Thermal Power Station Advice - Reciprocating Engines Study

Report for the Electricity Commission

NOVEMBER 2009

Prepared By:

DISCLAIMER NOTICE

Report for the Benefit of the Electricity commission

This report has been prepared exclusively for the benefit of the Electricity Commission. PB New Zealand Ltd (PB) will not be liable to any other persons or organisation and assumes no responsibility to any other person or organisation for or in relation to any matter dealt with or conclusions expressed in the Report, or for any loss or damage suffered by any other persons or organisations arising from matters dealt with or conclusions expressed in the report (including without limitation matters arising from any negligent act or omission of PB or for any loss or damage suffered by any other party relying upon the matters dealt with or conclusions expressed in the Report). No person or organisation other then the Electricity commission is entitled to rely upon the Report or the accuracy or completeness of any conclusion and such other parties should make their own enquiries and obtain independent advice in relation to such matters.

Reliance on Data

In preparing this Report, PB has relied on information supplied by and gathered from a number of sources including public domain and proprietary data services, internet sites, news services as well as parties involved in the industry. Any projections are estimates only and may not be realised in the future. No blame or responsibility should be attached to any of these sources for any factual errors or misinterpretation of data in the Report. PB has not independently verified the accuracy of this information and has not audited any financial information presented in this Report.

Limitations

This Report covers technical data relating to thermal generating plants and is based on the facts known to PB at the time of preparation. This report does not purport to contain all relevant information on all plant. PB has made a number of assumptive statements throughout the Report, and the Report is accordingly subject to and qualified by those assumptions. The uncertainties necessarily inherent in relying on assumptions and projections mean that it should be anticipated that certain circumstances and events may differ from those assumed and described herein and that such will affect the results.

***PB** Quality System:*

Document Reference :	153012A Task 003 Reciprocating Engines Report 004 final.doc
Report Revision :	004
Report Status :	Final
Prepared by :	Neil Wembridge, Nigel McGimpsey
Reviewed by :	Nick Barneveld
Approved by :	Nick Barneveld
Date Issued :	6th November 2009

Over a Century of Engineering Excellence Quality Management System Certified to ISO 9001: 2000

Contents

List of tables

List of figures

1 Introduction

1.1 Background

This review of reciprocating engines accompanies the previous report[1] on thermal plant lives and LRMCs submitted to the Electricity Commission (Commission), dated July 2009.

PB has been engaged to provide an overview of the costs and performance of diesel fuelled reciprocating engines.

The "diesel fuelled" descriptor above is used somewhat loosely. It is intended to embrace the whole family of compression-ignition engines, which burn a variety of liquid fuels other than diesel, and which, when suitably modified for such purpose, also burn a variety of gaseous fuels. This is consistent with the way the more common term, "diesel engine" is also often used to describe the whole family of compression-ignition engines, without regard to the particular fuel being used for a specific installation.

1.2 Scope

The scope of this overview of the costs and performance of "diesel fuelled" (compression-ignition) reciprocating engines includes:

- Typical unit sizes and arrangements
- Heat rates, efficiency
- Fixed and variable O&M Costs
- Capital costs

The study focuses on the diesel fuelled variants for three reasons.

- Firstly, as noted in section 1.1 above, the term "diesel engine" in common usage embraces the whole family of compression-ignition engines regardless of fuel type.
- Secondly, gas engines, including the spark-ignition type, are typically derived from diesel engine models and may even use common basic major components.
- Thirdly, "diesel engines", burning actual diesel as one would buy it "at the pump" comprise the most common reciprocating power generator in New Zealand. Presently, these are the emergency, standby, back-up, and black-start generators of choice in the New Zealand context. In other countries, such engines burn diesel and other fuels and provide the baseload generation.

---

[1] PB New Zealand Ltd. Thermal Power Station Advice: Report for the Electricity Commission. July 2009.

A significant portion of distributed generation in New Zealand is provided by bio-gas and landfill gas fuelled, “diesel engine” derivative, gas engines.

At the Commission’s request, other fuel types discussed are:

- Natural gas (including LNG)
- Liquefied Petroleum Gas (LPG)
- Landfill gas
- Biogas

1.3 Methodology

PB has used a combination of public domain information and information from its own experience with reciprocating engines to compile this report.

This study has also used information contained in a PB report[2] provided to the Commission which discussed the costs and performance of thermal peaking plant in New Zealand.

1.4 Exchange rates

All dollar values are quoted in 2009 New Zealand Dollars unless otherwise stated.

Currency conversion rates used for the purposes of this report are as follows:

- 1 USD = 1.5 NZD
- 1 GBP = 2.5 NZD
- 1 AUD = 1.2 NZD

[2] PB Associates. Thermal peaking plant costs. June 2008.

2 Study

2.1 Introduction

2.1.1 Reciprocating engine basics

Reciprocating engines, also known as piston driven engines, or more commonly as internal combustion (IC) engines, are a widespread and well-known technology. They provide the motive force for almost all automobiles, trucks, construction and mining equipment, marine propulsion, lawn care, and a wide range of other machinery and equipment. They also provide for a diverse range of power generation applications.

Reciprocating engines can be categorised using a number of criteria:

- **Ignition source -** there are two categories: spark ignition (SI), typically fuelled by gasoline or natural gas, and compression ignition (CI), typically fuelled by diesel oil or heavier fuel oils. CI engines can be fuelled with natural gas and the ignition source provided by a small amount of CI pilot fuel (e.g. diesel).

  This study is primarily concerned with the diesel fuelled, CI engine.

- **Number of piston strokes** it takes to complete a combustion cycle - a two-stroke engine completes its combustion cycle in two strokes (one revolution of the crankshaft), and a four-stroke engine completes the combustion process in four strokes (two revolutions of the crankshaft).

The four-stroke, diesel fuelled, CI engine is the work-horse of the world and its use for power generation has been an adaptation of the mass produced engines for road (trucks), rail (traction) and marine (ship propulsion) transport.

The term "diesel" engine generally implies the four-stroke, diesel fuelled, CI engine, but may also include the larger, low speed, two-stroke CI engines.

Because the speed of an engine basically determines its weight and size in relation to its power output, diesel engines are generally categorised according to speed. Typical size ranges for diesel generator sets of each speed category are also shown.

- **High Speed**: over 1,000 rpm under 2 MW

  High-speed engines are derived from automotive or truck engines and typically operate at up to 3,600 rpm. For power generation these engines typically operate at 1500 rpm (for 50 Hz) and 1800 rpm (for 60 Hz). These engines generate the most output per unit of displacement and have the lowest capital costs, but also have the poorest efficiency. They are also usually restricted to the cleanest or premium fuel, the diesel one would buy "at the pump" in New Zealand.

- **Medium Speed**: 400 – 1,000 rpm 1 – 10 MW

  Medium-speed engines are derived from locomotive and small marine engines, have higher capital costs, and also have higher efficiency than high speed engines. These engines can operate on a variety of fuels including diesel, crude oil, and heavy fuel oil (residual oil).

- **Low Speed**: up to 400 rpm 3 – 80 MW

  Low-speed engines are derived from large ship propulsion engines and are designed to burn low-quality (and lowest cost) residual fuels. They have the highest capital cost and also the highest efficiency compared to high and medium speed engines. They tend to be practical for power generation where there is a large price differential between heavy oil and natural gas, or where there is no natural gas available.

There are differences in the literature between definitions of low and medium speed engines. Some make the distinction at 275 rpm instead of 400 rpm as above. Others, such as the editors of *Diesel & Gas Turbine Worldwide* use four speed categories:

- Under 300 rpm
- 300 – 600 rpm
- 720 – 1,000 rpm
- Above 1,000 rpm.

2.1.2 Largest engine

For interest, the most powerful, and also the most efficient, diesel engine in the world is reputed to be the 14 cylinder, Wartsila-Sulzer RTA96-C turbocharged two-stroke diesel engine. Each cylinder bore is 960 mm in diameter and the stroke is 2.5 m. Each cylinder alone displaces 1,810 litres and produces 5.8 MW. The 14 cylinder version is 26.59 m long, 13.52 m high, weighs 2,300 tonnes, spins at 92 – 102 rpm, and produces a rated 80 MW at 102 rpm.

It is available in 6 through 14 cylinder versions, and all are inline engines. These engines were designed primarily for very large container ships or bulk carriers. Ship owners like a single engine/single propeller design, without a gearbox. At the maximum economy settings the engine exceeds 50% thermal efficiency.

2.1.3 Ratings

For a diesel generator set in the high and medium speed range, its nominal kW rating is typically expressed in terms of:

- **Standby**: for periodic operation during interruption of normal power, for no more than 2 hours in 24
- **Prime**: for power generation but at varying load, and capable of 10% overload
- **Continuous**: capacity for base load operation comprising continuous operation at full rated load without interruption, and capable of 10% overload.

2.1.4 Applications

The reciprocating engine is widely available and the most commonly used technology for distributed generation applications. Reciprocating engine driven generators for distributed power applications, commonly called “gensets”. The technology is mature, and reciprocating engines are manufactured in large quantities by a number of vendors.

Reciprocating engines start quickly, follow load well, have good part-load efficiencies, and generally have high availability (> 90% EAF[3]) and high reliability (< 3.5% FOF[4])[5]. Multiple reciprocating engine units further increase overall plant capacity and availability. Reciprocating engines have higher electrical efficiencies than gas turbines of comparable size, and thus lower fuel-related operating costs. In addition, the capital costs of reciprocating engine gensets are generally lower than gas turbine gensets up to 3 - 5 MW in size.

The larger medium and low speed gensets are base load electricity generators for some Pacific island nations, and for many of the remote mining and resource extraction industries throughout Australia and Papua New Guinea. Such large gensets may be used as base load, grid support, or peak-shaving devices.

High speed gensets are frequently used as a backup (emergency or standby) power supply in residential, commercial, and industrial applications. When used in combination with a 1 - 5 minute UPS (uninterruptible power supply), the system is able to supply seamless power during a utility outage. They are also used for distributed generation (e.g. by Orion in Christchurch), and as the sole electricity generators for some small towns and villages in remote rural areas. In smaller sizes high speed gensets are used for aid posts, hospitals, and the like in remote rural areas.

The editors of *Diesel & Gas Turbine Worldwide, October 2008* have published the results of a Power Generation Order Survey, which shows that for the period June 2007 to May 2008, 36,154 units were ordered. Of these:

- 59% of these were in the 500 kW – 1.0 MW range, and 32% in the 1.01 – 2.0 MW range
- 90% were diesel fuelled and 8% natural gas fuelled
- 45% were for standby duty, 30% for peaking, and 25% for continuous duty
- 96% were high speed engines (over 1,000 rpm), and 3% were medium speed engines.

2.1.5 Largest diesel genset power plant

The 200 MW GMR Vasavi (Basin Bridge) Power Plant in Chennai (Madras), India is reputed to be the world's largest diesel power plant. Its nominal capacity of 200 MW is made up of four 50 MW Hyundai-MAN B&W 12K90MC-S low speed, two-stroke, diesel generating sets.

[3] EAF = Equivalent Availability Factor = (‘available hours’/Period Hours) x 100 (%), where ‘available hours’ includes derated hours.
[4] FOF = Forced Outage Factor = (Forced Outage Hours/Period Hours) x 100 (%)
[5] Based on data from North American Electric Reliability Corporation (NERC) Generating Availability Data System (GADS), 2004 – 2008 Generating Unit Statistical Brochure – All Units Reporting

2.1.6 Largest natural gas genset power plant

For interest, the largest natural gas-fuelled reciprocating engine power plant in the world is reputed to be the Plains End plant, owned by Cogentrix and located near Denver, Colorado, in the US. The Plains End plant consists of 20 Wärtsilä 18V34SG gensets commissioned in 2002, and 14 Wärtsilä 20V34SG gensets commissioned in 2008, providing a total generating capacity of 227 MW.

Annual operating hours at Plains End is 500 - 1500 hours. Both operating time and dispatch frequency are heavily dependent on the balancing requirements made by the Xcel Energy system, which includes significant wind power. The normal fluctuations that result from wind power generation systems are balanced by the Plains End regulation reserve service. Xcel's energy generation mix also includes large coal plants, and Plains End also provides spinning and non-spinning reserve to cover any disturbances to this source of generation.

The main benefits provided by the reciprocating engine gensets are high efficiency at minimum load with all gensets in operation, and high levels of starting reliability. Because reciprocating engine power plants offer high levels of efficiency at part load, generators can profit by selling into both the energy market and the ancillary service market simultaneously.[6]

2.2 Typical unit sizes and arrangements

2.2.1 Unit sizes

Unit sizes range from less than 500 kW from a high speed, four stroke diesel, automotive derivative, to around 80 MW from a low speed, two-stroke diesel, marine derivative.

Synchronous generator speeds for 50 Hz applications in the 1 – 5 MW range are 1500, 1000, 750, 600, 500, 428 and 300 rpm. It follows that 1 – 5 MW diesel generators are found in all of the speed categories (high, medium and low).

2.2.2 Arrangements

High speed (typically 1,500 rpm) diesel generator sets comprise the bulk of the emergency, standby and black-start capacity throughout industry. High speed sets of around 1 – 1.5 MW are available as self-contained, skid mounted or containerised, mobile or re-locatable sets. 2 MW appears to be about the limit for self contained, containerised mobile or re-locatable large sets.

Mobile or re-locatable units are typically provided in sound attenuated housings (modified shipping containers) and come complete with radiators and fuel tanks, only requiring electrical connection. They are usually fitted with 415 V generators.

Medium speed diesel generator sets in the 2 – 5 MW size range are typically mounted on a combined underbase, which in turn is mounted on anti-vibration mountings on a fairly simple rectangular foundation. The gensets may not always come with integral radiators and fuel tanks. This means that separate cooling

[6] Power Industry News, Largest Natural Gas Reciprocating Engine Plant, May 19, 2009

systems and separate fuel tanks may have to be provided. They may also be indoor type plants, requiring a building. They are more likely to have 11 kV generators.

5 MW appears to be about the limit for medium speed skid mounted sets. If not skid mounted, custom-built foundations would be required. Separate cooling systems, air intake/filter, exhaust silencer and stack, and fuel storage may be required in this size range.

A building would also be required, and noise attenuation would be required. Where an integral radiator cooling system is not provided, cooling could be provided by a remote air blast (fan cooled) radiator, or by a cooling tower, which would require make-up water. If located near to the sea, seawater cooling with heat exchangers may be feasible.

Low speed diesel generator sets are normally chosen for base load or continuous power generation applications, where longevity, or high operating hours between overhauls is advantageous. Custom-built foundations with large spread footings would be required, with separate cooling systems, air intake/filter, exhaust silencer and stack, and fuel storage. A building would also be required, and noise attenuation would be required.

Engine manufacturers (e.g. Wartsila and MAN Diesel (formerly MAN B&W Diesel)) are offering complete designs of modular power plants comprising multiple engine-generator units. A 40 MW power station would typically utilise multiple gas or liquid fuelled engines each having a power output of 5 - 8 MW which would result in a power station containing approximately 6 engines.

This number of engines gives flexibility in terms of the ability to only operate the number of engines required to meet the demand. It can also result in higher reliability because the impact of a single engine outage is much less than if a single engine of a larger unit size was utilised.

2.2.3 Manufacturers

There are a significant number of diesel, dual fuel, and gas engine genset manufacturers. Some of the better known manufacturers are:

- Caterpillar/MAK
- Cummins
- Deutz
- Waukesha
- GE Jenbacher
- MAN Diesel
- MTU Friedrichshafen
- Mitsubishi Heavy Industries
- Niigata
- Rolls-Royce

- Wartsila
- Yanmar

2.2.4 Construction Time

The reciprocating engine industry in general has lower lead times and the plant is easier to construct than gas turbine power stations. However, although ex-factory lead times can be as little as 7 to 8 months, they can vary significantly depending on the market demand for engines. One to two years ago ex-factory lead times were 20 months for some sizes and model of engine. Typically, depending on the size of the power plant, total build time might be around 18 months, and for a large multi-engine station it could be up to 2 years. The modular approach also enables plant to be constructed and commissioned in a phased manner which can reduce lead times to first generation and also facilitate later expansion.

2.3 Performance

2.3.1 Heat rate & efficiency units

"Heat rate" and "efficiency" are measures of the same thing: the amount of heat energy in the fuel that is manifest as shaft power or electric power as a result of the engine's energy conversion process. The terms are related as follows:

Efficiency, % = [3,600 / Heat rate (kJ/kWh)] x 100

Heat rate, kJ/kWh = [3,600 / Efficiency (%)] x 100

Note that heat rate is effectively the inverse of efficiency and heat rates increase as efficiencies decrease.

Diesel engine manufacturers quote engine heat rates/efficiencies in terms of ***brake specific fuel consumption*** (BSCF) in g/kWh, that is, grams of fuel consumed for each kWh of shaft power or electric power produced.

The use of BSFC implies the use of a standard fuel and a standard set of ambient conditions. BSFC figures for heavy fuel oil engines are typically quoted for fuel of lower calorific value (LHV) 42.7 MJ/kg, and ISO standard reference conditions are:

- Total barometric pressure: 1.0 bara
- Suction air temperature: 25 °C
- Relative humidity: 30%

Therefore, on that basis:

Heat rate, kJ/kWh = BSFC x 42.7

Efficiency, % = [3600 / (BSFC x 42.7)] x 100

The other factor to be taken into account in all calculations and expressions of heat rate or efficiency is the heating value of the fuel. There two heating values for each fuel: the lower heating value (LHV) (also known as net calorific value or net CV), and the higher heating value (HHV) (also known as the gross calorific value or gross CV).

The HHV includes the heat of condensation of the water vapour in the combustion products. In engineering and scientific literature the LHV, which does not include the heat of condensation of the water vapour in the combustion products, is often used.

Practically speaking, the difference between the HHV and the LHV is the energy you pay for that is never converted into power, at least not in the vast majority of power generation plants, including reciprocating engine gensets. The HHV can be measured in a laboratory test and is the basis of payment for fuels, when it is energy and not mass or volume that is being purchased. The LHV cannot be measured in a laboratory but must be calculated from the HHV.

To complicate matters, all gas turbine and reciprocating engine manufacturers quote heat rates in terms of the LHV of the fuel. The LHV heat rate is also used by European utilities. However, British Commonwealth and US utilities prefer to use the HHV heat rate, and likewise the HHV efficiency. Unless it is clearly stated which is being used, it can make heat rate and efficiency comparisons problematic.

In effect, a 'rule of thumb' (i.e. not precise) is that the difference between HHV and LHV amounts to around 6% for liquid fuels and 11% for natural gas. This represents the amount energy in the fuel that is generally unrecoverable in a combustion process.

The 'bottom line' is that gas turbine and reciprocating engine performance data is usually quoted on an LHV basis, but the energy in fuel you buy is calculated on an HHV basis (because it can be readily determined and verified by laboratory test).

2.3.2 Engine efficiencies

CI diesel engines are among the most efficient simple-cycle power generation options available. Efficiency levels increase with engine size and range from about 35% for small high-speed diesels up to 55% (on an LHV basis) for the large bore, slow speed engines (33% - 52% on an HHV basis).

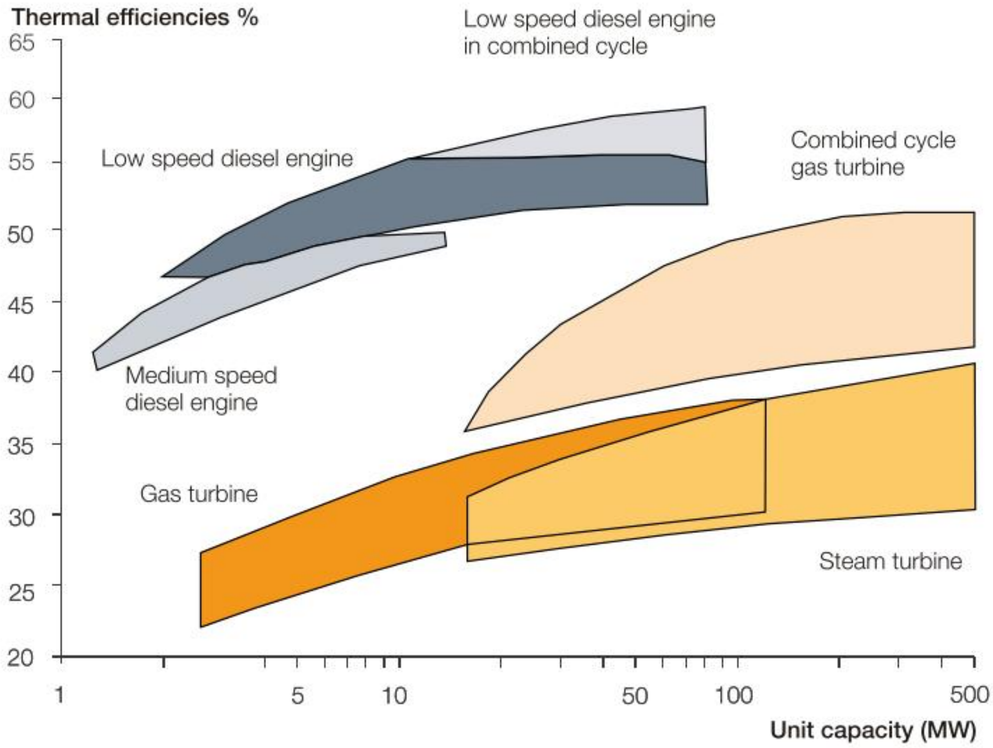
Diesel gensets in the 5 MW range will achieve operating efficiencies of between 40% and 45% on an LHV basis depending on the type and technology. In terms of relative efficiency this is significantly better than open cycle gas turbines and slightly worse than the average combined cycle power station.

Natural gas spark ignition engine efficiencies are typically lower than diesel engines because of their lower compression ratios. However, large, high performance lean burn engine efficiencies approach those of diesel engines of the same size. Natural gas engine efficiencies range from about 28% for small engines (<50 kW) to 42% (on an LHV basis) for the largest high performance, lean burn engines (>3 MW) (25% - 38% on an HHV basis).

Current research and development efforts target lower fuel consumption and shaft efficiencies up to 50 - 55% in large engines (>1 MW). Efficiencies of natural gas engines, in particular, are expected to improve and approach those of diesel engines.

The following Figure 2-1 from an MAN Diesel brochure compares the efficiencies, on an LHV basis, of the main power generation technology options (according to a MAN Diesel brochure).

Figure 2-1 MAN Diesel power efficiency comparison at ISO 3046[7]



Note:

- The implication of ***ISO 3046*** with respect to the above chart is that the power efficiency data is referenced to ambient air inlet conditions of 25°C, 1000 mbara, and 30% relative humidity (RH). Gas turbine (and therefore combined cycle plant) performance data is normally referenced to 15°C, 1013 mbara, and 60% RH. Air inlet temperature alone has a significant effect on gas turbine performance, with output reducing 0.5% - 0.9% for every 1°C rise in temperature, and with a proportionate increase in heat rate (decrease in efficiency). Thus the gas turbine performance data depicted on the above chart is derated by up to 9% compared to typical published "ISO" data.
- The steam turbine data depicted on the above chart appears to show only conventional, subcritical technology performance, and not modern supercritical technology performance.

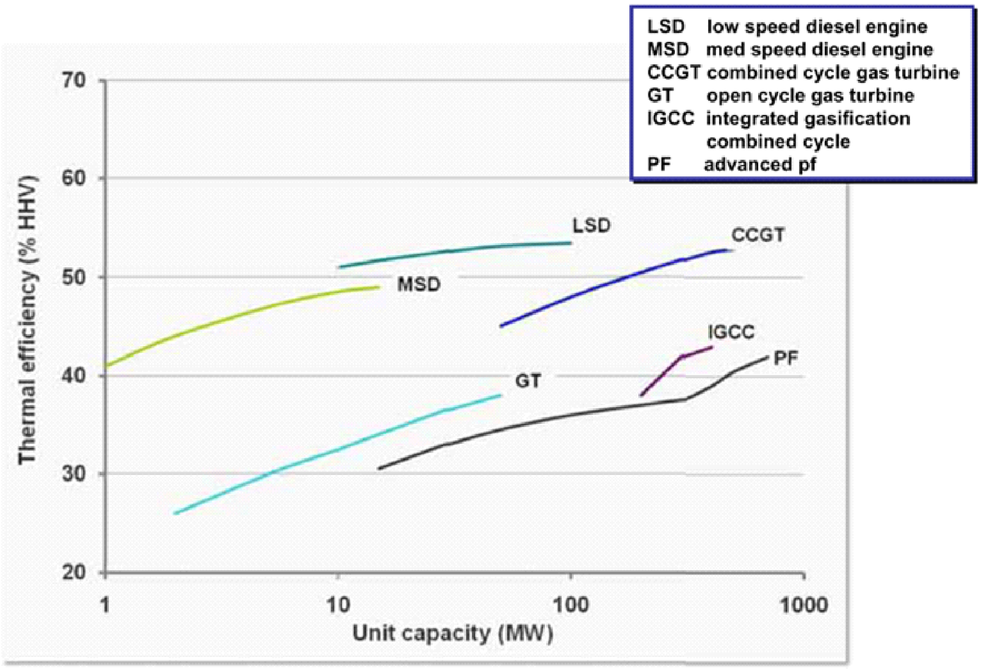
---

[7] From MAN Diesel brochure: Two-stroke Low Speed Diesel Engines, for Independent Power Producers and Captive Power Plants, May 2009

- There are a number of assumptions implicit in the construction of such a chart as shown above, and it is likely that a combination of assumptions has been chosen to favour the low speed diesel engine options.

The following Figure 2-2 from a CSIRO (Australia) presentation also compares the thermal efficiencies of the main electricity generation technologies.

Figure 2-2 CSIRO thermal efficiency for electricity generation[8]



Note: the CSIRO is the "Commonwealth Scientific and Industrial Research Organisation" and is Australia's national science agency.

It can be seen that while the CSIRO use 'lines' instead of 'areas', the thermal efficiency differential between the diesel options (MSD & LSD) and CCGT in the case of the CSIRO presentation is much reduced compared to the MAN Diesel chart. This is a result of adopting different "implicit assumptions".

2.3.3 Part load efficiency

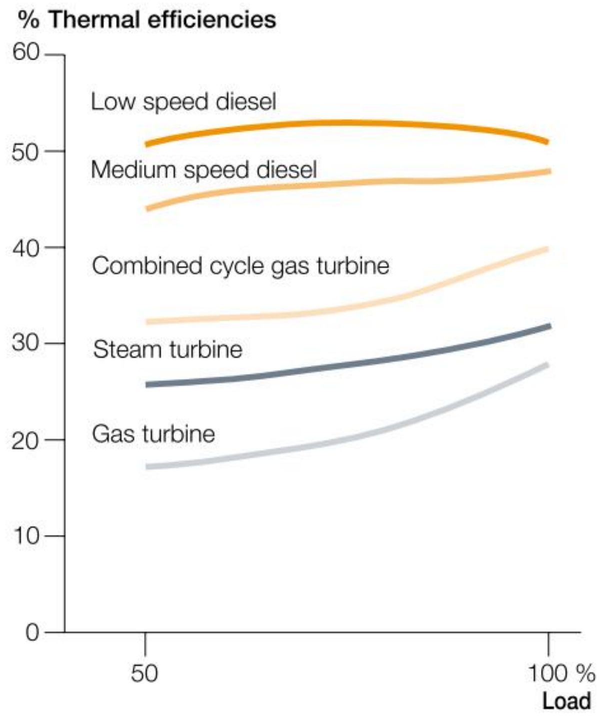
Diesel engines have very favourable part-load characteristics, and the efficiency curve for diesel engines is comparatively flat between 50 and 100% load. For a typical lean burn natural gas engine, the efficiency at 50% load is approximately 8 to 10% less than full-load efficiency. As the load decreases further, the curve falls away more steeply.

Spark ignition gas engines compare favourably to gas turbines, which typically experience efficiency decreases of 15 to 25% at half-load conditions.

The following Figure 2-3 compares the part load efficiencies, on an LHV basis, of the main power generation technology options (according to a MAN Diesel brochure).

[8] CSIRO (Louis Wibberly) presentation: Alternative Pathways to Low Emission Electricity, presented to NSW Clean Coal Summit, NSW Parliament House, Sydney, 7 May 2008

Figure 2-3 MAN Diesel typical part load efficiencies at ISO 3046[7]



The notes applying to Figure 2-1 also apply to the above Figure 2-3.

Gas engines are also available which provide ignition by using a small percentage of liquid fuel with the gas. The liquid fuel is injected just before top dead centre (TDC) on the compression stroke. This results in fuel consumption and part load characteristics similar to those for a liquid fuelled engine.

2.3.4 Emissions - general

The waste (exhaust) gases from reciprocating engines are typical of those from other combustion processes. The main energy contributing components of fuels are carbon and hydrogen. When these are combusted (burned) in an engine, or in any other appliance, they result primarily in carbon dioxide (CO_2) and water vapour (H_20).

The exhaust gases may contain unburned fuel and incompletely burned fuel, which appear as volatile organic compounds (VOC), aerosols, particulate matter, and carbon monoxide (CO). These emissions are a direct waste of fuel energy, which comprises the greater portion of the total operating cost. Therefore every effort is made in the design and operation of reciprocating engines to ensure that the fuel is completely burned and these emissions are minimised.

The exhaust gases will also contain nitrogen oxides (NOx), which arise from both the nitrogen in the fuel (if any) and the nitrogen in the combustion air. If sulfur is present in the fuel, the exhaust gases will contain sulfur oxides (SOx). SOx emissions are directly dependent on the sulfur content of the fuel, which may range from virtually nil for natural gas, to up to 5% for high sulfur fuel oil (HSFO).

Nitrogen oxides (NOx) are the emissions of greatest concern because uncontrolled NOx emissions from reciprocating (internal combustion (IC)) engines (especially diesel engines) are the highest among distributed energy technologies. Volatile organic compounds (VOC), aerosols, particulate matter, and carbon monoxide (CO) are of equal concern from an environmental health and safety perspective, however they are more readily controlled by design. Under normal operating conditions, a well-maintained engine will produce negligible unburned fuel and particulate matter. Carbon monoxide (CO) emissions however, are a feature of all reciprocating engines.

2.3.5 NOx and CO emissions

NOx and CO emission rates for a particular type and size range of engine varies from manufacturer to manufacturer. Similarly, emission rates for each type of engine within a manufacturer's product line may vary considerably from the smallest to the largest units in the line. Reasons for these variations include differences in combustion chamber geometry, fuel air mixing patterns, fuel/air ratio, combustion technique, and ignition timing from model to model.

Selected NOx and CO emission levels for reciprocating engines are listed in Table 2-1:

Table 2-1 Reciprocating engine NOx & CO emissions

	Natural gas fuel	**Diesel fuel**
	Exhaust gas, ppmv @15% O_2	**Exhaust gas, ppmv @15% O_2**
Uncontrolled NOx	45 - 200	450 - 1,600
NOx with SCR	4 - 20	45 - 160
Uncontrolled CO	140 - 700	40 - 140
CO with Oxidation Catalyst	10 - 70	3 - 13

Note: NOx and CO are not greenhouse gases and therefore have no CO_2 equivalence.

Three basic types of post-combustion catalytic control systems for reciprocating engines include:

- Three-Way Catalyst (TWC) Systems - reduce NOx, CO and unburned hydrocarbons by 90% or more. TWC systems are widely used for automotive applications.
- Selective Catalytic Reduction (SCR) - SCR is normally used with relatively large (>2 MW) lean-burn reciprocating engines. In SCR, a NOx-reducing agent, such as ammonia is injected into the hot exhaust gas before it passes through a catalytic reactor. The NOx can be reduced by about 80-95%.
- Oxidation Catalysts - promote the oxidation of CO and unburned hydrocarbons to CO_2 and water. CO conversions of 95% or more are readily achieved.

2.3.6 Greenhouse gases

The main greenhouse gases emitted from reciprocating engines (along with water vapour), and their 100-year global warming potential (GWP) compared to carbon dioxide are:

- carbon dioxide (CO_2) - 1 x
- methane (CH_4) - 25 x more powerful
- nitrous oxide (N_2O) - 298 x more powerful

CO_2 emissions are entirely fuel dependent. Methane (CH_4) emissions are fuel dependent and combustion process dependent, with the highest methane emissions being produced by reciprocating engines burning natural gas (which is mostly methane). Nitrous oxide (N_2O) emissions are also fuel and combustion process dependent.

CO_2 emission factors for the fuels that could typically be burned in reciprocating engines used for power generation in New Zealand are published by the Ministry for the Environment (MfE).[9] Emission factors for CH_4 and N_2O applying to reciprocating engines used for power generation are not published by the MfE but were previously published by the Australian Greenhouse Office.[10] Such fuels and their emission factors are shown in Table 2-2.

Table 2-2 Greenhouse emission factors

Fuel	Greenhouse gas emission factor		
	t CO_2/TJ	t CH_4/PJ	t N_2O/PJ
Natural gas (Maui)	51.8	240	0.1
Diesel	69.5	4.0	0.6
LPG	60.4	-	-
Heavy fuel oil	73.5	4.0	0.6
Light fuel oil	72.0	4.0	0.6
Biogas	101.0	-	-

2.3.7 Engine life

With proper maintenance, large engines have an operating life of 20 - 30 years, while smaller engines (<1 MW) tend to have shorter operating lives, of around 15 years.

- Engine heads and blocks are rebuilt after about 8,000 hours of operation
- Regular oil and filter changes are required at 700 - 1000 hours of operation

[9] http://www.mfe.govt.nz/publications/climate/nir-apr06/html/page15.html
[10] Australian Greenhouse Office, Energy, Workbook for Fuel Combustion Activities (Stationary Sources), 1998

2.3.8 Other performance issues

Other performance-related items for reciprocating engines include:

- Start-up times range between 0.5 and 15 minutes
- They have a high tolerance for starts and stops
- Compared with combustion turbines, a lower amount of waste heat can be recovered.
- Engine performance deratings of about 2 - 3% for each additional 300 m above sea level are common.
- Deratings of 1 - 2% for every 5°C above the reference temperature (usually 30°C) are common.

2.4 Fuels

2.4.1 General

Reciprocating engines can operate on a wide spectrum of fuels including natural gas, diesel, landfill gas and digester gas.

2.4.2 Liquid fuels

High-speed diesel engines generally require high quality fuel oil with good combustion properties. No. 1 and No. 2 distillate oil comprise the standard diesel fuels. Low sulfur distillate is preferred to minimize SO_2 emissions.

High-speed diesels are not suited to burning oil heavier than distillate. Heavy fuel oil requires more time for combustion and the combination of high speed and contaminants in lower quality heavy oils cause excessive wear in high-speed diesel engines.

Medium and low speed diesel engines however are able to burn heavier oils including low grade residual oils or Bunker C oils.

2.4.3 Natural gas

The simplest natural gas engines operate with natural aspiration of air and fuel into the cylinder (via a carburettor or other mixer) by the suction of the intake stroke. High performance natural gas engines are turbocharged to force more air into the cylinders.

Natural gas SI engines operate at modest compression ratios (compared with diesel engines) in the range of 9:1 to 12:1 depending on engine design and turbo-charging. Modest compression is required to prevent auto-ignition of the fuel and detonation (engine knock), which can cause serious engine damage.

Natural gas spark ignition engine efficiencies are typically lower than diesel engines because of their lower compression ratios. However, large, high performance lean burn engine efficiencies approach those of diesel engines of the same size.

Many natural gas spark ignition engines are derived from diesel engines, i.e., they use the same block, crankshaft, main bearings, camshaft, and connecting rods as the diesel engine. However, natural gas spark ignition engines operate at lower cylinder pressure levels to prevent detonation (knock). Owing to the derating effects from pressure, the SI versions of diesel engines often produce only 60 to 80% of the power output of the parent diesel.

Manufacturers often enlarge cylinder bores about 5 to 10% to increase the power, but this is only partial compensation for the derated output. Consequently, the $/kW capital costs of natural gas spark ignition engines are generally higher than the diesel engines from which they were derived. However, by operating at lower cylinder pressure and bearing loads, as well as in the cleaner combustion environment of natural gas, SI engines generally offer the benefits of extended component life compared to their diesel parents.

2.4.4 Alternative gas fuels

Spark ignition (SI) engines operate on a variety of alternative gaseous fuels including:

- Liquefied petroleum gas (LPG) – propane and butane mixtures
- Sour gas - unprocessed natural gas as it comes directly from the gas well
- Biogas – any of the combustible gases produced from biological degradation of organic wastes, such as landfill gas, sewage digester gas, and animal waste digester gas
- Industrial waste gases – flare gases and process off-gases from refineries, chemical plants and steel mill
- Manufactured gases – typically low and medium-Btu gas produced as products of gasification or pyrolysis processes.

Factors that impact the operation of a SI engine with alternative gaseous fuels include:

- Volumetric heating value – Since engine fuel is delivered on a volume basis, fuel volume into the engine increases as heating value decreases, requiring engine derating on fuels with very low Btu content. Derating is more pronounced with naturally aspirated engines, and depending on air requirements turbo-charging partially or totally compensates.
- Auto-ignition characteristics and detonation tendency
- Contaminants that may impact engine component life or engine maintenance, or result in air pollutant emissions that require additional control measures.
- Hydrogen-containing fuels may require special measures (generally if hydrogen content by volume is greater than 5%) because of hydrogen's unique flammability and explosion characteristics.

2.4.5 Dual fuel engines

Dual fuel engines are diesel CI engines predominantly fuelled by natural gas with a small percentage of diesel oil as the pilot fuel. The pilot fuel auto-ignites and initiates combustion in the main air-gas fuel mixture. Pilot fuel percentages can range from 1 - 15% of total fuel input.

Dual fuel operation is a combination of CI and SI in concept, except that instead of a spark to ignite the air-fuel mixture, it is ignited by the pilot fuel combustion.

Most dual fuel engines can be switched back and forth “on the fly” between dual fuel and 100% diesel operation.

2.4.6 LPG

LPG is composed primarily of propane and/or butane. Propane used in natural gas engines requires retarding of ignition timing and other appropriate adjustments. LPG often serves as a back-up fuel where there is a possibility of interruption in the natural gas supply. LPG is delivered as a vapour to the engine.

LPG use is limited in high-compression engines because of its relatively low octane number. High butane content LPG is recommended only for low compression, naturally aspirated engines. Significantly retarded timing avoids detonation.

2.4.7 Biogas

Biogases (landfill gas and digester gas) are predominantly mixtures of methane and CO_2 with HHV in the range of 10 – 25 MJ/Nm^3.

Biogases are produced essentially at atmospheric pressure and so must be compressed for delivery to the engine.

After compression, cooling and scrubbing or filtration is usually required to remove compressor oil, condensate, and any particulates entrained in the original gas. Landfill gas in particular often contains chlorine compounds, sulfur compounds, organic acids and silicon compounds, which require pre-treatment. Scrubbing with a caustic solution may be required if acid gases are present.

Because of the additional requirements for raw gas treatment, biogas powered engine facilities are generally more costly to build and operate than natural gas-based systems.

2.5 Costs

2.5.1 General

Reciprocating engine gensets do not show typical economies of scale when costing industrial equipment of different sizes. Smaller genset packages are typically less costly on a unit cost basis ($/kW) than larger gensets. Smaller engines typically run at a higher rpm than larger engines and often are adapted from higher volume production runs from other markets such as automotive or truck engines. These two factors combine to make the engine package costs lower than the larger, low-speed engines.

The *World Alliance for Decentralised Energy* (WADE) advises that through time reciprocating engines have achieved low initial capital costs, strong O&M support networks, and high partial load efficiency. They achieve greatest economic benefits when used in small to medium size applications from 1 kW - 5 MW.

2.5.2 Capital costs

In 2006 WADE estimated the Installed Capital Cost for reciprocating engines in the 800 kW – 20 MW range (assumed to be unit size) to be US$900 – 1,300/kW. By direct exchange rate conversion this equals NZ$1,350 - $1,950/kW (2006).[11]

For the largest engine sizes, the low speed, high efficiency 2-stroke diesel, CSIRO has estimated the capital cost at "slightly less than current supercritical pf".[12] According to the US DOE, "current" (2007) supercritical pf had a total plant capital cost of US$1,549/kW.[13] If "slightly" was interpreted to mean around 3 - 5% then the low speed diesel capital cost would be US$1,470 - 1,500/kW. By direct exchange rate conversion this equals NZ$2,200 - $2,250/kW (2007).

Based on the above, and on the two case studies presented in sections 2.5.5 and 2.5.6 below, the total (installed) capital cost of reciprocating engine gensets, in 2009 New Zealand dollars, is estimated to be:

- High speed: NZ$1,200 – 1,800/kW
- Medium speed: NZ$1,500 – 2,400/kW
- Low speed: NZ$2,100 – 2,500/kW

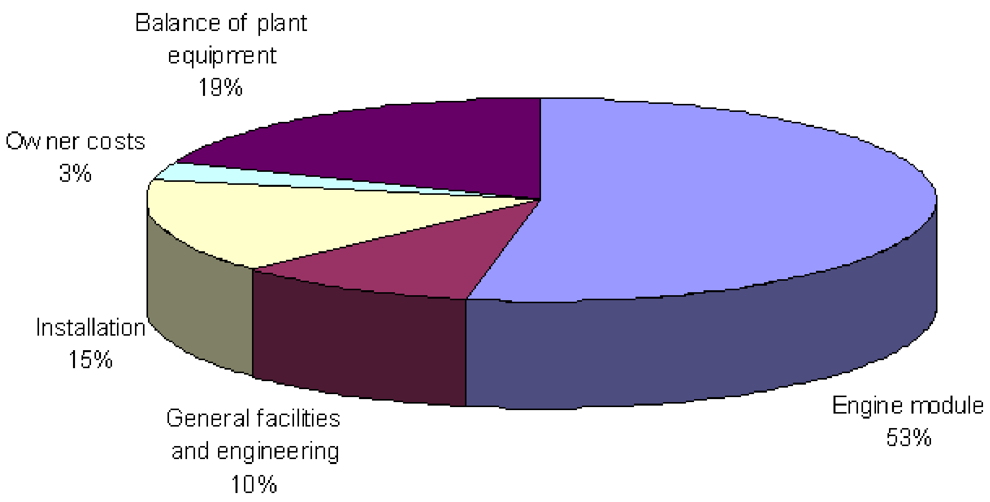
The above ranges are wide and overlapping because of a number of implicit assumptions that must be made relating to site specific factors, engine unit sizes and number of units installed in the power plant.

2.5.3 Capital cost breakdown

Figure 2-4 below shows the breakdown for a 500 kW genset.

[11] http://www.localpower.org/deb_tech_re.html
[12] CSIRO (Louis Wibberly) presentation: Alternative Pathways to Low Emission Electricity, presented to COAL21 Conference 2007, 18-19 September, Crown Plaza, Hunter Valley
[13] US DOE, National Energy Technology Laboratory, Fossil Energy Power Plant Desk Reference, DOE/NETL-2007/1282, May 2007

Figure 2-4 Breakdown of total installed cost for 500 kW genset



There are no reciprocating engines manufactured in New Zealand. The OEMs (original equipment manufacturers) listed in section 2.2.3 are mostly based in Europe, Japan and the US, although they may have licensees and/or manufacturing plants in other parts of the world. The same applies to generators and transformers for power generation applications.

Based on the above breakdown, it is estimated that 60 – 75% of the capital value comprises imported equipment, which will include the engine-generator module. The same proportion of the capital cost is therefore exposed to foreign exchange risk.

2.5.4 O&M costs

Reciprocating engines have a large number of moving parts, increasing all-in maintenance costs to over $10/MWh.

In 2006 WADE estimated the non-fuel Operating and Maintenance cost for reciprocating engines in the 800 kW – 20 MW range (assumed to be unit size) to be US cents 0.5 – 1.5/kWh. By direct exchange rate conversion this equals NZ cents 0.75 – 2.25/kWh.

PB has recently (June 2009) estimated non-fuel O&M costs for high and medium speed engines. Based on these and the above WADE estimates, the O&M costs for reciprocating engine gensets, in 2009 New Zealand dollars, are estimated to be:

O&M cost parameter	**Engine speed**		
	High	Medium	Low
Fixed cost, NZ$/kW	35	15 - 19	12 - 16
Variable cost, NZ cents/kWh	2.5	1.8 – 1.9	1.3
Total non-fuel O&M cost, NZ cents/kWh	2.9	2.1	1.5

2.5.5 Case study – Wellington landfill gas engine

In 2008, Nova Gas, Bay of Plenty Energy and Wellington City Council completed an onsite generation plant to convert the landfill gas to electricity. Nova Gas owns and operates the landfill gas extraction and collection system. Collected gas is supplied to the onsite electricity generation plant owned and operated by Bay of Plenty Energy.[14]

The engine is a 1.063 MW GE Jenbacher, type JGC 320 GS-L.L, with 20 cylinders in a 70° 'V' formation. The engine has a bore of 135 mm, stroke of 170 mm, and a total displacement of 48.7 litres.

According to Clarke Energy, the GE Jenbacher engine genset was packaged, supplied, installed, commissioned, and fully tested at Todd Energy's Happy Valley site in Wellington in March 2008, by Clark Energy. Clarke Energy has also been contracted to undertake the scheduled maintenance of the unit under a maintenance contract.[15]

Figure 2-5 below shows the containerised unit with exhaust silencer and cooling towers mounted on top of the container.

Figure 2-5 Todd Energy's Happy Valley landfill gas power plant

The Happy Valley landfill gas power plant is estimated to have cost NZ$1,900 – 2,000/kW. However this specific capital cost includes a gas compressor skid, landfill gas piping, and provision for a further genset to be added in the future. When these features are deducted the specific capital cost is estimated to be NZ$1,500/kW.

These 2008 capital costs compare favourably with the WADE 2006 estimates.

[14] Energy Matters, a Bay of Plenty Energy Newsletter, August/September 2008
[15] Clark Energy, Project Profile: Happy Valley Landfill Power Station

2.5.6 Case study – offshore location

In June 2009 PB completed a preliminary evaluation of prospective independent power producer (IPP) bids for a nominally 20 MW power plant at an offshore location. Dual fuelled reciprocating engines were required, operating initially on liquid fuel (diesel or heavy fuel oil) and converting to natural gas after an estimated 4 years.

The following Table 2-3 lists the pertinent details of the engines offered and PB's estimate of capital and O&M costs. There are country and site specific issues associated with this project which means that the costs would not necessarily be applicable in New Zealand.

Table 2-3 Recent 20 MW reciprocating engine power plant costs

Engine maker	**MWM**	**Wartsila**	**Wartsila**	**Wartsila**
Engine type	TCD 2020 V16 G3	16V34DF	12V50DF	20V34DF
Nominal rating, MW	1.76	6.97	11.06	8.73
Speed, rpm	1,500 (High)	750 (Medium)	500 (Medium)	750 (Medium)
No. of gensets	13	4	3	4
Efficiency, net, HHV, liquid	38.0%	38.5%	38.9%	38.5
Efficiency, net, HHV, gas	35.9%	36.8%	40.1%	36.8
Liquid fuel	Diesel only(1)	Heavy oil	Heavy oil	Heavy oil
Specific capital cost, NZ$/kW	**1,890**	**2,440**	**2,140**	**2,140**
Specific non-fuel O&M costs:				
Fixed NZ$/kW	35	19	16	15
Variable, NZ cents/kWh	2.5	1.9	1.9	1.8

Notes:

(1) The MWM engines could not be converted to natural gas operation. The approach taken was to swap out the engines for new gas fuelled units at the first major overhaul.

These 2009 costs compare favourably with the WADE 2006 cost estimates, given that the former are 3 years older.

2.5.7 Comparison with Gas Turbines

On sites where liquid fuel is the primary fuel the breakeven point between an industrial gas turbine and a diesel engine is at approximately 2% capacity factor. Above 2% it can be more economical to use reciprocating engines. Note that this breakeven point considers initial investment costs as well as fixed and variable O&M.

On sites where gas fuel is the primary fuel the corresponding breakeven point is at approximately 5% capacity factor.

For sites greater than 50 MW the use of reciprocating engines becomes slightly problematical because of the number of engines required. The alternative is to utilise slow speed rather than medium speed reciprocating engines, however these engines are really only suitable for continuous duty. PB is of the opinion that multiple 5 MW reciprocating engines should be considered as a viable alternative to gas turbines up to 50 MW total power station capacity.

A summary of the advantages of reciprocating engines relative to gas turbines is:

- Fast start and loading – 3 mins to synchronising, 7 mins to full load
- Better efficiency than open cycle gas turbines
- Ambient temperatures up to approx 40°C have little impact on performance therefore in New Zealand rated power is available throughout the year
- No maintenance penalty on the number of starts or loading cycles
- Usually no need for gas compressors
- Power plant construction times 30% to 50% of GT times
- Incremental expansion easy to accomplish
- High reliability (see section 2.1.4)

The main disadvantage for reciprocating engines is that the lower power density means that over a certain capacity the physical size or quantity of equipment can become an issue.

2.5.8 Future trends

Cogeneration and On-Site Power Production, Volume 10, Issue 2, March, 2009 reported that, "*developments in the design and operation of gas, diesel and dual-fuel reciprocating engines continue (though slowly), with improvements to efficiency and lower atmospheric emissions being the main aims*."

The article then outlined the following "*latest technical developments*":

"*The aim is to reduce exhaust emissions still further, whilst improving thermal and electrical efficiencies and delivering reduced maintenance requirements. For example, Waukesha, Caterpillar and Cummins have been working with the US Department of Energy (DOE) to improve all of these parameters.*

So what are the latest reciprocating engine developments? Current research and development drives include: achieving better combustion and volumetric efficiencies, better combustion chamber optimization, more sophisticated turbochargers (having variable turbine geometries for optimum exhaust temperatures/compressed air volumes) and (for diesels) better high-pressure common rail fuel injection equipment (FIE). Improvements also derive from bore-cooled cylinder liners and higher compression ratios. Special lower carbon-cutting rings, such as in Rolls-Royce's K-gas G4.2 gas engine, can reduce 'dead space' for the air/gas mixture around the piston's top land – this increases the amount of mixture in combustion and improves thermal efficiency while reducing unburned *hydrocarbon (UHC) emission. Further improvements will come about through special piston ring pack designs and better tribology/hydrodynamic design to reduce friction.*

The latest electronics control systems provide ultimate engine optimization, control and monitoring. For example, Guascor's SFGLD gas engines have speed, load and other parameters electronically controlled so they can operate at constant limited emissions. The engines adapt to different gas qualities and can switch from natural gas to biogas with no interruption. Spark plug condition is automatically reported and ignition advance can be adjusted remotely. A detonation detection and control system enables working under severe conditions without knock.

A significant area of development is providing individual ignition adjustments (by cylinder speed/load/emissions/energy requirement etc). Generally, automated load-sharing between cylinders allows higher loads and efficiencies, and adaptive load balancing enables wider engine operating regimes.

Note that having a high electrical efficiency is often considered more important than high thermal efficiency, and engine control systems are now often linked to plant control and management systems. These may be optimized to take as much energy out of the fuel as possible for efficient electricity generation. Exhaust heat is often a secondary consideration, but trade-offs are possible using the latest engine control and management techniques.

These developments have a bearing on CHP applications, because the engines' exhaust gas and cooling water temperatures/flows – the heat output needed to obtain heat or steam for processes – are crucially important. However, as Anders Ahnger, general manager of combined technologies at Wärtsilä Power Plants, commented: 'With the gas engine, we are now starting to reach temperature limits, so while I would always like a hotter running engine to supply heat for CHP plants, we cannot now do this without developing new high temperature materials – there is much R&D going on into this.' "[16]

[16] Cogeneration and On-Site Power Production, "Cleaner, more power and heat, less fuel ...today's reciprocating engines must deliver", by James Hunt, Volume 10, Issue 2, March 2009

2.6 Summary table

Table 2-4 Summary Table

Criteria	Units	Low Speed	Medium Speed	High Speed	50 MW gas turbine
Unit sizes	MW	**3 - 80**	**1 - 10**	**< 2**	**50**
Construction time	months	up to 36	18 - 24	18 - 24	24
Heat rate, HHV, liquid fuel	kJ/kWh	6,900	9,000	11,250	11,800
Efficiency, HHV, liquid fuel	%	52%	40%	32%	30.5%
Efficiency, HHV, natural gas	%	N.A	38%	25%	31%
Part load (50% load) efficiency, HHV, liquid fuel	%	52%	39%	30%	25.4%
Engine Life	years	20 - 30	15 - 20	15	25
Lube oil type		low cost mineral	low cost mineral	low cost mineral	high cost synthetic
Lube oil consumption	g/kWh	0.8	0.5	0.2	0.005
Maintenance frequency - major overhaul	hours	30,000	20,000	15,000	24,000
Start-up times, to full load	minutes	10 - 15	3 - 10	0.5 - 7	20
Capex	$/kW	2,100 - 2,500	1,500 - 2,400	1,200 - 1,800	1,250 - 1,350
Variable Opex	$/MWh	13	18 - 19	25	8
Fixed Opex	$/kW/y	12 - 16	15 - 19	35	16
Capex exposure	%	60 - 75%	60 - 75%	60 - 75%	70 - 80%
Carbon emissions, Diesel	t CO_2e/PJ	69,779	69,779	69,779	69,779
Carbon emissions, Natural gas (Maui)	t CO_2e/PJ	57,830	57,830	57,830	52,030
Carbon emissions (specific), Diesel	t CO_2e/GWh	481	628	785	823
Carbon emissions (specific), Natural gas (Maui)	t CO_2e/GWh	N.A.	548	833	604

3 Glossary

Term	Definition
BSFC	Brake Specific Fuel Consumption
Capex	Capital Expenditure
CI	Compression Ignition
CO_2	Carbon Dioxide
EOH	Equivalent Operating Hours
FOM	Fixed Operations and Maintenance costs
GT	Gas Turbine
GWh	Gigawatt-hour
HHV	Higher Heating Value
HP	High Pressure
IC	Internal combustion (engine)
IPP	Independent Power Producer
kWh	Kilowatt-hour
LHV	Lower Heating Value
LPG	Liquefied Petroleum Gas
MW	Megawatt
NCF	Net Capacity Factor
O&M	Operations and Maintenance
OCGT	Open Cycle Gas Turbine
OEM	Original Equipment Manufacturer
PB	Parsons Brinckerhoff
SI	Spark ignition
VOM	Variable Operations and Maintenance costs