bounded using the data from Table 2 which is based on ABB (2015).

7.9. Rectifiers

Rectifiers have two electrical ports. The input port is typically a three-phase ac power port and the output port is a dc power port.

Table 5 Run matrix

Run	Temp (F)	Speed (knots)	Generator set 1 (25 MW rating)	Generator set 2 (25 MW rating)	Generator set 3 (10 MW rating)	Generator set 4 (10 MW rating)	Motor 1 (MW) (15 MW rating)	Motor 2 (MW) (15 MW rating)	Motor 3 (MW) (15 MW rating)	Motor 4 (MW) (15 MW rating)	ELOAD 1 (stbd) (MW)	ELOAD 2 (port) 2(MW)	Note
1	10	17	Offline	Offline	Swing	9.5 MW	5.46	Offline	Offline	5.46	2.1	2.4	Economic transit
2	50	17	Offline	Offline	Swing	9.5 MW	5.46	Offline	Offline	5.46	1.8	2.2	Economic transit
3	100	17	Offline	Offline	Swing	9.5 MW	5.46	Offline	Offline	5.46	2.0	2.3	Economic transit
4	10	27	23.75 MW	23.75 MW	Offline	Swing	10.94	10.94	10.94	10.94	2.1	2.4	Surge to theater
5	50	27	23.75 MW	23.75 MW	Offline	Swing	10.94	10.94	10.94	10.94	1.8	2.2	Surge to theater
6	100	27	23.75 MW	23.75 MW	Offline	Swing	10.94	10.94	10.94	10.94	2.0	2.3	Surge to theater

For fuel rate calculations, the principal property for rectifiers is the efficiency curve. The efficiency of a rectifier depends on the technology employed.

If the losses of the rectifier being modeled are known, then the known data should be used in parameterizing the rectifier model.

Although passive rectifiers have high efficiency, they also have high levels of harmonic currents that must be addressed in the system design. The results of notional designs for passive rectifiers ranging from 3 to 30 MW indicate that a constant efficiency of .999 is reasonable for nominal system voltages above 1 kV. This assumes that conduction losses are dominate, and commutation losses are minimal.

For active and controlled rectifiers with rated power above 100 kW, performance depends on rectifier topology (Wu et al. 2015; Abeynayake et al. 2021) and is usually bounded by

- Low efficiency: 96% efficiency at rated power, no-load losses of 1% of rated output power.
- High efficiency: 99% efficiency at rated power, no-load losses of .5% of rated output power.

This translates into

$$0.005 \leq \frac{P_{\text{noLoadLoss}}}{P_{\text{rated}}} \leq 0.010, \quad (30)$$

$$0.0051 \leq \frac{P_{\text{rated}} R_{\text{loss}}}{V_{\text{out}}^2} \leq 0.0317, \quad (31)$$

The displacement power factor on the ac input to the rectifier is generally close to unity; the voltage and current waveforms are usually close to being in phase. The distortion power factor measures the impact of frequencies other than the fundamental frequency on the ratio of real power to apparent power; it depends on the type of filtering used with the rectifier. Hence, the total power factor, which is the product of the two, depends heavily on the distortion power factor. In many fuel rate analyses, the impact of the distortion power factor is ignored. Ignoring distortion power factor in early stages of design is reasonable since the design detail is not sufficient to adequately estimate its impact, and the impact is likely within the bounds of error acceptable during early stage design. In later stages of preliminary and contract design when more detail is known, the impact of the distortion power factor should be incorporated.

7.10. Inverters

Inverters have two electrical ports. The input port is a dc power port and the output port is a three-phase ac power port. For fuel rate calculations, the principal property for inverters is the efficiency curve. The efficiency of an inverter depends on the technology employed.

If the losses of the inverter being modeled are known, then the known data should be used in parameterizing the inverter model.

The loss mechanisms of an inverter are similar to that for a rectifier; hence, the loss/efficiency curves are similar.

Low efficiency: 96% efficiency at rated apparent power, no-load losses of 1% of rated output apparent power.

High efficiency: 99% efficiency at rated apparent power, no-load losses of .5% of rated output apparent power.

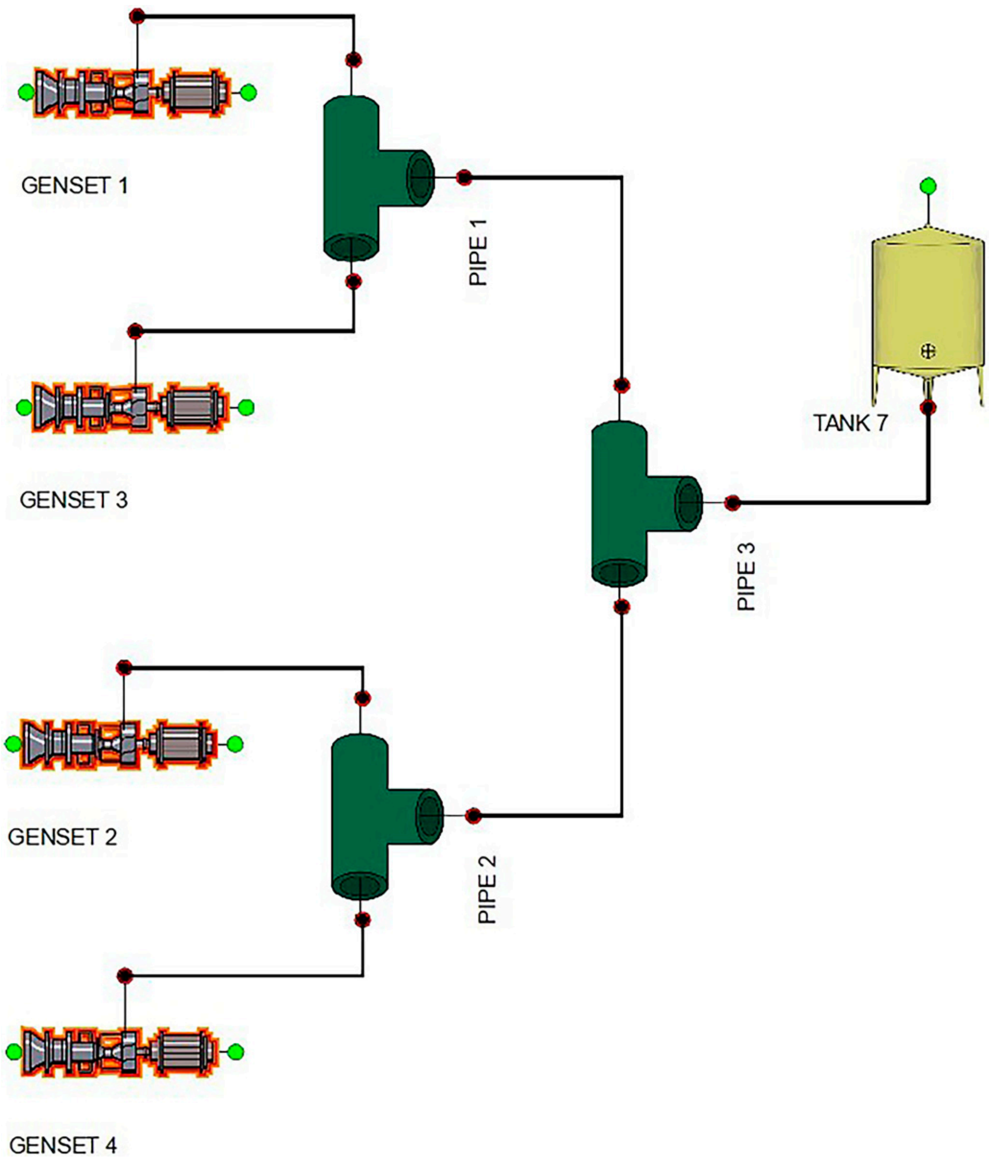

Fig. 9 Modeling proxy fuel system to calculate total fuel rate

Table 6 Fuel rate results

Run	Temp (F)	Speed (knots)	Fuel rate (kg/s)	Ambient condition profile
1	10	17	.972	.25
2	50	17	.944	.50
3	100	17	.961	.25
	Ambient cond. profile	17	.955	
4	10	27	3.34	.25
5	50	27	3.31	.50
6	100	27	3.33	.25
	Ambient cond. profile	27	3.323	

This translates into

$$0.005 \leq \frac{P_{\text{noLoadLoss}}}{S_{\text{rated}}} \leq 0.010, \qquad (32)$$

$$0.0051 \leq \frac{S_{\text{rated}} R_{\text{loss}}}{3V_{\text{out}}^2} \leq 0.0317, \qquad (33)$$

7.11. Propulsion motor drives

Propulsion motor drives convert the power from the voltage and frequency of the main power distribution system to the voltage and frequency needed by the motor.

Table 7 Example ship service electrical load

	Ship service load (kW)			
	Cruise with self defense		Mission	
Temperature (°F)	Starboard	Port	Starboard	Port
10	2100	2400	3600	3900
59	1800	2200	3300	3700
100	2000	2300	3500	3800

Table 8 Example operational profile

Operational profile	
Speed (knots)	Fraction time
5	.250
10	.350
15	.250
20	.100
25	.050

If the input power from the distribution bus is dc, then one or more inverters may be used to model the motor drive. At low power levels, one or more inverters may be shut down to reduce the losses and thereby improve efficiency.

If the input power from the distribution bus is ac, then a motor drive is typically modeled as one or more rectifiers powering one or more inverters. In some cases, the inputs and outputs of the rectifiers are connected in parallel, and the inputs and outputs of the inverters are connected in parallel; the group of paralleled rectifiers is connected in series with the group of paralleled inverters. In other cases, the series connections of a rectifier and an inverter are paralleled. At low power levels, one or more rectifiers and inverters may be shut down to reduce the losses and improve efficiency.

Often, an input transformer is included in motor drives connected to an ac distribution bus. This transformer may be used to adjust voltage levels as well as reduce the magnitude of harmonic currents.

The propulsion system concept of operations should provide guidance on the number of online rectifiers and inverters for a given propulsion power level.

In conducting the fuel rate analysis, it may prove beneficial to combine the multiple transformer, rectifier, and inverter models into a single model with a single efficiency/loss curve. This combined model should account for impacts, if any, of the propulsion system concept of operations.

When combining component models, the modeler should be cognizant that each component comprising the motor drive may have different rated powers. The power rating for a rectifier for example, should be equal to or greater than the power rating of the inverter divided by the efficiency of the inverter at rated power. As such, working directly with losses rather than efficiencies is less likely to result in calculation errors.

7.12. Propulsion motors

Propulsion motors convert the electrical power from the motor drive to the rotational mechanical power provided to the propeller and shafting. The behavior of the propulsion motor is defined by its efficiency curve as a function of percent rated mechanical power. The efficiency is the ratio of the output mechanical power divided by input electrical power.

Some designs incorporate multiple propulsion motors on the same shaft. In these cases, the propulsion system concept of operations should identify how the mechanical power is shared among the motors on the same shaft. At low powers, one of the motors may be turned off to conserve power.

Some motors have the ability to turn off sections of the motor at low speeds to improve efficiency. Once again, the propulsion system concept of operations should indicate when sections of the motor are turned off.

The efficiency of a propulsion motor depends on the technology employed. Figure 6 depicts efficiency curves for several types of propulsion motors. If actual efficiency data are not available for a particular study, these curves may be employed as a representative. The loss curve coefficients may be derived from this figure.

In some cases, it may be easier to model the propulsion motor as an electrical load that is a function of the ship speed. This model combines the impact of the propeller and shafting with the propulsion motor.

The power factor of the motor depends on the technology of both the motor and the motor drive. Most modern drives operate the propulsion motor at a power factor close to 1.0.

7.13. Multi-port power conversion equipment

Some power systems incorporate power electronic power conversion equipment with more than one input port or more than one output port. The efficiency of these components depends on their internal architecture and the technologies used to implement subcomponents. Typically, the subcomponents can be modeled as transformers, inverters, or rectifiers and their behaviors combined to develop an overall model of the equipment.

7.14. Energy storage

Whether to and how to model energy storage depends on the intended purpose of the energy storage. As described by Doerry

Table 9 Speed power profile

Speed	Power (MW)
0	.000
1	.002
2	.018
3	.060
4	.142
5	.28
6	.48
8	1.14
10	2.22
12	3.84
15	7.50
17	10.92
20	17.78
22	23.66
25	34.72
27	43.74
30	60.00

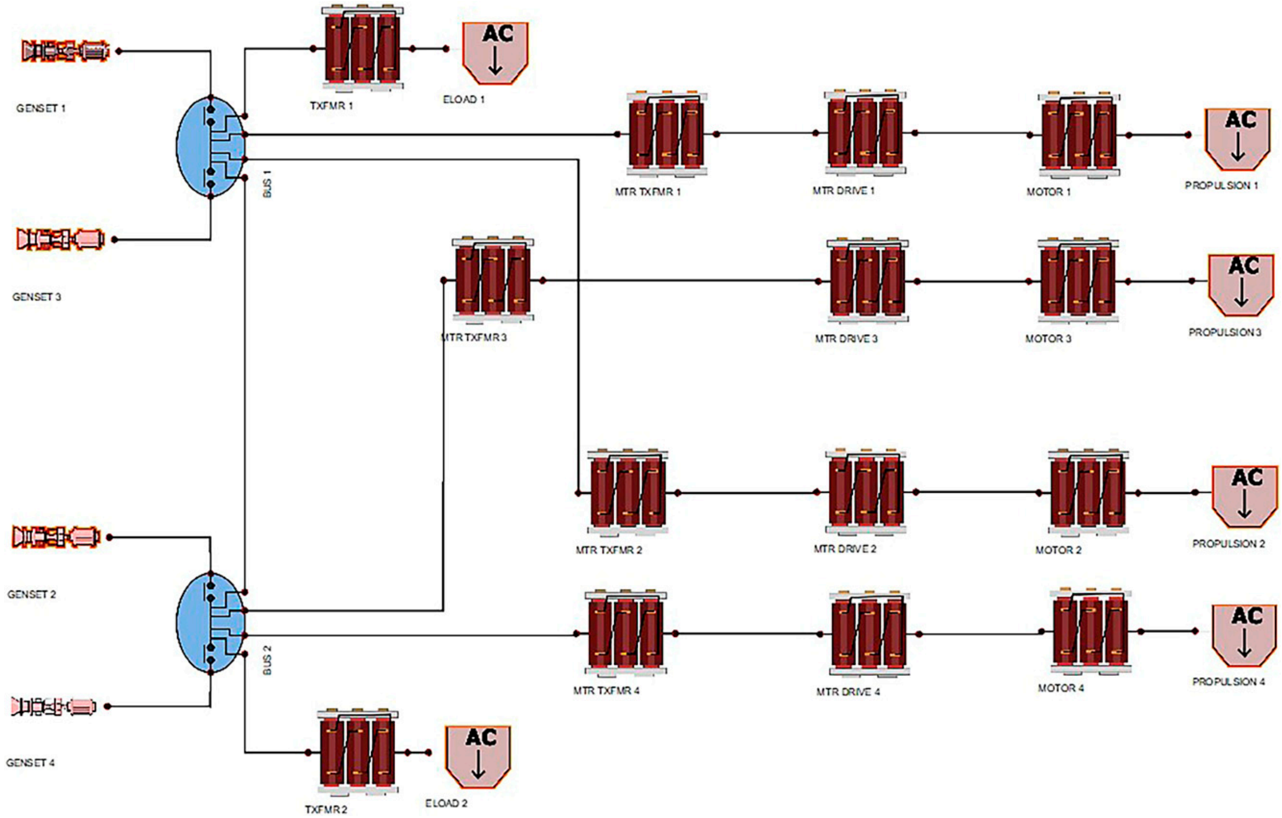

Fig. 10 Example 1 S3D using electrical diagram

Table 10 Representative data sheet data for generator sets

	Generator set 1	Generator set 2	Generator set 3	Generator set 4
Power rating (MW)	25	25	10	10
Rated voltage (kV)	13.8	13.8	13.8	13.8
sfc at 50% power (kg/kW-h)	.328	.328	.208	.208
sfc at 75% power (kg/kW-h)	.283	.283	.204	.204
sfc at 100% power (kg/kW-h)	.261	.261	.202	.202

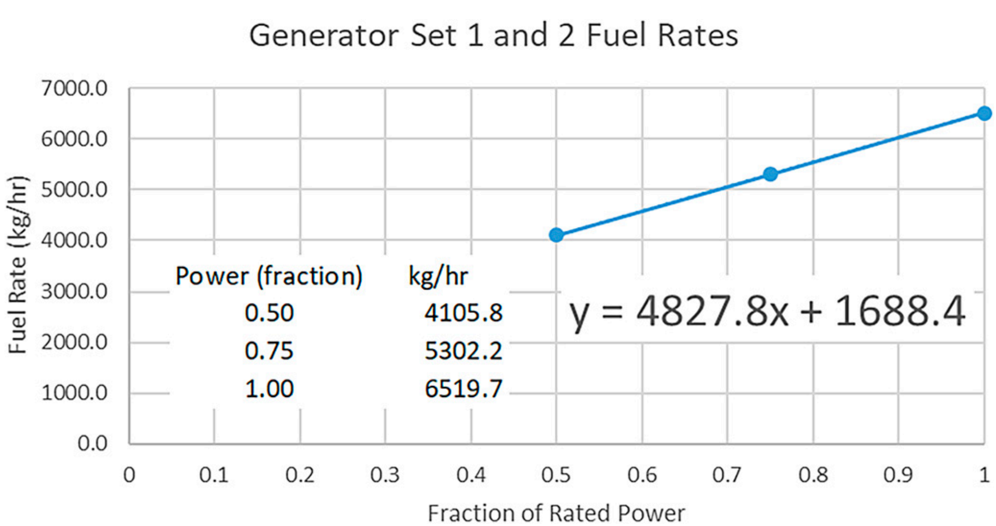

Fig. 11 Linear regression for generator sets 1 and 2 fuel rates

Table 11 Calculated and original sfc data points for generators 1 and 2

Fraction of rated power	Power (MW)	Fuel rate (kg/h)	SFC (calc) (g/kW-h)	SFC (data) (g/kW-h)
.10	2.50	2171	868	
.15	3.75	2413	643	
.20	5.00	2654	531	
.25	6.25	2895	463	
.30	7.50	3137	418	
.40	10.00	3620	362	
.50	12.50	4102	328	328
.60	15.00	4585	306	
.75	18.75	5309	283	283
.90	22.50	6033	268	
1.00	25.00	6516	261	261

Table 12 Calculated and original sfc data points for generators 2 and 3

Fraction of rated power	Power (MW)	Fuel rate (kg/h)	SFC (calc) (g/kW-h)	SFC (data) (g/kW-h)
.10	1.00	258	258	
.15	1.50	356	237	
.20	2.00	454	227	
.25	2.50	552	221	
.30	3.00	650	217	
.40	4.00	846	211	
.50	5.00	1041	208	208
.60	6.00	1237	206	
.75	7.50	1531	204	204
.90	9.00	1825	203	
1.00	10.00	2021	202	202

and Amy (2011) and Doerry (2017) and aligned with IEEE Std. 45.1, (IEEE 2017) possible energy storage functions include

ESM-F1: Hold up mission critical loads that require uninterruptible power during short term power interruptions during the clearing of faults and during reconfiguration. The time period is on the order of milliseconds to seconds.
ESM-F2: Provide back-up power when there is insufficient generation capacity online for as long as it takes to bring the backup generator online. The time period is on the order of minutes.
ESM-F3: Provide emergency power to start a generator set. The time period is on the order of minutes.
ESM-F4: Provide load leveling and peak shaving to provide a near constant or slowly changing load to the prime movers.
ESM-F5: Provide Primary power for the ship. The energy storage may provide all the power required by the ship or may augment the power provided by generator sets.

Energy storage intended to fulfill functions ESM-F1 and ESM-F3 is typically not modeled in fuel rate studies; the energy storage has minimal impact on fuel consumption.

Energy storage implementing ESM-F2 or ESM-F4 impacts system modeling primarily through the electrical power system concept of operations. The ESM-F2 function, with appropriate energy and power rating, can enable loads to be served should an online generator trip offline; thereby improving fuel efficiency by enabling fewer generator sets to be online for redundancy. The ESM-F4 function can enable operating generator sets closer to their rated load; fuel economy can be improved by delaying bringing on additional generator sets.

Energy storage implementing ESM-F5 should be modeled because the energy storage will reduce or eliminate the power provided by the generator sets. It may be necessary to model both the case where the energy storage is providing energy, and the case where the energy storage is depleted, and the generator sets are providing all the power.

To properly model the discharge of energy storage implementing ESM-F5, the discharge efficiency as a function of discharge power (kW) should be defined as well as the rated energy capacity (kJ) of the energy storage, the depth of discharge, and the state of charge (SOC). The rated energy capacity is the energy that can be extracted from the energy storage assuming the discharge efficiency is 1.0. The depth of discharge is the fraction of the rated energy capacity that can be effectively used without causing damage to the energy storage. For a given discharge power, the time to

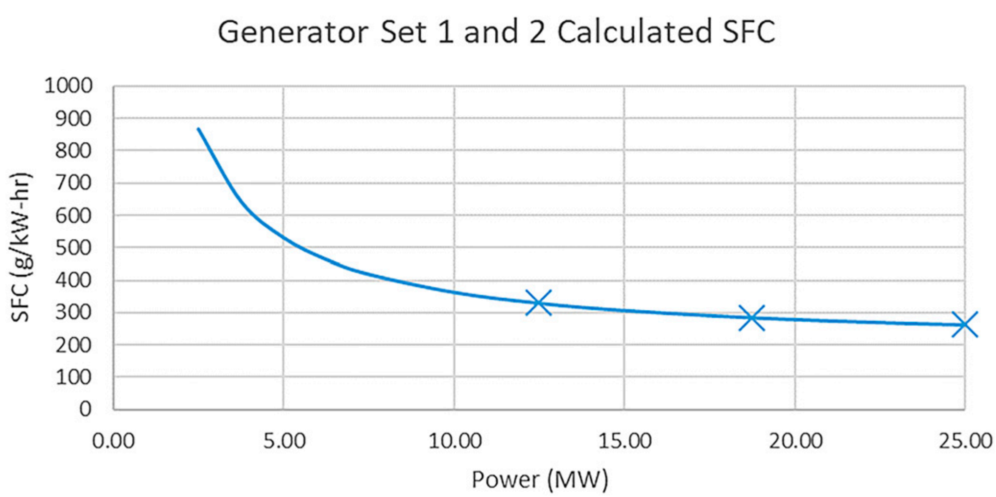

Fig. 12 Generator sets 1 and 2 calculated sfc curve

Table 13 Ship service transformer efficiency

percent of rated MVA	Efficiency
1.08	94.23
2	96.79
3	97.83
4	98.35
5	98.66
6	98.87
8	99.12
10	99.27
12	99.37
14	99.43
17	99.49
20	99.52
30	99.56
40	99.54
50	99.50
70	99.39
100	99.20

deplete ($t_{\text{discharge}}$) the energy storage is given by

$$t_{\text{discharge}} = \frac{\begin{pmatrix}(\text{SOC}) - (1 - \text{Depth of Discharge})\end{pmatrix} \\ (\text{Rated Energy Capacity})(\text{Discharge Efficiency})}{(\text{Discharge Power})}, \quad (34)$$

The electrical power system concept of operations should define the initial SOC that should be used for endurance calculations as well as the method to calculate the endurance conditions to incorporate the time; the energy storage is discharging as well as the time that the system is powered without energy storage.

If batteries are used for energy storage, they are typically rated in Amp-hours and their discharge characteristics measured in terms of their 1C-rate which is the amount of current (A) that can be drawn from the battery to completely discharge it from a SOC of 1.0 in 1 hr. A 5C rate would be five times the 1C rate.

Table 14 Propulsion transformer efficiency

percent of rated MVA	Efficiency
1.03	94.39
2	97.02
3	97.98
4	98.47
5	98.76
6	98.95
8	99.18
10	99.32
12	99.40
14	99.46
17	99.52
20	99.55
30	99.57
40	99.55
50	99.51
70	99.39
100	99.20

Table 15 Propulsion drive efficiency

Percent of rated MW	Efficiency
1.02	40.47
2	57.12
3	66.62
4	72.65
5	76.81
6	79.86
8	84.00
10	86.67
12	88.53
14	89.89
17	91.35
20	92.38
30	94.22
40	95.01
50	95.35
60	95.46
70	95.44
80	95.34
90	95.19
100	95.00

At the 1C rate, the total energy extracted (kW) from the battery would be

$$\text{Energy Extracted} = (1\text{C rate})(\text{Voltage})(3600\text{ s}) \times 10^{-3}, \quad (35)$$

The efficiency at the 1C rate is thus

$$\text{Efficiency at 1C rate} = \frac{\text{Energy Extracted}}{\text{Rated Energy Capacity}}, \quad (36)$$

If the no-load losses are assumed to be zero, then $\left(\frac{P_{\text{rated}} R_{\text{loss}}}{V_{\text{out}}^2}\right)$ can be calculated based on equation (5).

The energy storage component may incorporate power electronics between the battery or other energy storage technology and the electrical distribution bus. This power converter should either be

Table 16 Propulsion motor efficiency

Percent of rated MW	Efficiency
1.01	23.96
2	38.42
3	48.33
4	55.49
5	60.90
6	65.13
8	71.31
10	75.61
12	78.77
14	81.18
17	83.89
20	85.88
30	89.84
40	91.88
50	93.07
60	93.82
70	94.32
80	94.64
90	94.86
100	94.99

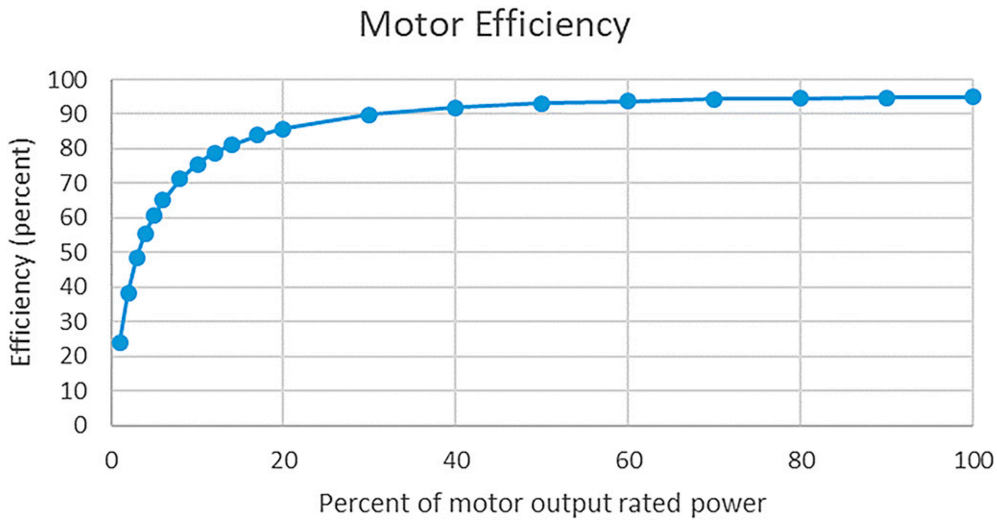

Fig. 13 Propulsion motor efficiency curve

Table 17 Example 1 generator set scheduling table

	Generator set 1	Generator set 2	Generator set 3	Generator set 4
Rating (MW)	25	25	10	10
$2 < \text{Total load} \leq 10.5\,\text{MW}$	Offline	Offline	Swing	1 MW
$10.5 < \text{Total load} \leq 19\,\text{MW}$	Offline	Offline	Swing	9.5 MW
$19 < \text{Total load} \leq 25.75\,\text{MW}$	Swing	Offline	Offline	2 MW
$25.75 < \text{Total load} \leq 33.25\,\text{MW}$	23.75 MW	Offline	Offline	Swing
$33.25 < \text{Total load} \leq 42.75\,\text{MW}$	23.75 MW	Offline	9.5 MW	Swing
$42.75 < \text{Total load} \leq 47.5\,\text{MW}$	Swing	23.75 MW	Offline	Offline
$47.5 < \text{Total load} \leq 57\,\text{MW}$	23.75 MW	23.75 MW	Offline	Swing
$57 < \text{Total load} \leq 66.5\,\text{MW}$	23.75 MW	23.75 MW	9.5 MW	Swing
$66.5 < \text{Total load} \leq 70\,\text{MW}$	25 MW	25 MW	10 MW	Swing

modeled as a separate component, or its efficiency combined with the efficiency of the energy storage.

7.15. Ship service loads

Ship service loads, including all loads not associated with electric propulsion, are estimated for each operational condition and ambient condition based on the results of an EPLA as detailed in NAVSEA DDS 310-1 Rev 1 (also known as DPC 310-1) or IEEE Std. 45.1 (IEEE 2017). Ship service loads include mission loads. An alternate approach is to estimate the ship service load based on analogy with similar ships.

The detail to which the ship service load is estimated depends on the system architecture. In many cases, the ship service load can be lumped together into a proxy load at the switchboard level. In other cases, it may be necessary to model the ship service load at the load center level.

If the electrical load of a component is large, variable, and depends on the electrical load of other equipment, then it may be desirable to directly model these components within the system simulation. This may be the case for ships with modern chilled water systems.

8. System concepts of operations

A system concept of operations defines how the designer intends for the system to be configured and employed for different operational conditions. For fuel rate calculations, the electrical power system concept of operations and the propulsion system concept of operations are required at a minimum.

Table 18 Example 1 propulsion motor scheduling

	Propulsion motor 1	Propulsion motor 2	Propulsion motor 3	Propulsion motor 4
Rating (MW)	15	15	15	15
$0 < \text{Total propulsion} \leq 30\,\text{MW}$	1/2 Power	Offline	Offline	1/2 Power
$30 < \text{Total propulsion} \leq 60\,\text{MW}$	1/4 Power	1/4 Power	1/4 Power	1/4 Power

Table 19 Example 1 run matrix

Run	Temp (F)	Speed (knots)	Generator set 1 (25 MW rating)	Generator set 2 (25 MW rating)	Generator set 3 (10 MW rating)	Generator set 4 (10 MW rating)	Motor 1 (MW) (15 MW rating)	Motor 2 (MW) (15 MW rating)	Motor 3 (MW) (15 MW rating)	Motor 4 (MW) (15 MW rating)	ELOAD 1 (stbd) (MW)	ELOAD 2 (port) (MW)	Note
1	10	17	Offline	Offline	Swing	9.5 MW	5.46	Offline	Offline	5.46	2.1	2.4	Economic transit
2	50	17	Offline	Offline	Swing	9.5 MW	5.46	Offline	Offline	5.46	1.8	2.2	Economic transit
3	100	17	Offline	Offline	Swing	9.5 MW	5.46	Offline	Offline	5.46	2.0	2.3	Economic transit
4	10	27	23.75 MW	23.75 MW	Offline	Swing	10.94	10.94	10.94	10.94	2.1	2.4	Surge to theater
5	50	27	23.75 MW	23.75 MW	Offline	Swing	10.94	10.94	10.94	10.94	1.8	2.2	Surge to theater
6	100	27	23.75 MW	23.75 MW	Offline	Swing	10.94	10.94	10.94	10.94	2.0	2.3	Surge to theater
7	10	5	Offline	Offline	Swing	1 MW	.14	Offline	Offline	.14	3.6	3.9	Operational presence
8	50	5	Offline	Offline	Swing	1 MW	.14	Offline	Offline	.14	3.3	3.7	Operational presence
9	100	5	Offline	Offline	Swing	1 MW	.14	Offline	Offline	.14	3.5	3.8	Operational presence
10	10	10	Offline	Offline	Swing	9.5 MW	1.11	Offline	Offline	1.11	3.6	3.9	Operational presence
11	50	10	Offline	Offline	Swing	9.5 MW	1.11	Offline	Offline	1.11	3.3	3.7	Operational presence
12	100	10	Offline	Offline	Swing	9.5 MW	1.11	Offline	Offline	1.11	3.5	3.8	Operational presence
13	10	15	Offline	Offline	Swing	9.5 MW	3.75	Offline	Offline	3.75	3.6	3.9	Operational presence
14	50	15	Offline	Offline	Swing	9.5 MW	3.75	Offline	Offline	3.75	3.3	3.7	Operational presence
15	100	15	Offline	Offline	Swing	9.5 MW	3.75	Offline	Offline	3.75	3.5	3.8	Operational presence
16	10	20	23.75 MW	Offline	Offline	Swing	8.89	Offline	Offline	8.89	3.6	3.9	Operational presence
17	50	20	23.75 MW	Offline	Offline	Swing	8.89	Offline	Offline	8.89	3.3	3.7	Operational presence
18	100	20	23.75 MW	Offline	Offline	Swing	8.89	Offline	Offline	8.89	3.5	3.8	Operational presence
19	10	25	Swing	23.75 MW	Offline	Offline	8.68	8.68	8.68	8.68	3.6	3.9	Operational presence
20	50	25	Swing	23.75 MW	Offline	Offline	8.68	8.68	8.68	8.68	3.3	3.7	Operational presence
21	100	25	Swing	23.75 MW	Offline	Offline	8.68	8.68	8.68	8.68	3.5	3.8	Operational presence

Table 20 Example 1 results from simulation and fuel calculations

Run	Temp (F)	Speed (knots)	Fuel rate (kg/s)	Ambient condition profile	Operational profile	Operational profile fuel rate (kg/s)	Required range (NM)	Required time (hr)	Burnable fuel (t)
1	10	17	.971	.25					
2	50	17	.943	.50					
3	100	17	.960	.25					
	Ambient cond. profile	17	.954		N/A		5000	294.1	1061
4	10	27	3.82	.25					
5	50	27	3.8	.50					
6	100	27	3.81	.25					
	Ambient cond. profile	27	3.808		N/A		2000	74.1	1066
7	10	5	.542	.25					
8	50	5	.514	.50					
9	100	5	.530	.25					
	Ambient cond. profile	5	.525		.25	.131			
10	10	10	.648	.25					
11	50	10	.621	.50					
12	100	10	.637	.25					
	Ambient cond. profile	10	.632		.35	.221			
13	10	15	.942	.25					
14	50	15	.914	.50					
15	100	15	.931	.25					
	Ambient cond. profile	15	.925		.25	.231			
16	10	20	1.97	.25					
17	50	20	1.94	.50					
18	100	20	1.96	.25					
	Ambient cond. profile	20	1.953		.10	.195			
19	10	25	3.44	.25					
20	50	25	3.41	.50					
21	100	25	3.43	.25					
	Ambient cond. profile	25	3.423		.05	.171			
			Operational presence fuel rate (kg/s) =			.950		300	1077

When conducting the EPLA, additional system concepts of operations may be required. These systems have loads that are significant and their load models depend on how they are operated. Consideration should be given to defining operating assumptions for at least the following:

- Mission Systems
- Chilled Water Plant
- Distilling Plant
- Heating and Ventilation
- Fire Pumps

Table 21 Example 1 calculations for fuel tank volume requirements

Economical transit burnable fuel load (t)	1061
Surge to theater burnable fuel load (t)	1066
Operational presence burnable fuel load (t)	1077
Design burnable fuel load (t)	1077
Tailpipe allowance	.95
Endurance fuel load (t)	1134
Density of fuel (kg/L) = (t/m^3)	.84
Fuel tank volume requirement (m^3)	1447

8.1. Electrical power system concept of operations

The electrical power system concept of operations defines, for a given total electrical power demand and operational condition

1) The state (open or closed) of all switchgear switches (or circuit breakers).
2) Which generator sets and other sources are online. Normally presented as a generator set scheduling table.
3) How real and reactive (if applicable) power is shared among the online generator sets.

In establishing the generator set scheduling table, the following should be considered:

- For a given power level, the combination of generator sets that can together can supply the power at the lowest fuel rate while

Table 22 Example 2 generator set scheduling table

Rating (MW)	Generator set 1 25	Generator set 2 25	Generator set 3 10	Generator set 4 10
Gensets 3 and 4 power own ship service load and own motor up to 95% loading.	Offline	Offline	Swing	Swing
Genset 1 powers own ship service load and both motors up to 95% loading. Genset 4 powers own ship service load	Swing	Offline	Offline	Swing
Genset 1 and 3 power own ship service load and both motors up to 95% loading of Genset 1. Genset 4 powers own ship service load	Swing	Offline	2 MW	Swing
Genset 1 and 3 power own ship service load and both motors up to 95% loading of Genset 3. Genset 4 powers own ship service load	23.75 MW	Offline	Swing	Swing
Gensets 1 and 2 power own ship service load and own motor up to 95% loading.	Swing	Swing	offline	Offline
Gensets 1 and 3 and 2 and 4 power own ship service load and own motor up to 95% loading of Gensets 1/2.	Swing	Swing	2 MW	2 MW
Total load ≤67.5 MW	23.75 MW	23.75 MW	Swing	Swing

meeting other constraints, such as quality of service (IEEE 45.1 IEEE 2017), the ability to support large cycling. momentary, or pulsed loads, and the ability to rapidly increase ship speed, should be used.

- For early stage calculations where precise knowledge of fuel rates is not known, online generator sets sharing load in proportion to their rating should be close to the optimum power sharing strategy. If detailed knowledge of generator set fuel rates is known, the methods of Doerry (2022) should be considered.
- In many cases the fuel rate of a generator set as a function of power is nearly linear with a y intercept equal to the no-load fuel rate. If two generator sets are paralleled, preference for supplying power should be given to the one with the lower slope of this function. The no-load fuel rate is the "price of entry" for bringing the generator set online.
- Usually, the lowest fuel rate will occur when the fewest number of generator sets are online; one pays the "price of entry" of no-load losses the fewest number of times. In some cases, multiple small generator sets may be more fuel efficient than a single large generator set. This is often the case when a power system has a combination of small diesel generator sets (with very low no-load losses) and large gas turbine generator sets (with large no-load losses).
- If energy storage fulfilling ESM-F2 is not installed, then at least two generator sets should be online at all times the ship is underway.
- If the ship has adequate controls to prevent overloading of generator sets, or the ship has energy storage fulfilling ESM-F4, then generator sets may be loaded up to their maximum rating. Otherwise generator sets should be loaded up to a maximum of 95% of their maximum rating.
- If possible, generator set scheduling should avoid having generator sets operate lightly loaded. Data sheets should be consulted to determine the lowest load at which a prime mover should continuously operate. For modern gas turbines and diesels, this is typically on the order of 20% of the generator set rating.
- The operational condition, regulation or stated operator preference may call for a generator set loading optimized for a utility function other than fuel economy. The generator set loading should reflect the stated optimization utility function. Examples of alternate utility functions would be a requirement for rolling reserve (excessive generation capacity) for infrequently used but important high-power equipment or rolling reserve to enable continued mobility when in restricted maneuverability. Warships typically have a requirement for rolling reserve during battle conditions.
- Maintenance costs of generator sets are usually proportional to the number of operating hours. To minimize life cycle costs, if two combinations of online generator sets have nearly the same fuel rate for the same load, the combination with the fewest number of online generator sets is preferred.

For example, an electrical power system consisting of two 20 MW generator sets and two 5 MW generator sets are normally operated with all online generator sets paralleled. This system has no associated energy storage. The electrical power system concept of operations would state

1) All breakers in the switchboards are closed.

Table 23 Example 2 propulsion motor scheduling table

Rating (MW)	Propulsion motor 1 15	Propulsion motor 2 15	Propulsion motor 3 15	Propulsion motor 4 15
Genset 3 and 4 online, Genset 1 and 2 offline. Propulsion <20 MW	1/2 Power	Offline	Offline	1/2 Power
Genset 1 online Genset 2 offline Propulsion ≤30 MW	1/2 Power	1/2 Power	Offline	Offline
Genset 1 and 2 online, Propulsion ≤30 MW	1/2 Power	Offline	Offline	1/2 Power
30 MW < Propulsion < 60 MW	1/4 Power	1/4 Power	1/4 Power	1/4 Power

Table 24 Example 2 run matrix

Run	Temp (F)	Speed (knots)	Generator set 1 (25 MW rating)	Generator set 2 (25 MW rating)	Generator set 3 (10 MW rating)	Generator set 4 (10 MW rating)	Motor 1 (MW) (15 MW rating)	Motor 2 (MW) (15 MW rating)	Motor 3 (MW) (15 MW rating)	Motor 4 (MW) (15 MW rating)	ELOAD 1 (stbd) (MW)	ELOAD 2 (port) (MW)	Note
1	10	17	Offline	Offline	Swing	Swing	5.46	Offline	Offline	5.46	2.1	2.4	Economic transit
2	50	17	Offline	Offline	Swing	Swing	5.46	Offline	Offline	5.46	1.8	2.2	Economic transit
3	100	17	Offline	Offline	Swing	Swing	5.46	Offline	Offline	5.46	2.0	2.3	Economic transit
4	10	27	23.75 MW	23.75 MW	Swing	Swing	10.94	10.94	10.94	10.94	2.1	2.4	Surge to theater
5	50	27	23.75 MW	23.75 MW	Swing	Swing	10.94	10.94	10.94	10.94	1.8	2.2	Surge to theater
6	100	27	23.75 MW	23.75 MW	Swing	Swing	10.94	10.94	10.94	10.94	2.0	2.3	Surge to theater
7	10	5	Offline	Offline	Swing	Swing	.14	Offline	Offline	.14	3.6	3.9	Operational presence
8	50	5	Offline	Offline	Swing	Swing	.14	Offline	Offline	.14	3.3	3.7	Operational presence
9	100	5	Offline	Offline	Swing	Swing	.14	Offline	Offline	.14	3.5	3.8	Operational presence
10	10	10	Offline	Offline	Swing	Swing	1.11	Offline	Offline	1.11	3.6	3.9	Operational presence
11	50	10	Offline	Offline	Swing	Swing	1.11	Offline	Offline	1.11	3.3	3.7	Operational presence
12	100	10	Offline	Offline	Swing	Swing	1.11	Offline	Offline	1.11	3.5	3.8	Operational presence
13	10	15	Offline	Offline	Swing	Swing	3.75	Offline	Offline	3.75	3.6	3.9	Operational presence
14	50	15	Offline	Offline	Swing	Swing	3.75	Offline	Offline	3.75	3.3	3.7	Operational presence
15	100	15	Offline	Offline	Swing	Swing	3.75	Offline	Offline	3.75	3.5	3.8	Operational presence
16	10	20	Swing	Offline	Offline	Swing	8.89	8.89	Offline	Offline	3.6	3.9	Operational presence
17	50	20	Swing	Offline	Offline	Swing	8.89	8.89	Offline	Offline	3.3	3.7	Operational presence
18	100	20	Swing	Offline	Offline	Swing	8.89	8.89	Offline	Offline	3.5	3.8	Operational presence
19	10	25	Swing	Swing	Offline	Offline	8.68	8.68	8.68	8.68	3.6	3.9	Operational presence
20	50	25	Swing	Swing	Offline	Offline	8.68	8.68	8.68	8.68	3.3	3.7	Operational presence
21	100	25	Swing	Swing	Offline	Offline	8.68	8.68	8.68	8.68	3.5	3.8	Operational presence

Table 25 Example 2 results from simulation and fuel calculations

Run	Temp	Speed (knots)	Fuel rate (kg/s)	Ambient condition profile	Operational profile	Operational profile fuel rate (kg/s)	Required range (NM)	Required time (hr)	Burnable fuel (t)
1	10	17	.972	.25					
2	50	17	.944	.50					
3	100	17	.961	.25					
	Ambient cond. profile	17	.955		N/A		5000	294.1	1062
4	10	27	3.84	.25					
5	50	27	3.81	.50					
6	100	27	3.83	.25					
	Ambient cond. profile	27	3.823		N/A		2000	74.1	1070
7	10	5	.54	.25					
8	50	5	.513	.50					
9	100	5	.529	.25					
	Ambient cond. profile	5	.524		.25	0.131			
10	10	10	.648	.25					
11	50	10	.62	.50					
12	100	10	.637	.25					
	Ambient cond. profile	10	.631		.35	.221			
13	10	15	.942	.25					
14	50	15	.914	.50					
15	100	15	.931	.25					
	Ambient cond. profile	15	.925		.25	.231			
16	10	20	1.97	.25					
17	50	20	1.94	.50					
18	100	20	1.95	.25					
	Ambient cond. profile	20	1.950		.10	.195			
19	10	25	3.44	.25					
20	50	25	3.41	.50					
21	100	25	3.43	.25					
	Ambient cond. profile	25	3.423		.05	.171			
Operational presence fuel rate (kg/s) =						.949		300	1077

2) For a given total ship electric load, the online generator sets to use in the calculations. See Table 3 for an example.
3) When generator sets are sharing, they share both real and reactive power in proportion to their rating.

A generator set schedule (such as depicted in Table 3) may include relevant special cases, such as if all the generator sets are required to be online for a specific operational condition independent of the amount of electrical load. Each operational condition may (or may not) have its own generator set schedule.

If the electrical power includes energy storage fulfilling the ESM-F2 and ESM-F4 functionality, then the electrical power system concept of operations could state

1) All breakers in the switchboards are closed.
2) For a given total ship electric load, the online generator sets to use in the calculations are as depicted in Table 4.
3) When generator sets are sharing, they share both real and reactive power in proportion to their rating.

For fuel rate calculations, if any subset of multiple generator sets of the same rating is to be online, and if the total fuel rate is not dependent on particular generator sets being online, then the generator set scheduling table may be arbitrary as to which particular generator sets of the subset are online.

In naval ship applications, the electrical system is often operated in "split plant" where circuit breakers are opened to create two independent subsystems (known as "islands" in terrestrial

Table 26 Example 2 calculations for fuel tank volume requirements

Economical transit burnable fuel load (t)	1062
Surge to theater burnable fuel load (t)	1070
Operational presence burnable fuel load (t)	1077
Design burnable fuel load (t)	1077
Tailpipe allowance	.95
Endurance fuel load (t)	1133
Density of fuel (kg/L) = (t/m^3)	.84
Fuel tank volume requirement (m^3)	1445

Table 27 Example 3 ship state participation table

Operational mode/ship state	Inport—shore (shore power)	Underway economical transit	Underway surge to theater	Underway mission	Fraction of time in operational mode
Maintenance mode	.9	.05	0	.05	.1
Operation mode A	.4	.2	.1	.3	.4
Operation mode B	.1	.2	.2	.5	.5

microgrids) each of which is supplied by one or more generator sets. A separate generator set schedule is typically created for each subsystem.

Furthermore, with integrated power systems featuring dual propulsion motors on each shaft, the two subsystems may be asymmetrically loaded to improve fuel efficiency. This condition may result in an interdependence between the electrical power system concept of operations and the propulsion system concept of operation.

8.2. Propulsion system concept of operations

The propulsion system concept of operations defines for a given ship speed and operational condition the propulsion system configuration and operation. It is often described in terms of a propulsion system schedule depicting as a function of ship speed

1) Which propulsion prime movers or propulsion motors are online.
2) How propulsion power is shared among different shafts.
3) How propulsion power is shared among prime movers and propulsion motors on the same shaft.

For certain operational conditions, such as those requiring restricted maneuvering or having the ability to quickly transition to maximum speed (such as battle), all available propulsion prime movers and propulsion motors may be designated to be online.

For twin-shaft propulsion systems where each shaft is powered by either two motors or two prime movers, the schedule is straightforward:

- One motor/prime mover powers each shaft equally up to the propulsion capacity of the one motor/prime mover per shaft.
- At higher power levels, all motors/prime movers are online and share power equally.

This schedule may be adjusted for several reasons.

- At low speeds, only one shaft may be powered while the other is allowed to freewheel. This operation is known as a trail shaft. The propulsion system should be evaluated to ensure the required torque speed characteristic for trail shaft operation is within its operating profile.
- Certain combined plants with an “or” configuration will use one motor/prime mover at low speeds, and the other motor/prime mover at high speeds. The transition speed is determined by the motor/prime mover at low speeds.
- Some propulsion systems include a combining gear which enable both shafts to be powered from a single prime mover.

9. Modeling systems using s3d

Figure 7 depicts a system model, using S3D, of a representative electrical system for a commercial type power system architecture as described in IEEE Std. 45.1 (IEEE 2017). In this system model, the ship service loads are lumped into two electrical loads, one attached to each of the switchboards. A cable is inserted between each generator set and the switchboard to enable the system solver to converge on a solution for reactive power. Figure 8 depicts a system model using S3D of the corresponding propulsion system. Each shaft has two propulsion motors; a propulsion motor is powered by each of the two switchboards. Although in reality the two propulsion motors are mounted to the same shaft, S3D does not currently have the capability of modeling this configuration. Instead, a lossless gearbox is used to combine the outputs of the two propulsion motor shafts. In this model, the shaft and thrust bearing losses are included in the propeller model.

While the systems depicted in Figs. 7 and 8 are relatively simple, S3D has the capability of modeling much more complex systems.

10. Calculating fuel rates

This section describes how to create a run matrix to guide the execution of the modeling and simulation tool and how to collect and store the fuel rate results.

First, all of the component properties should be estimated and the system modeled in an analysis program such as S3D. To configure the system model to calculate necessary fuel rates, a run matrix similar to the one depicted in Table 5 should be constructed. This run matrix lists all of the component properties that may change between each system condition for which a fuel rate is required. The run matrix example depicted in Table 5 identifies six configurations to calculate the economical transit and surge to theater endurance fuel requires; each requires three calculations corresponding to the three temperatures defined in the default ambient condition profile. The run matrix should reflect the electrical power system concept of operations and the propulsion system concept of operations; a change to either may require a change to the run matrix.

Table 28 Example 3 ship state fuel rates

	Inport—shore (shore power)	Underway economical transit	Underway surge to theater	Underway mission
Fuel rate (kg/h)	0	3435	13,707	3420

Table 29 Example 3 annual fuel usage calculations

Operational mode/ship state	Inport—shore (shore-to-ship power) (annual fuel usage (t))	Underway—economical transit (annual fuel usage (t))	Underway—surge to theater (annual fuel usage (t))	Underway—mission (annual fuel usage (t))	Total annual fuel usage (t)
Maintenance mode	0	151	0	150	300
Operation mode A	0	2409	4806	3598	10,813
Operation mode B	0	3011	12,016	7495	22,522
			Annual total (t) =		33,636

If the operational presence condition must be calculated, the run matrix should have entries for each speed, temperature, and ship service load associated with the operational profile. The run matrices for examples 1 and 2 in Section 12 include rows for operational presence.

Additional rows may be added to the run matrix to determine the sensitivity of the results to fuel rate (sfc) curves and loss (efficiency) curves. One approach is to use a most likely set of parameters, a best-case set of parameters, and a worst-case set of parameters.

The analysis program should be executed for each row of the run matrix to determine the combined fuel rate of all online prime movers. Modeling a proxy fuel system as depicted in Fig. 9 may prove desirable in that the combined fuel rate is directly calculated by the analysis program.

The results of the analysis program for each row of the run matrix can be stored as depicted in Table 6. Table 6 also applies the ambient condition profile to the fuel rates for each temperature to determine an overall endurance condition fuel rate. An ambient condition profile provides a list of ambient conditions and the fraction of time spent in each ambient condition. An ambient condition consists of an outdoor (atmospheric) temperature and associated relative humidity. The ambient condition profile accounts for the dependency of certain ship service loads (such as heating and air conditioning) on the outdoor temperature. NAVSEA DDS 200-1 Rev 1 provides a default ambient condition profile.

11. Postprocessing results

Once the fuel rates for all of the rows of the run matrix have been calculated, determining the endurance fuel requirements/annual fuel usage is straightforward.

For the economical transit and the surge to theater conditions, the burnable fuel load is determined by

- Dividing the required range (nautical miles) by the speed in knots to obtain hours.
- Multiply the hours by the applicable fuel rate with the ambient condition profile applied.
- Multiply the results by the plant deterioration allowance (typically 1.05) to obtain the burnable fuel load. The plant deterioration allowance models the increase in fuel consumption as equipment ages.

Table 30 Example 3 annual fuel usage converted to barrels

Annual fuel usage (t)	33,636
Density of fuel (t/m^3)	.84
Annual fuel usage (m^3)	40,043
42 gal barrel (m^3)	.1590
Annual fuel usage (barrels)	2,51,861

For the operational presence condition, the burnable fuel load is determined by

- Applying the operational profile to the fuel rates (with the ambient condition profile applied) at each ship speed to obtain the operational presence average fuel rate.
- Multiply the operational presence time by the operational presence average fuel rate.
- Multiply the results by the plant deterioration allowance (typically 1.05) to obtain the burnable fuel load.

The burnable fuel load is converted to a fuel tank volume by

- Dividing the burnable fuel rate by the tailpipe allowance.
- Converting the result into volume by dividing by the density of fuel (typically use .84 for F76).
- Multiply the result by 1.05 to account for fuel expansion.
- Adjust the result to account for structure inside the fuel tank (typically divide by .98).

For annual fuel calculations, the fuel rates (after the ambient condition profile is applied) of the various ship states are arranged into a vector. The participation table is converted to a matrix and multiplied by the fuel rate vector to produce a vector of fuel rates for each operational mode. The number of hours spent annually in each operational mode is multiplied by the fuel rate for that operational mode to produce the total amount fuel estimated to be annually consumed in that operational mode. The sum of the fuel consumed annually for all operational modes is the annual fuel consumption.

12. Examples

12.1. Example 1: endurance fuel—common bus

For the system described by Figs. 7 and 8, the following endurance fuel requirements are given

1) Economic transit distance: 5000 NM
2) Endurance speed: 17 knots
3) Surge to theater distance 2000 NM
4) Sustained speed requirement: 27 NM
5) Operational presence time: 300 hr
6) Ship service electric load: see Table 7
7) Operational profile: see Table 8
8) Ambient condition profile: default from NAVSEA DDS 200-2:
    a) 25% at 10 deg F with 95% relative humidity
    b) 50% at 59 deg F with 95% relative humidity
    c) 25% at 100 deg F with 40% relative humidity

Table 31   Example 4 generator set scheduling table

Rating (MW)	Generator set 1 25	Generator set 2 25	Generator set 3 10	Generator set 4 10
Total load $\leq$ 10 MW	Offline	Offline	Offline	Swing
10 $<$ Total load $\leq$ 20 MW	Offline	Offline	10 MW	Swing
20 $<$ Total load $\leq$ 25 MW	Swing	Offline	Offline	Offline
25 $<$ Total load $\leq$ 35 MW	25 MW	Offline	Offline	Swing
35 $<$ Total load $\leq$ 45 MW	25 MW	Offline	10 MW	Swing
45 $<$ Total load $\leq$ 50 MW	Swing	25 MW	Offline	Offline
50 $<$ Total load $\leq$ 60 MW	25 MW	25 MW	Offline	Swing
60 $<$ Total load $\leq$ 70 MW	25 MW	25 MW	10 MW	Swing

9) Tailpipe allowance: .95
10) The electrical power system concept of operations assumes the port and starboard switchboards are always connected together, resulting in the port and starboard busses being common.
11) If possible, the generator sets should not be loaded beyond 95%.
12) If possible, the generator sets should be loaded to at least 20%.
13) At least two generator sets should be online at all times.
14) The speed—power (at the motor shaft) curve is as listed in Table 9. The power is the sum of the power on the two shafts. The power is equally shared by the two shafts. At 30 knots the shaft speed is 150 rpm. The shaft speed is proportional to the ship speed. This curve incorporates the impact of sea state and fouling.

Because of limitations in the S3D propeller component model at the time the simulations were performed, the alternate S3D configuration as depicted in Fig. 10 was employed instead of the configurations depicted in Figs. 7 and 8. In this model, the motor drives and motors are modeled as transformers using the appropriate efficiency curves. The propulsion load is modeled as an electric load. This representation requires the propulsion power to be calculated outside of S3D and assigned to the propulsion loads. An update to the S3D propeller component model to improve usability is anticipated in FY24.

Additionally, since reactive power does not have a significant impact on these calculations, the dc load flow solver was used in S3D. Using the dc load flow solver also allowed modeling the system without the cables between the generator sets and the switchboards.

The notional generator sets have the characteristics shown in Table 10; these characteristics would normally be found in a datasheet.

The generator set model requires definition of an sfc curve in terms of the sfc (kg/kW-h) versus power (MW). Since the generator sets will likely at times operate below 50% power, perhaps as low as 10% power, additional points should be calculated over more power levels. The first step is to convert the given sfc points to fuel rates and determine the best linear regression through them as shown in Fig. 11.

The resulting equation can then be used to calculate fuel rates and sfcs at other power levels as shown in Table 11 and Fig. 12. Note that the calculated fuel rate data replicate the original sfc data points.

As depicted in Table 12, a similar process may be used to develop the calculated sfc curve for generator sets 3 and 4.

For the ship service transformers, the MVA rating should be used for the transformer rating in the model. Typical datasheet data for the ship service transformers would be

- Rating (MVA): 5.0
- No-load losses (kW): 3.3
- Losses due to the load (kW): 37.

The loss model elements are therefore

$$\frac{P_{\text{noLoadLoss}}}{S_{\text{rated}}} = \frac{3.3}{5000} = 0.00066, \tag{37}$$

$$\frac{S_{\text{rated}} R_{\text{loss}}}{3V_{\text{out}}^2} = \frac{37}{5000} = 0.0074, \tag{38}$$

These translate into efficiency as shown in Table 13. In S3D efficiency tables can be stored in comma-separated values (.csv) files. Having unique first values (1.08 for Table 13) makes it easier to identify within S3D if one has uploaded the proper efficiency table.

Typical datasheet data for the propulsion transformers are

- Rating (MVA): 18.0
- No-load losses (kW): 11
- Losses due to the load (kW): 135.

The loss model elements are therefore

$$\frac{P_{\text{noLoadLoss}}}{S_{\text{rated}}} = \frac{11}{18000} = 0.000611, \tag{39}$$

$$\frac{S_{\text{rated}} R_{\text{loss}}}{3V_{\text{out}}^2} = \frac{135}{18000} = 0.0075, \tag{40}$$

These translate into efficiencies as depicted in Table 14.

Typical datasheet data for the propulsion motor drives are

- Rating (MW): 17.0
- No-load losses (% of rating) 1.5%
- Full load efficiency = 95%

The loss model elements are therefore

$$\frac{P_{\text{noLoadLoss}}}{S_{\text{rated}}} = .015, \tag{41}$$

$$\frac{S_{\text{rated}} R_{\text{loss}}}{3V_{\text{out}}^2} = \left(\frac{1}{.95} - 1\right) - .015 = 0.03763, \tag{42}$$

These translate into efficiencies as depicted in Table 15.

For propulsion motors, typical datasheet values for a 15 MW motor would be given as

- efficiency at 100% power .95
- efficiency at 50% power .93
- efficiency at 20% power .86.

Table 32 Example 4 run matrix

Run	Temp	Speed (knots)	Generator set 1 (25 MW rating)	Generator set 2 (25 MW rating)	Generator set 3 (10 MW rating)	Generator set 4 (10 MW rating)	Motor 1 (MW) (15 MW rating)	Motor 2 (MW) (15 MW rating)	Motor 3 (MW) (15 MW rating)	Motor 4 (MW) (15 MW rating)	ELOAD 1 (stbd) (MW)	ELOAD 2 (port) (MW)	Note
1	10	17	Offline	Offline	10 MW	Swing	5.46	Offline	Offline	5.46	2.1	2.4	Economic transit
2	50	17	Offline	Offline	10 MW	Swing	5.46	Offline	Offline	5.46	1.8	2.2	Economic transit
3	100	17	Offline	Offline	10 MW	Swing	5.46	Offline	Offline	5.46	2.0	2.3	Economic transit
4	10	27	25 MW	25 MW	Offline	Swing	10.94	10.94	10.94	10.94	2.1	2.4	Surge to theater
5	50	27	25 MW	25 MW	Offline	Swing	10.94	10.94	10.94	10.94	1.8	2.2	Surge to theater
6	100	27	25 MW	25 MW	Offline	Swing	10.94	10.94	10.94	10.94	2.0	2.3	Surge to theater
7	10	5	Offline	Offline	Offline	Swing	.14	Offline	Offline	.14	3.6	3.9	Operational presence
8	50	5	Offline	Offline	Offline	Swing	.14	Offline	Offline	.14	3.3	3.7	Operational presence
9	100	5	Offline	Offline	Offline	Swing	.14	Offline	Offline	.14	3.5	3.8	Operational presence
10	10	10	Offline	Offline	10 MW	Swing	1.11	Offline	Offline	1.11	3.6	3.9	Operational presence
11	50	10	Offline	Offline	10 MW	Swing	1.11	Offline	Offline	1.11	3.3	3.7	Operational presence
12	100	10	Offline	Offline	10 MW	Swing	1.11	Offline	Offline	1.11	3.5	3.8	Operational presence
13	10	15	Offline	Offline	10 MW	Swing	3.75	Offline	Offline	3.75	3.6	3.9	Operational presence
14	50	15	Offline	Offline	10 MW	Swing	3.75	Offline	Offline	3.75	3.3	3.7	Operational presence
15	100	15	Offline	Offline	10 MW	Swing	3.75	Offline	Offline	3.75	3.5	3.8	Operational presence
16	10	20	25 MW	Offline	Offline	Swing	8.89	Offline	Offline	8.89	3.6	3.9	Operational presence
17	50	20	25 MW	Offline	Offline	Swing	8.89	Offline	Offline	8.89	3.3	3.7	Operational presence
18	100	20	25 MW	Offline	Offline	Swing	8.89	Offline	Offline	8.89	3.5	3.8	Operational presence
19	10	25	Swing	25 MW	Offline	Offline	8.68	8.68	8.68	8.68	3.6	3.9	Operational presence
20	50	25	Swing	25 MW	Offline	Offline	8.68	8.68	8.68	8.68	3.3	3.7	Operational presence
21	100	25	Swing	25 MW	Offline	Offline	8.68	8.68	8.68	8.68	3.5	3.8	Operational presence

Table 33 Example 4 fuel rate calculations

Run	Temp (F)	Speed (knots)	Fuel rate (kg/s)	Ambient condition profile	Operational profile	Operational profile fuel rate (kg/s)	Required range (NM)	Required time (hr)	Burnable fuel (t)
1	10	17	.97	.25					
2	50	17	.943	.50					
3	100	17	.959	.25					
	Ambient cond. profile	17	.954		N/A		5000	294.1	1060
4	10	27	3.83	.25					
5	50	27	3.8	.50					
6	100	27	3.81	.25					
	Ambient cond. profile	27	3.810		N/A		2000	74.1	1067
7	10	5	.524	.25					
8	50	5	.497	.50					
9	100	5	.514	.25					
	Ambient cond. profile	5	.508		.25	.127			
10	10	10	.648	.25					
11	50	10	.617	.50					
12	100	10	.637	.25					
	Ambient cond. profile	10	.630		.35	.220			
13	10	15	.941	.25					
14	50	15	.914	.50					
15	100	15	.93	.25					
	Ambient cond. profile	15	.925		.25	.231			
16	10	20	1.97	.25					
17	50	20	1.94	.50					
18	100	20	1.96	.25					
	Ambient cond. profile	20	1.953		.10	.195			
19	10	25	3.44	.25					
20	50	25	3.41	.50					
21	100	25	3.43	.25					
	Ambient cond. profile	25	3.423		.05	.171			
Operational presence fuel rate (kg/s) =						.945		300	1072

The use of the pseudo-inverse method results in the values of

$$x = \left| \begin{matrix} \left(\dfrac{P_{\text{rated}} R_{\text{loss}}}{V_{\text{out}}^2} \right) \\ \left(\dfrac{P_{\text{noLoadLoss}}}{P_{\text{rated}}} \right) \end{matrix} \right| = \left| \begin{matrix} 0.02067 \\ 0.03205 \end{matrix} \right|, \tag{43}$$

Using equation (6), the elements of x are used to calculate the efficiencies of Table 16. Figure 13 plots the points depicted in Table 16.

The electrical power system concept of operations includes

- All circuit breakers are closed.
- Operate the generator sets as indicated in Table 17.

The construction of Table 17 recognizes that the no-load fuel rate for generator sets 1 and 2 are much higher than for generator sets 3 and 4, but the slope of the fuel rate with respect to power is slightly less for generator sets 1 and 2. This implies that one should prefer having generator sets 3 and 4 online, but if either or both generator sets 1 and 2 are needed to be online, they should be loaded up to their limit if possible.

The propulsion system concept of operations states that the propulsion motors and associated drives are operated as indicated in Table 18.

All of the system components are now sufficiently defined to conduct the endurance fuel calculations. For the three endurance fuel requirements, the fuel rates for 21 configurations must be calculated. These configurations are depicted in the Run Matrix of Table 19.

The results of running the 21 cases of Table 18 using S3D are displayed in the shaded cells of Table 20. The outlined cells are the results of calculations to determine the burnable fuel required for each of the three endurance requirements. In this example, the operational presence condition is limiting since it requires the largest burnable fuel.

The burnable fuel load is used to calculate the fuel tank volume requirement as detailed in Table 21. The fuel tank volume requirement includes a factor of 1.05 to account for fuel expansion and 2% of the internal volume taken up by structure.

Table 34 Example 4 annual fuel usage calculations

Operational mode/ship state	Inport—shore (shore-to-ship power) (annual fuel usage (t))	Underway—economical transit (annual fuel usage (t))	Underway—surge to theater (annual fuel usage (t))	Underway—mission (annual fuel usage (t))	Total annual fuel usage (t)
Maintenance mode	0	150	0	149	300
Operation mode A	0	2408	4809	3579	10,796
Operation mode B	0	3010	12,023	7455	22,489
			Annual total (t) =		33,584

With the fuel tank volume requirement calculated, the analysis is complete.

12.2. Example 2: endurance fuel—split bus

In this second example, the endurance requirements, system architecture, and component properties are the same as for Example 1. The only difference is that the electrical system must operate as a "split plant" at all times.

The principal difference between Example 2 and Example 1 is the electrical system and propulsion system concepts of operation. One could operate the port bus and the starboard busses completely independently of each other, but this will not likely lead to the most fuel-efficient strategy. Because the propulsion loads can within limits be powered by either bus, asymmetric operation is likely to prove more fuel efficient.

For Example 2, the electrical power system concept of operations includes

- All circuit breakers except those connecting the two switchboards are closed. The breakers connecting the two switchboards are open.
- Operate the generator sets as indicated in Table 22. In Table 21, the first row where the load condition is met applies.

For Example 2, the propulsion system concept of operations states that the propulsion motors and associated drives are operated as indicated in Table 23. In Table 23, the first row where the load condition is met applies.

With advanced controls, more fuel-efficient generator set scheduling tables and propulsion motor scheduling tables are possible.

These new scheduling tables result in the run matrix depicted in Table 24.

The results of running the 21 cases of Table 24 using S3D are displayed in the shaded cells of Table 25. Once again, the outlined cells are the results of calculations to determine the burnable fuel required for each of the three endurance requirements. In this example, the operational presence condition is again limiting. Table 26 provides the associated required fuel tank volumes.

Note that in the surge to theater condition, Example 2 operated with all four generators online while Example 1 operated with only three generators online. However, because generator sets 3 and 4 are much more fuel efficient than generator sets 1 and 2, the fuel rate for Example 2 is less than for Example 1. Here is a situation where the operator must decide between lower maintenance costs associated with operating three generator sets and lower fuel costs associated with operating all four generator sets.

Table 35 Example 4 annual fuel usage converted to barrels

Annual fuel usage (t)	33,584
Density of fuel (t/m^3)	.84
Annual fuel usage (m^3)	39,981
42 gal barrel (m^3)	.1590
Annual fuel usage (barrels)	2,51,472

12.3. Example 3: annual fuel usage—no energy storage

For Example 3, the desire is to calculate the annual fuel using the fuel rates calculated for the endurance fuel requirements of Example 1. Specifically, the ship state participation table depicted in Table 27 defines the fraction of time the ship spends in each ship state for each of the operational modes. Table 27 also defines the fraction of a year spent in each operational mode. Table 28 depicts the fuel rate expressed in kg/h for each ship state as calculated in Example 1.

Table 29 combines the elements of Tables 27 and 28 to produce the annual fuel usage estimate measured in metric tons. In many cost studies, the cost of fuel is provided per 42-gallon barrel. Table 30 converts the annual fuel usage estimate from metric tons to barrels.

12.4. Example 4: annual fuel usage—with energy storage

For Example 4, annual fuel usage is calculated as in Example 3, but with the generator set scheduling table modified to reflect the incorporation of energy storage fulfilling functions ESM-F2 and ESM-F4. The generator set scheduling table depicted in Table 31 reflects operating only a single generator set when desirable, and operating generator sets to their rated value instead of to .95 times their rated value.

The propulsion motor scheduling table of Example 1 (Table 15) is used. The resulting Run Matrix is depicted in Table 32. The results of the analyses are depicted in Tables 33–35.

13. Conclusions

This paper has demonstrated how to model shipboard power and propulsion system components for the purpose of calculating endurance fuel requirements and annual fuel consumption. Endurance fuel requirements are used to determine the size of the fuel tanks while annual fuel consumption is used to establish budgets for fuel and fuel infrastructure. Specific recommendations include

- Use losses instead of efficiency when interpolating and extrapolating data points for equipment.
- Use fuel rates instead of sfc when interpolating and extrapolating data points for prime movers.
- For complex studies, create a study guide as part of the planning process.
- Create an electrical power system concept of operations and a propulsion system concept of operations to clearly and

consistently configure simulation models in a way that reflects how the designer intends for the ship's crew to operate the systems.
- Use a run matrix when performing the system simulations/calculations.
- Consider technologies, such as energy storage, to enable modifying the concepts of operations in a way that reduces fuel consumption.
- Model losses and fuel rates at partial loads to accurately reflect fuel consumption.

Examples using S3D and associated spreadsheets provide complete demonstrations of the modeling and analysis process.

Future work includes formalizing how uncertainty in the component parameters should be considered in establishing the required fuel tank volume and annual fuel consumption estimates. Formalizing how uncertainty in component parameters should be considered when comparing the fuel consumption of two different concepts. Between two concepts, the uncertainty will often be correlated; the uncertainty of the differences between the two could be less than the uncertainty of each concept alone.

Acknowledgments

The authors appreciate the support of the Office of Naval Research, and in particular, Ms. Kelly Cooper.

References

ABB. 2011 Technical specification, AMG 0500AA04, Document 8AMG 5860508 of 29 Aug 2011 Downloaded 12/20/2022 from: https://library.e.abb.com/public/86ebee706982603c4825791900304bec/5860508-A-AMG%200500AA04%20Technical%20specification.pdf.

ABB. 2015 Technical guide, The MV/LV transformer substations (passive users), 1VCP000591 - Rev - EN - 2015 11. Downloaded 12/23/2022 from: https://new.abb.com/docs/librariesprovider27/default-document-library/abb-transformerstations_ebook.pdf?sfvrsn=2.

Abeynayake, G., Li, G., Joseph, T., Liang, J., and Ming, W. 2021 Reliability and cost-oriented analysis, comparison, and selection of multi-level MVdc converters, *IEEE Transactions on Power Delivery*, **36**(6), 3945–3955. DOI 10.1109/TPWRD.2021.3051531.

Doerry, N. 2022 Optimal generator set loading for energy efficiency, *ASNE Naval Engineers Journal*, **134**(2), 101–111.

Doerry, N. 2017 *The Marine Engineering Series, Integrated Electric Propulsion*, *In*: Parsons, M. G., Editor, Alexandria, VA: SNAME. ISBN 0-692-96115-5.

Doerry, N. 2014 *Technical and Research Bulletin 7-10 Guide for Conducting Technical Studies*, Alexandria, VA: The Society of Naval Architects and Marine Engineers.

Doerry, N. 1991 Advanced numerical methods for simulating nonlinear multirate lumped parameter models, Cambridge, MA: MIT Doctoral thesis.

Doerry, N. H. and Amy, J. V. 2011 Implementing quality of service in shipboard power system design, Presented at IEEE ESTS, April 11–13, Alexandria, VA.

Guenther, C. 1989 Application and characteristics of diesel engines for high-speed marine vehicles, Lecture 18, Thirteenth Graduate School Design Techniques for Advanced Marine Vehicles and High Speed Displacement Ships, Delft University of Technology, Oct 23–Nov 1, The Netherlands.

IEEE 2017 *IEEE Std. 45.1 Recommended practice for electrical installations on shipboard – design*, New York, NY: IEEE.

Komar, I., Vulić, N., and Roldo, L. 2013 Hydrodynamic and elastohydrodynamic lubrication model to verify the performance of marine propulsion shafting, *Transactions of FAMENA*, **37**(1), 15–27.

Radzevich, S. P. 2012 *Dudley's Handbook of Practical Gear Design and Manufacture*, 2nd ed, Boca Raton, FL: CRC Press.

Michaelis, K., Höhn, B.-R., and Hinterstoißer, M. 2011 Influence factors on gearbox power loss, *Industrial Lubrication and Tribology*, **63**(1), 46–55.

Mowers, G. P. 1992 Reduction gears, *In*: Harrington, R. L., Editor, *Marine Engineering*, Jersey City, NJ: The Society of Naval Architects and Marine Engineers, pp. 325–352.

NAVSEA DDS 200-1 Rev 1 (T9070-AW-DPC-010/200-1) (DPC 200-1) 2011 Design data sheet: calculation of surface ship endurance fuel requirements, October 4, 2011.

NAVSEA DDS 200-2 (T9070-AW-DPC-020/200-2) (DPC 200-2) 2012 Design data sheet: calculation of surface ship annual energy usage, annual energy cost, and fully burdened cost of energy, August 7, 2012.

NAVSEA DDS 310-1 Rev 1 (T9070-A3-DPC-010/310-1) (DPC 310-1) 2012 Design data sheet: electric power load analysis (EPLA) for surface ships, September 17, 2012.

Patel, M. R. 2012 *Shipboard Propulsion, Power Electronics, and Ocean Energy*, Boca Raton, FL: CRC Press.

United States Naval Academy (USNA) 1979 *EN100 introduction to naval engineering*, Annapolis, MD: USNA.

Woud, H. K. and Stapersma, D. 2015 *Design of Propulsion and Electric Power Generation Systems*, London: IMarEST, ISBN 1-901536-47-9.

Wu, L., Qin, J., Saeedifard, M., Wasynczuk, O., and Shenai, K. 2015 Efficiency evaluation of the modular multilevel converter based on Si and SiC switching devices for medium/high-voltage applications, *IEEE Transactions on Electron Devices*, **62**(2), 286–293.