Gas Turbine Inlet Cooling Options to Maximize Power Output in Response to Changing Operating Dynamics

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Summary

A gas turbine inlet cooling system has been developed which can be installed quickly with minimal disruption to operation, and which provides a fast response to the changing dynamics of gas turbine power generation and gas transmission.

The concept involves the installation of high capacity rotary atomisers on the dirty air side of filters with a rigorous control system which provides fine tuning of downstream temperature while ensuring that filter differential pressure is not adversely affected by the cooling process.

1.0 Introduction

The demand side for power is constantly evolving. A background of increased power utilization will be partially offset by demand regulation such as smart appliances which may trim demand during peak periods.

Set against the increasing demand pattern, there is a permanent change with respect to installed renewable power generation which takes precedence in many markets. Power generation supplied from gas turbines, whether simple cycle of combined cycle, is being squeezed between base load generation and stochastic renewables.

This change in supply patterns necessitates faster response from gas turbine installations. Inlet cooling of combustion air is known to contribute to incrementally higher output and simultaneously lower heat rate. But can inlet cooling be dispatched quickly onto a pre-existing plant, and can inlet cooling be an active part of plant management in a dynamic market place?

This paper develops a response which can deliver incremental power gains and fuel savings in a timely and appropriate manner.

2.0 Emerging Demand Patterns

The hourly demand for power off a regional grid system is changing due to a combination of increasing power consumption and increasing off-grid generation, in particular through the provision of solar PV systems. The California Independent System Operator shows a projection of

- Increasing morning and evening demand (higher consumption)
- Lower midday demand (off-grid supplies displacing centrally generated power)

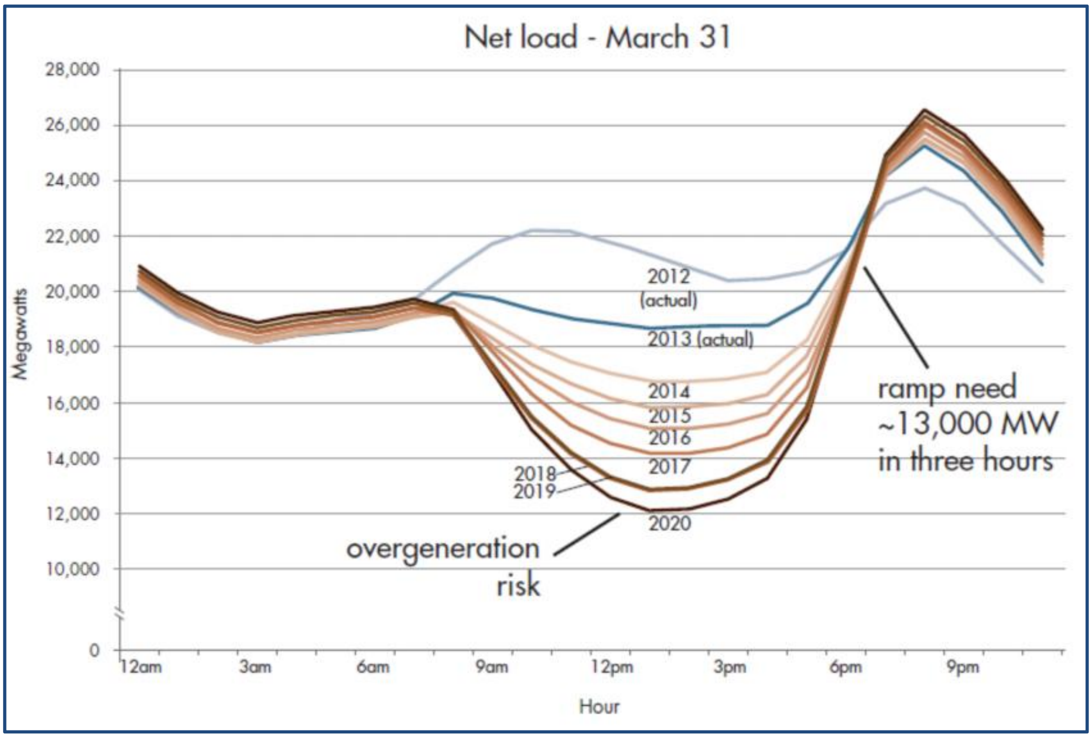

Figure 1 Trends of grid demand (CAISO)

Figure 1 shows a trend of two demand peaks, with a deepening trough between 09:00 and 17:00. The minimum grid demand during the trough is forecast to decrease due to increasing use of off-grid renewables, in particular PV panels. A similar trend has been identified in European power markets. Figure 2 shows consumption in Germany, characterized by morning and late afternoon peaks.

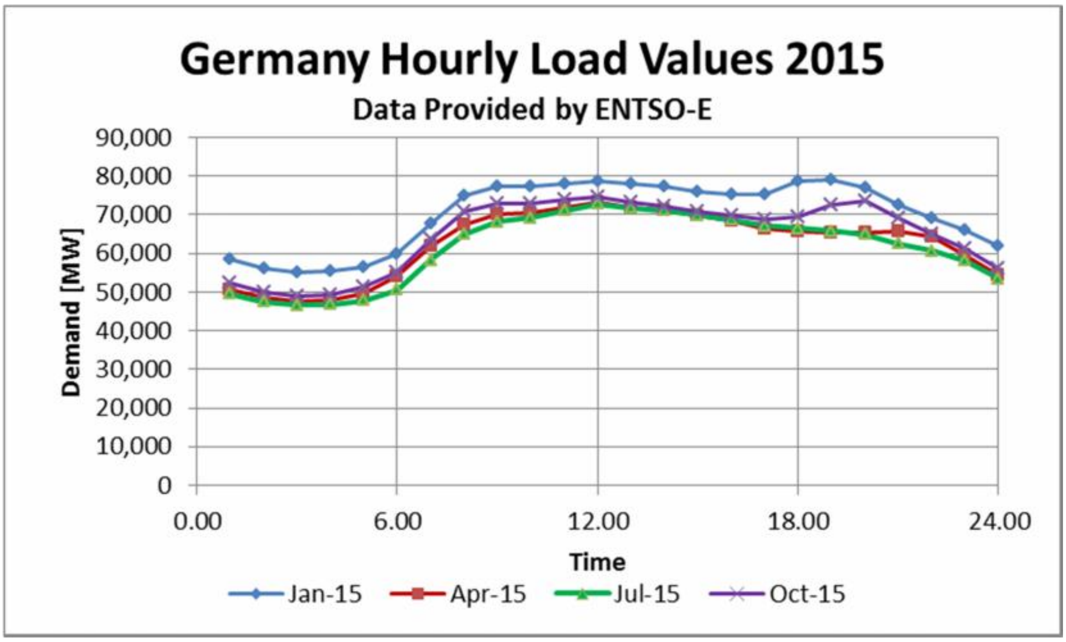

Figure 2 Germany 2015 Daily Patterns per ENTSO-E

UK patterns also show two peak demands per day, each peak approximately equal.

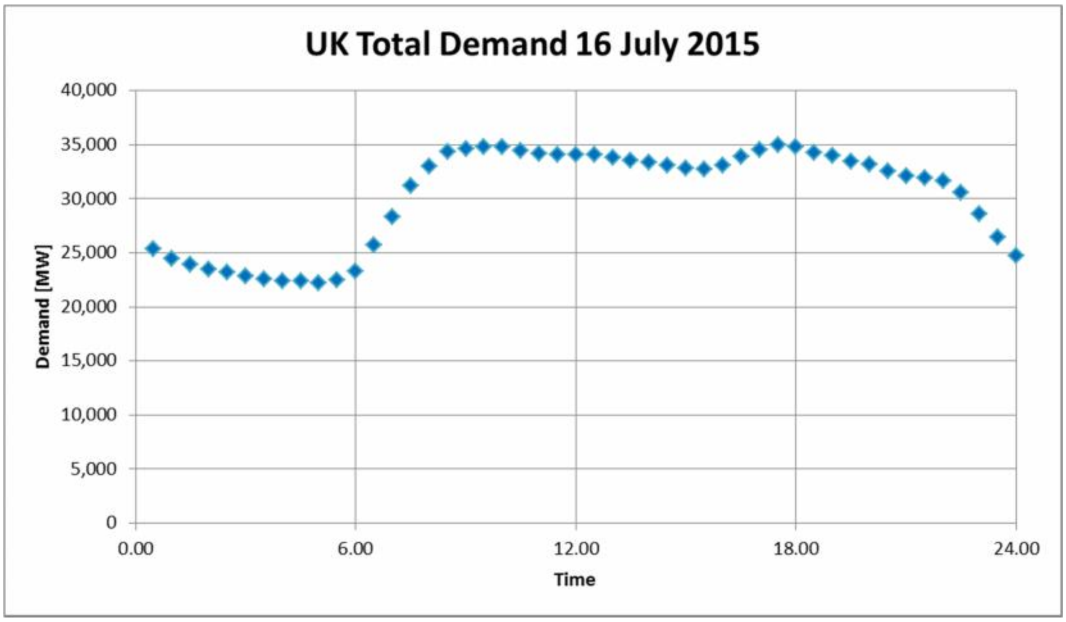

Figure 3 UK demand per National Grid

The morning and evening peaks were 35,000 MW on the date reported, and the daytime trough was 32,500 MW. If the trends projected by CAISO apply, then the daytime trough will deepen, and the morning and afternoon peaks will increase in magnitude.

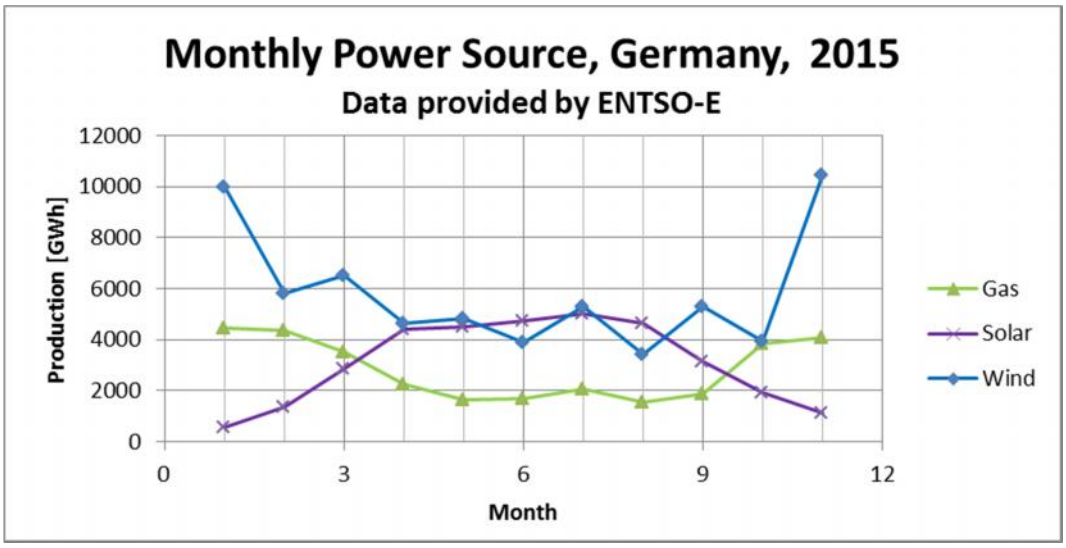

Figure 4 Power sources by month, Germany 2015

The in-roads of PV will be more significant during summer. Figure 4 shows an inverse relationship between gas powered electricity and grid-connected solar in Germany in 2014. This leads to less demand for gas turbine output from 10:00 to 15:00, with greater demand to ramp up.

3.0 Power Generation Demand and Capacity

But how is this demand pattern achieved? Across Europe in 2008, the largest contribution was from nuclear power generation (27.7%) followed by gas powered generation (22.9%). A number of trends are likely to change the fuel mix including decommissioning of base load nuclear and coal fired power stations, and increasing use of renewables.

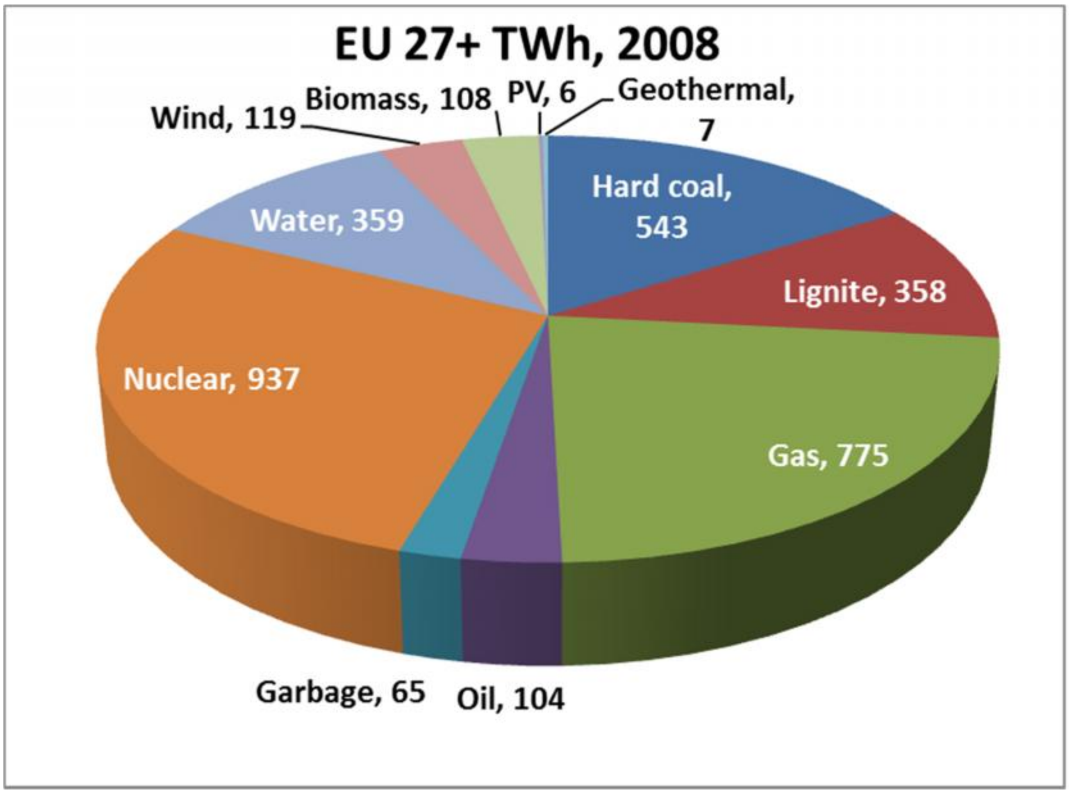

Figure 5 EU 27+ Power Production 2008 (Eurel Electrical Power Vision 2040)

Eurel also estimates the contribution of different fuel mixes to power generation to 2050. Figure 6 shows output (TWh) trends with renewables supplying an increasing proportion of power demand. Fossil fuels show a range of power output inversely proportional to additional renewable output.

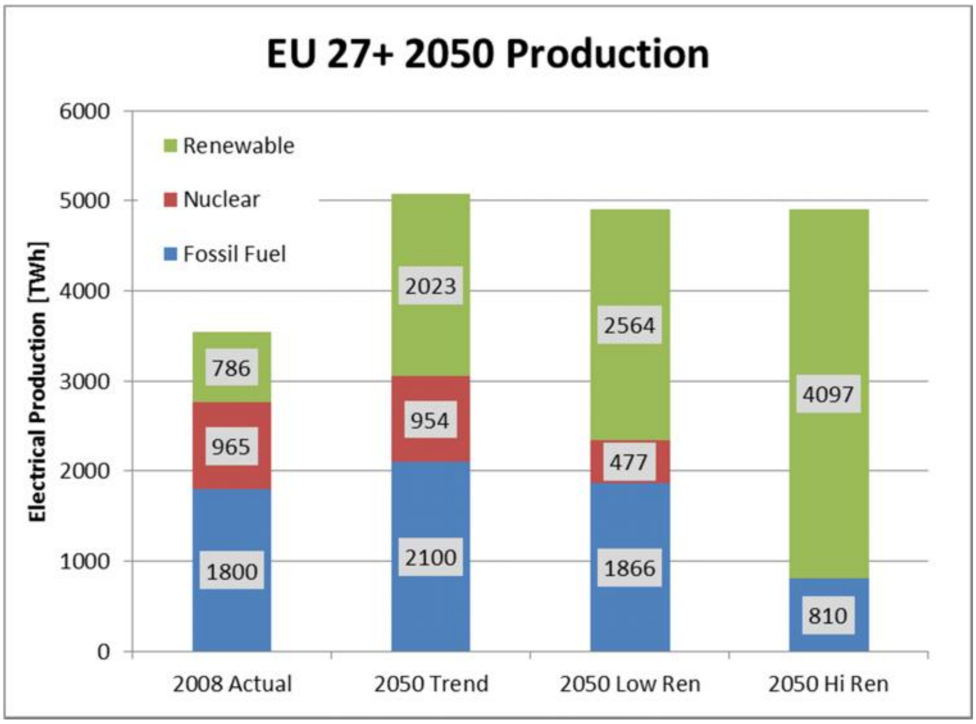

Figure 6 Projected 2050 production, TWh

The trend for fossil fuels is to increase from 1880TWh to 2100 TWh, with a sensitivity range of 810 TWh to 1866 TWh according to the extent of renewable installations. Conversely, the capacity of fossil fuels is forecast to increase from 467 GW installed to 1,000 GW installed.

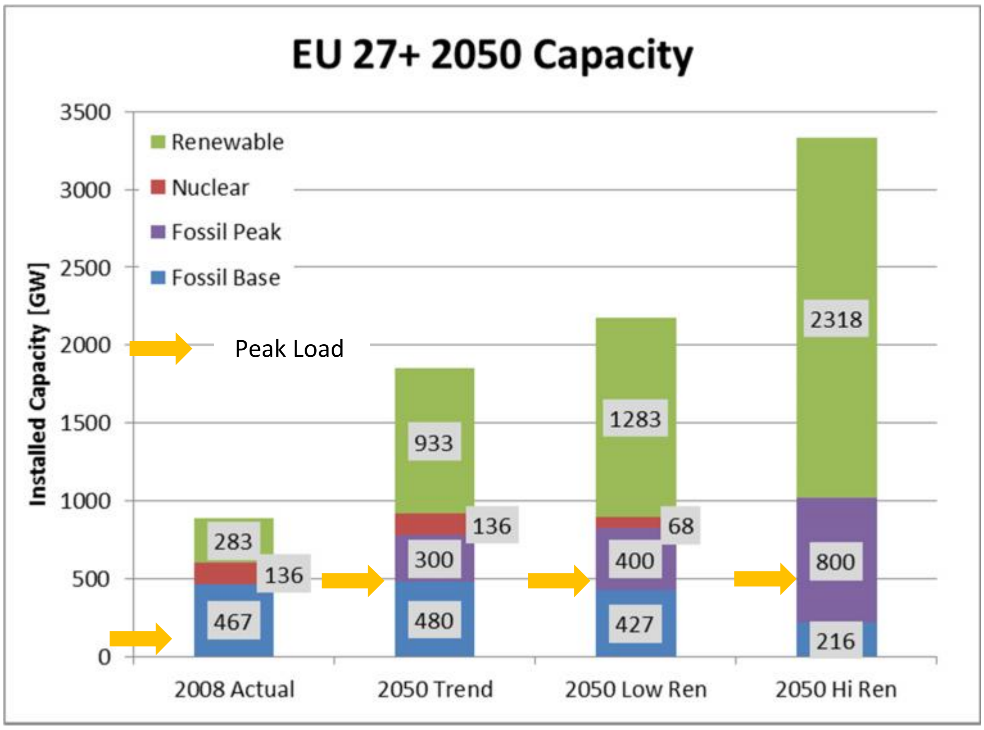

Figure 7 Installed Power 2050, GW

This forecast of installed power shows a two-fold increase in installed capacity for fossil fuels in all scenarios, with significant installed renewables, but a relatively constant peak load which is at least three times the installed capacity. This scenario of increased fossil fuel capacity is in favour of gas turbines, if coal fired power generation is wound down over the next 35 years.

4.0 Dynamic Response of Gas Turbines

The forecasts indicate increased gas turbine capacity yet lower utilization. Figure 8 shows an example of how demand is met on one particular day.

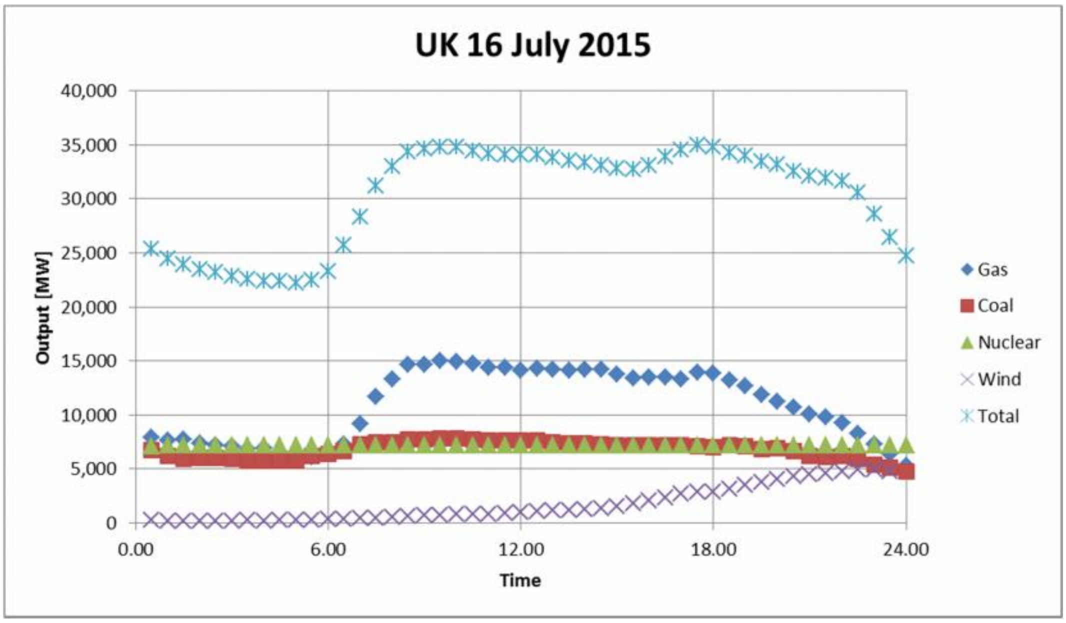

Figure 8 UK National Grid 16 July 2016

The daily peaks are essentially met by coal and gas. Gas turbines have the major role in achieving peak load against base loads (hydro and nuclear), a variable renewable supply (wind) and a less elastic fossil fuel (coal). The power demand from gas turbines ranged from 6,000 MW, to 15,000. Clearly variations in demand are met by dispatching gas turbine output onto the grid.

The hourly rate of change of output is shown in Figure 9.

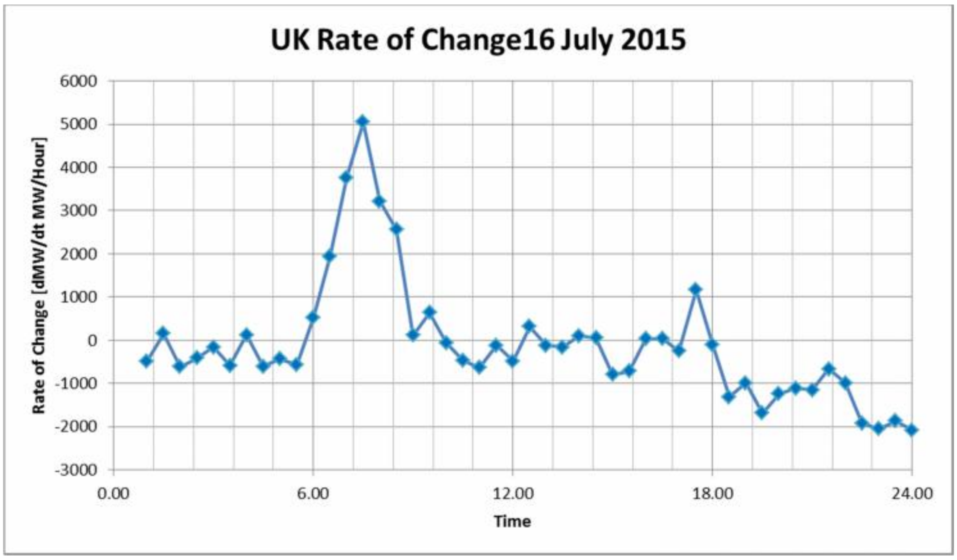

Figure 9 GT Rate of Change UK 16 July 2015

The maximum rate of change occurred in late morning, with 5000 MW additional power being provided by gas turbines in one hour. The hourly rate of change in late afternoon reached 1200 MW.

Gas turbines are mostly responsible for meeting instantaneous dynamic load demands. The improving flexibility of gas turbines together with lower installed cost will lead to a combination of base load to replace decommissioned nuclear and coal fired plants, plus prime position as back up capacity to intermittent renewables.

5.0 Speed of Gas Turbine Ramp Up

Ramp up times for new gas turbines are decreasing to meet the evolving demands of the market place.

From	Technology	Time from Notice to Deviate from Zero to Grid Synchronization (Minutes)	Time from Synchronization to Full Load (Minutes)
Hot Start	CCGT	15	25
Warm Start	CCGT	15	80
Cold Start	CCGT	15	150 - 240
All	Large SC	2 – 5	15 – 30
All	Small Frame SC	2 – 5	10 - 15
All	Aero SC	2 – 5	4 – 8

Table 1 – Time to Full Load

Gas turbine rotors are able to synchronise to the Grid within 15 minutes of ignition for large combined cycle gas turbines, and as early as 2 minutes for simple cycle gas turbines.

A modern CCGT plant may be capable of reaching full load within 150 minutes.

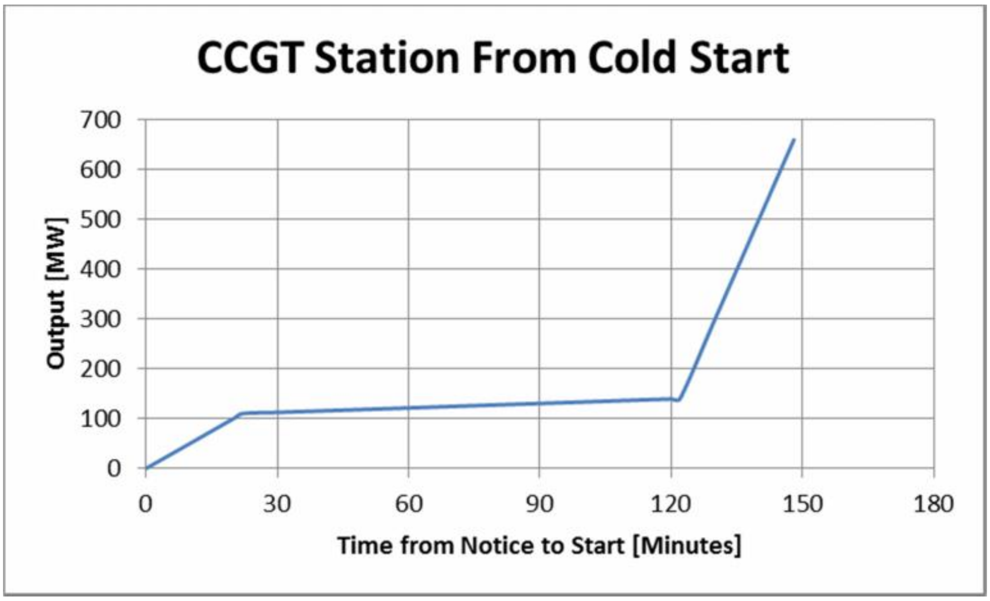

Figure 10 CCGT time to Full load from Cold Start

The plant in Figure 10 reaches full load from a cold start in 150 minutes. The same plant would achieve full load at 45 minutes from a hot start.

6.0 Role of Inlet Cooling

Gas turbines are constant volume machines, but their performance is affected by the mass flow of air through the compressor to the combustion section. As the temperature of incoming ambient air increases, the density of the air decreases, and the mass flow through the gas turbine also decreases. The consequence is that as ambient temperature increases, the gas turbine output decreases and the fuel rate increases.

While each gas turbine has specific characteristics, Figure 11 represents the effect of temperature on gas turbine output.

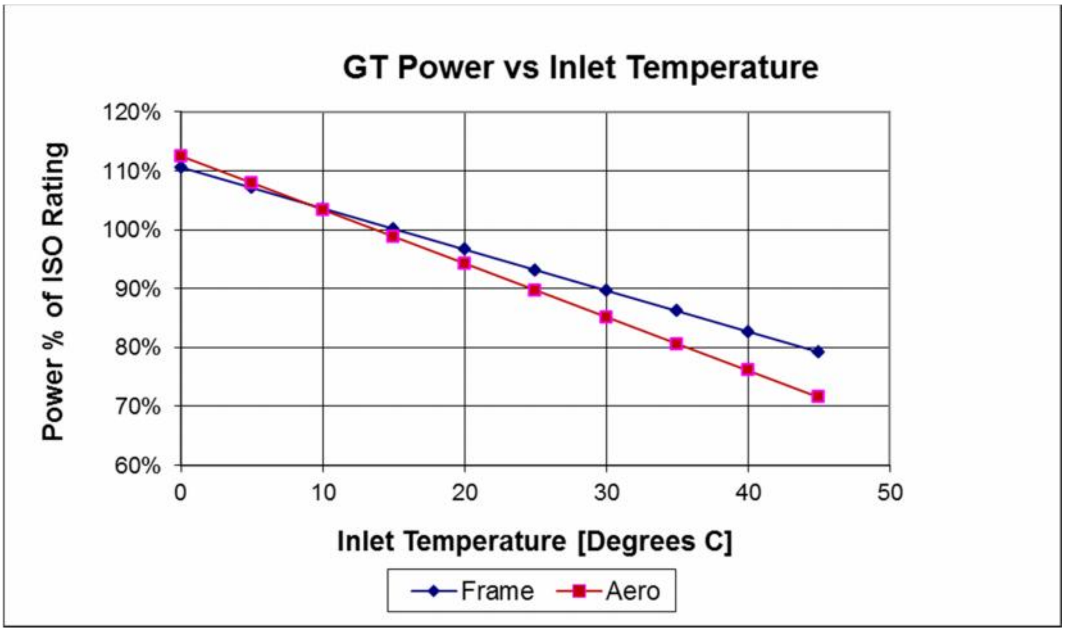

Figure 11 GT Power Output vs Air Inlet Temperature

The industry norm, ISO point, indicates that the engine is rated at 100% of its capacity at 15°C. The deterioration in performance is more marked for an aero-derivative engine. At 40°C, a frame size gas turbine will produce less than 85% of its rated output – derating approximately 0.7% per degree C.

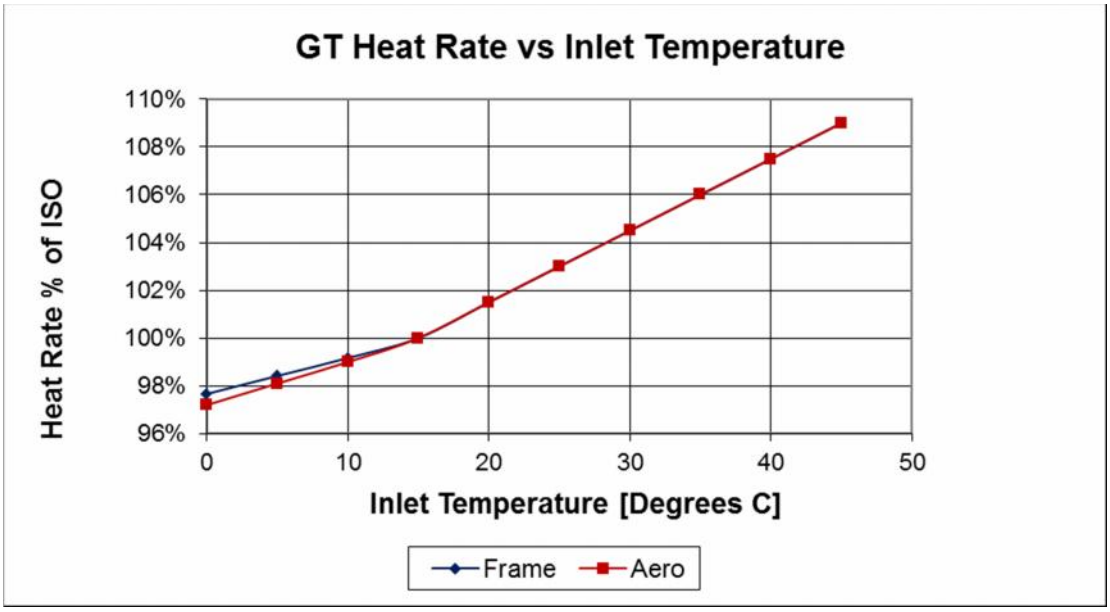

Figure 12 GT Heat Rate vs Air Inlet Temperature

As air inlet temperature increases, the gas turbine efficiency reduces, leading to an increased unit heat rate. From Figures 11 and 12, it can be deduced that cooling of inlet air will increase power output and reduce unit fuel consumption.

Inlet cooling provides the following advantages:

- Incremental power - greater utilization of installed capacity, contribute to rate of change.
- Reduced heat rate – lower fuel costs, reduced CO_2 per MWh.

For the geographic centre of Europe, peak temperature reaches 33.6°C (at 34% Relative Humidity) in summer, leading to a reduction of approximately 13% power output against ISO, and an additional 5.5% fuel consumption.

7.0 Cooling Methods

Cooling of inlet air can be achieved by two methods:

Adiabatic cooling interfaces a water supply with the incoming air. Sensible energy is given up by the air, providing latent heat of evaporation until the air reaches new equilibrium. No heat is removed from the system, the air enthalpy remains constant. The lowest theoretical temperature is the wet bulb temperature, which is a function of ambient temperature and relative humidity.

Chilled water cooling removes heat from the air via conduction of heat from the air to circulating water in coils. Chilled water is circulated in a closed loop through a mechanical chiller. In turn the chiller disperses the heat removed from the air via a condenser by a cooling tower or cooling fans. The lowest temperature is constrained by the chiller, and may be below the wet bulb temperature. Depressing air temperature below its dew point will produce condensate on the coils.

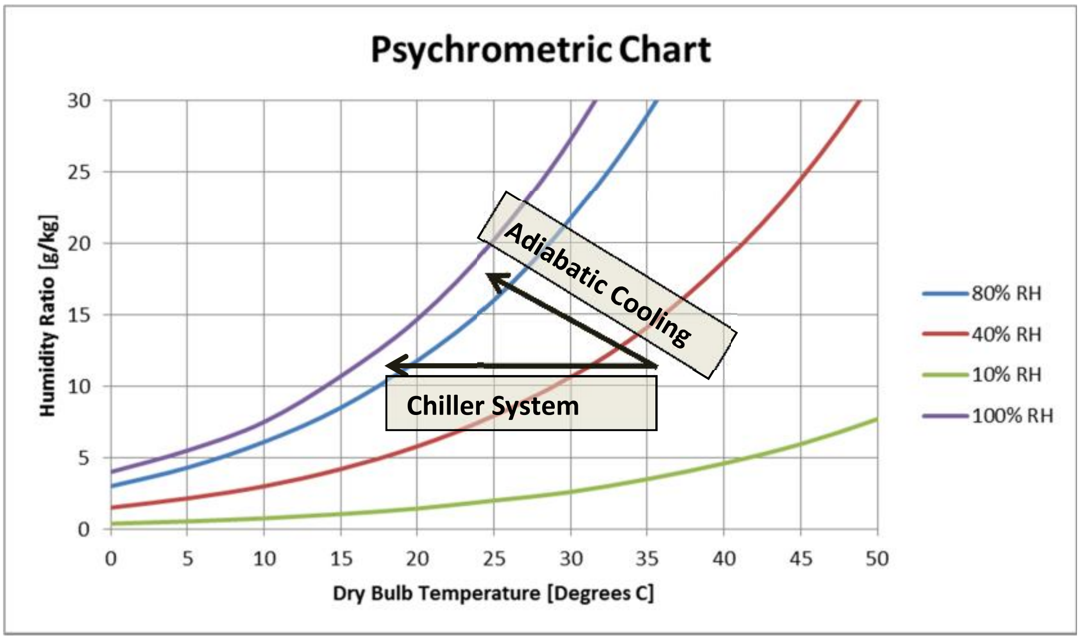

Figure 13

In Figure 13, the lowest theoretical temperature from adiabatic cooling would be 25°C, whereas chilling can cool below this temperature, providing enough capacity has been installed.

Chilled water systems have a cost factor of approximately ten times that of adiabatic cooling. As such they are most likely to be economic on base load systems, with high ambient temperature, but less so on peaking units with moderate ambient temperature.

8.0 Adiabatic Cooling

For European gas turbines, with highly variable loads, adiabatic cooling may present an opportunity to increase output and reduce heat rate when opportunities arise to meet peak demand quickly.

To date, the standard methods of adiabatic cooling have been:

- Media evaporative cooling
- High pressure fogging

Both systems have usually been located downstream of inlet filters to avoid issues of soaking the filters, creating high differential pressure, reduced filter effectiveness, reduced filter life, and potential trips of the gas turbine on a high dp signal.

With respect to the dynamics of power production, there are two elements considered;

- Speed of installation, in response to changing GT market conditions
- Response of installed system to demand changes

8.1 Speed of installation – Evaporative Cooler

Evaporative cooler media needs to be located downstream of the final filters, with a droplet catcher after the media to reduce free water in the intake ducts. For an existing installation, this requires two turbine shutdowns – one for a detailed survey of the intake system, and one for installation of the evaporative cooler.

An evaporative cooler system requires that the filter house is moved forwards by approximately 1800 mm, more if transitions are required. The lead time for an evaporative cooler system includes custom engineering design to suit the site specifics, order of proprietary items, fabrication and shipping.

Evaporative cooler systems require high quality water, to at least drinking water quality, which may require some form of water treatment.

A plant shutdown is required to split the filter house from the intake, and to insert stainless steel evaporative cooler modules.

8.2 Speed of installation – High Pressure fogging

High pressure fogging nozzles also need to be located downstream of the final filters, preferably in a dedicated fogging duct to provide residence time. A residence time of approximately two seconds is often quoted. At inlet duct speeds in the order of 12 metres per second, approximately 24 metres of ducting would be required to ensure complete evaporation of droplets. For an existing installation, this system requires two turbine shutdowns – one for a detailed survey of the intake system, and one for installation of the fogging nozzle array.

A typical fogging duct is approximately 2000 mm deep. The lead time for high pressure fogging system includes custom engineering design to suit the site specifics, order of proprietary items, fabrication and shipping.

High pressure fogging nozzles require a supply of demineralized water. This may require additional expenditure for a demineralization skid,

Activities requiring a shutdown include installation of a fogging duct and assembly of a nozzle array into the clean air side. Other modifications are necessary to protect the intake system against the corrosive effects of demineralized water and to provide drainage for excess water downstream.

8.3 System response

Evaporative coolers operate with a constant flow of water across the top of the media. At most, 20% of the water evaporates, and the rest is recirculated. This over-supply is necessary to ensure that the media is always fully wetted. Reducing the water flow according to ambient conditions will not affect the downstream temperature. Essentially, evaporative coolers are passive devices, which are either on or off.

High pressure fogging is controlled in stages. Each stage of nozzles is served by a fixed speed high pressure pump operating at 70 bar(g) 200 bar(g). The number of stages can be controlled from a suitable control signal. High pressure fogging is amenable to staged variable control in increments according to the number of stages. For instance a 6 stage system (6 pumps, 6 nozzle arrays) has a resolution of 16.7%.

9.0 A New Way

A new inlet cooling system has been developed by AAF International. InstaKool™ is a system which can be installed quickly, with minimal or zero shutdown of the gas turbine, and which is infinitely responsive to control inputs. In this respect, the system can be deployed quickly and effectively to complement the evolving dynamics of power generation.

The system comprises of high capacity rotary atomisers located upstream of the final filters, with a rigorous control system which ensures that filter differential pressure is not compromised.

Figure 14 Rotary Atomiser

9.1 Protection of Filter Differential Pressure

A survey of thousands of operating hours across a range of gas turbines, filter types and location has indicated that filter differential pressure does not increases against a background at less than 85% Relative Humidity. On new filters, the point at which differential pressure increases is 95%, and the inflection point decreases to approximately 85% on filters with over 16,000 operating hours.

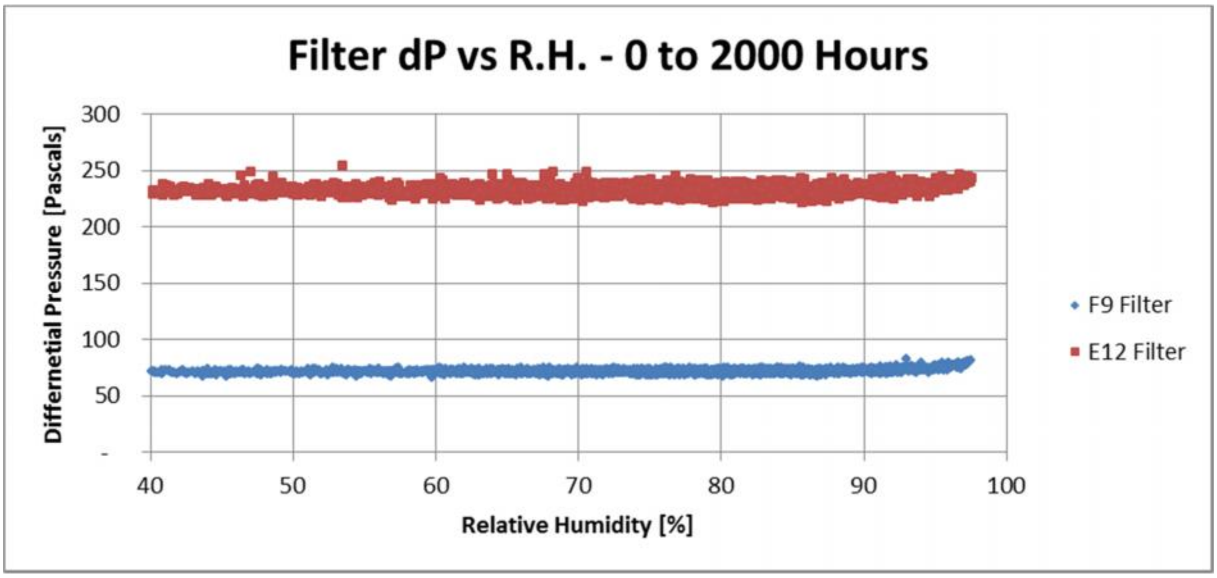

Figure 15 Coastal Plant – First 2000 Hours

Figure 15 is operating data for a plant located on a coastal estuary. The ambient conditions included relative humidity of 80% or more for 64% of the year.

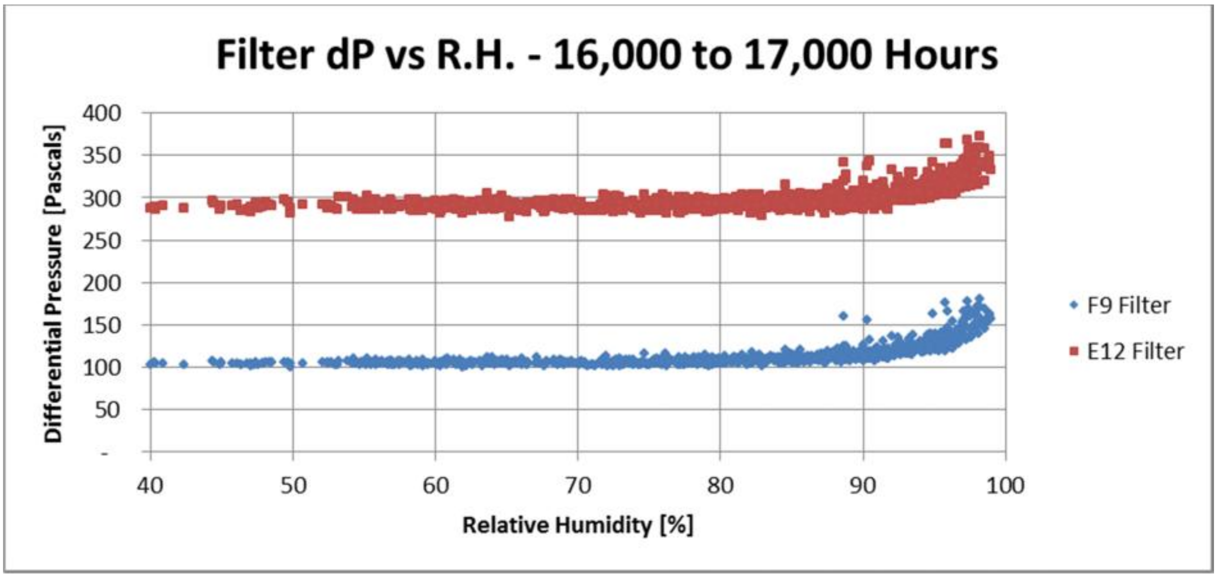

Figure 16 Coastal Plant, 16,000 to 17,000 Operating Hours

Figure 16 shows the same plant after 16,000 operating hours. Differential pressure starts to increase beyond 85% R.H.

9.2 InstaKool Description

Operating data from across a broad range of plants provides a context into which we have designed an inlet cooling system which can be located upstream of filters. InstaKool provides adiabatic cooling by the introduction of a fine mist into the air stream, ahead of the final filters. The mist delivery device is a high capacity rotary atomiser which only requires low pressure water. Varying the atomiser water flow rate does not affect the water droplet particle size distribution, which allows the system to be finely controlled from zero to 100% water flow.

Field instrumentation comprises temperature/relative humidity transmitters and a differential pressure transmitter.

Measurement of ambient temperature and relative humidity provides a permissive to operate, based on a minimum ambient temperature and maximum relative humidity. Downstream transmitters provide feedback on the resultant temperature and relative humidity. The water flow to the system is controlled via a feedback loop to ensure that relative humidity is maintained no higher than 80%, ensuring that filter differential pressure is not at risk.

A differential pressure transmitter provides a signal which acts as an additional safeguard.

9.3 Installation Dynamics

The InstaKool system has been designed to provide a fast response to cooling demands, essentially installed outside an existing intake envelope. High capacity rotary atomisers are located on simple supports prior to inlet filters. Modular control panels are located adjacent to the filter house, providing 200 Watts of power to each atomiser. Field instruments tie into the control panel, from which a PLC controls a modulating control valve. Each site simply needs to supply low pressure water to a single tie-in point, with a power supply connected by a standard 400-480V socket (16, 32 or 63 A depending on system size).

Because the system comprises of a multiple of standard parts, lead time is substantially shortened. On smaller projects, equipment will be available ex stock.

Further, because the equipment is not located in the clean air stream, installation does not necessarily require a plant shut down. Providing appropriate safety measures are instigated, most, if not all installation work can be carried out without shutting down the gas turbine. On peaking plants, with known shut down periods during each day, installation can of course be carried out on an incremental basis during off-hours.

Table 2 compares InstaKool with conventional cooling technologies.

Attribute	Media Evaporative Cooling	High Pressure Fogging	InstaKool
Installation	Approximately 14 days down time.	Approximately 7 days down time.	Zero down time
Unit capacity		Typically 0.2 litres per minute per nozzle	3 litres per minute per atomiser
Control	No control on air T or RH – passive reduction in temperature.	Cannot fine tune individual stages or nozzles without impacting droplet size. Resolution 16%	Continuous control with no impact on droplet quality.
Maintenance	Shut down GT to change media.	Shut down GT to inspect and change nozzles.	Can be inspected and maintained on-line.
Water quality	Potable (drinking) water or demineralized	Demineralized	No restriction on dissolved solids. Avoid suspended solids.

Water at bell mouth	Medium risk – site observations of water reported in duct	High risk – requires drainage system design	None
Foreign object damage	Requires stringent design, fabrication and inspection to ensure no loose parts ingested into GT. Medium risk.	Requires stringent design, fabrication and inspection to ensure no loose parts ingested into GT. Higher risk.	No risk.

Table 2 Adiabatic Installation Attributes

9.4 System Operating Dynamics

Gas turbines are increasingly being challenged to respond quickly to demand changes. As an example, UK gas turbines are currently providing an aggregate ramp rate of 5000 MW per hour. Individual gas turbine ramp-up times are decreasing in order to match the emerging demand scenario, with aero-derivative gas turbines capable of 2 to 4 minutes from synchronization to full load.

InstaKool provides a fast response to changes. Cascade control of differential pressure, followed by relative humidity protects filters from differential pressure excursions. A further supervisory control signal of downstream temperature increase can also be added. This strategy enables the gas turbine operator to trim output by adjusting the downstream temperature between ambient and the reduced temperature at 80% relative humidity.

Typical system response from a cold start is shown in Figure 17.

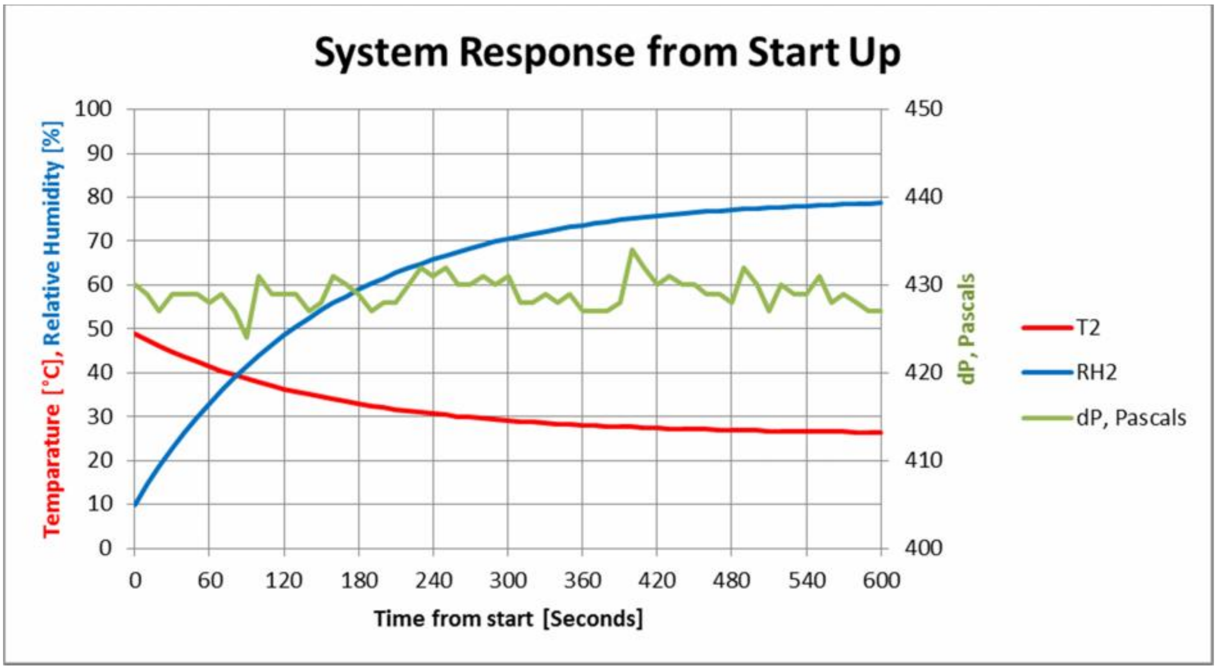

Figure 17 - System Dynamics, Arid Climate

From a cold start, additional power is available immediately, reaching 30°C after 5 minutes and a steady state of 28°C at 10 minutes.

9.5 EU Hottest Day Example

The geographical centre of the EU has moved around as the EU has expanded. One of the more recent contenders has been Geinhausen-Meerholz, Climate data from nearby Frankfurt am Main has been used to develop a case for cooling.

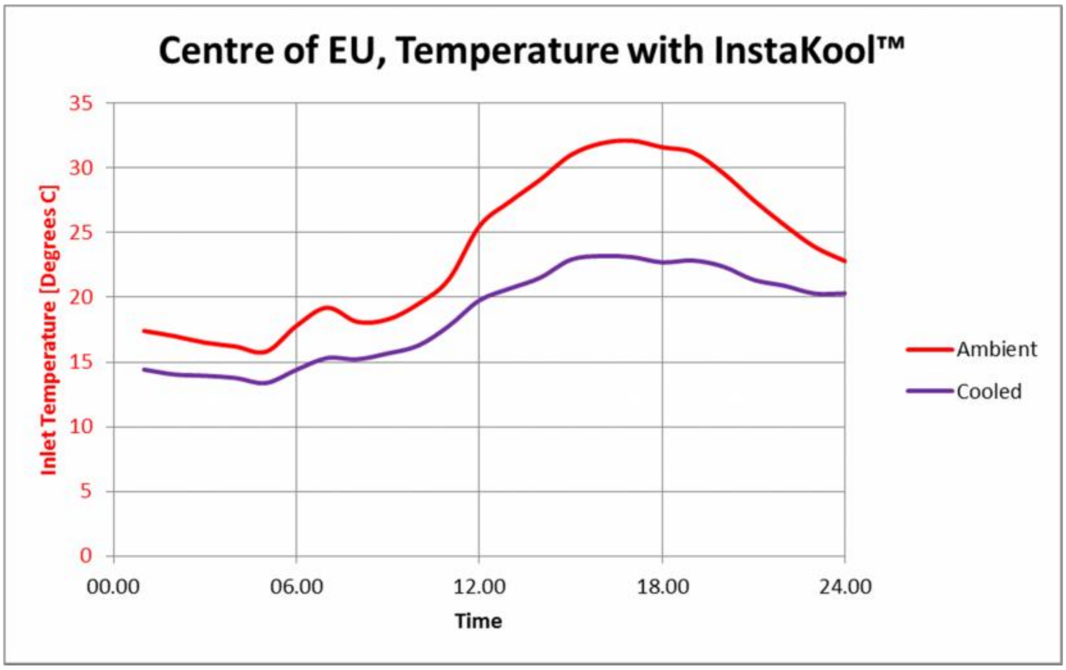

Figure 18 Ambient and Cooled Temperatures

On a hot summer day, InstaKool will reduce the inlet temperature from 32°C to 23°C, at 80% Relative Humidity.

Figure 19 superimposes an aggregate gas turbine demand curve over potential gas turbine output curves at ambient temperature and cooled temperature. The peak demand curve has been re-calculated as a percentage of the maximum GT capacity for this particular day.

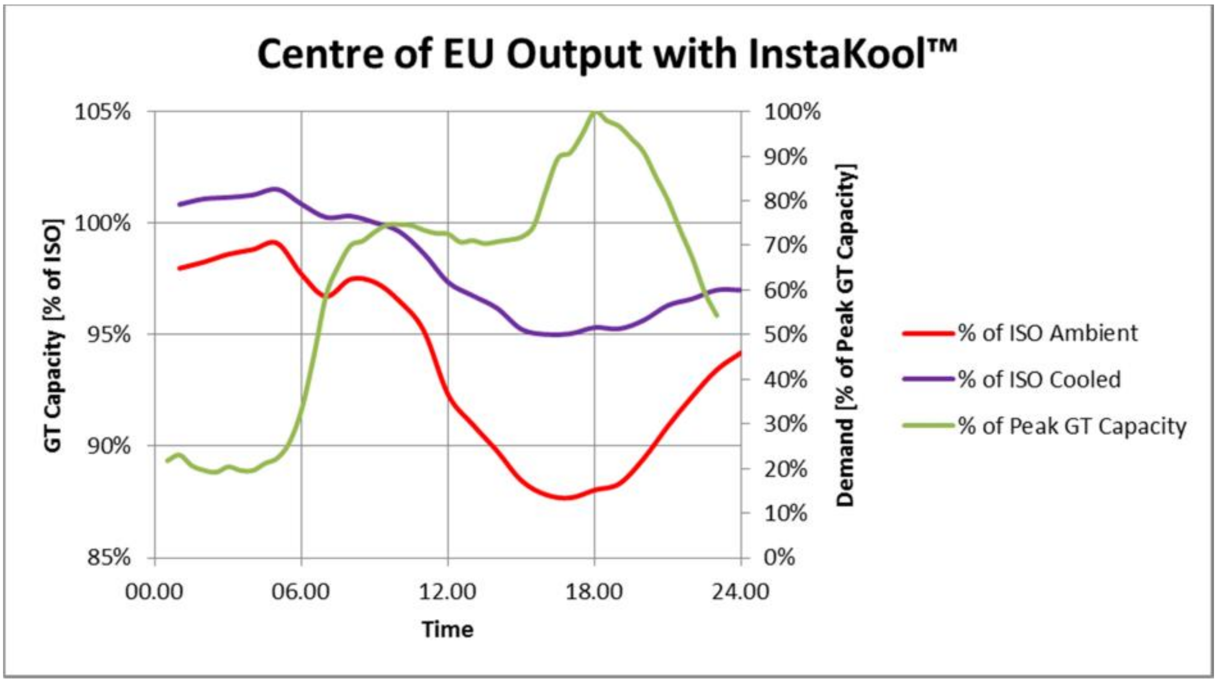

Figure 19 Demand Curve and Output curves

9.5.1 Morning Peak

Available GT output at ambient temperature dips from 97% of ISO at 09:00 to 88% of ISO at16:00. Morning demand peaks at 09:00 then tails off slightly. As more solar PV is installed this midday trough will deepen in future. GT capacity exceeds demand, and is matched up to 08:00. After this, demand is relatively constant, while capacity reduces due to increased ambient temperature.

9.5.2 Midday Trough

Demand drops 5% from 75% to 70% between 09:00 and 14:00, while GT output available drops further, by 9% from 97% to 88% of ISO. Demand stays relatively flat, but GT capacity falls by 10% from its morning level due to higher ambient temperature. As noted, in future scenarios of higher off-grid photo-voltaics, the demand trough will fall further.

9.5.3 Evening Peak

When demand picks up from 70% to 100% of peak GT demand, available output at ambient temperature ranges from 90%, dipping to 88%, then starts to recover as demand tails off. From 14:00 to 18:00, gas turbine capacity is out of synch with demand, with capacity falling as demand is rising.

9.6 Output Dynamics with InstaKool

Addition of InstaKool offsets the deepest loss of power and achieves 95% output at the hottest hour of the day, when an uncooled GT would be achieving 88% output.

In other words, a swift acting cooling system such as InstaKool would be able to provide an additional 7% output from a gas turbine just as demand ramps up to the early evening maximum. The cooling system can be trimmed to assist in ramping up and ramping down.

This ensures that gas turbine capacity is closer to being in synch throughout the evening peak demand cycle.

Overall heat rate is moderated by inlet cooling to the extent of 0.3% per degree C temperature reduction. The incremental heat rate of additional power from cooling at the site discussed is approximately 60% of the base heat rate. So, for instance a plant operating with an ISO heat rate of 10,000 kJ/kWh, would generate additional power at a heat rate of less than 6000 kJ/kWh. So, the additional power made available by cooling has a lower unit cost than the base power if cooling were not installed.

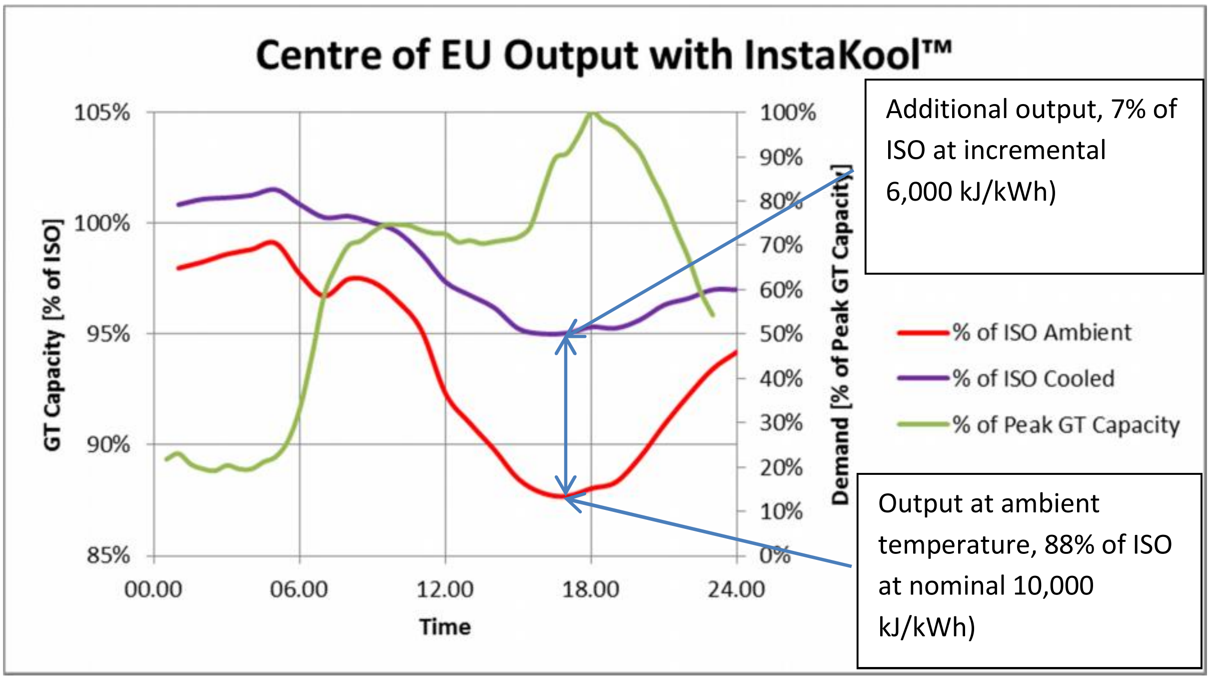

Figure 20 Incremental Output and Heat Rate

When gas turbine output is called to increase to match ramped up demand each afternoon and evening, InstaKool can be used to provide an additional 7% output, and the incremental heat rate of the extra power will be approximately 60% that of the base power being produced at ambient temperature. InstaKool can be incorporated into the plant control system to assist in ramping up and down to match demand.

10.0 Conclusions

Power demand from grid-connected generators is changing irreversibly against a backdrop of increasing consumption, increasing off-grid supply, increasing but stochastic renewables and phase out of baseload technologies.

Demand for power from many gas turbines is moving towards a cycle of two peaks per day. During summer operation the second early evening peak coincides with higher ambient temperature, which depresses gas turbine capacity, with gas turbine capacity and grid demand becoming out of synch.

An inlet cooling system has been developed which addresses the dual needs of fast implementation in a changing market, and a dynamic system response which matches gas turbine ramp rates and augments output during the early evening peak. For an example of central European climate, InstaKool can be brought on-line and used to augment power, with the incremental power having a heat rate of 60% of the base power without cooling.