GE Power

GAS TO POWER: THE ART OF THE POSSIBLE

The Fuel Flexibility of GE Power's Aeroderivative Gas Turbines

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INTRODUCTION

As the world's demand for electricity continues, there are numerous opportunities for gas turbines to be part of the generation solution. Due to their installation and operational characteristics, aeroderivative gas turbines play a key role in power generation. Adding to this capability, aeroderivative gas turbines are highly fuel-flexible, able to operate on a wide variety of gaseous and liquid fuels. This paper provides an overview of these fuel flexibility capabilities, including technical details and operational experience.

GE's AERODERIVATIVE GAS TURBINE FLEET

Today's aeroderivative fleet includes more than 5,000 gas turbines, with more than 135 million operating hours. The LM2500 fleet includes over 2,500 gas turbines, with more than 97 million operating hours. The fleet leader has more than 280,000 hours. The LM6000 fleet includes more than 1,300 gas turbines with more than 40 million operating hours. The LMS100 fleet includes over 75 gas turbines with greater than 730,000 operating hours.

Aeroderivative gas turbines are capable of operating on a wide variety of gaseous and liquid fuels. Below, Table 1 shows some of these fuels, with information as to which aeroderivative gas turbines can utilize these fuels. Descriptions of these fuels (and others), along with the experience from GE aeroderivative gas turbines operating on these fuels, are detailed in later sections.

Table 1 – Aeroderivative fuel flex capabilities

	Gaseous Fuels				**Liquid Fuels**			
Fuels	**High BTU:** ethane, propane, butane, LPG, isopentane	**Natural Gas & LNG**	**Medium BTU:** lean methane	**Low BTU:** syngas, steel mill, landfill	**Light Distillates:** diesel, kerosene, jet fuel (A, A1), naptha	**Biodiesel**	**Ethanol**	**Methanol**
Heating Value	>1,200 BTU/scf	~900 BTU/scf	~300-700 BTU/scf	<300 BTU/scf	~18,000-19,000 BTU/lbm	~16,500-18,000 BTU/lbm	~11,500 BTU/lbm	~8,500 BTU/lbm
	>44,900 kJ/Nm^3	>35,800 kJ/Nm^3	~11,200-26,000 kJ/Nm^3	<11,200 kJ/Nm^3	~42,000-44,000 kJ/kg	~39,500-18,000 kJ/kg	~26,850 kJ/kg	~19,800 kJ/kg
Gas Turbine								
LM/TM2500	✓	✓	✓	✓	✓	✓	✓	✓
LM6000	✓	✓	✓		✓	✓	✓	✓
LM9000		✓	✓		✓	✓		
LMS100	✓	✓	✓		✓	✓	✓	✓

GAS TURBINE FUEL FLEXIBILITY

Gas turbines are capable of operating on a wide variety of gas and liquid fuels, as shown by the graphic in Figure 1. Gaseous fuels include natural gas, liquefied natural gas (LNG), flare gases, lean methane, refinery gases, as well as ethane, propane, and other higher molecular weight hydrocarbons, i.e., natural gas liquids (NGLs) and liquid petroleum gas (LPG). Liquid fuels include diesel (also known as light distillate or diesel fuel oil #2), biodiesel, condensates, crude oils, and heavy/residual fuel oils. Details on the various fuel capabilities can be found in references 1–9. In fact, as of this writing, GE has more installed MW and more gas turbines installed for operation on alternative fuels than any other OEM; see Figure 2. In this context, alternative fuels are defined as any fuel except for natural gas, LNG, and diesel #2 fuel oil. In addition, GE has more installed aeroderivative gas turbine megawatts with alternative fuels than any other OEM.

The next sections provide details on the combustion systems and fuel flex capabilities of GE Power's aeroderivative gas turbines.

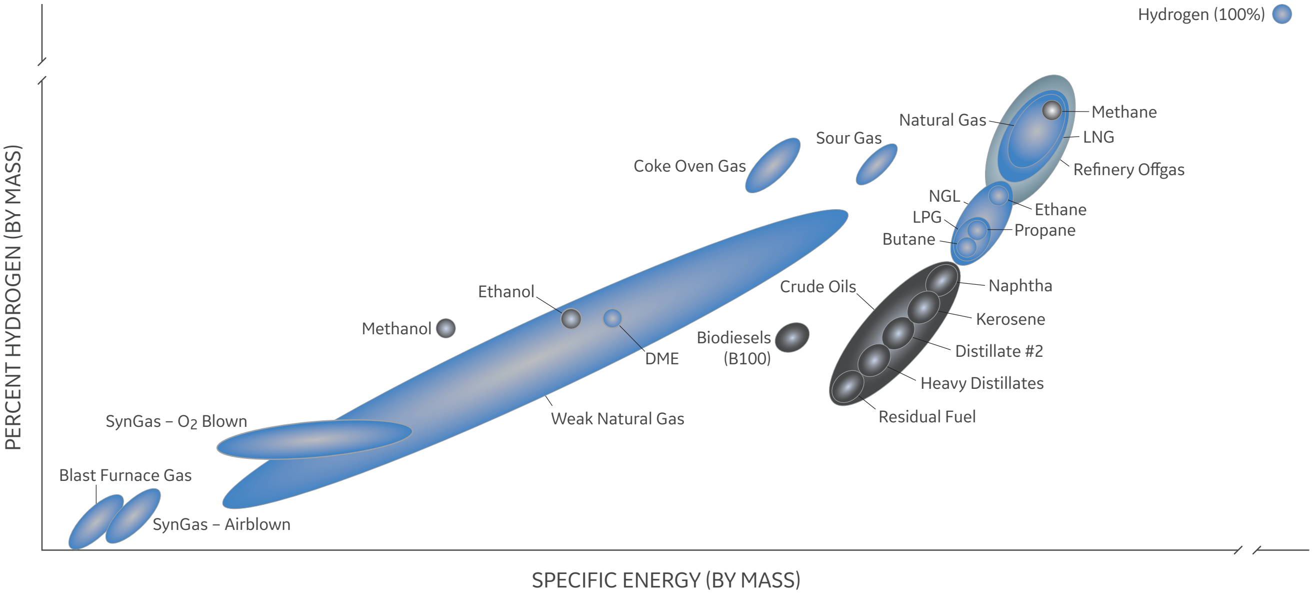


Figure 1 – Gas turbine fuel capabilities, per McCoy Power Reports, 1980-2017.

GE has the largest installed fleet of gas turbines for alternative fuel applications

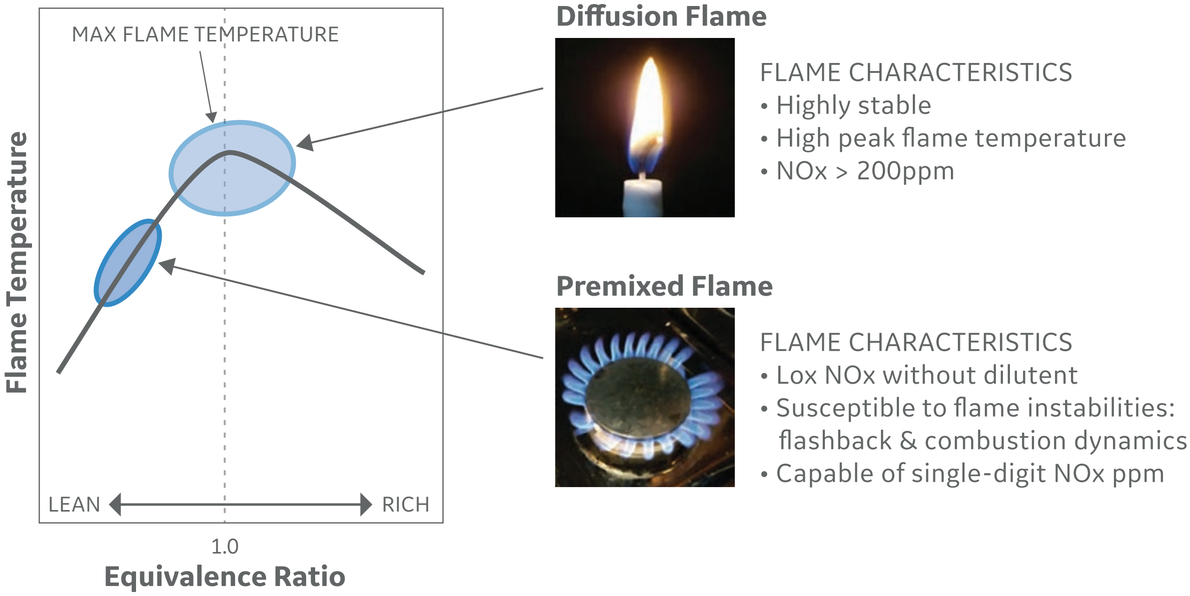
per McCoy Powers Reports, 1980-2017

Figure 2 – Global gas turbine fuel flex experience.

AERODERIVATIVE GAS TURBINE COMBUSTION TECHNOLOGY

Modern gas turbines that can utilize a wide variety of gaseous and liquid fuels must operate within a series of operational constraints, with combustor dynamics and emissions of NOx and CO being most notable. The formation of NOx compounds is (exponentially) dependent on the temperature of the reaction in the combustor. If fuel and air mix in stoichiometric proportion in a balanced chemical reaction, the flame will be at or near the highest temperature possible for the given fuel. In combustion science, the point at which fuel and an oxidizer react in chemical proportion is defined as having an equivalence ratio of ~1. Typically, combustion reactions with an equivalent ratio at or near 1 are generated by diffusion flames, which occur when the fuel and oxidizer mix (via diffusion) in proportion in the flame's reaction zone [10]. An example of a diffusion flame is a simple wax candle (See Figure 3.).

Although diffusion flames generate large amounts of NOx, they have operational advantages. For example, diffusion flames are highly stable and able to operate with fuels having a wide range of heating values, including fuels with very low heating values. When required, water or steam can be injected into a diffusion flame combustor to reduce firing temperature and reduce the formation of NOx.



Diffusion Flame

FLAME CHARACTERISTICS
- Highly stable
- High peak flame temperature
- NOx > 200ppm

Premixed Flame

FLAME CHARACTERISTICS
- Lox NOx without dilutent
- Susceptible to flame instabilities: flashback & combustion dynamics
- Capable of single-digit NOx ppm

Figure 3 – Diffusion vs. premixed combustion.

If extra air is introduced into the combustion reaction, the resulting lean mixture burns with a lower flame temperature and the reaction generates significantly lower levels of NOx. This is known as lean combustion and occurs in regions with an equivalence ratio of less than 1; see Figure 3. A lean premixed combustion system is one in which the fuel and air are mixed upstream of the flame; hence premixing implies mixing upstream of the flame. Lean premixed combustion systems are called "dry" because they do not require the injection of water (or steam) to reduce emissions.

GE Power's aeroderivative gas turbines can be configured with either a diffusion or premixed combustor (see Figure 4). These combustion systems are capable of operating on a variety of gas and liquid fuels and can be configured in a dual-fuel arrangement allowing for the use of a backup fuel when the primary fuel is not available.

Diffusion Combustion System — Single Annular Combustor (SAC)
GE's aeroderivative gas turbines can be configured with a single annular combustor (SAC). These combustors have an annular shape (like a torus) with a single row of fuel nozzles. These combustors are capable of operating on a variety of fuels, including propane, butane, process

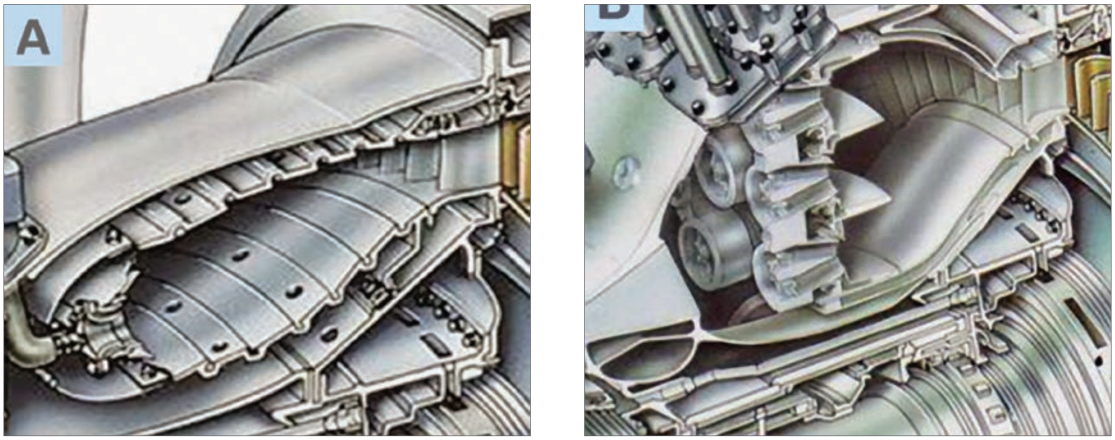


Figure 4 – GE aeroderivative gas turbine combustion systems — (A) SAC, (B) DLE.

fuels and fuel blends with hydrogen. The first SAC engine was sold in 1969, and today, the GE fleet has more than 2,600 aeroderivative gas turbines configured with this combustion system. These units have accumulated more than 105 million operating hours, providing customers with a multitude of benefits, including increased operational and fuel flexibility.

Lean Premixed Combustion System — Dry Low Emissions (DLE) Combustor

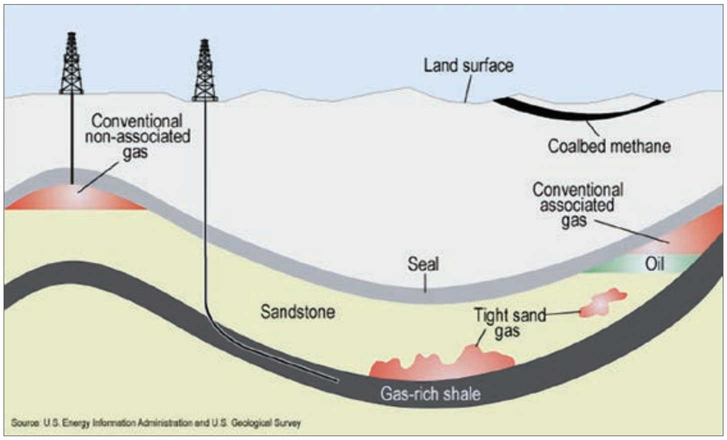
GE's DLE combustors are configured with multiple rows of fuel nozzles as shown in Figure 4. The lean-premixed nature of this combustion system achieves NOx emissions of 15 ppm without water or steam injection. To date, GE's DLE combustion technology has been installed on more than 1,170 gas turbines globally. Units with DLE systems have accumulated more than 32 million operating hours, displaying proven operational experience in providing customers with a multitude of benefits, including increased operational flexibility, reduced emissions, extended intervals, and higher performance while maintaining life cycle costs.

FUEL DEFINITIONS, SOURCES, AND CHARACTERISTICS

Power generation fuels used in gas turbines can be gases or liquids and include a wide range of hydrocarbons. The ultimate source for many of these fuels are underground pockets of gases and crude oil, as shown in Figure 5. Although the figure shows these pockets below land, they may also lie underneath the ocean floor, requiring off-shore drilling facilities. Many of the fuels that we use daily are produced from one of these sources. Other fuels are the direct product or a by-product of a man-made process. This section provides an overview of many key power generation fuels.

Natural Gas

Although natural gas is not an alternative fuel, it is important to understand this fuel as it is the source of many other fuels. Natural gas is produced from wells that generally fall into two categories: associated and non-associated. Associated gas comes from wells that primarily produce crude oil; in this case, the natural gas is called associated gas, as it is pumped along with the crude oil. In non-associated wells, the natural gas is pumped from dedicated wells without any crude oil production. As shown in Figure 5, natural gas can come from conventional wells of gas trapped in pockets capped (or sealed) by cap rock, or from gas-rich shale formations. By most definitions, gases labeled as natural gas can be used in gas turbines with little or no difficulty. The US EPA defines natural gas as having at least 70% (by volume) methane [12]. The European Union standard defines natural gas as having no more than 20% (by volume) of inerts, or in other words, as having at least 80% (by volume) methane [13].



Source: U.S. Energy Information Administration and U.S. Geological Survey

Figure 5 – Sources of fossil fuels [11].

Liquefied Natural Gas

Liquefied natural gas (LNG) is made from natural gas by removing most of the non-methane hydrocarbons and then condensing the remaining gas to a liquid by cooling to a temperature below the boiling point (-162°C). As a liquid, LNG takes up less than 1/600th the volume of a gas with the same energy content, enabling transport via ship around the world. Once a tanker containing LNG arrives at its destination, the liquid is expanded back into a gas and then distributed to end users.

As most of the non-methane hydrocarbons are removed from the natural gas, LNG tends to have a nominal methane concentration near 90%. Table 2 shows the compositions of LNG from various global sources. The table includes the temperature corrected or modified Wobbe index (MWI). (MWI is defined as the fuel's lower heating value, or LHV, divided by the square root of the product of the absolute fuel temperature and the fuel's specific gravity.) For comparison, a natural gas meeting the US pipeline standards might have an MWI (at 400°F) of ~42 BTU/scf/°R0.5. All the fuels listed in the table are within ±5.1% of the MWI of a nominal natural gas fuel, and within the acceptable range of variation for many modern gas turbines, including GE's aeroderivative gas turbines [14].

Table 1 – Aeroderivative fuel flex capabilities

	Methane CH_4	Ethane C_2H_6	Propane C_3H_8	Butane C_4H_{10}	Nitrogen N_2	Total	LHV	MWI @ 400°F
Country	**Volume %**						MJ/Nm^3	BTU/scf/R1/2
Algeria	87.6	9.0	2.2	0.6	0.6	100	39.8	43.6
Australia	89.3	7.1	2.5	1.0	0.1	100	40.0	43.8
Malaysia	89.8	5.2	3.3	1.4	0.3	100	40.1	43.8
Nigeria	91.6	4.6	2.4	1.3	0.1	100	39.5	43.6
Oman	87.7	7.5	3.0	1.6	0.2	100	40.8	44.2
Qatar	89.9	6.0	2.2	1.5	0.4	100	39.8	43.6
Trinidad & Tobago	96.9	2.7	0.3	0.1	0.0	100	36.8	42.3

Lean Methane — Natural Gas with High Levels of Inert Gases

Another special category for natural gases is lean methane, also referred to as medium BTU gas. These are fuels from gas fields that naturally have significant amounts of carbon dioxide (CO_2) or nitrogen (N_2). Gases from these fields may have as much as 60% CO_2 or N_2, resulting in methane concentrations as low as 40% (by volume). These fuels can have lower heating values (LHV) in the range of ~360-640 BTU/scf (~14.4 – 25.1 MJ/Nm^3); for reference, 100% methane has an LHV of ~911 BTU/scf (35.8 MJ/Nm^3). As a result of the lower heating value of the fuel, the fuel accessories system is specifically configured for this application. This may require larger pipes and valves to accommodate the increased mass flow, modifications to the control system, as well as changes to ventilation systems.

Some lean methane fuels may also have substantial amounts of sulfur (S) or hydrogen sulfide (H_2S). These fuels are typically labeled as "sour" and may require specific fuel and/or bottoming cycle configurations to avoid potential corrosion risks. See the next section for details.

Sour Gas

A gas is defined as being sour when it contains more than 314 parts per million by volume (ppmv) of sulfur, or 4 ppmv of hydrogen sulfide (H_2S). Fuels with increased levels of H_2S can be used in some gas turbines; each OEM sets their own upper limits. Regardless of the gas turbine limits, H_2S is a highly toxic gas; exposure to concentrations above 100 ppm for even a few minutes can cause physical harm or even death [16]. To resolve this issue, the fuel can be treated with commercially available systems to remove sulfur and H_2S. If the fuel is not treated, special safety constraints may be required for maintaining fuel and combustion systems to avoid human exposure.

Operating a gas turbine on a fuel with increased sulfur or H_2S concentrations may lead to increased emissions of sulfur dioxides (SOx), which may create environmental issues. The presence of increased levels of sulfur in the fuel may cause acid-based corrosion in gas turbine systems unless properly configured and operated. This may require modifications to the fuel accessory system as well as ensuring that exhaust gas temperatures remain above the dew point to avoid the formation of acid in the exhaust system.

Natural Gas Liquids, Ethane, and Propane

When natural gas comes out of the ground, it can be classified as wet or dry. Wet gas is defined as having a significant content of non-methane hydrocarbons, including ethane, propane, butane, pentane, etc. When these non-methane hydrocarbons (NMHC) are separated out, they are called natural gas liquids (NGLs) or condensate. The terms natural gas liquid and condensate are used as these hydrocarbons may condense into a liquid during the initial processing steps. Dry gas, on the other hand, is substantially free of natural gas liquids (NGLs). Dry gas is a product of processing "wet" natural gas; it can also occur naturally in wells that are substantially free of higher molecular weight hydrocarbons.

Once the raw gas stream is pumped from the well or field, it is sent to a processing facility (as shown in Figure 6), where among other processes, the dry gas is separated from the NGLs, which can be further processed to separate out individual components (i.e., ethane, propane, and butane). Higher molecular weight hydrocarbons (starting at pentane) can be grouped together and are called natural gasoline. The exact percentage of these compounds available from processing and fractionation is dependent on the composition of the gas from the gas well or field. This variation in content can impact the ability and/or operability when used in a gas turbine. In some cases, some portion of the NGLs (i.e., condensates) may be left unprocessed and used for a variety of purposes, including power generation.

An advantage for ethane, propane, and more generically condensates is that they can be stored as a liquid at moderate temperatures and/or pressures relative to LNG. This creates opportunities to use these as power generation fuels. However, a vaporizer is required to provide the energy needed to shift the fuel from the liquid to the gas phase. The energy required for the vaporizer must be considered when examining the auxiliary loads needed to operate a power plant.

Liquefied Petroleum Gas

Liquefied petroleum gas (LPG) is a subset of the gases separated out from the fractionation facility. Although there is no industry standard definition for LPG, it is typically a fuel that contains mostly propane and butane. The HD-5 version of LPG has a minimum propane concentration of 90% (by volume) with a maximum of 5% (by volume) of propylene (C_3H_6). Commercial grades of LPG as defined by ASTM D1835 are limited to 2.5% (by volume) of butane and higher molecular weight hydrocarbons. Other grades of LPG can contain as much as 40–50% (by volume) butane. Just like 100% propane, LPG fuels can be used in gas turbines for power generation and can be stored as a liquid at moderate temperatures and/or pressures.

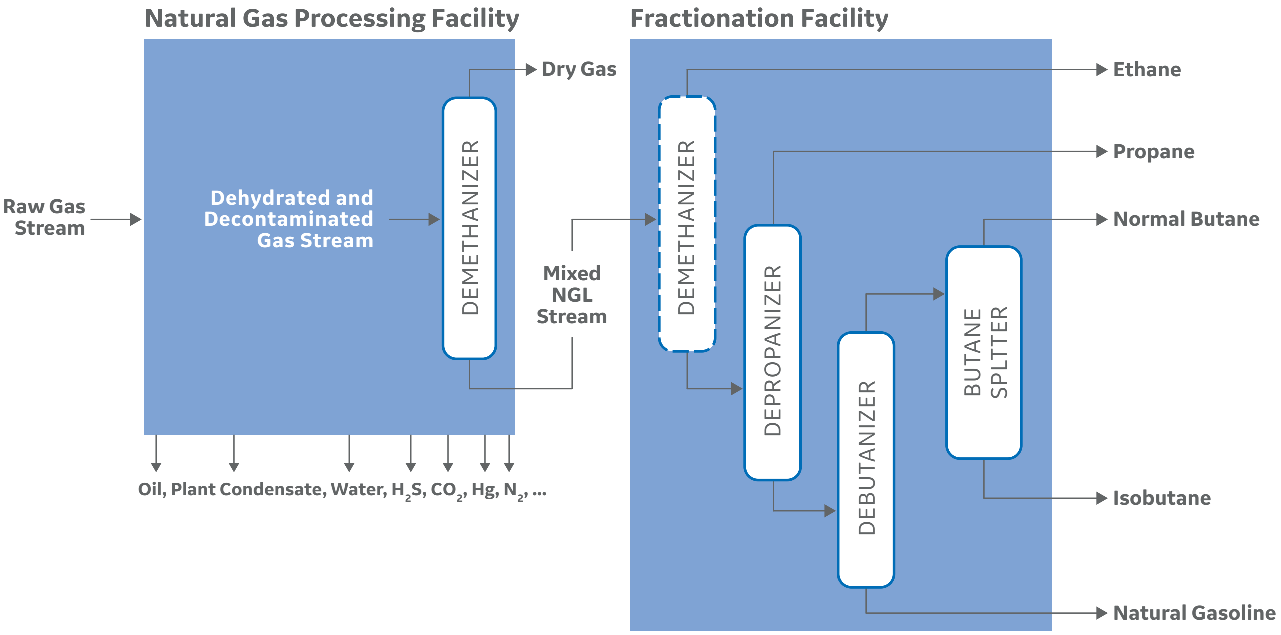


Figure 6 – Natural gas processing and fractionation schematic [17].

Synthetic & process gases

There are many gases that are the primary product of a chemical process (i.e., syngas) or are the waste product of a man-made process. These gases may be used to generate power in the same industrial complexes in which they were produced, to reduce the need for importing power from the electrical grid. Typical examples include blast furnace gas (BFG) and coke oven gas (COG), which are both produced during the production of steel.

Many process gases have lower specific energy (on a volumetric basis) than natural gas. For example, a typical LHV for natural gas is approximately 911 BTU/scf (~35 MJ/Nm3) while the LHV for steel mill gases is ~100–190 BTU/scf (~3.9–7.6 MJ/Nm3). When comparing the heating value of natural gas and steel mill gases, this shift represents a reduction of ~80–90% in the volumetric energy content of the fuel. Due to the significant reduction in heating value associated with these fuels, they are sometimes called low BTU or low calorific value (LCV) fuels.

To compensate for the large reduction in specific energy for these low BTU fuels, an increase in the fuel flow rate is required to maintain the same energy input into the gas turbine. This results in fuel systems and combustion systems that are configured for this specific application. In addition, some of these fuels, specifically the steel mill gases, are produced at relatively low pressures. This requires a compressor to boost the fuel pressure to the required level for injection into the gas turbine, which depending on the gas turbine, could be from 12–30 bar.

These fuels may have a wide range of constituents, including hydrogen (H_2), carbon monoxide (CO), and non-methane hydrocarbons. Hydrogen and some non-methane hydrocarbons (i.e., ethane) are significantly more reactive than methane and may have operability issues if used in a DLE combustion system. In addition, the increased fuel flow required for these fuels (to compensate for the low volumetric energy density) requires large fuel passages, which may not be practical on a DLE combustor due to operability limits. Thus, these fuels are typically used in diffusion combustion systems.

An additional concern for operating in industrial environments, especially in steel mills, is the level of particulates and other contaminants that could be present in the fuel. For these projects, additional steps are recommended for removing these particulates from the fuel prior to use in the gas turbine.

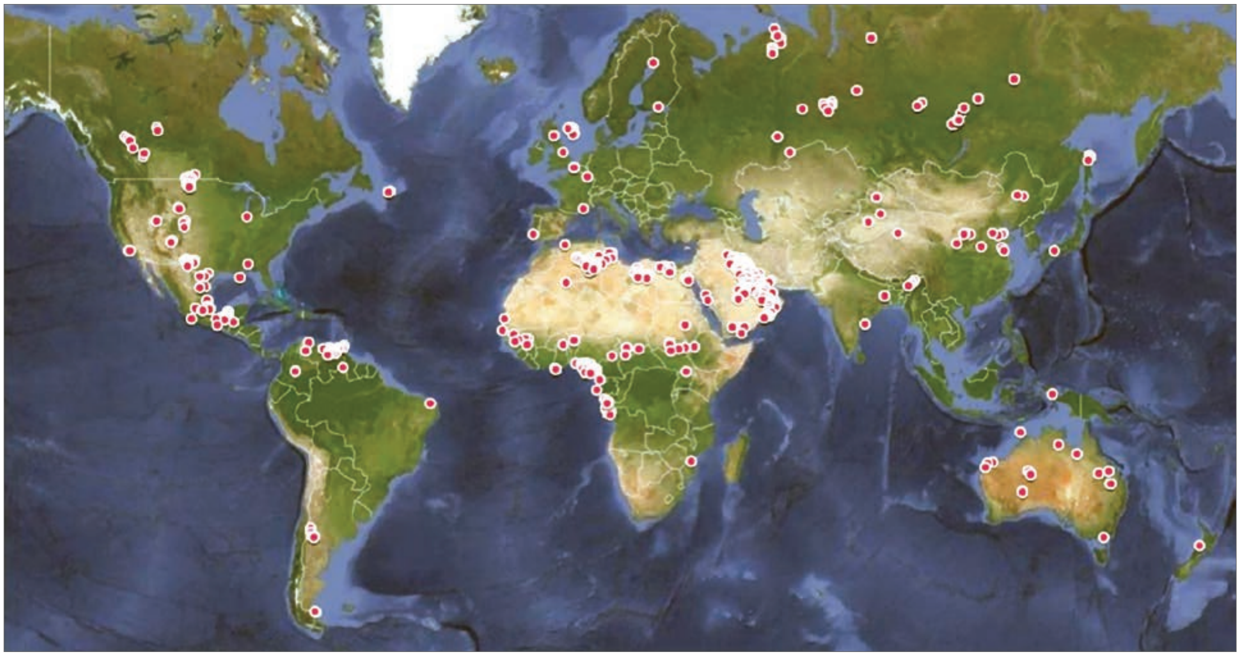


Figure 7 – Map of global flaring sites, Dec 2017. Data processing by NOAA's National Geophysical Data Center [19]; data was collected by the US Air Force Weather Agency.

The general category of process gases can also include "waste" and "flare" gases. These gases include by-products from a wide variety of industries. Some of the gases are hydrocarbon rich and can easily be used as fuel in a gas turbine.

Flare Gases

Flare gases constitute a wide array of hydrocarbons that are waste or by-products of oil and gas operations, or petrochemical processes. The World Bank's Global Gas Flaring Reduction Partnership has stated that "flaring gas wastes a valuable energy resource that could be used to support economic growth and progress" [18]. These typically include non-methane hydrocarbons and more likely may include heavier molecules such as pentane (C5). Flaring is a global phenomenon as shown in Figure 7.

There are generically two types of flare gas: upstream and downstream. Upstream flaring is used to burn natural gas and other hydrocarbons produced at oil and gas facilities that lack sufficient infrastructure to capture all the gas that is produced. If power generation facilities were present at these sites, they could generate power to support local demand. Downstream flaring is the burning of gas at oil refineries, natural gas processing facilities, coal mines, and landfills to dispose of gas in situations with an interruption in the normal use of process gases. As downstream flares are intermittent, they are not likely to be considered as sources of power generation fuel.

Hydrogen

Hydrogen (H_2), which can be used for power generation, can be generated by reforming natural gas or by using electrolysis to split water. Hydrogen, like syngas and steel mill gases, has a low volumetric heating value, ~274 BTU/scf (10.7 MJ/Nm^3), requiring specifically configured fuel accessory systems. Gas turbines are capable of operating on hydrogen blended with natural gas, as well as fuels with high levels of hydrogen. The use of fuels with significant levels of hydrogen, like process gases, may require the use of a diffusion flame combustor. The specific hydrogen limits are a function of the particular gas turbine. More details on the hydrogen capability and experience of GE gas turbines can be found in a recent white paper, GEA33861 [20].

Distillate Oil and Other Refined Liquid Fuels

Diesel fuel (also known as distillate, distillate fuel oil, or just fuel oil #2) is the product of refining crude oil. The process of refining creates more than just traditional diesel fuel; it produces a wide variety of liquid hydrocarbons, many of which are typical liquid fuels used for power production and transportation. As shown by the schematic in Figure 8, refineries use a distillation process in which crude oil is heated and individual hydrocarbons are separated from the crude oil based on their boiling point [21, 22]. The result is a series of liquid products, each with a well-defined initial and final boiling point, as well as uniform chemical and physical properties. Many of the liquid fuels used in aeroderivative gas turbines today are produced from refining crude oil, including distillate fuel oil (diesel #2), naphtha, and kerosene (i.e., jet fuel). In addition, diesel is easy to transport and is used as a backup power generation fuel for hundreds of gas turbines across the globe.

Crude Oil, Residual Oil, and Heavy Fuel Oil

As mentioned in the last section, crude oil is the feedstock for many refined liquid fuels, but crude oil itself cannot be used as a power generation fuel in aeroderivative gas turbines due to the presence of vanadium (V).

In a gas turbine (as well as boilers and engines that use crude oil and heavy fuel oils), vanadium reacts with oxygen to become vanadium pentoxide (V_2O_5), which is a molten salt at typical temperatures in a gas turbine hot section. This compound rapidly attacks the oxide coatings present on many gas turbine components, which may in turn impact hardware durability. The typical mitigation is the use of a magnesium-based corrosion inhibitor, which creates a non-corrosive ash. However, this ash sinters at relatively low temperatures (~2,000 °F) becoming a hard, glassy, or ceramic type of material. The current aeroderivative liquid fuel specification (MID-TD-0000-2) limits vanadium content to less than 0.2 ppm. For this reason, even fuels with small amounts of vanadium cannot be used in aeroderivative gas turbines. This includes crude oils, residual oil, and heavy fuel oils.

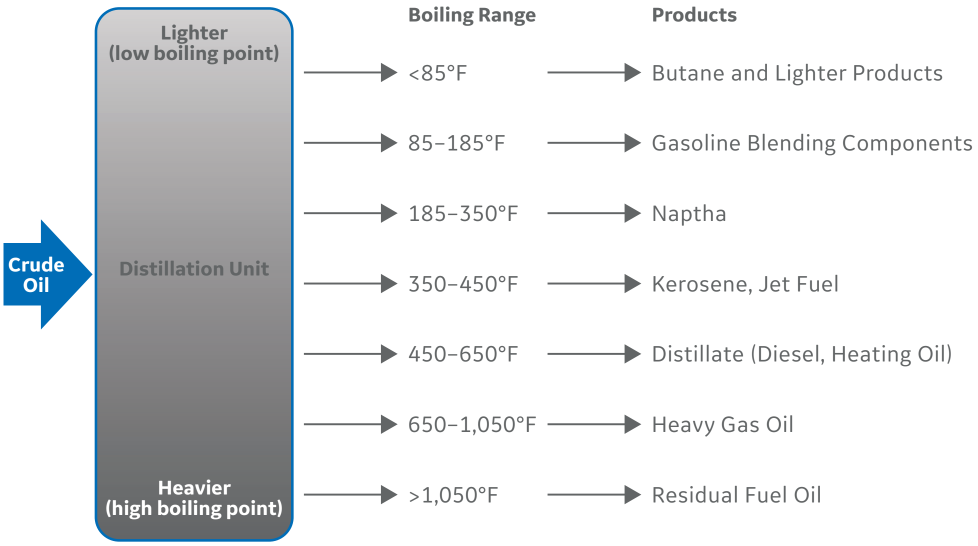


Figure 8 – Crude oil distillation [21].

Biofuels

Not all liquids fuels are produced from crude oil. Many are created using renewable feedstocks and are generically called biofuels. This broad category includes ethanol derived from natural sugars (i.e., sugar cane) as well as biodiesels produced from the oils of various seeds including corn, palm, soy, rapeseed, and more [23]. Although these fuels can be very similar to diesel, they may have physical properties and/or components that do not match a true distillate.

Depending on the method used to create these fuels, they may have more alkali metals than allowed by the OEM gas turbine fuel specifications. Alkali metals, which include sodium (Na), potassium (K) and lithium (Li) can contribute to hot section corrosion, and therefore, most OEMs have limits on the amount allowed. For GE's aeroderivative gas turbines per the liquid fuel spec MID-TD-0000-2, this limit is 0.2 ppm. If a (non-alcohol) fuel has an alkali metal content higher than the OEM limit, it may still be possible to use in a gas turbine as these contaminants can be easily removed. The process requires a water wash, which can be completed with commercially available equipment.

Synthetic Fuels

Not all liquid fuels are directly derived from crude oil. Some are generated via other chemical processes. One example of this type of fuel is dimethyl ether (DME). Synthetic liquid fuels (and some biofuels) may have poorer lubricity characteristics relative to diesel. This is important as some rotating equipment in the liquid fuel accessory system utilizes the inherent lubricity of the fuel to keep properly lubricated. This issue can be mitigated with the use of a lubricity additive.

AERODERIVATIVE FUEL FLEX CAPABILITIES & FIELD EXPERIENCE

The primary fuel for many aeroderivative gas turbines, as it is for heavy-duty gas turbines, is natural gas and/or LNG. Many units are configured as dual fuel systems, providing the ability to operate on a liquid fuel if the primary fuel is not available. In most cases, the secondary or backup fuel is distillate fuel oil #2. Aeroderivative gas turbines, having been developed from aircraft flight engines, are also capable of operating on kerosene and jet-A as part of their aviation heritage. But, GE's aeroderivative gas turbines are capable of operating on many of the alternative fuels detailed in the previous section. Many of these fuel flex capabilities were evaluated at a GE Power facility in Houston, Texas [24]. This section will focus on the specific capabilities and field experience for alternative fuels, including LPG, biofuels, flare gases, and more.

Liquefied Petroleum Gas (LPG)

LPG has been used as fuel in gas turbine power plants for over 25 years, typically as an alternative to natural gas and liquid fuels, on both aeroderivative and heavy-duty gas turbines.

GE's first use of LPG in the aeroderivative platform was in the late 1980s as a backup fuel on three LM2500 gas turbines at a site in the US. The gas turbines were configured for dual fuel operation with a SAC combustion system. The primary fuel was natural gas blended with steam for NOx emissions control. Vaporized LPG blended with compressed air was used as a backup fuel. Four 30,000-gallon tanks were used to store LPG as a liquid, providing a 72-hour back-up supply at load. The next application for LPG was in 2007 in Japan. An LM6000 was installed and operated on LPG for multiple years, accumulating ~12,500 fired hours with ~880 starts. The unit stopped operating due to commercial constraints not related to fuels.

Today, GE's aeroderivative gas turbines are capable of operating on a wide range of LPG fuels, from 100% propane to 100% butane. This has been enabled primarily by upgrades to the controls and fuel accessory systems to deal with the large difference in vaporization temperature between propane and butane.

Commercially, there has been an increased interest in the use of LPG as it is a cleaner alternative to heavy fuel oil (HFO) and other liquid fuels. Projects that are in development or are nearing commercial operation include:

- In the US Virgin Islands, an LM2500 provided by APR is being commissioned on LPG, with commercial operation expected later in 2018.
- In Ghana, GE is supplying aeroderivative gas turbines that will operate on LPG. These are being developed in two-phases; the initial phase will be LM2500 gas turbines operating in simple cycle configuration. The second phase will include additional aeroderivative gas turbines in combined cycle configuration. Once completed, the power plant is expected to produce 400 MW of power and will be the "biggest of its kind in the world" [25, 26].
- In July 2018, GE signed a memorandum of understanding (MoU) with the Beximco Group to create Bangladesh's first LPG-based power plant to generate 150 MW of electricity. Plans are targeting generating power from this plant within two years. [27]

In addition to stationary power generation applications, GE's aeroderivative gas turbines were selected to power a next-generation LPG fueled ferry. These ships will be configured with GE's Combined Gas Turbine Electric and Steam (COGES) system [28], which will provide for all ship power including propulsion. The compact COGES arrangement—lighter and smaller than comparable diesel engines—allows for more revenue generating space on board ships and lower lifecycle costs. See the COGES system arrangement in Figure 9. Maintenance of the COGES system requires only about 300 man-hours per year, and the entire turbine can be removed and replaced within 24 hours, reducing downtime for minimal interruption to ship operations. With regards to environmental regulations, these gas turbines meet International Maritime Organization Tier III and United States Environmental Protection Agency Tier 4 standards now without exhaust after treatment and no methane slip.

Hydrogen & Steel Mill Gas

Until recently, most hydrogen experience with GE's aeroderivative gas turbines has been in the petrochemical industry, utilizing by-product gases such as excess hydrogen from steam reforming. Table 3 summarizes GE's aeroderivative turbines' commercial experience with hydrogen-containing fuels. From 1986 until recently, the LM5000 package (33 MWe, ISO conditions) in Germany operated on various mixes of methane with up to 50% hydrogen. Other packages include the LM2500 (22MWe) in the US and Brazil, and the LM6000 (42 MWe) in the US and Japan.

For gas turbines configured with DLE combustion systems, the hydrogen content is limited to 5% by volume. The limit is due to fast flame speeds from high hydrogen fuels that can result in flashback or primary zone re-ignition. For SAC systems, limits range from 35% hydrogen by volume for larger turbines (up to 100 MWe), to about 85% by volume for smaller turbines in the 18 MWe to 30 MWe power range. Engineering factors include combustor geometry, airflow, and cooling patterns.

GE recently introduced the LM2500+ series of aeroderivative gas turbines, which can utilize coke oven gas (COG) as fuel for power generation. The LM2500 is an ideal fit for steel mill applications because it requires minimal changes and best fits the available volumes of COG and power demand found at typical coking facilities. COG has very high hydrogen content (up to 65% by volume) and contains many by-products such as BTX (benzene, toluene, and xylene), naphthalenes, tar, sulfur compounds, and alkali metals. With the right fuel treatment, conditioning, and fuel delivery system, COG fuel used in a gas turbine is both a cost-effective solution and significantly reduces the environmental impact of the steel-making process. The first two GE aeroderivative COG units entered commercial service in the summer of 2011 (see Figure 10); they generate 60 MW in a combined cycle configuration.

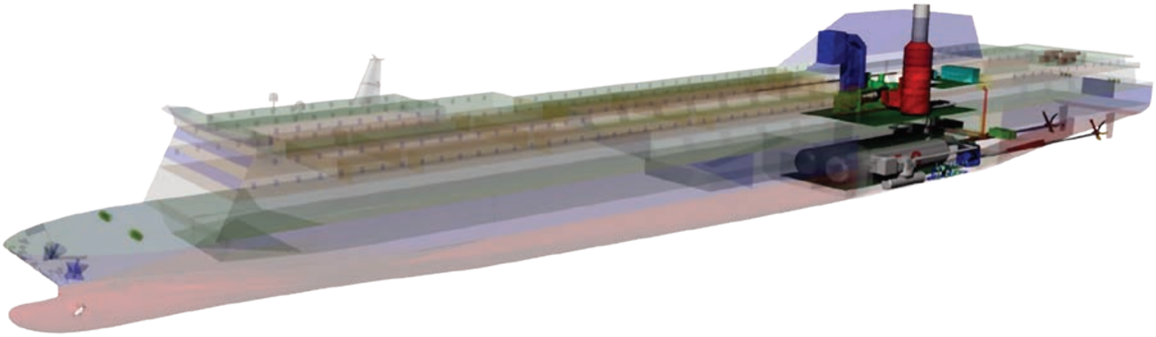


Figure 9 – Image of COGES powered ferry [28].

Table 3 – Aeroderivative experience on hydrogen fuels

Engine	Country	Fuel LHV		Fuel details
		BTU/lbm	BTU/scf	
LM2500	USA	18,148	1,003	12.9% (by vol) hydrogen; 12% olefin
LM2500+	Brazil	18,974	1,048	14.2% hydrogen, 21.5% olefin
LM2500+ and +G4	China	17,363	462	58.5% (by vol), hydrogen
		15,385	458	
LM5000	Germany	24,893	594	50% (by vol) hydrogen
	USA	18,016	954	29.5% hydrogen, 12.5% olefin
LM6000	USA	19,185	904	32.8% hydrogen, 16.5% olefin
	Japan	21,994	904	10% hydrogen

Lean Methane

Although much of the natural gas used worldwide has a low level of inerts, there are pockets of gases with significant amounts of CO_2 and/or N_2. In support of customers interested in operating on these fuels, GE Power's gas turbine engineering team evaluated the use of these fuels in an aeroderivative combustion system. These tests were run in a GE facility specifically with capabilities that allow gas blending to support alternative fuels testing; see Figure 11. The results provided confirmation that lean methane fuels can be successfully used in an aeroderivative gas turbine.

Figure 10 – LM2500 gas turbine generating power from COG at a steel mill plant in China.

Figure 11 – GE aeroderivative gas turbine test facility.

Figure 12 – 2 X LM2500 power plant operating on lean methane fuel.

These fuels have also been used successfully in the field for many years. An LM1600 gas turbine located in the US operated on a lean methane fuel with $N_2 + CO_2$ being ~30% (by vol) of the fuel. In addition, a pair of LM2500 gas turbines in Argentina operated on a lean methane fuel with a heating value in the range of ~420–630 BTU/scf (~16,500 – 24,714 kJ/Nm3). The CO_2 content of the fuel has varied over time, ranging from ~ 48–69% (by volume). These units, shown in Figure 12, have accumulated over 200,000 hours on this fuel.

Flare Gases

Gas turbines are capable of operating on a wide range of gaseous hydrocarbons, including methane (CH_4), ethane (C_2H_8), propane (C_3H_{10}), butane (C_4H_{12}), and heavier hydrocarbons, which are the main components of flare gases. Thus, gas turbines are very capable of operating on these fuels.

The concept of flare gas for power is being developed too with the announcement by GE and Marinus Energy for the Atuabo Waste to Power Independent Power Project in Ghana. Instead of flaring excess isopentane, this power plant will use this hydrocarbon stream to power a set of TM2500 aeroderivative gas turbines [29, 30]. This power plant will not only generate power for 100,000 households, but it will do so while reducing emissions (relative to a flare stack).

Biofuels

The category of fuels generically called biofuels includes a range of liquid fuels with sources that are associated with renewable feedstocks. These include not only alcohols (i.e., ethanol) but also the broad category of biodiesels.

One issue of concern with biofuels, including both alcohols and biodiesels, is that they may contain higher levels of alkali metals (sodium, potassium) than are allowed by GE's liquid fuel specifications. If this happens for a biodiesel, a pre-treatment of the fuel is required. This is not possible for alcohols as they are soluble in water, so traditional water wash systems will not work. In addition, biodiesel fuels may contain compounds that impact long-term durability of some materials used for mechanical seals in the fuel accessory system. The composition of a biodiesel fuel should be reviewed before using in an aeroderivative gas turbine.

Figure 13 – Biodiesel delivery and fuel connections.

Once these issues are resolved for a given fuel, they can be used for generating power. For example, in 2007, two sites in the US evaluated the performance of operation on a B100 (100% biodiesel) fuel. One of these sites has an LM1600 and the other an LM6000. Preliminary results from the LM1600 test showed lower CO, NOx and total UHC emissions when operating on biodiesel relative to ultra-low sulfur diesel (ULSD). The LM6000 evaluation used biodiesel that met GE's aeroderivative liquid fuel specification as well as ASTM D6751. For this test, fuel truck tankers delivered and stored the biodiesel; see Figure 13. The emissions analysis showed lower than expected values for NOx and particulate matter [31].

In 2010, two GE LM6000 gas turbines in Brazil were converted to operate on sugarcane-based ethanol [32, 33]. The demonstration consisted of ~1,000 hours of testing (actual gas turbine operating time on ethanol), including load variation, water injection variation, fuel transfers between natural gas and ethanol, and startup and shutdown of the gas turbine on ethanol. The demonstration included interim borescope inspections, and at the conclusion of the demonstration, the gas turbine was disassembled for a detailed component inspection. The performance of the gas turbine was equivalent to the same gas turbine operating on natural gas, and the emission levels of sulfur dioxide (SO_2), aldehydes, carbon monoxide, and unburned hydrocarbons were very similar. Nitrous oxide (NOx) emissions were reduced when compared to distillate fuels, and all the carbon emissions were from renewable sources. Hot section component deterioration was comparable to distillate fuel operation for the same run time [8].

FUEL BLENDING

Fuel blending or bi-fueling is a capability available for many gas turbines, including GE Power's aeroderivative gas turbines. Fuel blending is when different fuels are mixed (or blended) together to use as a single fuel in the gas turbine. The blending or combining of the different fuels can happen upstream of the power plant and then the blended fuel can be transported to the power plant. Alternatively, the fuels can be supplied to the power plant separately and then mixed together just before being injected into the gas turbine combustion system. Fuel blending can be done for both gas and liquid fuels; Figure 14 shows fuel mixing skids that were used to blend together two gases for injection into a gas turbine.

Figure 14 – Fuel blending systems for multiple F-class gas turbines.

Fuel blending is typically performed when there are not sufficient quantities of a given fuel to fully load a gas turbine. In these situations, a second fuel is added to provide the necessary energy to allow the gas turbine to operate at 100% load. This is illustrated in Figure 15, which demonstrates fuel blending (or bi-fueling) in a situation in which LPG is used with natural gas to ensure that the gas turbine is operating at 100% load at all times even though the supply of natural gas will vary over time.

In other situations, a fuel may not meet OEM's specifications due to higher than allowable levels of a contaminant or because a fuel characteristic is outside of the limits of the OEM fuel specification. If a specific fuel property is out of spec, fuel blending (with a fuel that meets the OEM fuel specification) can be used to improve the out-of-bounds fuel characteristic by creating a blended fuel that meets the OEM requirements. In a third scenario, the primary fuel of interest is too expensive, and so a lower cost fuel is blended with the primary fuel to reduce costs.

One example of fuel blending already mentioned in previous sections pertains to biofuels. A B20 fuel is a blend of 20% biodiesel with 80% being standard diesel fuel oil. This fuel could be delivered to a power plant as a blend, or as two, independent fuel streams that need to be blended together.

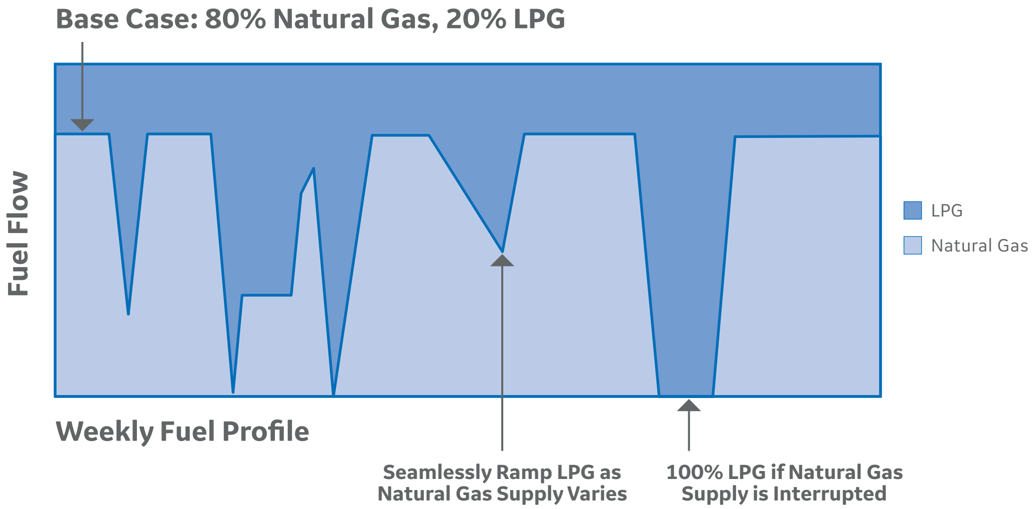


Figure 15 – Example of bi-fueling with varying fuel supply profiles.

THE ECONOMIC VALUE OF FUEL FLEXIBILITY

The ability of a gas turbine to operate on multiple fuels—or to be reconfigured to operate on newer fuels—means that a power plant is never locked-in to a single fuel. There are multiple benefits for changing fuels, ranging from improved emissions to reduced costs. One reason not typically considered is "future proofing" the gas turbine. For example, in some regions, natural gas and LNG are the preferred power generation fuels, but not yet available. In these situations, a traditional approach is to configure the gas turbine with a dual fuel capability, offering the ability to operate on diesel until natural gas (or LNG) becomes available. An alternative to diesel not typically considered is LPG, which could offer benefits for the power plant.

Environmental Factors

Although liquid fuels, such as diesel or HFO, are typically considered when natural gas or LNG is not available, these fuels can have characteristics that negatively impact emissions. For example, relative to gaseous fuels some liquid fuels contain increased levels of nitrogen, particulates, trace metals, and sulfur. These may lead to increased emissions of NOx, SOx, and particulate matter (PM). Gaseous fuels like LPG are a cleaner option (relative to liquid fuels) as they produce significantly less particulate matter and little to no SOx emissions.

In addition, many regions are becoming more concerned with CO_2 emissions. As gas turbines in a combined cycle configuration can provide efficiency greater than 50%, this provides a power generation solution which reduces CO_2 emissions relative to other power generation technologies. (A platform with higher efficiency is able to produce the same power consuming less fuel. This translates into less CO_2 being generated and released into the atmosphere.)

Consider the emissions impact from an aeroderivative gas turbine operating on LPG in comparison to a reciprocating engine operating on HFO. Given the same operational profile, the aeroderivative gas turbine will emit ~190,000 tons less CO_2 emissions than the reciprocating engine when operating. This is equivalent to removing the CO_2 emissions from ~20,000 cars. In addition, the aeroderivative gas turbine will emit less NOx, particulate matter, and sulfur as shown in Table 4.

Table 4 – Comparison of aeroderivative and reciprocating engine emissions

		Reciprocating engine	**Aeroderivative gas turbine**
Emissions	**Units**	**HFO**	**LPG**
NOx @ 15% O_2	mg/Nm³	> 700	~3.5X less
Particulate matter	mg/Nm³	>30	~2X less
Sulfur emissions	mg/Nm³	> 500	< 2

Economic Value

Operating a gas turbine power plant requires large volumes of fuel to keep operating. For this reason, fuel is typically the single largest cost of operating a power plant, ranging from 50% to 80% of a power plant's annual operating budget. Therefore, even small changes in fuel price can have a large impact on the overall cost of operating a power plant.

For example, let's examine a case with an LM2500 gas turbine that operates for 8,000 hours per year on a fuel that costs $4/MMBTU. If this plant could switch to a fuel that costs $3/MMBTU (a one-dollar per MMBTU savings), this will result in cost savings of ~2.1 million US dollars per year! Figure 16 highlights the savings for this example using an online tool that is available via GE Power's fuel capability web page: https://www.ge.com/power/gas/fuel-capability. This tool allows the user to select the gas turbine model and configurations from a drop-down list, then select the number of annual operating hours, and set the price of a baseline and alternative fuel. The tool then calculates the annual fuel savings, a 10-year fuel cost savings, and a 20-year NPV on these fuel savings.

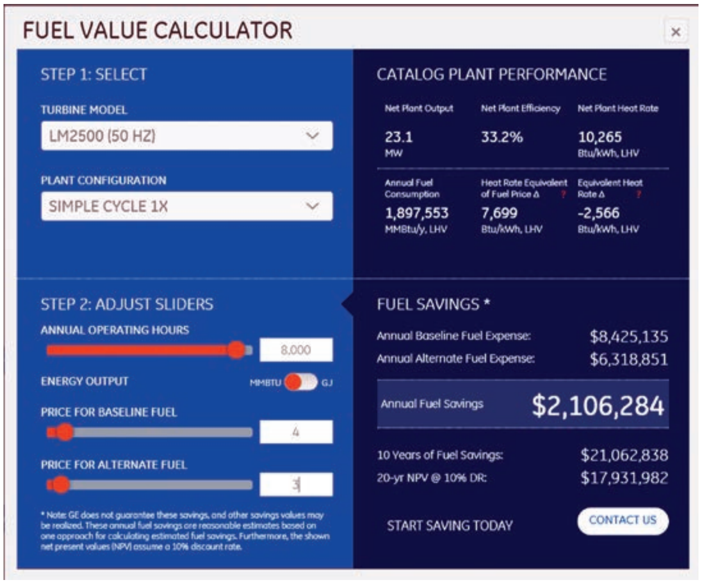
Another factor in the economics of fuel switching is the efficiency of the gas turbine. When operating on a gas fuel, an aeroderivative gas turbine configured with a DLE combustor typically has a higher efficiency than the same gas turbine operating with a SAC combustor. This typically happens as the SAC combustor is using water to mitigate the higher NOx emissions level that comes from operating with a diffusion flame. As an example, we can consider two LM2500 gas turbines operating on natural gas, but one configured with a DLE combustor and the other with a SAC combustor. The turbine configured with the SAC combustor will generate ~1.5 additional MW relative to the other turbine (due to the injection of water to mitigate increases in NOx). But, the gas turbine with the DLE combustor will have 1.5 points of additional efficiency [13].

There are alternative fuels that offer both environmental and economic benefits. For example, propane (LPG) is both a lower cost fuel and offers improved emissions (fewer particulates, less SOx) than some liquid fuels, including high sulfur diesel fuels and HFO. Figure 17 shows that propane spot prices have been historically lower than diesel, with propane being ~50% of current diesel prices as of November 2018.

FUEL FLEXIBILITY & ECONOMICS: GAS TURBINES vs. RECIPROCATING ENGINES

As presented in this white paper, aeroderivative gas turbines are able to operate on a wide variety of fuels, but there are some that cannot be utilized. Heavy fuel oil (HFO), which is a widely used fuel due to its low cost, is among the list of fuels that cannot be used in an aeroderivative gas turbine. But, cost of fuel is not the only metric to consider when selecting fuel and the associated generating technology.

Ultimately, the full cost of generating power needs to include fuel and the overall capital and operating expenses for the power plant. The efficiency of the generating equipment can have a direct impact on the ultimate economics. A power plant operating at a higher efficiency will use less fuel and therefore have lower fuel costs than a plant with lower efficiency. This statement is independent of technology. Other considerations in defining overall costs include auxiliary power loads that may be required for a given fuel. For example, HFO must typically be heated to reduce the viscosity in order to pump the fuel and have it flow more easily; this additional power load impact reduces the overall power plant efficiency.



FUEL VALUE CALCULATOR

STEP 1: SELECT

TURBINE MODEL: LM2500 (50 HZ)

PLANT CONFIGURATION: SIMPLE CYCLE 1X

CATALOG PLANT PERFORMANCE

Net Plant Output	Net Plant Efficiency	Net Plant Heat Rate
23.1 MW	33.2%	10,265 Btu/kWh, LHV

Annual Fuel Consumption	Heat Rate Equivalent of Fuel Price Δ	Equivalent Heat Rate Δ
1,897,553 MMBtu/y, LHV	7,699 Btu/kWh, LHV	-2,566 Btu/kWh, LHV

STEP 2: ADJUST SLIDERS

ANNUAL OPERATING HOURS: 8,000

ENERGY OUTPUT: MMBTU

PRICE FOR BASELINE FUEL: 4

PRICE FOR ALTERNATE FUEL: 3

* Note: GE does not guarantee these savings, and other savings values may be realized. These annual fuel savings are reasonable estimates based on one approach for calculating estimated fuel savings. Furthermore, the shown net present values (NPV) assume a 10% discount rate.

FUEL SAVINGS *

Annual Baseline Fuel Expense: $8,425,135

Annual Alternate Fuel Expense: $6,318,851

Annual Fuel Savings $2,106,284

10 Years of Fuel Savings: $21,062,838

20-yr NPV @ 10% DR: $17,931,982

Figure 16 – GE's fuel value calculator (https://www.ge.com/power/gas/fuel-capability).

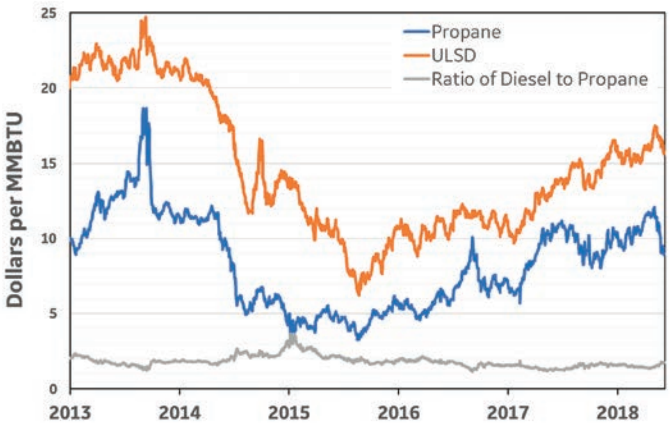


Figure 17 – NY Harbor ULSD and Mont Belvieu Propane spot prices (Source: www.eia.gov).

As an example, consider an aeroderivative gas turbine operating on propane versus a reciprocating engine operating on HFO. Table 5 shows that the total delivered price for HFO is less expensive than propane, but due to the higher efficiency of a gas turbine operating on propane relative to the efficiency of a reciprocating engine on HFO, the cost per kW of electricity is actually lower for the gas turbine. Assuming that these power plants are configured to generate 50MW, the cost of electricity for the aeroderivative per year (8,000 hours) will be $3.9 million (~10%) less than the cost for the reciprocating engine. Given a fixed tariff for electricity, the power plant with the aeroderivative gas turbine should earn more profit than the plant with the reciprocating engine.

Table 4 – Comparison of aeroderivative and reciprocating engine emissions

	Unit	Propane	HFO
Technology		Aeroderivative gas turbine	Reciprocating engine
Fuel price	$/MMBTU (HHV)	$9.9	$10.9
Delivery cost	$/MMBTU (HHV)	$3.0	$1.1
Total fuel cost	$/MMBTU (HHV)	$12.9	$12.0
Efficiency	(LHV)	49.5%	41.5%
Cost of electricity	$/kWh	0.0889	0.0987
% savings on CoE		~9.93%	

SUMMARY

GE's aeroderivative gas turbines have experience on a wide range of gas and liquid fuels and can be operated on many alternative fuels that are available across the globe. Many of these fuels may be available at a lower cost than other (more traditional) fuels, providing an economic benefit in terms of reduced cost of electricity. Many of these fuels also generate fewer emissions and therefore provide an additional environmental benefit.

NOMENCLATURE

BFG	Blast furnace gas
BTU	British thermal unit
CH_4	Methane
C_2H_6	Ethane
C_3H_8	Propane
C_4H_{10}	Butane
CO	Carbon monoxide
CO_2	Carbon dioxide
COG	Coke oven gas
DLE	Dry low emissions
EPA	Environmental Protection Agency
H_2	Hydrogen
H_2S	Hydrogen sulfide
HFO	Heavy fuel oil
HHV	Higher heating value
kg	Kilogram
kJ	Kilojoule
lbm	Pound mass
LHV	Lower heating value
LM	Land and Marine
LMS	Land and Marine Systems
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MJ	Megajoule
MMBTU	Million BTU
MW	Megawatt
MWe	Megawatt electric
MWI	Modified Wobbe index
N_2	Nitrogen
NGL	Natural gas liquid
Nm^3	Normal cubic meter (cubic meter at standard conditions)
NMHC	Non-methane hydrocarbons
NPV	Net present value
NOx	Nitrogen oxides
OEM	Original equipment manufacturer
PM	Particulate matter
ppm	Parts per million
ppmv	Parts per million (by volume)
SAC	Single annular combustor
SOx	Sulfur oxides
scf	Standard cubic foot
UHC	Unburned hydrocarbons
°C	Celsius
°F	Fahrenheit
°R	Rankine

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