The Future of Gas Turbine Technology
8th International Gas Turbine Conference
12-13 October 2016, Brussels, Belgium

Paper ID Number (08-IGTC16)

IMPROVING THE FLEXIBILITY AND EFFICIENCY OF GAS TURBINE-BASED DISTRIBUTED POWER PLANT

Michael Welch
Siemens Industrial Turbomachinery Ltd

Waterside South
Lincoln LN5 7FD
United Kingdom
+44 1522 584000
welch.michael@siemens.com

ABSTRACT

As electricity usage continues to grow, there is a growing trend towards Distributed Power Generation, locating smaller power plants close to the consumer load centres. However, even a distributed generation plant has the same issues in today's electricity network as a centralized power plant: the need for improved efficiency, reduced emissions/environmental impact and the flexibility to compensate for large power fluctuations caused by power generation from intermittent renewable energy sources such as wind power, particularly when these sources are connected to the distribution grid.

This paper examines the option of using multiple small gas turbines with power outputs between 5 and 60MW in place of one or two larger units, to provide flexible, fast response distributed power plant between 25MW and 300MW in output. In addition to helping to ensure secure local power supplies, by placing the power plant closer to the consumers, distributed generation increases the possibility to utilize the waste heat from power generation as the source for process heating within local industry and communities. Distributed power plant can also help optimize electricity network operation by providing voltage support, or even by operating as a synchronous condenser.

The multiple unit configuration allows the power plant to be built in discrete modules with short construction times, helps maintain high efficiency under part-load operating conditions, and offers fast response times due to the characteristics of small light industrial and aero-derivative gas turbines. Such plant also offer high availability and low maintenance downtimes due to the 'core swap' capability of such gas turbine designs, and can be despatched at low load demand times where single larger units have to be taken off-grid due to emissions restrictions. In addition, it may be possible to operate such a plant on a wider range of fuels than a traditional centralized plant can use, enabling better use of locally available fuel sources, and the potential to make use of 'renewable' fuel sources, such as landfill gas.

With water availability and consumption also a growing concern in some parts of the World, the paper also examines the use of Organic Rankine Cycle (ORC) technology for combined cycle applications.

1. INTRODUCTION

For the past 100 years across most of the World consumers have received their electricity from large central power plants which provide energy to the entire system from a single location via a network of transmission lines. This model, which relies heavily on fossil fuels, is facing a number of challenges in today's environment.

The major initial efforts to reduce the environmental impact of power generation focussed on fuel switching from coal to natural gas, with plans for massive centralised coal-fired power stations giving way to more efficient, less polluting, natural gas-fired power plant in the so-called 'dash for gas', changing the power mix from predominantly thermal coal-fired steam turbine plant to a more even split between coal and combined cycle gas turbines.

With concerted global efforts to further reduce Greenhouse Gas emissions, there is an increasing penetration of intermittent and variable renewable energy. Both wind and solar generation output vary significantly over the course of hours to days, sometimes in a predictable fashion, but often imperfectly forecast. This intermittency and variability of wind and solar power generation presents challenges for grid operators to maintain stable and reliable grid operation, especially in countries or power networks where renewable power is given despatch priority. This requires redundancy and flexibility in fossil-fuelled power generation so that the system can respond quickly to these fluctuations, outages and grid support obligations, as shown in Figure 1 below. Without sufficient system flexibility, system operators may need to curtail power generation from wind and solar sources. Predominantly to date this flexibility has been achieved by operating central fossil fuel power plant so that they maintain their connection to the grid but run at part-load so that they can rapidly respond to transients on the system network. Power plants initially designed for base load operation are in many markets being forced to operate as mid-merit or even peaking plant, with multiple start/stop cycles as well as load cycling, with increasingly fast ramp rates being demanded to meet system demands.

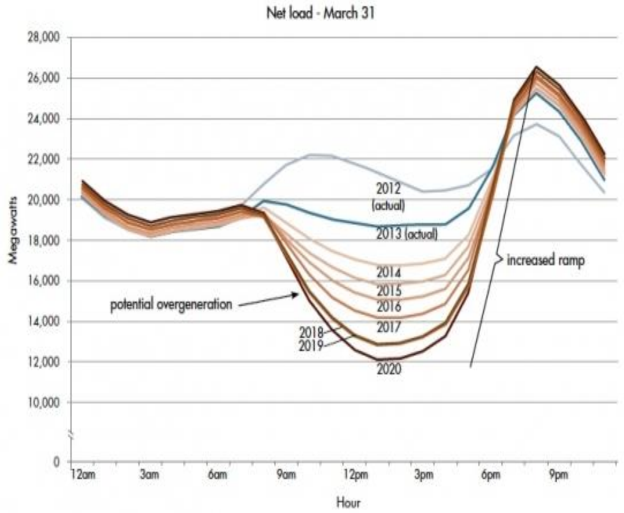

Figure 1: The California ISO 'Duck Curve' illustrating impact of Intermittent Renewable Power Generation

The centralised power generation model has created a trend over the past century towards ever larger unit sizes, based on the assumption that larger units and bigger plant provided lower cost power generation due to economies of scale, with small increases in power generation efficiency also contributing to this. The accepted penalty was losses in the transmission and distribution networks, and the potential for consumers to lose their power supply in case of transmission or distribution system outages. However, as shown in Figure 2 below, maximum efficiency occurs at full-load, so operating a large central plant at part-load reduces the efficiency of power generation considerably, and the need for part-load operation may impact on the operational range of the power station due to the need to comply with emissions legislation. In addition, cycling of the units, ramping up and down in load, can create the need for more frequent maintenance and power station outages. A large utility-scale turbine undergoing major maintenance can require in excess of 3 weeks for disassembly, inspection, parts replacement and reassembly. Cycling may also reduce part life and severely impacts plant economic returns and in some cases, overall viability.

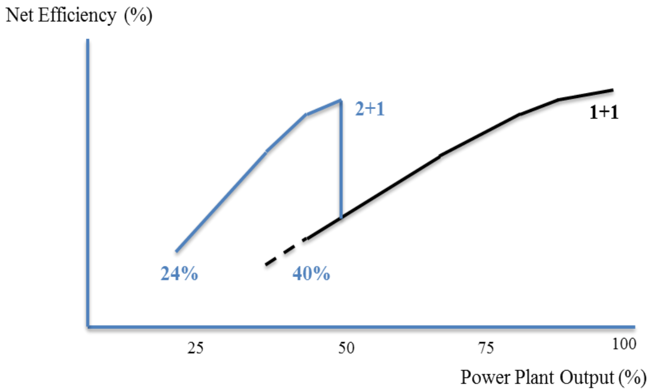

Figure 2: Variation of efficiency with load for a CCGT plant based on one or two gas turbines feeding a single steam turbine

Another issue facing centralised power generation is water usage. In many parts of the World, water is a scarce resource for which power generation competes with agricultural, industrial and domestic needs. In 2010, World Bank estimates indicated 15% of the World's water withdrawals were used for energy production, and with electricity demand expected to grow 35% by 2035, water usage for power generation will increase significantly, especially in systems relying on the centralised generation model.

Distributed Generation can help address all the above issues. By building smaller, more flexible power plant closer to the actual load centres, network operators can better compensate for the intermittency of renewables, reduce transmission system losses and improve security of supply and reduce capital expenditure on capacity expansion/augmentation while the power plant operators by using multiple units can optimise the plant design to meet the needs of the network operators with fast ramp up and turn down and the ability to operate at low output levels (deep turn-down), while still maintaining high efficiencies, low emissions and low power plant maintenance downtimes. Distributed Generation is also enabler for enhanced smart grid capabilities.

2. THE FLEXIBILITY OF A MULTIPLE GAS TURBINE SOLUTION

Conventional modern large-scale Combined Cycle Gas Turbine power plant (CCGT) are usually based on a single gas turbine with a single steam turbine (1+1 configuration), or two gas turbines with a common steam turbine (2+1 configuration). While this configuration offers very high efficiencies at full load, in excess of 60% today, the efficiency falls as load reduces. There is also a minimum emissions compliance load and a minimum steam flow through the steam turbine, which limits the operating range of the power plant. With around 1/3 of the total station power generated by the steam turbine, it can take over 30 minutes to achieve full station load. In addition, with the gas turbine shut down for maintenance in a 1+1 configuration, the complete station is offline, whereas in a 2+1 configuration, an outage of one gas turbine will reduce station power generation to less than 50% of its rated output. A solution based on multiple gas turbines may offer much greater flexibility, improved efficiency across the power range and enhanced operability compared to a conventional CCGT solution.

2.1 Cogeneration, 'Steam' Combined Cycle and Organic Rankine Cycle

While it is perfectly feasible to generate electricity from an open cycle gas turbine, it is usually not economic to do so unless the plant only operates for a low number of hours per year, as occurs in peaking duties. The efficiency of power generation from gas turbines can be significantly improved by utilising a combined cycle concept, where the waste heat contained in the exhaust gas stream is used to generate additional electricity. This waste heat can alternatively be used to provide process heat (or cooling) for industry or Municipalities – a configuration known as Cogeneration or Combined Heat and Power (CHP). Cogeneration permits Distributed Power Plant to be located on a host site that has a suitable heat load, and this enables very high overall energy efficiencies to be achieved, sometimes over 90%. A Cogeneration plant offering such high energy efficiencies not only provides valuable grid support and security of local power supplies, but also offers a significant reduction in global carbon dioxide emissions compared to separate generation of heat and power.

However, it is not always possible to find a suitable host site with a heat demand, so pure power generation in a combined cycle configuration can also be considered. Traditionally water (steam) has been used in the Rankine Cycle to generate electricity from heat. In combined cycle gas turbine plants, this process involves recovering the waste energy in the gas turbine exhaust, generating superheated steam in a Waste Heat Recovery Unit and then using this steam in a steam turbine to generate additional power. The improvement in electrical efficiency achievable is significant: for utility scale heavy duty gas turbines which are optimised for combined cycle operation, the open cycle gas turbine efficiency of around 40% is increased to over 60% in today's modern units.

The lower power industrial and aero-derivative gas turbines upon which a multi-unit solution would be based, while having similar or better open cycle efficiencies as the heavy duty designs, tend to have lower exhaust gas temperatures and flows and so cannot necessarily produce the steam conditions required to optimise the power generation from the steam turbine. Thus overall electrical efficiencies in combined cycle configuration in the range of 50% to 57% are achievable, as opposed to over 60% that is being achieved by the heavy duty gas turbines. Some of the smaller gas turbines, especially those capable of operating on poor quality fuels, have exhaust gas temperatures that restrict the temperature and degree of superheat that can be achieved in the steam generation. This reduces the cycle efficiency still further.

Additionally 'steam' combined cycle requires water, and frequently water is a scarce or contested commodity, as a limited supply is fought over by domestic users, industry and agriculture. This is leading power generators to consider water-free solutions. For a gas turbine, this means looking at alternative forms of combined cycle such as Organic Rankine Cycle (ORC). By changing the working fluid, a low enthalpy drop can be achieved, the need for superheating eliminated, as condensation within the turbine can be avoided, and the same efficiency as a low pressure, low temperature steam system achieved at a lower working pressure. Improved efficiencies at part-load are also attainable using ORC turbo-generators compared to conventional low pressure steam turbines. Organic Rankine Cycles for small gas turbines tend to use a high molecular weight hydrocarbon (organic) fluid such as cyclopentane, or silicone oil, as the working fluid for the turbine. The enthalpy drop for an organic fluid is low because of the fluid properties, and as the ratio of the enthalpy drop across the turbine and the square of the peripheral velocity must be maintained within a certain range, this leads to a lower peripheral velocity allowing high efficiency, larger diameter turbines to be utilised, operating at lower speeds, typically 3000rpm, with low mechanical stress – unlike small steam turbines which operate at speeds up to around 10000rpm. The combination of working fluid and turbine speed leads to much reduced maintenance requirements, as well as eliminating the need for water in the process. Multiple gas turbines can be connected to a single ORC turbo-generator, providing the maximum output rating of the ORC turbo-generator is not exceeded. This helps reduce the cost/kW of a power plant based on multiple gas turbines as the cost of the ORC system is spread across multiple units. In addition, thanks to ORC working fluid peculiarities (no need for superheating and a wide range of condensation pressure), the plant flexibility and efficiency at part load is not reduced. The ORC unit can be operated at between 10% and 110% of its nominal load automatically, while still maintaining high efficiency even at partial load - as shown in the figure 3 below, at 50% of the load, the ORC still has an efficiency of 90% of nominal full load efficiency).

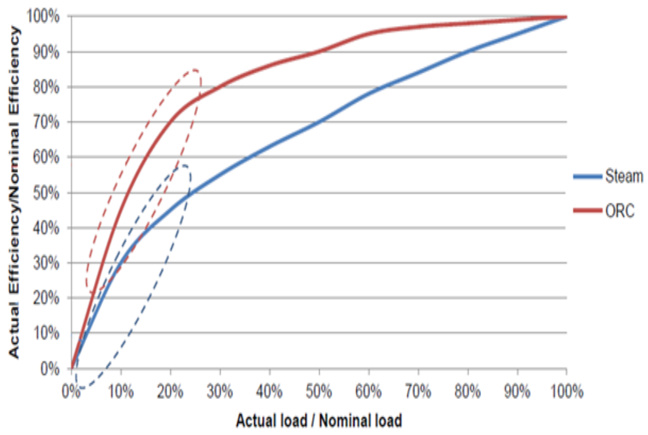

Figure 3: Direct comparison in efficiency versus load for similarly-sized low pressure steam turbine generator and ORC turbogenerator

While a combined cycle plant based on a high pressure steam system offers the highest electrical efficiency, it is also the most expensive for a multi-unit solution. The capital cost and overall efficiency of ORC and a low pressure steam system are very similar, so for low temperature exhaust gases, the improved part load efficiency and elimination of the need for water make ORC look an attractive alternative. Figure 4 below shows that below 200MW a multiple gas turbine power plant employing ORC technology to create a combined cycle configuration has comparable investment costs to a conventional 1+1 or 2+1 high pressure steam combined cycle configuration.

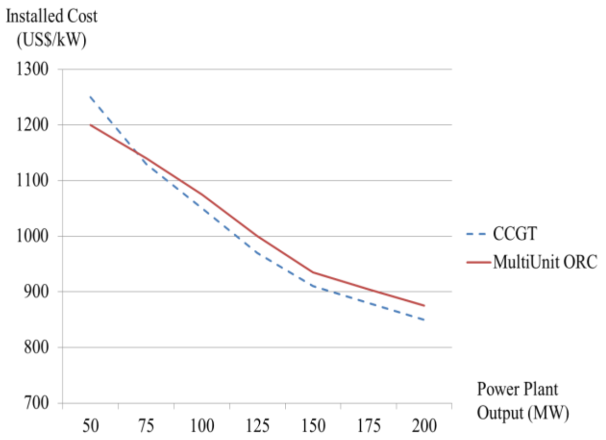

Figure 4: Cost trend for conventional 1+1 or 2+1 CCGT and multi-unit solutions with ORC (CCGT data from Gas Turbine World 2015 Handbook)

2.2 Improving Part-Load Efficiency and Extending Turndown

While a smaller gas turbine may not be optimised for combined cycle operation, and so a CCGT plant based on multiple small units may have a lower full load efficiency than a larger gas turbine optimised for combined cycle operations, the operational flexibility benefits can outweigh this efficiency shortfall. With a multiple unit installation, as shown in Figure 5 below, a high efficiency can be maintained across a wider load range by switching units on and off as required to meet the desired load. Plant turndown to a lower level is also achieved as a single unit can be run if necessary – with 5 or more units installed, plant turndown below 10% of rated station load can be achieved.

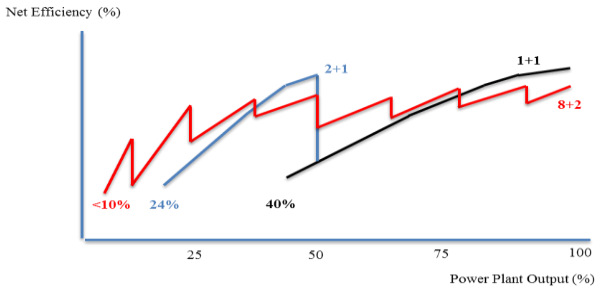

Figure 5: Comparison of part-load efficiency and turndown of conventional 1+1 or 2+1 CCGT designs with a multi-unit configuration

As discussed in section 2.1, there are different potential solutions available to create a combined cycle plant. While high pressure steam offers the highest efficiencies both at full load and across the load range, Organic Rankine Cycle offers a water-free alternative that still has a much superior electrical efficiency compared to an open cycle gas turbine. Figure 6 below shows a typical comparison for a multi-unit solution for the three main alternatives considered for power generation.

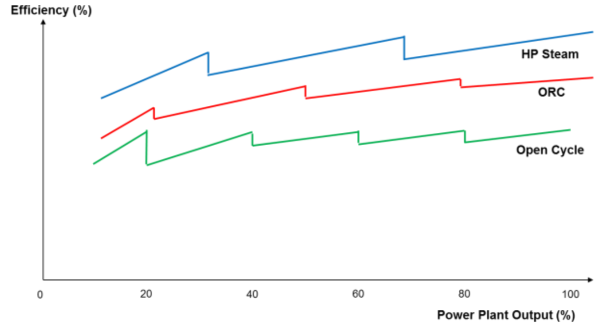

Figure 6: Comparison of electrical efficiency for a multiple gas turbine power plant in open cycle, with ORC and with an HP steam CCGT configuration

2.3 The Advantages of Modularity

Modularity can help enhance plant flexibility and reliability. As discussed in section 2.1, having multiple units enables the power plant to operate efficiently over a much wider load range within the permitted emissions limits than a conventional CCGT configuration can achieve. Future plant expansion is easy to achieve simply by adding one or more units whenever required, either at the same location or at a different tactical point in the power network, rather than having to build a new large power plant and associated transmission system. Having a power plant based on smaller modules also enables more accurate load demand forecasting and capital efficiency, as short term forecasts are by nature more accurate than long-term forecasts, so the power plant can be expanded at a rate that maximises asset utilisation, and reduces the risk of having over-capacity or stranded assets.

By distributing capacity in this way a ‘virtual generation’ benefit is also achieved via loss offset in the transmission network. The modular attributes also enable plant to be moved easily if market conditions change or the plant is sold. This reduces operational and financial risk which is beneficial for accessing finance at more favourable terms.

Small gas turbines (below 70MW) tend to come in pre-designed, pre-assembled standardised packages which have undergone significant levels of factory testing and require only a simple concrete foundation. This reduces the amount of planning, engineering, site installation and construction work required compared to a conventional power plant, enabling the power plant to be brought online faster, while still maintaining a competitive first cost, and reduces the risk of construction delays and associated contract penalties in addition to lost revenue. In addition, these packages can be supplied with weather-proof acoustic enclosures, eliminating the need for buildings. All the auxiliary systems required for turbine operation – including the control system - can be mounted either within the enclosure, adjacent to the enclosure or on the enclosure roof, minimising the number of interconnections required. A typical outdoor package design is shown below in Figure 7.

Figure 7: Industrial Trent Generator Set Package

Having multiple units also helps maintain high power plant availability and output. As mentioned earlier, with a single gas turbine installation, a maintenance outage means that the entire power station has to be taken offline. A power plant of similar output but based on, say, 5 smaller gas turbines can still generate 80% of rated station output with one turbine out of service, 60% with two turbines out etc. Decentralised power plant using this concept have been used for many years in the Oil & Gas industry for onshore fields and offshore platforms with no possibility to connect to a power grid, with many Oil & Gas operators choosing the so-called ‘N+1’ configuration so that there is a spare unit to ensure 100% power output is available even with one gas turbine out of service.

2.4 Start Up times and Ramp Rates

The ability of a power plant to respond rapidly to variable grid demands is critical in today’s power environment with a high percentage of intermittent renewable power generation. Multiple small gas turbines allow the full plant load to be achieved relatively quickly from pushing the start button as the units can ramp up in parallel.

The ramp rates of small gas turbines typically range between 100kW/second and 200kW/second, although some models can load at over 350kW/second. However, gas turbines can also accept step load applications while still maintaining power generation within the required frequency and voltage limits. The maximum acceptable step load depends on the gas turbine design – a single shaft gas turbine can accept a larger single load application than a twin-shaft variant – but this ability to step load enables the turbines to reach full load much faster than by employing a simple ramp rate for loading. Single-shaft gas turbine designs can accept greater step loads, varying from 50% to 100% of rated gas turbine load depending on the model, rating and site conditions. In the case of a 50MW single-shaft gas turbine, it is possible to load the unit from zero to full load in two steps within 30 seconds. With multiple units all starting and ramping up together, it is therefore possible to bring large powers online within very short time periods.

Fast start and loading times are usually considered to be the main benefit of a reciprocating engine compared to a gas turbine. However, when considering small industrial gas turbines and aero-derivative models, it is possible to start from cold and achieve full load in similar times as a ‘warm’ or ‘hot’ start on a medium or low speed reciprocating engine. While a reciprocating engine may be able to get to synchronising speed faster than a gas turbine, the superior loading capability of a gas turbine often means that 100% load is achievable faster for the gas turbine (see Figure 8 below)

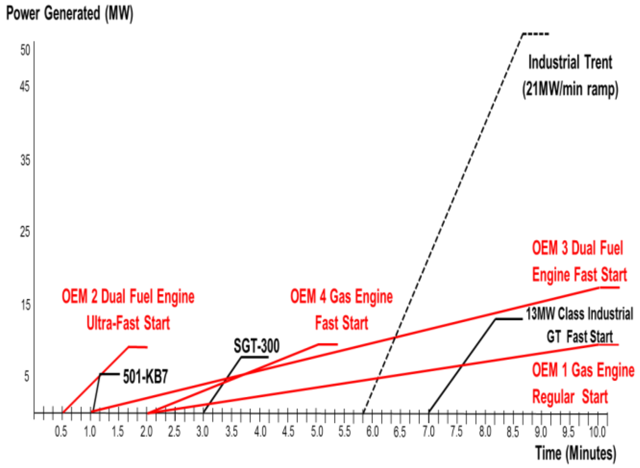

Figure 8: Comparison of times from start to full load for a variety of gas turbine models compared to Reciprocating Engines

Figure 8 of course considers only the gas turbine, and not the steam turbine portion of a combined cycle plant. The steam side can slow down the ability to achieve full plant load considerably – typically this will take 30 minutes from plant start to achieve. However, it is possible to modify the steam system design and undertake measures to keep the steam side in hot standby condition to speed up this process. An ORC system can also be kept in a warm condition to speed up start times, and if designed correctly, full load on the ORC turbogenerator can be achieved within ten minutes, only slightly slower that the gas turbines themselves.

Several papers have been written on the so-called ‘Pulse Operation’, where the power plant is required to start up, operate for just a few hours and then shut down again. Most economic comparisons for this type of operation have been done by comparing Internal Combustion Engines (ICE) - gas engines - either in open cycle or combined cycle, with a conventional 1+1 or 2+1 CCGT utilizing heavy duty gas turbines. Every start on a heavy duty or industrial gas turbine, especially a fast start, leads to increased wear and tear on components, which is accounted for in an Equivalent Operating Hours (EOH) calculation. This implies that every start has a cost, so the heavy duty and industrial gas turbines are penalisd in the economic calculations for pulse load operation. The long start up time and high maintenance penalties for multiple starts (or the start costs) of the heavy duty gas turbines used in this comparison indicate the economics of pulse load operation favour the gas engine, which has no inceased maintenance requirement and hence no start-up cost penalty, even for multiple daily starts . However, with fast start up and shutdown times, high ramp rates and no start-up costs also available on aero-derivative gas turbines due to their aircraft engine background, the economic argument for utilising gas engines rather than an aero-derivative gas turbine such as the Industrial Trent becomes much less compelling.

		Gas Engine	CC Gas Engine	Trent DLE OC	Trent DLE CCGT	Trent + ORC
Full Load Net Efficiency	%	44	49.2	41.87	53	52
Start-up time	Mins	5	50	10	40	20
Shut-down time	Mins	1	20	5	20	10
O&M costs (2000 hrs/yr operation)	EUR/ MWh	5	5	3.50	4.5	4
Start-up costs	EUR/ MW	-	-	-	-	

Table 1: Assumptions for Pulse Load Calculations for 100MW case

When calculating the cost and efficiency of a ‘pulses’ of different length (see reference 2), fuel and operating costs for the start-up and shut down periods, which lie outside the settlement period (or pulse) were included in the calculation. Thus the faster the unit starts up and shuts down, the lower the fuel cost and the greater the pulse efficiency. While the open cycle gas engine solution is slightly more efficient and potentially starts slightly faster than the Industrial Trent, the additional fuel used during the operational pulses is compensated for by the lower maintenance cost of the gas turbine option. With a less obvious economic argument between the technologies, other factors such as emissions profile, availability, reliability and start reliability need to be considered.

The Industrial Trent economic argument in such applications can be improved by including combined cycle configurations. It is possible to achieve full plant load in a conventional steam combined cycle within 40 minutes from start-up, compared to the 50 minutes quoted for gas engines in combined cycle, and as low as 10 minutes using Organic Rankine Cycle technology kept in a hot standby condition. For a comparison of combined cycle configurations, the Industrial Trent has a faster start-up, lower maintenance costs and a higher efficiency solution that improves the overall economics.

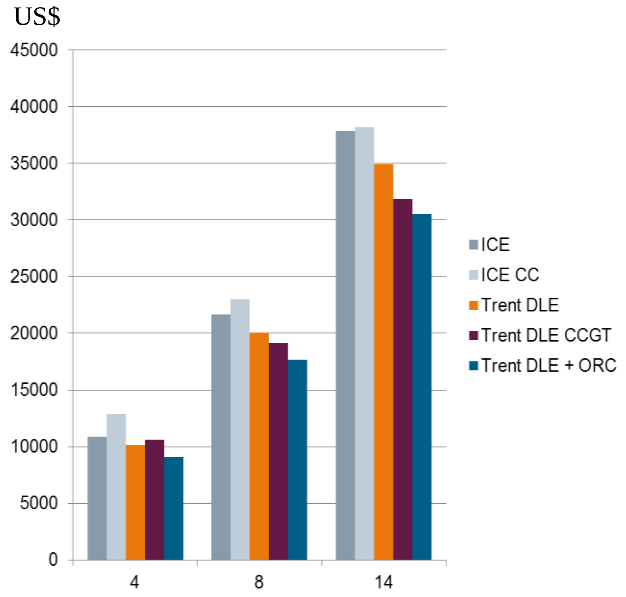

Figure 9: Approximate cost comparisons for different length pulses for gas engine and Industrial Trent configurations for a 100MW power plant

From Figure 9, it can be concluded that for short 'pulse' operating periods an open cycle gas turbine configuration, and for longer 'pulses' a combined cycle gas turbine configuration, is the most attractive economic solution.

2.5 Reducing Maintenance Outages

When scheduled maintenance is required and parts need to be replaced, the large utility scale gas turbines (and reciprocating engines) require considerable downtime as the unit has to be disassembled on site, parts changed and then the unit reassembled. The smaller gas turbines are generally of Light Industrial or Aero-derivative designs which, while many variants have the capability for on-site maintenance as well, are primarily designed for off-site maintenance employing gas generator and turbine module exchange programmes. This reduces the turbine outage times for major inspections from several weeks per unit to between 1 day and 5 days depending on the gas turbine model and the type of maintenance intervention required. Meanwhile in a power plant based on multiple units, the remaining units are still available to generate power, enabling the power station to stay online generating revenue, with only a relatively small percentage of total plant output unavailable.

Routine maintenance requirements during plant operation are also low, with no requirement for highly skilled maintenance personnel to be permanently based on site and low consumption of consumables such as lubricating oil. The various gas turbine OEMs are all working on further developments to improve system reliability and remote monitoring systems to enable unmanned operation for prolonged periods of time.

As has been well-documented elsewhere, the output of a gas turbine is dependent on ambient temperature: as ambient air temperature rises, a gas turbine's power output reduces. Conversely this means that if you design a power plant to give a specific output at the maximum ambient temperature foreseen, on cooler days more power is available for despatch. If there are distribution or transmission system constraints that limit the amount of power that can be exported, then on cooler days, while still producing maximum station output, the gas turbines will operate at part-load. Most GT OEMs calculate the time between overhaul (TBO) for the various different gas turbine models based on an Equivalent Operating Hours (EOH) formula – part-load operation can help extend the TBO reducing the maintenance requirements still further.

Many industrial and heavy duty gas turbine models have a 'start penalty' where more than around 50 starts per year leads to an increase in stress on components, so each additional start is considered under an EOH calculation to adjust the time between overhauls. This leads to an increase in the maintenance costs for a unit that is required to undertake multiple stop/start cycles on a daily basis. Most aero-derivative gas turbines do not attract this start penalty and are therefore provide the ideal solution for a Distributed Power Plant that is required to operate in such a way. Figure 10 shows an actual operating condition experienced by an Industrial Trent aero-derivative gas turbine on a peaking plant in North America: the chart shows 5 starts and shutdowns, along with frequent load changes, during a 24 hour period. This was achieved at no additional maintenance cost or interventions over a unit that would operate as a base load unit, 24 hours per day, 7 days per week: the Industrial Trent is capable of 25000 hours continuous operation or 5500 cycles between overhaul, whichever occurs first.

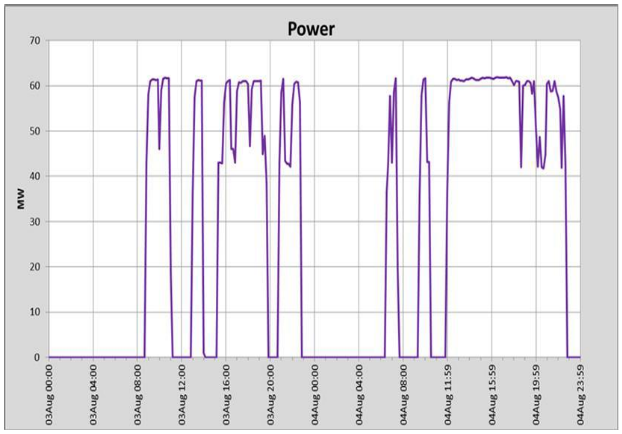

Figure 10: High stress operating cycle chart for an Industrial Trent peaking gas turbine unit

2.6 Fuel Flexibility

While Utility-scale gas turbines are designed primarily for operation on pipeline quality natural gas with a premium liquid fuel such as diesel as an alternative or back-up fuel, the majority of smaller gas turbine models are able to operate on a much wider range of gaseous and liquid fuels. Low emissions combustion systems have also been developed that will operate on non-standard gas fuels, including those with variable compositions. This is a potentially important feature for decentralised power plant as it enables the power plant to operate on a locally available fuel, which, as some of these are classified as waste gases, may also be more economical than utilising pipeline quality natural gas. Examples of such potential gas fuels are landfill gas, digester gas, high hydrogen content gases such as refinery gas or syngas, ethane and propane. It is potentially possible to use two completely different gas fuels and switch between these fuels as necessary, determined by fuel availability or pricing.

Most gas turbines are available in dual fuel configuration, able to operate on either gas fuel or liquid fuel. The turbines can operate on 100% gas fuel or 100% liquid fuel, with rapid automatic changeover between the fuels with no requirement to temporarily reduce load to undertake the fuel change. The liquid fuels that may be considered are typically #2 diesel, kerosene, LPG and naphtha, although there are gas turbine models available that can utilise Light, Intermediate and Heavy Fuel Oils, Residual Oils, Bio-Oils and even Heavy Crude Oils. On some gas turbines it is possible to simultaneously operate on both gas and liquid fuels – commonly referred to as bi-fuelling or mixed fuel operation - using one fuel type to compensate for shortage of another.

There are examples of tri-fuel gas turbine installations, with units capable of operating on a gas fuel and two different liquid fuels, or a liquid fuel and two different gas fuels. Figure 11 below is of a gas turbine installed in a Cogeneration plant at a University in the United States of America and configured to operate on either pipeline quality natural gas or a processed landfill gas, with diesel as a back-up fuel in case of loss of gas supplies, while still meeting strict combustion emissions limits.

Figure 11: 7.7MW tri-fuel gas turbine installed in a cogeneration plant in the USA

3. CONCLUSIONS

In order to address the challenges faced by the electricity market, novel solutions are required. Distributed Power Plants based on multiple small industrial or aero-derivative gas turbines can provide a reliable, flexible, fast-responding solution for generators and system operators to compensate for the high grid penetration of intermittent renewable power generation. Where Cogeneration is not possible, combined cycle configurations can be employed to achieve high electrical efficiencies without impacting greatly on the flexibility or response times of the power plant. By understanding the operational regime the Distributed Power Plant is likely to experience, the correct gas turbine technology and configuration can be selected to maximise system reliability and minimise operating costs.

ACKNOWLEDGEMENTS

The author would like to thank his many colleagues within Siemens for their support, and Nicola Rosetti and his colleagues at Turboden for their contributions on ORC technology.

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