

GE Power



AERODERIVATIVE GAS TURBINES

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ABSTRACT

Offering advantages that reciprocating engines can't match

GE Power is one of the leaders in power generation, with deep domain expertise to help customers deliver electricity from a wide spectrum of fuel sources. We have the world's largest renewable and gas turbine fleet. Our philosophy is that innovative technologies and digital offerings can help make power more affordable, reliable, accessible, and sustainable.

What are aeroderivative gas turbines? The term “aeroderivative” means they are derived from GE’s line of aviation turbines. Essentially, a turbine that powers a Boeing 747 jumbo jet can be used on land or at sea to provide about 50 megawatts (MW) of power in a very fuel-efficient manner, with advanced aviation technology.

Why use aeroderivative turbines and not reciprocating engines? In summary, aeroderivatives have three major advantages: they can provide cheaper power, a better-quality grid, and cleaner power with lower emissions—compared to heavy fuel oil reciprocating engines, the current source running in many regions of the world.

Reciprocating engines is a very broad term. There are many different types of engines that fall under this definition and vary widely in performance. According to the EPA, “High speed diesel engines (>=1,000 rpm) are available for up to about 4 MW in size. Low speed diesel engines (60 to 275 rpm) are available as large as 80 MW. Medium speed diesel engines (400–1000 rpm) are available for up to approximately 17 MW”. Furthermore, depending on their fuel type, reciprocating engines may be spark ignited lean burn, rich burn, or compression ignited (typically for liquid fuels). Although this paper discusses reciprocating engines in general, distinction is made where necessary.

Another important characteristic of aeroderivatives is the speed of implementation and installation. Units can be installed in a matter of months and, in the case of the mobile unit TM2500, power can be available in just a few weeks after the order.

Take a closer look at the advantages of the aeroderivative turbine:

1. Cheaper power
2. Higher quality power
3. Cleaner power
4. Faster and more mobile power

CHEAPER POWER

- Higher efficiencies in combined cycle result in better use of fuel.
- Lube oil consumption is about 200 times lower than with reciprocating engines.
- Higher availability of aero gas turbines (over 98%) lowers CAPEX costs per unit of generated power.
- Aeroderivatives require on average 10 times less operational and maintenance manpower and over 15 times fewer maintenance events than reciprocating engines in 3 years of operation.
- Aeroderivatives have no maintenance penalty for daily starts.

HIGHER EFFICIENCIES

When comparing heat rates or efficiencies between aeroderivative gas turbines and reciprocating engines, three important points must be emphasized:

1. Reciprocating engines have a $\pm 5\%$ fuel consumption tolerance, while gas turbines in simple cycle, by applicable standards, do not allow this tolerance. A higher fuel consumption of up to 5% above the expected consumption can occur with reciprocating engines.
2. Besides fuel consumption, lube oil consumption in reciprocating engines must also be considered as a consumable cost, further increasing the actual cost of electricity. Reciprocating engines may use up to 400 mL/MWh of lube oil, while an LM2500 will only consume approximately 2 mL/MWh, or 200 times less. Lube oil alone can represent a saving of over 1 million US\$ per year for a 100 MW aeroderivative power plant compared to a reciprocating engine plant.
3. The additional cost of a combined cycle plant, yielding higher efficiencies, pays off. When the LM2500 generator set is used in a combined cycle configuration, the annual fuel savings can be up to \$16 million, thanks to a much lower combined cycle heat rate when compared to reciprocating engines. For power plants that operate most of the year in regions where fuel is above \$6/MMBTU, the extra cost of the combined cycle is quickly paid for.

Another characteristic of aeroderivatives is that they do not have a minimum turndown and can operate indefinitely with no load. Furthermore, by nature, and since aircraft normally use their engines at partial load during cruising, aeroderivatives also provide excellent efficiency, even at partial loads. The LMS100, for instance, can still provide 40% simple cycle efficiency at a 50% load.

| 115 MW System | Aero GT | Diesel Recip | Gas Recip |
|-------------------------------|--------------|--------------|--------------|
| Specif. Lube consump. (L/MWh) | 0.002 | 0.667 | 0.334 |
| Fuel type | NG or Diesel | Diesel | NG |
| Lube oil consumed (L/yr) | 1,914 | 638,730 | 319,365 |
| Cost (US\$/yr) | ~\$6k | ~\$2 million | ~\$1 million |

Reference Engine:
Source: OEM Web Page

LM2500 3x1 Combined Cycle

CAT CM25C

CAT GCM34

HIGHER AVAILABILITY

Aeroderivative gas turbines have the highest availability of any thermal power technology. An aeroderivative gas turbine can be replaced in a few days for a major inspection, providing a unit availability of over 98% (source: ORAP data). This directly follows the maintenance practices in the aviation industry, where an aircraft never stops for engine maintenance; the engine is simply swapped out overnight, leaving the aircraft to resume a profitable operation. Due to a lower availability, reciprocating engines require an N+1 configuration to maintain high plant availability, increasing CAPEX.

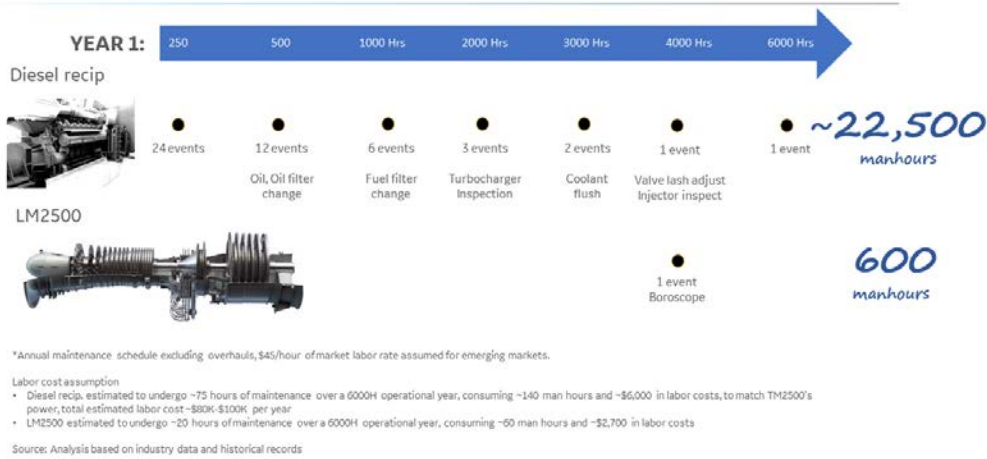
LOWER O&M COSTS

Maintenance events are about 50 times more frequent each year with high-speed reciprocating engines than with aeroderivative turbines. After just 500 hours, each unit in multi reciprocating engine installation could require up to 36 OEM stated maintenance events; by comparison, aeroderivatives have their first, and only, maintenance event of the year at 4,000 hours. In a large multi unit reciprocating engine plant, this typically means much higher man-hours for operations and maintenance versus an aeroderivative installation.

As a result, aeroderivative gas turbines require significantly fewer operational and maintenance interventions. They also save a considerable number of man-hours, requiring only 1,800 man-hours of maintenance during a 3-year cycle, compared to over 15,000 man-hours for reciprocating engines, in an equivalent sized plant.

50 times less in annual maintenance events

Annual maintenance schedule LM2500 versus Diesel Recip*
Illustration for 250 MW plant



THE VALUE IS CLEAR

The dollars-and-cents difference in operating expense—as a result of an aeroderivative turbine’s faster installation, greater fuel flexibility, simpler maintenance, and increased efficiency—is tremendous. A typical 115-MW plant using three LM2500s in combined cycle may cost more than a similar sized reciprocating engine installation—but can save over \$10 million dollars per year when compared to cheaper, and much more polluting, heavy fuel oil (HFO), considering savings of lube oil, maintenance costs, and all such expenses.

| 115 MW System | Aero GT Combined Cycle | Recip Engines |
|-----------------------------------|------------------------|---------------|
| Fuel | LPG | HFO |
| Cost of Fuel (\$mil/year) | 83.70 | 84.84 |
| Power Output (MW) | 115 | 115 |
| Declared Heat Rate (kJ/kWh) | 6990.3 | 7362.0 |
| HR Tolerance | 0% | 5% |
| Actual Heat Rate (kJ/kWh) | 6990.3 | 7730.1 |
| Fuel Cost (\$/MMBTU) | 12.00 | 11.00 |
| Cost of Maintenance (\$mil/year) | 2.62 | 9.57 |
| Cost of Lube Oil (\$mil/year) | 0.00 | 1.91 |
| TOTAL SAVINGS (\$MIL/YEAR) | 10.00 | |

HIGHER QUALITY POWER

- Aeroderivatives have much higher reliability and availability than reciprocating engines.
- Aeroderivatives have a very high capability of controlling grid frequency. They respond faster to frequency fluctuations on the grid, reducing the occurrence of blackouts.
- Aeroderivatives can burn multiple fuels, capable of switching without shutting down, thus increasing power security.

CONTROLLING GRID FREQUENCY

Aeroderivative gas turbines are potentially more reliable and may have a higher availability than reciprocating engines (98.2% vs. 93% availability, according to ORAP), meaning they could be a more sensible investment for grid firming. In fact, over half of GE's global aeroderivative fleet (3,000+ units) have demonstrated a 100% reliability rate and over 98% availability rate, under certain specific conditions and with appropriate fuel.

All of GE's aeroderivative gas turbines have at least two separate shafts, one shaft providing the necessary air flows and the other driving the generator. What this means, in practice, is that in case of a frequency drop in the grid, the other shaft can quickly increase its speed, and consequently the unit's power, even while the generator is being slowed down. This results in a much faster response to frequency fluctuations, helping to ensure a much more stable and reliable grid.

Another important aspect of grid stability is the characteristic of the generator. Not only are aeroderivatives larger machines, in themselves, already providing a high system inertia, but they also all operate at 3,600 rpm (for 60 Hz), further increasing the system inertia when compared to medium speed reciprocating engines that usually run at 900 rpm. After all, inertia is a result of mass and speed squared, so four times the speed results in 16 times the inertia, for the same size generator. This extra inertia provided by aeroderivatives ensures lower frequency fluctuations that may cause grid blackouts.

Ramp-rates: Typical medium speed reciprocating gas engines have a ramp rate of about 5 MW/min, due to the engine dynamics and the nature of the combustion system. GE's aeroderivative gas turbines, on the other hand, all have a nominal ramp rate of 50 MW/min, providing a much faster frequency control response in small grids. Real ramp rates, however, can be much higher than those for smaller load steps.

An aeroderivative main gas metering valve, for instance, has a rated opening time, from idle to full load of only 200 ms (milliseconds), providing an instant response when needed. Another important feature when considering ramp rates is that aeroderivatives have no under-frequency trips, assuring they will remain online, even during the most intense frequency fluctuations.

FUEL FLEXIBILITY

Fuel flexibility is a major advantage of aeroderivatives. These turbines can operate on gas or liquid fuels without significant power derate nor pilot fuel requirements. Gas turbines can operate on natural gas, LNG, LPG, or diesel, among many other fuels, switching between these fuels without stopping and without a power reduction. They use the same combustion system for a wide fuel spectrum, starting with lean gas, high hydrogen content, coke oven gas, butane, LPG, light liquid distillates up to diesel fuel, or aviation kerosene. This flexibility gives customers the option to switch between fuels when economically preferred, as well as providing reliable power generation capabilities with fuels coming from different sources.

While high-speed diesel reciprocating engines could potentially be made to run on fuels such as ethane, butane, and propane, the result is commonly a significant performance drop and output derating. Only aeroderivatives can operate using these non-traditional fuels without suffering any performance and output derating. They can easily switch from running on 100% diesel to 100% natural gas, whereas a high-speed diesel reciprocating machine can burn no more than 70% natural gas in a mix with 30% diesel. (Equipping a high-speed diesel reciprocating unit with a factory dual fuel kit that allows it to burn 70% natural gas would cost an estimated \$80,000.)

Fuel Flexibility Means Security



The 87 MW Juiz de Fora Power Plant in Brazil, with two LM6000s, was the world's first totally flexible power plant, capable of running on natural gas, diesel, biodiesel, naphtha, or ethanol, increasing the power security by a diverse option of fuels.

An all-natural gas-fired aeroderivative solution versus the high-speed diesel reciprocating engine alternative yields immense savings on fuel, anywhere from \$12 million to \$43 million per year*, while still ensuring a reliable operation by diversifying the sources of fuel.

Fuel flexibility can also be an interesting characteristic when considering locally available fuels. For instance, a country that is a net exporter of naphtha or LPG would have the security of using that domestic resource in aeroderivative units. If it had to use reciprocating engines—which don't burn naphtha—that country might have to import expensive diesel.

*based on a natural gas price range between

\$1–4/MMBTU; diesel price range between \$6– 12/MMBTU (Source: Original White Paper).

Leveraging the aero superior fuel flexibility

Aero flexible to run on a variety of fuels without performance degradation

| Fuel Type | Aero | Diesel Recip* |
|-------------|------|---------------|
| Natural Gas | ✓ | ✓ |
| Ethane | ✓ | XX |
| Propane | ✓ | XX |
| Butane | ✓ | XX |
| Naphtha | ✓ | X |
| Diesel/LFO | ✓ | X |
| LCO/HDK | ✓ | X |
| Methanol | ✓ | X |

*\$/MMBtu; **Oct '18 CIF NEW; High Speed

✓ Capable, no significant derating

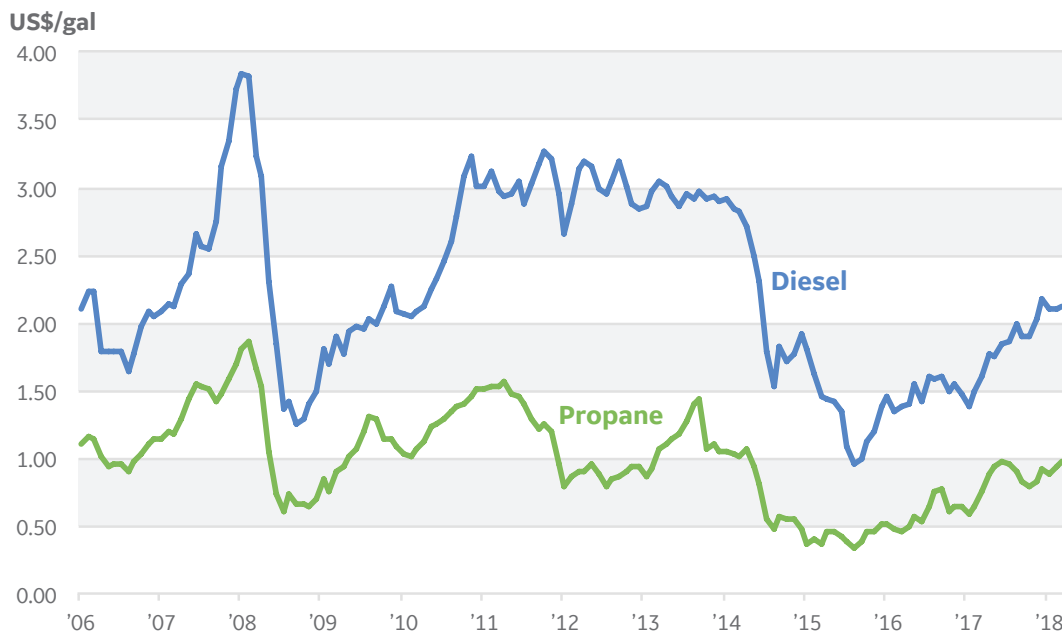
X Not capable

X Performance derated ~10% vs gas

XX Performance and output derated

Sources: EIS, AMAI, Platts

Fuel price divergence—opportunity to leverage aero flexibility



Mont Belvieu TX Propane Spot Price FOB Monthly
Source: U.S. Energy Information Administration

CLEANER POWER

- Aeroderivatives provide 90% lower emissions than reciprocating engines.
- Propane or natural gas lower emissions even further, compared to liquid fuels.
- Aeroderivatives allow for better integration of renewables in the grid, by providing a more stable grid. Solar power cannot stay connected to the grid with high frequency variation.
- 75% smaller footprint frees land for other uses (like renewable solar).

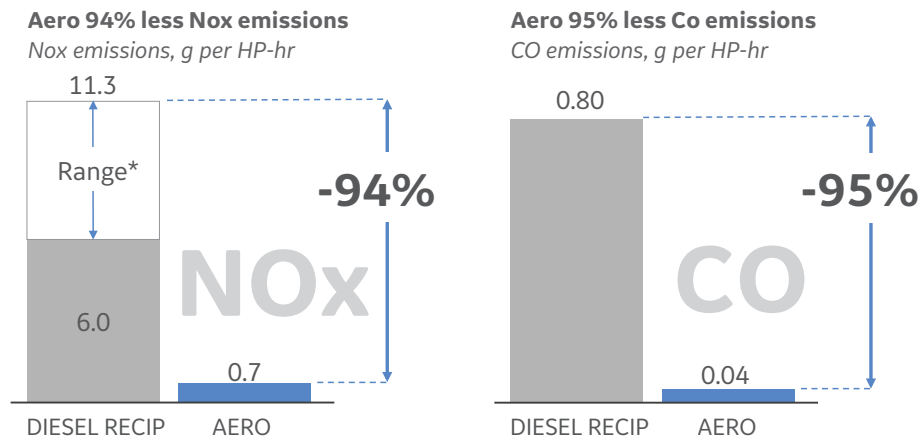
LOWER EMISSIONS

Aeroderivatives use best-in-class combustion systems and can offer 15 or 25 ppm NOx (depending on the specific model, fuel, and configuration), without the need of SCRs (selective catalytic reduction) or the use of ammonia—thereby meeting strict EPA, World Bank, and international environmental requirements.

Reciprocating engines can produce almost 10 times more NOx, 10–17 times more CO, six times more particulate matter, and six times more VOC, even when operating with the same fuels and under the same conditions. Furthermore, when operating on certain HFOs, reciprocating engines also emit a high volume of sulfur gases, while aeroderivatives operating on natural gas or LPG have no sulfur emissions.

Aero has lower emissions

NOx and CO emissions comparison with diesel recip



RENEWABLE INTEGRATION

One downside of renewables is that we cannot control when or where they will generate power. For example, solar power is unavailable at night, during an overcast day, or even a quick passing cloud. This apparent unavailability must be controlled and compensated to provide reliable and continuous power to the grid.

The nature of aeroderivative gas turbines lets them work hand-in-hand with renewables, allowing them to operate when needed, saving fuel and maintenance when renewables are available. At the end of the day, when the sun goes down, the turbines can quickly take over and keep the lights on. But more importantly than balancing demand and power generation is maintaining a stable grid to allow the integration of more renewables. Due to the nature of renewables—especially solar—frequency inverters must be used to convert DC power into grid AC power. These frequency inverters demand a stable grid frequency, otherwise, they cannot stay connected. There are many examples around the world where poor frequency control has inhibited the introduction of more renewables. Solar panels are installed but cannot deliver power to the grid effectively as they continuously disconnect.

Gas turbines may provide excellent frequency control, which may allow the increase of solar power, further reducing fuel costs. The poor frequency control capability of reciprocating engines could result in solar being disconnected and in frequent blackouts. Aeroderivative gas turbines provide better frequency control, and thus a more stable and reliable grid, potentially avoiding or decreasing blackouts.

SMALLER FOOTPRINT

Aeroderivative generator sets have much higher power density—with about 22 times more power output per unit— than high-speed diesel reciprocating engines. Aeroderivatives offer advantages in the cost of land, power density, maintenance area, and storage facilities. A GE aeroderivative power plant has a footprint that is three to four times smaller than a typical reciprocating engine plant option for equivalent power. In an island grid, real-estate can represent a significant part of power generation costs.

Not only are aeroderivative units smaller, but they are also much lighter per MW than their high-speed diesel reciprocating engine counterparts. The lighter weight leads to higher mobility, and it is a great complement to fuel flexibility. In Ecuador, for instance, six TM2500 mobile generator sets were installed to run on diesel for immediate relief of a drought-related electricity crisis. A few years later, they were easily relocated 200 miles away to burn natural gas from a nearby field. Picking up and moving a high-speed diesel reciprocating engine farm in the same way—or building a whole new power plant—would have been considerably more cumbersome, time-consuming, and expensive.

FASTER POWER SPEED OF INSTALLATION/DEPLOYMENT

How soon can these turbines provide power to the grid? The TM2500 is a version of the LM2500 gas turbine built on a movable trailer, hence the name “TM” for Trailer Mounted. These units can rapidly be deployed anywhere in the world to provide power quickly in a fast, clean, reliable, and economical fashion.

The TM2500+ solution can be deployed more than 6 times faster than other technologies

Customers may immediately generate incremental electricity revenue



*Note: The TM2500+ can be in commercial operation approximately 30 days after an order is placed, but these times may vary based on project location, site readiness, permitting process, and other variables

Due to their small size and modular nature, aeroderivatives can be transported, installed, and commissioned very quickly. As an example, two TM2500 units, rated at 34 MW each, were transported, installed, and started producing power in Puerto Rico, following Hurricane Maria, in only four weeks! Transportation cost and time: compared to the aeroderivative LM2500, reciprocating engine transport costs are at least three times higher due to a factor of 42X weight, adding in cost and special transport considerations for a 100 MW plant. Air freight is not possible for major reciprocating engine components, requiring longer transport times, while some aeroderivative gas turbines can be delivered rapidly by air anywhere in the world.

START-UP TIME

Reciprocating engines require pre-warming, lube oil, and cooling conditions to start, so start times should be assessed for a “hot” and “cold” engine. GE’s aeroderivative gas turbines have a time of cold start to maximum power delivered to the grid in 5 minutes.

Furthermore, during downtime, aeroderivative gas turbines consume no auxiliary loads, while reciprocating engines require a considerable parasitic load to maintain start readiness, keeping the engine and lube oil warm.

Aeroderivatives also have no minimum operating run time or stop time, so they can always be immediately re-started after a shutdown if required. Furthermore, they have no maintenance cost penalties for daily starts, so are also ideal for peaking applications or for balancing renewables.

CONCLUSION

State-of-the-art aviation technology can provide cheaper, cleaner, and better power for many grids around the world, ensuring a cleaner and safer operation with a high penetration of renewable energy sources.

With 50 years’ experience in aeroderivatives, over 150 million operating hours, and over 3,000 units in operation, GE has the experience and the expertise to support any power needs.

