High Flexibility Distributed Power Plant to support Intermittent Renewable Power Generation

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Abstract

As electricity demand continues to grow, there is a growing trend towards Distributed Power Generation, locating smaller power plant closer to the consumer load centres. However, a distributed generation plant has similar issues in today’s electricity network as centralised power plants: 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, particularly when these sources are connected to the distribution grid.

This paper examines the use of multiple small gas turbines with power outputs between 5 and 60MW to provide flexible, fast response distributed power plant to support a small decentralised or islanded power system highly reliant on renewables. As well as improving power generation efficiency through the use of combined cycle configurations distributed generation increases the possibility to utilize the waste heat from power generation as the source for process heating or cooling within local industry and communities. Distributed power plants can also help optimize electricity network operation by providing voltage support, or by providing reactive power and inertia to the local grid, while helping to ensure secure local power supplies due to their location close to the consumers.

The multiple unit concept maintains high efficiency under part-load operating conditions, enabling electricity despatch at low load demand times while still meeting emission legislation requirements. They offer fast response times due to the characteristics of small light industrial and aero-derivative gas turbines, with high availability and low maintenance downtimes due to the ‘core swap’ capability of such as turbine designs. It is also possible to operate these units on a wide range of fuels, offering the potential to make use of local ‘renewable’ fuel sources, such as landfill gas, or syngas from biomass and waste gasification.

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 an increasing 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 mix of coal and combined cycle gas turbines. Today in some countries, natural gas has even overtaken coal as the predominant source of power.

With increasing 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 where renewable power is given despatch priority, requiring redundancy and flexibility in fossil-fuelled power generation so that the system can respond quickly to these fluctuations, outages and grid support obligations. Predominantly to date this has been achieved by operating central 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. Without sufficient system flexibility, system operators may need to curtail power generation from wind and solar sources.

An unbalanced power generation portfolio with the introduction of subsidised intermittent renewable power generation with despatch priority is destabilising electricity markets and Grid systems by removing capacity from transmission grids for firm generators. This is forcing fossil fuel power plants previously designed for base load into cycling mid-merit and peak load applications. These intermittent operating periods are destroying the market pricing structures needed for long term investment decisions and increasing the market exposure of generators.
through forward contract trading imbalance. These factors are negatively impacting the economics of existing power plants, requiring grid operators to consider capacity payment mechanisms that support the installed assets and ensure security of supply, or develop strategies to encourage operators of power plants to operate assets as spinning reserve, negating the low carbon benefits of natural gas. On top of this, environmental legislation and political uncertainties are removing existing coal capacity and casting doubts over the future of nuclear power.

The historical generation portfolio of power plants has no correlation upon future generation requirements due to the increasing levels of intermittent renewable power generation. With electricity traded forward in half hour blocks, this favours intermittent renewable power generation, such as wind, as it enables more accurate forecasting of available generation than previous market designs where electricity was traded hours in advance. However, intermittent renewable power generation requires back-up power generation to balance the system and ensure supply security and system stability. Closing the trading gate down to 15 minutes in advance caused the existing power plants to provide this balance, leading to them becoming increasingly stressed both economically and mechanically due to the cycling and faster starting times required. Moves in some parts of the World to reduce the gate closure time still further to 10 minutes will exacerbate the problem still further.

Figure 2: The impact of Renewable Power Generation on Grids
Another issue facing 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 and support the integration of large, intermittent renewable power sources into the electricity networks. 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. However, it should be noted that Distributed Generation does not necessarily mean small-scale power generation: technologies from a few kiloWatts up to hundreds of MegaWatts can be applied to Distributed Generation depending on the local load demand.

**The Benefits of Decentralised Power**

Power generation is a relatively inefficient process. Even with the most efficient technologies, a large proportion of the energy contained in the fuel is wasted as heat to atmosphere. By locating the power plant closer to the load demand centres, it is possible to find potential uses for this heat, such as industrial processes, or district heating or cooling networks. Combining the supply of power and heat, known as Cogeneration, is a highly efficient way of maximising overall energy efficiency.

Even if a suitable heat load cannot be found, distributed generation still offers significant benefits both to consumers and grid operators. By locating decentralised power plant in the correct locations, this power plant can help provide the voltage and frequency stability on the electricity network, while for the consumer, having a power plant generating at the distribution voltage level helps provide security of power supply due to transmission line outages. Thus power system enhancements can be carried out on a more modest scale at a lower cost than the traditional centralised model.

A decentralised system is also an enabler for SmartGrid or MicroGrid control technology to help integrate and control multiple power generation sources of different types to achieve minimum cost of electricity and minimum CO₂ footprint.
Figure 3: Chart showing typically achievable overall energy efficiencies for different types of decentralised power plant

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). This configuration offers very high efficiencies at full load, in excess of 60% today, although the efficiency reduces as load reduces. There is also a minimum emissions compliance load, 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, while maybe not achieving the same efficiency levels at full load, may offer much greater flexibility, improved efficiency across a wide load range and improved power plant operability by turning machines on and off to match the load demand and optimising the operational profile.

If no heat load is available, then to optimise energy efficiency it is usual to consider gas turbines in combined cycle configuration, using the waste heat in the exhaust gas stream to generate additional power in a bottoming cycle. The water/steam Rankine Cycle is the most commonly adopted solution, enabling significant efficiency enhancement. Light Industrial and Aero-derivative gas turbines however are not usually optimised for combined cycle operation – they tend to have a lower exhaust gas temperature than the heavy duty units, as illustrated in Figure 4, which limits the efficiency of the steam cycle.
This efficiency concern is further exacerbated by any need for the gas turbine to operate at part-loads. As shown in Figure 5 below, the exhaust gas temperature can vary greatly as load on the gas turbine changes.

However, an efficiency deficit at full load is compensated for in a multi-unit solution by the improved efficiency and turn-down capability of the power plant during part-load operation. By switching gas turbines on and off as load changes, it is possible to operate each individual gas
turbine at loads which achieve the optimum efficiency. The fast start times of light industrial and aero-derivative gas turbines permit this to be a realistic operating scenario, especially for those models which have no lock-out on shut-down.

For a 1+1 or 2+1 CCGT configuration, there are also limits on the minimum plant load that can be achieved due to the need to ensure emissions regulations are met under all operating points. On most current gas turbine models, the minimum load to maintain emissions compliance is 50% of full load, although most OEMs are developing combustion systems that have extended turndown capabilities. For a single gas turbine, this limits power plant turndown to around 40% of nominal station output, while for a 2 unit installation turndown to around 25% station load is achievable. With multiple units, not only does switching off ‘unnecessary’ units maintain a high efficiency, it helps extend the turndown range – in theory just one gas turbine could operate as indicated in Figure 6 to provide a minimum station load of less than 10% of rated power output while maintaining emissions compliance.

![Figure 6: Chart showing efficiency at varying station loads for a single unit (1+1) CCGT solution and a multiple unit CCGT solution](image)

The reduced exhaust temperatures that could be experienced on light industrial and aero-derivative gas turbines make high efficiency steam cycles expensive, if not impossible, to achieve. Coupled with the challenge of maximizing power generation efficiency in a water-constrained environment, it may be a more cost-efficient option to look at alternatives to steam-based combined cycle. With low exhaust gas temperatures, often in the 400°C to 500 °C range and sometimes as low as 350°C, Organic Rankine Cycle (ORC) is a potentially interesting technology to boost energy efficiency but at an acceptable cost. ORC employs heavy molecular
weight working fluids that guarantee dry vapor expansion in all operating conditions. These systems are typically preferred for smaller size heat to power systems (up to 20 MW) due to the higher efficiencies achievable with lower heat source temperatures compared to steam cycles, and maximum ease of operation at minimum running costs (no dedicated operating personnel are necessary). The most widely used organic fluids are hydrocarbons (e.g. pentane, butane, etc.), siloxanes (employed also in the cosmetic industry) and refrigerants (more common in HVAC and refrigeration systems).

ORC offers similar efficiencies in combined cycle configurations as a medium pressure steam Rankine Cycle design. Like the steam alternative, multiple gas turbines can be linked to a single ORC turbogenerator set to maximize flexibility, maintain high efficiency over a wide load range and extend plant turndown capability. An ORC system offers better part-load characteristics than medium pressure steam due to the flat efficiency characteristic of the ORC turbine – efficiency drops just 10% from nominal full load efficiency at 50% load (see Figure 7 below).

**Gross Efficiency (%)**

![Graph showing the comparison of part-load efficiency characteristics of a 13MW class gas turbine and an ORC turbine](image)

Figure 7: Comparison of part-load efficiency characteristics of a 13MW class gas turbine and an ORC turbine

Operation and maintenance of a multi-unit gas turbine plus ORC power plant is also simplified. With no water treatment plant, no steam blow-down, no make-up water requirement and core swap capability on the gas turbines to minimize maintenance interventions, it is a simple, low maintenance combined cycle configuration with the potential to reduce manpower requirements compared to a conventional ‘steam’ CCGT. The ORC systems can also start relatively quickly compared to a traditional steam system, which improves the flexibility and response times of power plant.
While ORC technology is available commercially and well-demonstrated today, new alternative cycles for water-free operation are also being investigated. Supercritical CO\textsubscript{2} technology is among the most advanced and most promising alternatives, offering efficiencies close to those of seam combined cycle designs. This technology looks especially promising when combined with gas turbines with relatively high exhaust gas temperatures (over 500°C) although it can also show advantages for temperatures down to about 400°C in the right circumstances.

The Advantages of Modularity

Modularity can help enhance plant flexibility and reliability. By having multiple units, load can be shared across them, and units switched on and off to match the required load. This enables the power plant to operate efficiently over a much wider load range within the permitted emissions limits than a conventional CCGT 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. 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.

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.
Peaking and Cycling for Grid Support

In peaking applications or applications where frequent start/stop and load cycling is expected, conventional economic models are not applicable. The key evaluation criteria are not $/kW or heat rate, but the Internal Rate of Return (IRR) on through life costs. Hence the lower CAPEX and reduced O&M of a power plant based on open cycle gas turbines, and particularly aero-derivative gas turbine models, may outweigh higher efficiency options in an economical evaluation because of the limited number of operating hours.
In these applications, fast response and high availability are two key attributes required by the generators. With the ability to start from cold and have 100% load available for despatch in less than 10 minutes, aero-derivative gas turbines such as the Industrial Trent offer probably the fastest power response time on the market. In addition, aero-derivative gas turbines are highly suitable for cyclic applications with no Equivalent Operating Hours (EOH) penalty associated with cycling or multiple daily starts for high stress operating cycle duty as shown below in Figure 11, and there are no lock-out periods after shutdown. The Industrial Trent for example has a 25,000 hour overhaul regime and is capable of 7,500 cold starts between overhauls. Rapid load changes are not counted as effective starts, and so do not influence EOH calculations. Additionally, small gas turbines tend to have very low black start and standby power requirements: the Industrial Trent gas turbine will start up and commence power generation on gas pressures of 22 barg with a power requirement of less than 350kW.

Figure 10: Typical Power Generation Economics Chart

Figure 11: High stress operating cycle chart for an Industrial Trent peaking gas turbine unit
The chart below (Figure 12) shows a typical start curve for an Industrial Trent aero-derivative gas turbine with a load ramp of 21 MW/minute, but under certain circumstances the ramp rate can be increased – up to 75 MW/minute has been demonstrated on one site enabling full load to be achieved in around 8 minutes from cold. Thus with 2 units installed on a site, a power plant ramp rate between 42 and 150 MW/minute is achievable. This compares very favourably with both heavy duty gas turbines and reciprocating engines, where OEM marketing material suggests 5 to 10 minutes to full load can be achieved on hot or warm starts, although it has to be noted that this applies to gas engines with power outputs of 20% to 40% of the output of the Industrial Trent.

The start times of aero-derivative and light industrial gas turbines are very competitive compared to reciprocating engines. With just the lubricating oil needing to be kept at the correct temperature, gas turbines can achieve full load from a ‘cold’ start as fast as or even faster than reciprocating engines can achieve on a ‘hot’ or ‘warm’ start basis. A comparison of typical start times is shown in Figure 8 below and it can be clearly seen that the Industrial Trent can produce in excess of 50 MW faster than full power of around 18 MW can be achieved by the larger gas and dual fuel engines. In certain circumstances, faster ramp rates than 21 MW/minute can be achieved. Figure 13 also shows that the smaller industrial and aero-derivative gas turbines can achieve full load in a similar time or faster than reciprocating engines of similar power outputs.
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. For example, the a twin-shaft 12MW gas turbine can reach full load using the maximum permissible load steps for this particular gas turbine model in half the time compared to a steady ramp rate. Single-shaft gas turbine designs can accept greater step loads, varying from 50% to 100% 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.

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 natural gas Internal Combustion Engines (ICEs), either in open cycle or combined cycle, with a conventional 1+1 or 2+1 CCGT utilizing heavy duty gas turbines (1). 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. However, with the fast start up and shutdown times, high ramp rates and no start-up costs of an aero-derivative gas turbine, the economic argument for utilising gas engines becomes much less compelling.

(1) See reference 6, ‘Maximizing Profits through efficient Pulse Load Operation’
When calculating the cost and efficiency of a ‘pulses’ of different length (see reference 6), 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, but the costs of energy required to keep the systems in ‘hot standby’ mode for fastest start capability are excluded. 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 as well.

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 from cold within 40 minutes from start-up, compared to the 50 minutes quoted for gas engines in combined cycle, and in less than 20 minutes using Organic Rankine Cycle technology, with potentially less than 10 minutes achievable if the ORC working fluid is 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 which further improves the overall economics compared to an ICE option.
From Figure 14, 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. The economics are impacted considerably by the start-up and shutdown costs, so the shorter start times of ORC compared to steam make this look a more attractive proposition in this example.

**Reducing Maintenance Outages**

When scheduled maintenance is required and parts need to be replaced, outage times become critical. Light industrial and aero-derivative gas turbines are primarily designed for off-site maintenance employing gas generator and turbine module exchange programmes, although many variants have the capability for on-site maintenance as well. This reduces the outage times for major inspections from several weeks per unit for some technology types to between 1 day (breaker to breaker) 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, while one unit is undergoing maintenance, 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.

**Fuel Flexibility**

While most operators consider gas turbines as being 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 5 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 emissions limits.

![Figure 16: 7.7MW tri-fuel gas turbine installed in a cogeneration plant in the USA](image)

**Utilising Multi-Unit Distributed Power Plant to support Renewable Energy**

The flexibility of multi-unit distributed power plant makes them ideal to support a power network with a substantial penetration of intermittent renewable power generation technologies.
The fast reaction times to grid changes and fast start times enables a stable, secure energy supply to be maintained for the local consumer, while maximising the amount of renewable energy supplied to the system. Renewable heat sources, such as Solar Thermal or biomass combustion can also be linked in to a power plant by pre-heating water in a steam CCGT or working fluids in other cycles to maximise energy recovery.

By combining the power generation technologies with energy storage technologies and SmartGrid or MicroGrid control technologies, it is possible to optimise energy production within this distributed system to maximise efficiency and economics, while minimising environmental footprint. For example a system could be designed to incorporate renewable power generation, cogeneration and a stand-alone power plant to ensure heat loads are met by the cogeneration plant, while prioritising renewable power for despatch. Energy storage technologies, such as batteries, could be used to provide almost instantaneous power while the gas turbine power plant starts and ramps up to full load, or to smooth out peaks in power requirements, while being recharged by surplus renewable energy or when the gas turbines are only required by the grid operator to run at part-load conditions.

The fuel flexibility of a decentralised power plant based on smaller units also opens up new possibilities. Much has been written about natural gas being the ‘bridging fuel’ to a zero-carbon future., but by building power plant on a smaller scale and using local, readily available renewable fuel sources, such as non-recyclable wastes and biomass, a decentralised power plant could be fuelled entirely by ‘renewable’ sources. Natural gas could, in theory, be relegated to the role of a back-up fuel in a future Renewable Energy scenario.

Figure 17: Potential ‘Zero Fossil Fuel’ Distributed Energy Scenario
It is potentially possible to take a further step to create a zero CO\textsubscript{2} scenario, even when natural gas is required as a back-up fuel. CO\textsubscript{2} capture can be deployed on the power plant and the CO\textsubscript{2} utilised to generate additional revenues in applications such as Enhanced Oil Recovery or the Food & Beverage Industry. It is even possible to combine the captured CO\textsubscript{2} with hydrogen produced by surplus renewable power to produce high value chemicals or proteins in a truly sustainable manner.

Conclusions

Distributed Power Plant offer many advantages over the conventional centralised power generation model, not least in the lower actual investment costs, the improvement in security - and quality - of power supplies, and the ease of system expansion without having to forecast demand years ahead.

By designing these power plants on multiple small units, both electrical and overall energy efficiencies and operational flexibility can be optimised to ensure the necessary support for an electrical network with a high degree of penetration of intermittent renewable power generation with low emissions across a wide load range. In addition, combining multiple small gas turbines with ‘dry’ combined cycle technologies, such as ORC or supercritical CO\textsubscript{2}, permits engineers to design power plant with no requirement for a water supply. Combining these modular power plant with other technologies, such as energy storage and SmartGrid technology, could help provide cities and districts with green energy at a minimal cost, while offering greater flexibility and a lower CO\textsubscript{2} footprint than could be achieved under the conventional centralised power generation model.

The fuel flexibility of small, modular power plant also opens up the possibility of a carbon-free energy system, providing communities and whole cities with ‘green’ electricity and heat, and even ‘green’ transport fuels, relegating fossil fuels to the role of a back-up fuel supply.

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