Power Generation

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1. Introduction

Power generation converts energy stored in fuel or some other form of energy from the environment or other shipboard systems into electrical power for use by electrical loads via the electrical power distribution system. The most common type of power generation onboard ship today is a generator set that integrates either a diesel engine or a gas turbine to a synchronous electrical generator. Generator sets that used a steam turbine integrated with a synchronous electrical generator were once common, but are seldom encountered in non-nuclear powered ships. Fuel cells and photo-voltaic systems can be occasionally found in specialty applications.

For a more in-depth discussion of shipboard power generation, see Doerry (2020), Patel (2012), or Sun, Patel, and Hou (2020).

2. Generator set components

Figure 1 depicts a generic ac generator set that could be either gas turbine or diesel engine powered. A dc generator set would have an additional rectifier connected between the generator and the switchboard. If the prime mover is a gas turbine, there may also be a reduction gear between the engine and the generator in order to be capable of producing either 50 or 60 Hz. Power. Many times, the prime mover and generator are within an enclosure. This enclosure reduces the amount of heat and noise transmitted into the machinery room from the generator set. Enclosures can also be used to contain engine fires.

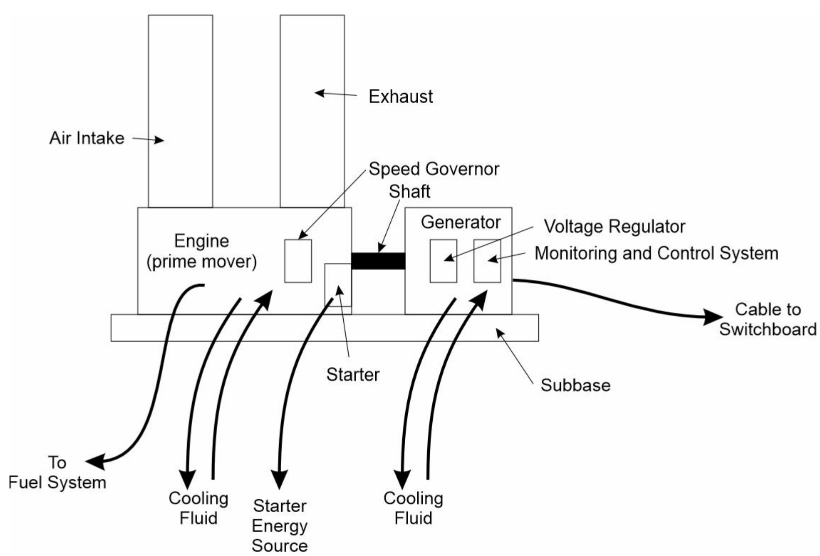

Figure 1: AC generator set components

2.1. Engine (prime mover)

The purpose of the engine (prime mover) is to convert fuel and air into rotational mechanical power for further conversion by the generator to electrical power. In shipboard power systems, the engines are typically either diesel engines or gas turbines. Diesel engines are typically larger and heavier than gas turbines, but usually have better fuel efficiency. If a ship is severely weight or volume constrained, it will often employ gas turbines. If fuel economy is of greatest importance, then diesel engines are often used. Some ships will have a combination of gas turbine generator sets and diesel generator sets to best meet its operational profile.

Some ship designs incorporate lightweight gas turbine generator sets high in the superstructure in order to minimize the volume consumed by air intakes and exhaust.

2.2. Generator

The generator converts rotational mechanical power to ac electrical power. The frequency of the electrical power depends on the shaft speed and the number of pole pairs the generator has:

$$f = \frac{n}{60}p \qquad \text{or} \qquad n = 60\frac{f}{p}$$

where:

f = frequency in Hz
n = shaft speed in rpm
p = number of pole pairs (positive integer)

If constant frequency 60 Hz power is desired, then the shaft speed is required to be a submultiple (the number of pole pairs) of 3600 rpm. Typical design shaft speeds for 60 Hz operation are 3600 rpm, 1800 rpm, 1200 rpm, and 900 rpm. Medium speed diesel engines typically operate in the range of 900 to 1800 rpm. While some gas turbines can supply full power at 3600 rpm, most can only do so at higher speeds. Consequently, many gas turbine generator sets employ a reduction gear to provide 1800 rpm to the generator. 1800 rpm, corresponding to 2 pole pairs, is often the most economical design for a generator.

If the output of the generator is intended to be immediately rectified to dc power, then a frequency higher than 60 Hz is often desired to make it easier to filter out the voltage ripple on the dc waveform. For this reason, a reduction gear is generally not required or desired for gas turbine generator sets designed to produce dc power.

2.3. Subbase

The subbase provides a rigid structure that the other components of the generator sets are mounted on. The subbase enables the generator set to be constructed, aligned, and tested on shore before being installed onboard ship. On naval ships, the subbase may be either directly mounted to a foundation welded to the ship structure, or connected via shock and acoustic mounts to the foundation. While either mounting technique is possible with commercial ships, directly mounting the subbase to the foundation is normal.

2.4. Voltage regulator

The voltage regulator controls the excitation current in the field winding of the generator in order to regulate the voltage on the generator output. The voltage regulator also includes the capability to share reactive power among paralleled generators.

2.5. Speed governor

The speed governor controls the shaft speed of the generator in order to regulate the frequency of the voltage on the generator output. The speed governor also includes the capability to share real power among paralleled generators.

2.6. Starter

The prime mover requires a method to start. This starter can include technologies such as an electric motor, an air motor powered by high pressure air flasks or bleed air from online gas turbines, or a smaller starting engine mounted on a gas turbines shaft.

2.7. Air intake and exhaust

The air intakes provide combustion air to the prime mover and may also provide cooling air to the generator set enclosure. Often a fan is used to force air into the generator set enclosure. The air intake has a cross-sectional area large enough to keep the pressure drop from the atmosphere within a specified value. Small diesel engines may draw air from the machinery room ventilation system, otherwise air is drawn from the exterior of the ship.

The exhaust duct conveys the combustion products, as well as the generator set cooling air to the exterior of the ship. The exhaust duct can also include noise silencers, emission scrubbers, waste heat recovery devices, and exhaust cooling equipment. The exhaust duct has a cross-sectional area large enough to keep the back-pressure on the engine within a specified value.

Usually, the exhaust exits the ship at the very top of a stack. On some ships, the exhaust occurs near or below the waterline. Designs should have provisions to prevent the ingestion of exhaust into the intakes of the ship's ventilation system.

2.8. Fuel system

Generator sets are provided fuel via a fuel system. This fuel system includes a "day tank" or "service tank" that typically is sized to provide sufficient fuel to last a specified number of hours. Fuel from the storage tanks (bunker tanks) is filtered and water removed before being pumped into the day / service tank. The day / service tanks are often located high in the engine room so as to enable gravity to provide sufficient pressure to supply the prime mover, especially when starting a standby generator set. A fuel pump may also be used to supply the prime mover from the service tank.

Some prime movers recirculate fuel that has not been consumed back to the day / service tank.

2.9. Cooling system

For many generator sets, the cooling systems for the engine and the generator are different.

The generator may be air cooled where the air is supplied and exhausted by the machinery room's ventilation system; or the generator employs a totally enclosed water-air cooled (TEWAC) design where the generator is totally enclosed and a fan circulates air between the generator and an air to seawater heat-exchanger. In the latter case, the seawater is obtained from the sea via an intake, filtered, and pumped through the heat exchanger before being discharged overboard.

Diesel engines are cooled through a freshwater cooling system (jacket water) that in turn is cooled via a freshwater to seawater heat exchanger. The freshwater usually contains anti-freeze and corrosion inhibitors. The source of seawater for the heat exchanger may be common with the generator.

Gas turbines may have multiple stages of cooling. The engine itself may be cooled with a high temperature synthetic oil. This synthetic oil is cooled by a more conventional oil in an oil-to-oil heat exchanger. Finally, the more conventional oil is cooled by seawater in an oil-to-seawater heat exchanger. As with the diesel engine, the source of seawater for this last heat exchanger may be common with the generator.

2.10. Monitoring and control system

The monitoring and control system coordinates all of the equipment comprising the generator set and communicates with external systems. The prime mover typically has a dedicated engine controller that interacts both with the speed governor and the monitoring and control system. Many sensors are directly monitored by the monitoring and control system and their values possibly exported to other networked systems. The monitoring and control system coordinates the starting and stopping of the generator set, as well as establishing setpoints while the generator set is in operation.

2.11. Rectifier (dc only)

Generator sets that produce dc also include a rectifier. Since the rectifier is generally insensitive to the frequency of the power provided to it, the prime mover need not operate at a constant speed. Instead, the shaft speed of the prime mover should be selected by the control system to minimize fuel consumption for the amount of power being generated. Variable speed operation can be very beneficial for diesel engines. Fuel efficiency is not increased as dramatically with gas turbines.

Because the generator is not limited to the type of power required by the power system interface standard, the generator can be configured to provide more than three phases of power in addition to variable frequency operation. Operating in the low 100s of Hz is often found to be optimal for minimizing equipment size and losses.

3. Fuel cell components

Figure 2 depicts a generic fuel cell system. While many different types of fuel cells exist, proton exchange membrane fuel cells (PEMFC) are the most commonly found type in maritime applications. Other types, such as molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC) are also applicable to shipboard power systems. As detailed by Sun, Patel, and Hou (2020), the major advantages of fuel cells include:

a. Clean exhaust – Fuel cells significantly reduce or eliminate NOx, CO_2, SOx and particulate emissions. The exhaust flow rate is also much reduced as compared to diesel engines and gas turbines.

b. High Efficiency – Fuel cell systems typically are more efficient than diesel or gas turbine generator sets. In particular, losses at low power levels may be significantly lower.

c. Modularity – The fuel cell consists of modular fuel cell stacks that provide a means for easily scaling the power rating of the fuel cell while retaining commonality with other fuel cells of different power ratings.

d. Noise and vibration – Fuel cells are very quiet and largely vibration free; only moving parts are the pumps and blowers.

The disadvantages of a fuel cell include:

a. Traditional fuels such as F76 and Marine Gasoil (MGO) cannot be directly used; they must be reformed to produce relatively pure hydrogen gas. In particular, removing sulfur is critical for most fuel cell types. Eliminating CO is also important for PEMFC.

b. Fuel cells have a slow dynamic response to transients; power systems typically require energy storage to provide the required dynamic response.

The air intake and exhaust requirements of diesel or gas turbine generator sets often precludes their placement all the way forward or all the way aft in a ship. The more limited air intake and exhaust requirements of a fuel cell may enable their placement at the extreme ends of the ship where they can better contribute to the survivability of the ship.

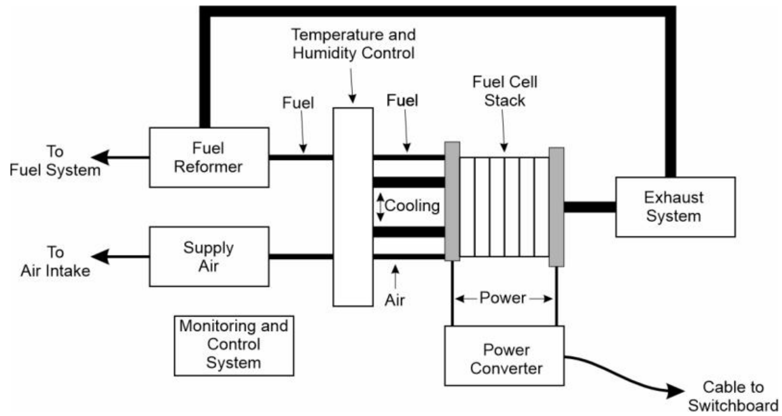

Figure 2: Fuel cell system components

3.1. Fuel cell stack

The fuel cell stack converts the fuel and air into water and generates electrical power. Since each cell typically produces less than 1 volt, a significant number of fuel cells are connected in series as part of a fuel cell stack to produce the desired voltage.

3.2. Power converter

The power converter converts the variable voltage dc power from the fuel cell stack to the type of power (ac or dc) and voltage required by the power system. Fuel cells generally respond slowly to transients; the power converter may incorporate energy storage to provide better transient response to meet the interface requirements at the connection to the switchboard.

3.3. Fuel reformer

The fuel reformer converts the fuel into a gas (typically H_2) that can be used by the fuel cell stack in addition to removing impurities such as sulfur (and in some cases CO) that can damage the fuel cell stack. While some fuel cells can perform the reforming internal to the fuel cell stack, most fuel cells use an external reformer as depicted in Figure 2.

3.4. Supply air

A blower is typically used to draw supply air from outside the ship or from the ship's ventilation system through a filter and into the temperature and humidity control component.

3.5. Temperature and humidity control

The temperature and humidity of the fuel supply, air supply, and fuel cell stack are important factors in the efficiency of the fuel cell. For a PEMFC, the air supply and fuel supply are preheated and the fuel cell stack is cooled in order to optimize efficiency.

3.6. Exhaust system

The exhaust of a fuel cell stack is primarily water. The exhaust may also contain unconsumed air and fuel, including contaminants as well as gasses produced by the reformer. The exhaust system either recycles the different constituents of the exhaust, or vents them offboard the ship.

3.7. Monitoring and control system

The monitoring and control system coordinates all of the equipment comprising the fuel cell system and communicates with external systems. Many sensors are directly monitored by the monitoring and control system and their values possibly exported to other networked systems. The monitoring and control system coordinates the starting and stopping of the fuel cell system, as well as establishing setpoints while the fuel cell system is in operation.

4. Photovoltaic system components

Photovoltaic systems can be found on a variety of ships. As will be shown below, the amount of power and energy that can be produced by photovoltaic systems is not large; hence photovoltaic systems onboard ships are generally used to augment other sources of energy or for very special purposes. Figure 3 depicts the components of a typical photovoltaic system.

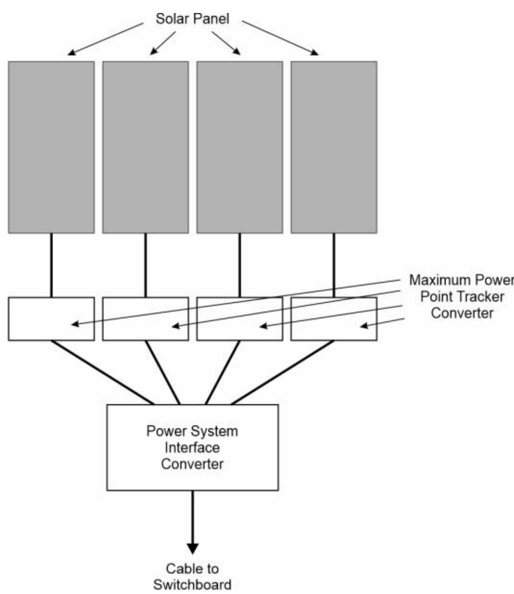

Figure 3: Photovoltaic system components

4.1. Solar Panels

Solar panels convert light directly into dc electrical power. A solar panel normally contains a series and parallel connections of a large number of photovoltaic cells. A single cell typically operates at about 0.5 volts while the solar panel operates typically between about 35 and 45 volts. Figure 4 depicts a notional power vs voltage curve for a photovoltaic cell operating at a specific level of irradiance; the peak power and the voltage at peak power are both dependent on the level of irradiance.

A typical residential solar panel installed in 2024 is rated at 405 watts and is about 22% efficient. Each panel has a surface area of about 2 m^2 and weighs about 22 kg. The rated power is under ideal conditions; one can expect at best to have a peak power from the solar panel of about 80% of the rated value. As a gross approximation, for each watt of rated power, one can expect about 1.2 kWh of energy to be produced in a year (depending on weather, panel location, etc.). In a day, this is equivalent to 3.3 watt-hours for each watt of rated power, or 0.67 kWh per square meter. Peak power in a day is about 160 watts per square meter.

To power a 100 kW load continuously requires 2400 kWh per day. This requires on the order of 3600 square meters of solar panels for the average day. Allocating this amount of surface area to solar panels for most ship topside design is challenging; hence one would expect solar power to contribute only a small part of a ship's total electrical load.

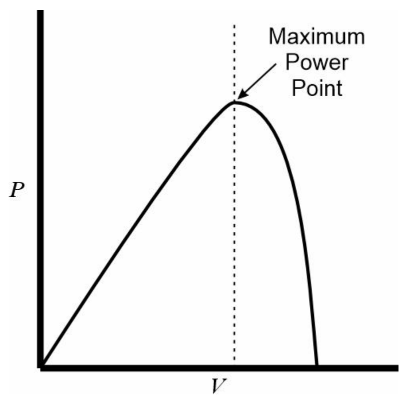

Figure 4: Photovoltaic cell power vs voltage curve

4.2. Maximum Power Point Trackers - Converters

A maximum power point tracker impresses a voltage onto the panel and extracts current from the panel. The impressed voltage is typically dithered to enable the maximum power point tracker to set the voltage at the maximum power point for the level of irradiance being experienced. The output of the maximum power point tracker – converter is electrical power adhering to a specific interface standard. In some cases, this interface is the same as needed by the power system and all the functions of the power system interface converter is fulfilled by the maximum power point tracker - converter, in other cases further power conversion and functionality are performed by a separate power system interface converter.

4.3. Power system interface converter (if necessary)

The power system interface converter, if provided, converts the power from the maximum power point trackers – converters to power adhering to the power system interface requirements. The power system interface converter may also perform fault protection functions. Under normal conditions, many power system interface converters operate in a "grid following" mode where they do not participate in either system voltage or frequency regulation; instead, they inject current into the power system based on their local measurements of voltage phase angle and frequency. Without the reference voltage frequency and phase angle, a grid following converter is not able to provide power during a black out. A "grid forming" converter does participate in system voltage and frequency regulation, hence it can operate during a black out. Many converters can automatically switch from grid following to grid forming during a black out.

5. Marine fuels

Significant changes are occurring in the selection of marine fuels to use onboard ships. The International Maritime Organization (IMO) has established a goal of net-zero greenhouse gas (GHG) emissions by 2050. This goal is in addition to existing regulations for controlling the emissions of sulfur oxides (SOx) and nitrogen oxides (NOx) in emission control areas (ECAs). The number and size of ECAs is also expanding. As a consequence, ships will likely be constructed or converted to using fuels other than those derived from crude oil. The following sections describe the marine fuels typically used today as well as fuels being evaluated for future use to meet IMO regulations.

5.1. Heavy Fuel Oil

Heavy Fuel Oil (HFO) is what remains after crude oil refining has removed lighter components. HFO has a high viscosity and usually must be preheated to enable it to flow through pipes. HFO is generally inexpensive, but may be high in sulfur which requires special scrubbing equipment to meet environmental laws. Sub-categories of HFO delineate the maximum amount of sulfur in the fuel. High Sulfur Fuel Oil (HSFO) has a sulfur content up to 3.5%. Low Sulfur Fuel Oil (LSFO) has a sulfur content up to 0.5% and Ultra-Low Sulfur Fuel Oil (ULSFO) has a sulfur content up to 0.1%.

5.2. Distillate Fuels

Distillate fuels are composed of lighter components of crude oil that are extracted from the crude oil during the refining process. Marine Gasoil (MGO) are marine fuels consisting exclusively of distillate fuels. Distillate fuels have a lower viscosity than HFO, and generally have a cleaner and more consistent combustion than HFO. Distillate fuels are usually more expensive than HFO. Common grades of distillate fuels include DMA, DMB, DMX, and DMZ. DMA is also known as Low-Sulfur Marine Gas Oil (LSMGO). Distillate fuels, depending on the grade, can also have relatively high sulfur content.

Naval ships in the U.S., NATO, and elsewhere use a distillate fuel called F76 (also known as Naval Distillate Fuel) which adheres to MIL-DTL-16884. This fuel can be used in gas turbines, diesel engines, and conventional steam boilers. Naval ships can also typically use JP-5 which is the primary fuel used by naval aircraft. Having to only manage two fuel types (F76 and JP-5) greatly simplifies naval logistics.

5.3. Blended Fuels

Fuels that blend HFO and distillate fuels are also known as Intermediate Fuel Oil (IFO). Marine Diesel Oil (MDO) is a blend of distillate fuels and HFO for marine applications. MDO is less expensive than distillate fuels and usually does not have to be preheated to flow through pipes.

5.4. Biofuels

As part of the effort to reduce SOx and GHG emissions, the marine industry is exploring the increased use of fuels derived from biological sources that are mostly compatible with existing prime movers. Biofuels may be blended with traditional crude-oil based fuels to increase this compatibility, or the prime movers may require modification to reliably operate with pure biofuels.

Two common biofuels are Fatty Acid Methyl Ester (FAME) and Hydro-treated Vegetable Oil (HVO). These two fuels use different methods to convert biomass material to a useable fuel. Biofuels generally have a shelf life of less than a year before degradation occurs.

5.5. Liquid Natural Gas

Liquid Natural Gas (LNG) is composed primarily of methane (CH_4). As compared to crude oil-based fuels, during combustion it generates less CO_2 per unit of heat. LNG has a very low sulfur content and particulate emissions. The availability of shore-based facilities for refueling LNG onboard ships is also increasing. For these reasons, the use of LNG is considered an important step to achieving IMO emission goals. Over 600 ships employing LNG are currently operational.

LNG is liquified by bringing its temperature to below -162° C. Storing and transporting the refrigerated fuel requires special equipment and provisions onboard ship.

Prime movers intending to use LNG are different from those that employ crude-oil based fuels.

5.6. Methanol

Methanol (CH_3OH) is a liquid alcohol that can be used as a fuel. It requires fewer modifications to a ship as compared to LNG. Methanol is generally available and is usually less expensive than LNG. It has many of the same emissions benefits as LNG. Challenges to its integration onboard ship include high toxicity and flammability.

5.7. Ammonia

Ammonia (NH_3) is carbon free; its combustion does not create CO_2. Prime movers intending to use ammonia are different from those that employ crude-oil based fuels. Ammonia is generally available and without CO_2 emissions, it is a promising fuel for meeting IMO emissions goals. Challenges to its integration onboard ship include toxicity and corrosiveness.

6. Fuel Rates

The design of a shipboard power system should account for the fuel efficiency of power generation under different operational conditions. As detailed by Doerry and Parsons (2023) fuel consumption for an engine or generator set is often expressed in terms of specific fuel consumption (SFC). SFC (kg/kW-h) is equal to the fuel rate (kg/h) divided by the power delivered by the engine or genset (kW) at a particular operating point. The fuel has a heating value which is the amount of heat (J/kg) that a unit of mass can produce when burned; when multiplied by the fuel rate (kg/s), results in the upper bound for the amount of power (W) that can be produced by the fuel. The efficiency of the engine is the power delivered by the engine divided by this upper bound; this efficiency is proportional to the inverse of the SFC.

When idling, an engine consumes fuel, but does not deliver any power. Consequently, an SFC vs power curve tends to infinity as it approaches 0 power. For this reason, it is often more instructive to work directly with fuel rates rather than SFC. For many engines, the fuel rate vs power curve (fuel rate in kg/h vs power in kW) is nearly linear with a y-intercept equaling the idle fuel rate.

When one examines a datasheet, the SFC curve reflects the mechanical power at the shaft if the datasheet is for the engine; the SFC curve reflects the electrical power delivered if the data sheet is for the generator set. The units for power and SFC used in datasheets are not standardized; one should always determine which units are used. If one intends to use an SFC for engine to determine the fuel rate for a generator set, the SFC curve should be adjusted to reflect the efficiency of the generator and any losses associated with auxiliary equipment. The SFC curves are also only valid for a specific environment and should be adjusted if the shipboard environment is different.

6.1. Gas Turbines

The fuel rate of a gas turbine is a function of both the power delivered by the gas turbine and the shaft speed. SFC, which can be used to calculate the fuel rate, can be represented as a surface plotted against power delivered and shaft speed. When this surface is represented by a series of iso-SFC curves, it is called an SFC map. Figure 5 depicts an SFC map for a generic gas turbine. In addition to the iso-SFC curves (depicted in green), an SFC map usually depicts the various operational limits (depicted in red) to include maximum intermittent power limit, maximum continuous power limit, maximum torque limit, maximum shaft speed limit, and minimum recommended power. The two blue lines on Figure 5 depict load lines for particular applications of the engine. The vertical line represents constant frequency operation where the output of the generator is directly connected to the power system. The curved line represents variable frequency operation where the output of the generator is connected to the power system via a power converter (typically a rectifier for dc systems). The variable frequency operation curve follows the minimum sfc for any given shaft power.

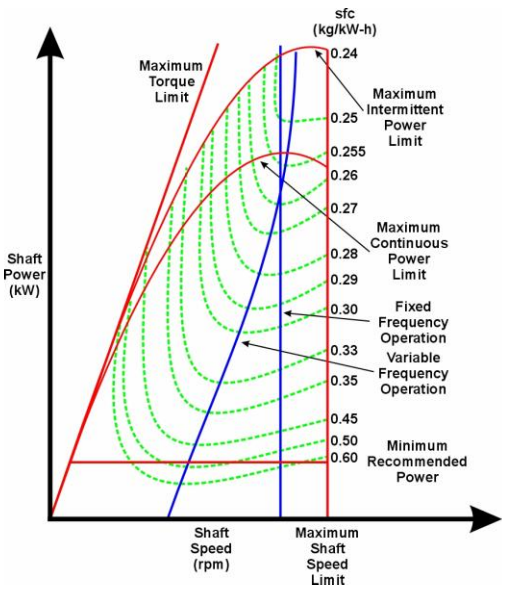

Figure 5: Gas turbine sfc map

For any particular application, the corresponding load line can be used to produce an SFC curve which plots the SFC as a function of power. Figure 6 depicts the two SFC curves corresponding to the two blue lines in Figure 5. As expected, the SFC curve for variable frequency operation is slightly lower than the curve for fixed frequency operation.

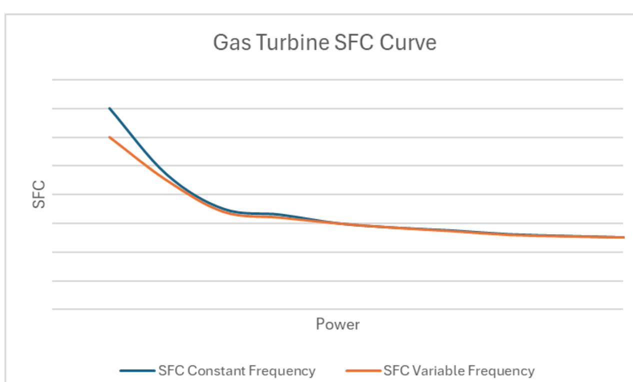

Figure 6: Gas Turbine SFC Curve

The SFC curve in turn can be converted to a fuel rate curve by multiplying each SFC point by the corresponding power. As depicted in Figure 7, the two fuel rate curves are predominately linear with the variable frequency operation fuel rate curve slightly lower than the fixed operation fuel rate curve. For this gas turbine example, variable frequency operation is not significantly more fuel efficient than constant speed operation.

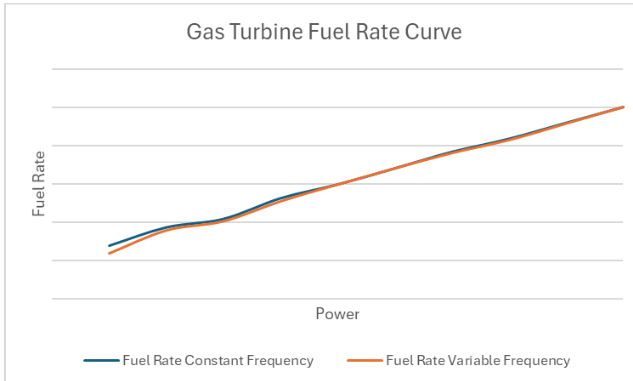

Figure 7: Gas Turbine Fuel Rate Curve

Some gas turbines have the ability to provide bleed air (compressed air taken from the gas turbine's compressor) for use by other systems, or for starting other engines. The amount of bleed air provided is another dimension to the SFC surface; if applicable, multiple SFC maps may be provided for different levels of bleed air.

6.2. Diesel Engines

SFC maps are also appliable to diesel engines. As depicted in Figure 8, the shape of a diesel engine SFC surface can be significantly different from gas turbine SFC surfaces. The iso-SFC contours are greatly influenced by the configuration of turbo-chargers and other control modes applicable to diesel engines. For diesel engines, the variable frequency operation load line is often near the maximum torque limit line as depicted in Figure 8. As depicted in Figure 9 and Figure 10, the differences in SFC and fuel rate between constant frequency operation and variable frequency operation is more pronounced than for the gas turbine example. Over the range of power between the minimum recommended power and the maximum continuous power limit for this example, the fuel rate for variable frequency operation is about 6 percent less than for constant frequency operation.

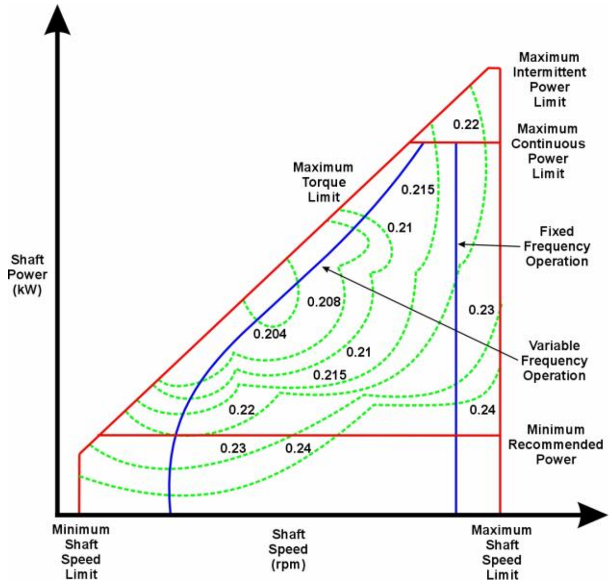

Figure 8: Diesel engine sfc map

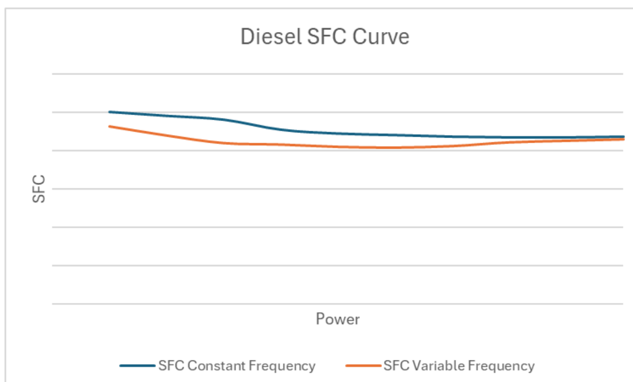

Figure 9: Diesel Engine sfc curve

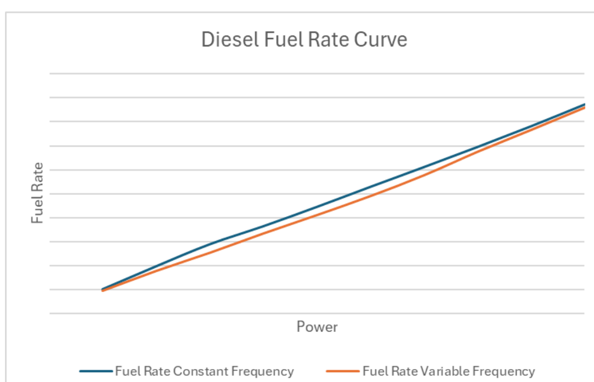

Figure 10: Diesel engine fuel rate curve

6.3. Fuel Cells

Calculating the fuel rate for a fuel cell system is usually a multi-step process. One is generally provided a thermal efficiency graph that plots the thermal efficiency of the fuel cell stack against the power produced by the fuel cell stack. A notional example of a stack efficiency vs stack power is shown in Figure 11. The fuel cell stack in this example is part of a fuel cell system that converts F76 fuel into hydrogen with a fuel reformer; hydrogen is employed as the fuel for the fuel cell stack.

Assuming the stack efficiency is based on the lower heating value of hydrogen (120 MJ/kg or 33.33 kWh/kg), the stack hydrogen consumption is computed by dividing the stack power by the stack efficiency and the lower heating value. The results are depicted in Figure 12.

If one assumes 42% of the mass of F76 can be ideally converted to hydrogen (see https://www.fuelcellstore.com/blog-section/fuel-cell-information/processing-alternative-fuels-for-fuel-cells) and the fuel reformer can achieve 85% of this conversion rate, the consumption of F76 is as shown in Figure 13. If the power used by the fuel reformer, converter, and other elements of the balance of plant is assumed to equal a fixed 4% of the stack rated power plus a variable amount that linearly increases from 0 to 6% of the stack rated power (from no stack power to 100% rated stack power), then the fuel rate of F76 as a function of power delivered to the power system is as shown in Figure 14.

Note that although the fuel cell stack for this example is rated for 1000 kW, subtracting off the power required for the balance of plant results in the fuel cell system having a maximum rating of 900 kW.

For comparison with other types of power generation, the SFC can be easily computed as shown in Figure 15 by dividing the fuel rate by the power. The SFC values for this particular example are generally lower than for equivalent gas turbine or diesel generator sets. An actual fuel cell system may perform even better than this example.

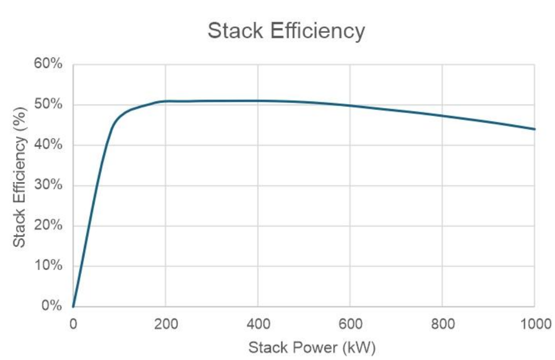

Figure 11: Fuel cell stack efficiency

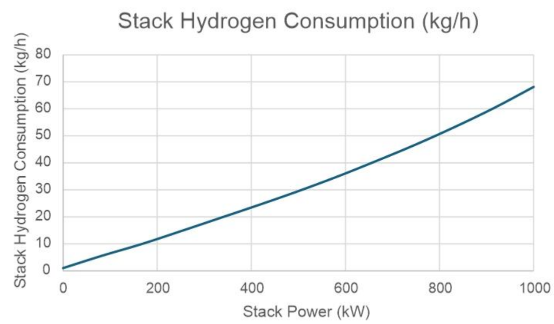

Figure 12: Fuel cell stack hydrogen consumption

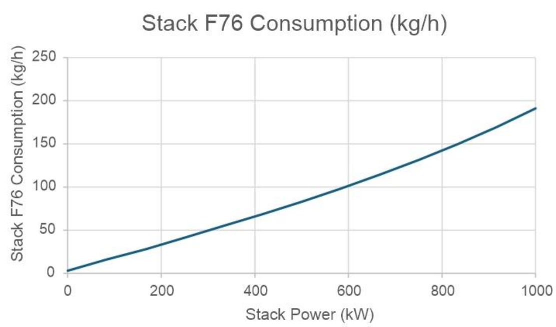

Figure 13: Fuel cell stack F76 consumption

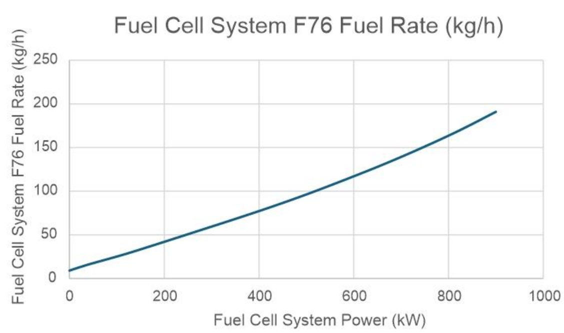

Figure 14: Fuel cell system F76 fuel rate

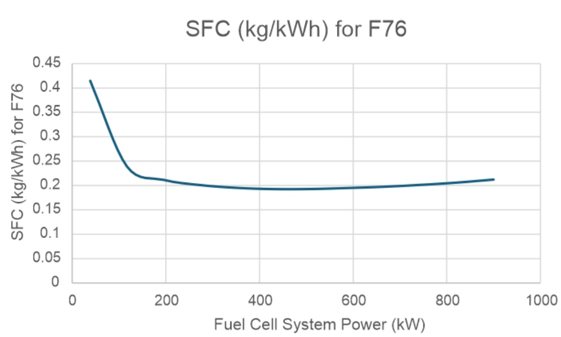

Figure 15: Fuel cell system sfc

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