

Combined cycle heat rates at simple cycle \$/kW plant costs

By Victor deBiasi

Fast full-load startup features make Cheng Cycle plants ideally suited for renewable energy backup to support solar and wind plants.

Cheng Power Systems is telling utilities that simple cycle gas turbine plants equipped for Cheng Cycle operation are able to produce more electricity at lower cost than any combined cycle plant designed around the same model gas turbine(s).

Both cycles are based on recovering and utilizing waste energy in the gas turbine exhaust to improve performance. The Cheng Cycle differs in that the energy is recycled directly and more effectively through the gas turbine instead of through a separate steam turbine generator.

In effect, the steam turbine and associated equipment are eliminated. Comparable plant site requirements, conversion costs and performance:

□ **Plant site.** Combined cycles require three times the land and twice the water of Cheng Cycle plants which typically operate on less than half the water combined cycles lose to air cooling tower evaporation.

□ **Conversion.** Cost of retrofitting a simple cycle LM6000PC gas turbine plant for Cheng Cycle is estimated at around \$15 million, less than half the \$33 million estimate for combined cycle conversion.

□ **Output.** Cheng Cycle has the potential to increase simple cycle gas turbine output by up to 70% and lower the heat rate by 40%, depending on gas turbine's OEM design parameters.

Major project cost factors for the utility industry are centered on capital

costs, fuel prices, emissions, operating and maintenance costs. To minimize those costs, the gas turbine industry has regularly invested large sums on improving efficiency and unit power output to reduce fuel consumption and lower \$/kW.

Currently, with the discovery of shale gas, the \$8/MMBtu (LHV) price of long-term natural gas fuel supply contracts in the US has dropped to somewhere below \$3.5/MMBtu, with spot market prices dipping to below \$2.50, so that the price of fuel has diminished in importance.

Top priority for both utilities and gas turbine OEMs has switched to faster response times, to support variability in intermittent wind and solar power generation, and higher part-load efficiencies.

Flexible GT designs

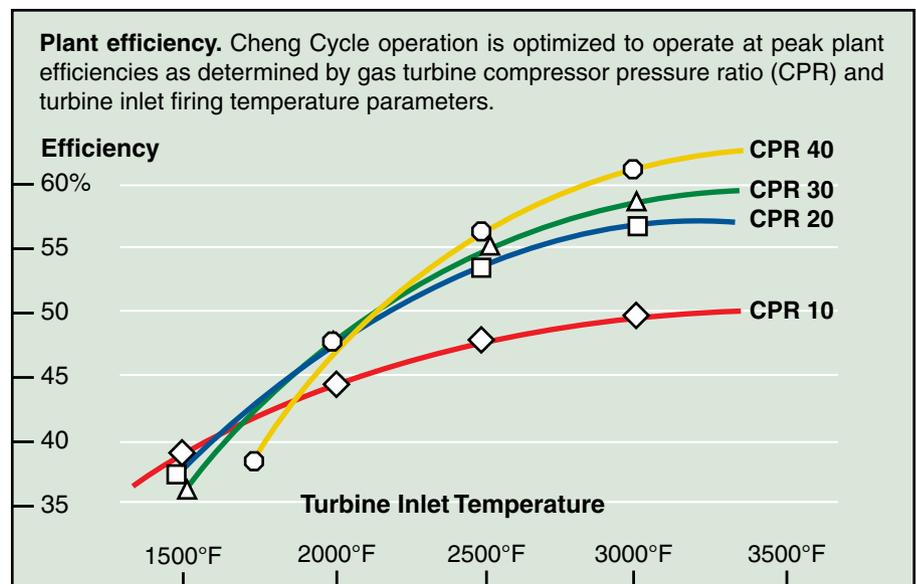
This has given rise to a new breed of

“flexible” gas turbines such as General Electric OpFlex and Siemens Flex Plant series which are designed for rapid start grid back-up, low turn-down idling capability, cyclic operation, high ramp rates (up and down), and good part-load efficiencies.

General Electric's new flexible Fr 7FA-05 will introduce a new family of compressor designs with dramatically improved surge margin and operating stability, capable of higher 17.8 to 1 pressure ratios and 1145 lb/sec mass flow.

Earlier E-class gas turbines like the 7111EA needed 17 stages of compression to achieve a 13 to 1 pressure ratio. By contrast, the new FA-05 class could operate at a 20 to 1 pressure ratio.

In simple cycle mode, the 7FA-05 is ISO rated at 215.8MW base load and 8830 Btu/kWh LHV heat rate (38.6% efficiency). If modified for



Source: Cheng Power Systems, March 2013

Cheng comparative combined cycle owning and operating cost study

Study is based on conceptual 3-on-1 Fr 7111EA and 2-on-1 Fr 7FA-05 combined cycle plant designs vs. two simple cycle Fr 7FA-05 gas turbines equipped for Cheng Cycle operation (without steam turbine cycle) operating a 5-day week, daily cycling and weekend shutdowns. Levelized cost of electricity is based on \$4 per MMBtu fuel and 25-year utility financing format.

	Single 3-on-1 7111EA CC plant	Single 2-on-1 7FA-05 CC plant	Cheng Cycle Fr 7FA-05 plant
Plant configuration			
Number of gas turbines	3 GTs	2 GTs	2 GTs
Number of boilers	3 HRSGs	2 HRSGs	2 HRSGs
Number of steam turbines	1 ST	1 ST	0
Plant design rating			
Nominal net plant output	363 MW	645 MW	720 MW
Net plant heat rate (HHV)	8,230 Btu/kWh	6,414 Btu/kWh	7,353 Btu/kWh
Net plant efficiency (HHV)	41.5%	53.2%	46.4%
Capital cost estimate			
Installed cost (\$/kW)	\$950 per kW	\$1,000 per kW	\$700 per kW
Total plant cost	\$344,850,000	\$645,000,000	\$504,000,000
O&M cost estimate (\$/yr)			
40% capacity factor (2,468 hrs)	\$20,882,000	\$25,845,000	\$21,267,000
60% utilization (3,702 hrs)	\$22,413,000	\$28,469,000	\$24,736,000
80% utilization (4,936 hrs)	\$25,142,000	\$33,220,000	\$28,760,000
Operating heat rate (HHV)			
40% capacity factor	9461 Btu/kWh	6895 Btu/kWh	7835 Btu/kWh
60% capacity factor	9737	6991	7892
80% capacity factor	9461	6895	7835
Fuel consumption (Btu/yr)			
40% capacity factor (2,468 hrs)	8,475,959 MM Btu	10,975,875 MM Btu	13,922,482 MM Btu
60% utilization (3,702 hrs)	13,084,834	16,693,040	21,035,652
80% utilization (4,936 hrs)	16,951,917	21,951,749	27,844,963
Power production (MWh/yr)			
40% capacity factor (2,468 hrs)	895,884 MWh	1,591,860 MWh	1,776,960 MWh
60% utilization (3,702 hrs)	1,343,826	2,387,790	2,665,440
80% utilization (4,936 hrs)	1,791,768	3,183,720	3,553,920
Cost of electricity *			
40% capacity factor (2,468 hrs)	9.6 cents/kWh	7.2 cents/kWh	6.3 cents/kWh
60% utilization (3,702 hrs)	7.9	5.9	5.4
80% utilization (4,936 hrs)	6.9	5.2	4.9

* Estimate, COE will vary for specific projects depending on actual plant, utilization, fuel and financing costs.

Source: Cheng Power Systems, March 2013.

Cheng Cycle operation, basically the same engine could be upgraded to 360.7MW base load (65% boost in power) and 6685 Btu/kWh heat rate LHV which is equivalent to 51.1% efficiency.

Comparative cost study

Cheng Power Systems recently completed a study on annual owning and operating costs of contemporary 7E and more advanced FA-05 gas turbine combined cycle plants vs. two simple cycle FA-05 gas turbines equipped for Cheng Cycle operation.

Fuel consumption and maintenance costs are calculated for base load output at 40%, 60% and 80% capacity factors which take into account the impact of start-stop cycles on heat rate (fuel consumption) and maintenance costs.

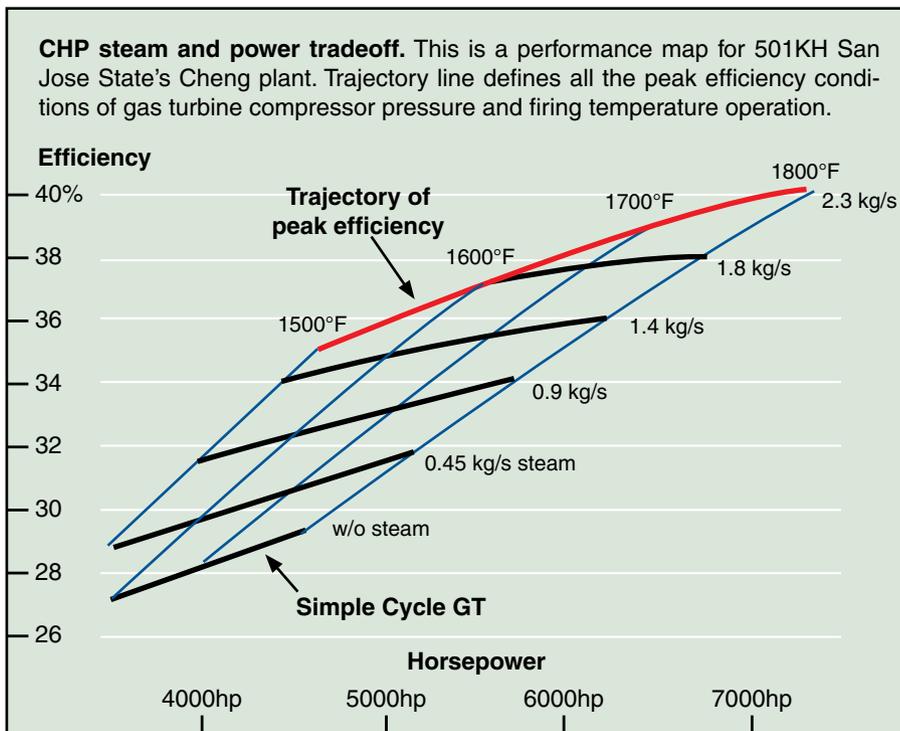
In this context, the term “capacity factor” is intended to represent the percentage of time a plant is utilized during the year at full load output. Duty cycle is based on 5 days per week of operation with daily start-stop cycling between weekend shut-downs.

The Cheng study parameters are modeled on those for an EPRI-funded Sargent & Lundy study in 1989 on annual owning and operating costs for a contemporary 3-on-1 Fr 7EA combined cycle, new (at that time) advanced 2-on-1 Fr 7FA combined cycle plant and a steam injected LM5000 simple cycle gas turbine.

The new study is based on year 2012 design ratings for a 3-on-1 Fr 7111EA and advanced 2-on-1 Fr 7FA-05 combined cycle plants vs. potential plant powered by two simple cycle Fr 7FA-05 gas turbines modified and equipped for Cheng Cycle.

Cost factors

Manpower costs to operate and maintain each of the plants are calculated on the basis of current average salary levels. The percentage of the total ownership cost set aside for maintenance follows the same format as



Source: Cheng Power Systems, March 2013

used for the earlier EPRI Report.

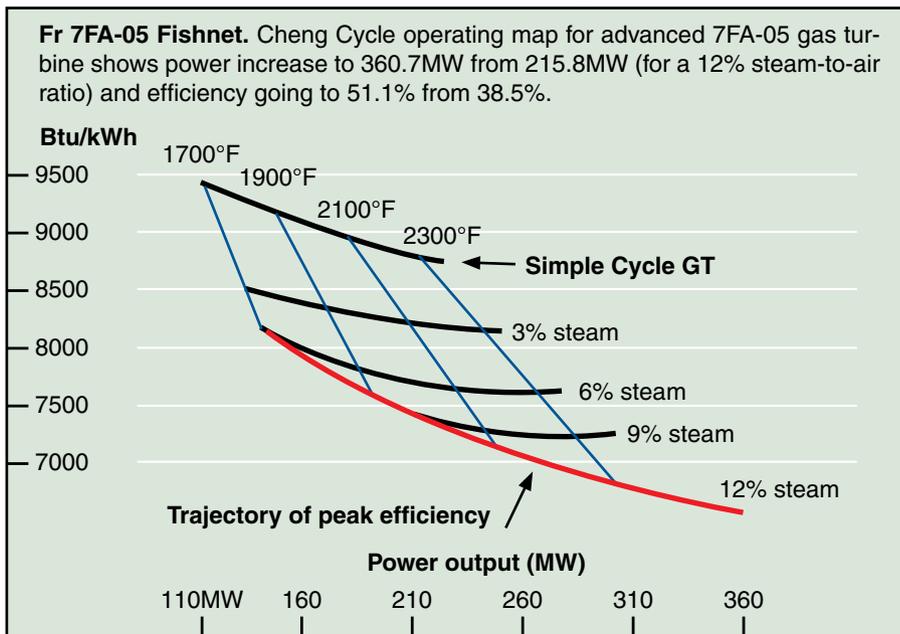
Fuel cost is based on a projected \$4/MM Btu price of natural gas (HHV) delivered under a long term supply contract. Base load heat rates used for calculating fuel consumption are adjusted for the differences in duty cycle at 40, 60 and 80% capacity factors.

Frequent start-stop cycling will increase fuel consumption because of inefficiency during plant start-up

before reaching full load output and during the time required to gradually reduce load during shut-down.

Plants operating at 40% capacity factor operating less than 9-10 hours a day will have fewer start-stop cycles than plants at 60% in service 14-15 hours of the day. Similarly, plants at 80% factor operating up to 19 hours a day will have fewer start-stop cycles (similar to 40% operation).

Multiplier factors based on in-



Source: Cheng Power Systems, March 2013

dustry experience in the operation of combined cycle plants in intermittent and base load services are used to adjust full output heat rates to reflect the impact of cycling on fuel consumption.

For the 3-on-1 Fr7EA plant, the multiplier is 1.15 times the OEM plant design heat rate for 40% capacity factor (fewer startups); 1.18 multiplier for 60% capacity factor operation (more frequent starts and shutdowns); and 1.15 multiplier for 80% capacity factor levels (fewer startups).

Adjusted heat rates for the single 2-on-1 7FA-05 CC plant is based on half the regular combined cycle multipliers. For the Cheng Cycle plant, the multiplier is 1.0395 for the 40% and 80% capacity factors – and 1.073 for 60% capacity operation.

Based on a projected long term natural gas fuel price of \$4 per MM Btu, and estimated 30 percent lower \$/kW plant cost, the Cheng Cycle plant shows the lowest cost of electricity and, therefore, a better return on investment than building a combined cycle plant.

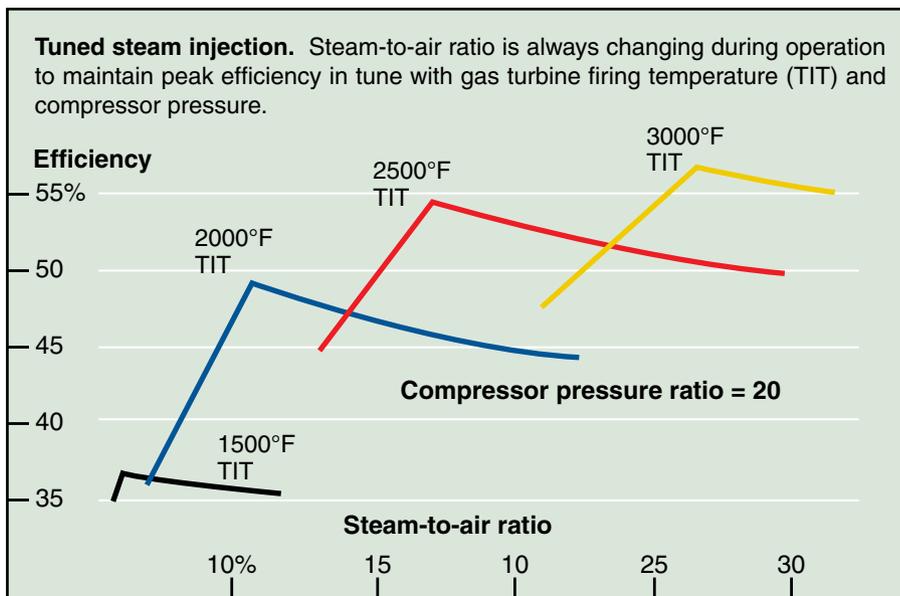
Cheng Cycle features

The Cheng Cycle is basically a “feedback” heat recovery cycle, with efficiency maximized by ever changing steam-to-air ratios highly tuned to gas turbine operating parameters.

On average, two-thirds of the power generated by the turbine component of a simple cycle gas turbine feeds back to the compressor to supply its power needs; only about one-third of the turbine power is available for generating electricity.

Similarly, with a steam Rankine cycle, approximately two-thirds of the heat input into the boiler is used to evaporate water into vapor. Overall, only about 40 percent of the fuel energy ends up as electrical power, with the balance going up the stack and lost to evaporation of cooling water used to condense the steam.

In the Cheng Cycle, steam generated by waste heat recovery of en-



Source: Cheng Power Systems, March 2013

ergy in the hot gas turbine exhaust is injected into the combustion chamber of the gas turbine. The injected steam is heated by additional fuel, reaches the working temperature of the gas turbine and mixes with the air as additional working fluid expanded through the turbine section.

Since the steam does not flow through the compressor, it will produce 3 times more power for generation. In addition, each pound of steam expanded through the turbine section produces net work equivalent to two pounds of air. Therefore, each pound of steam will produce 6 times the mass flow of the air in power output.

Moreover, there is an additional operational dividend in that the added mass flow through the turbine increases the amount of exhaust flow from which heat can be recovered to produce steam.

There are two choices open to Cheng Cycle plants for maximizing heat recovery effectiveness: 1) increase steam production, which requires more fuel and produces more power, or 2) increase steam temperature, closely as possible to the exhaust temperature, which minimizes the fuel required to heat the steam to working fluid temperature.

This tradeoff creates the peak efficiency trajectory of plant operation

as a function of a steam-to-air ratio based on cycle parameters (see chart). Since heat recovery depends on gas turbine pressure ratio and firing temperature, the steam-to-air ratio is highly tuned in sync with operational changes in pressure ratio and firing temperature.

This constantly changing steam ratio is what distinguishes the Cheng Cycle from other arbitrary steam injected systems known as STIG.

Control logic

The Cheng Cycle achieves high part-load efficiency throughout its operating domain by following an operational trajectory based on transient peak efficiency conditions of pressure ratio and firing temperature to optimize performance.

In part-load condition, for example, the logic control system picks up the peak efficiency point based on the engine’s characteristics of pressure ratio, firing temperature, and onset of power demand for fuel and steam-to-air ratio control.

Each firing temperature has a unique efficiency vs. steam-to-air ratio plot which peaks at a certain value of steam injection. Those peak efficiency points are then linked to set up an operating trajectory throughout the full range of engine operation.

Some gas turbines respond better than others

Simple cycle gas turbines from 4MW to over 200MW unit output can be equipped for Cheng Cycle operation with varying degrees of economic success determined in large part by original gas turbine pressure ratio, firing temperature and compressor design parameters.

Simple Cycle OEM Model	GT Power	LHV Heat Rate/kWh	SC Plant Efficiency	Cheng Power	LHV Heat Rate/kWh	Cheng Efficiency
R-R 501-KB5	3.9 MW	11,747 Btu	29.0%	6.4 MW	8509 Btu	40.1%
LM2500PH	19.1 MW	9667 Btu	35.3%	27.5 MW	7613 Btu	44.8%
LM6000PC	43.4 MW	8516 Btu	40.1%	62.4 MW	6916 Btu	49.3%
W501D5	120.5 MW	9840 Btu	34.7%	188.6 MW	7310 Btu	46.7%
GE 7FA-05	215.8 MW	8830 Btu	38.6%	360.0 MW	6684 Btu	51.1%

Source: Cheng Power Systems, March 2013

The steam injection performance map for a 501KH gas turbine Cheng Cycle plant built in 1984 at the San Jose State University shows a plot of that peak efficiency operating line (see CHP tradeoff chart).

CHP tradeoffs

The intersection of gas turbine firing temperature curves with steam injection rate curves defines plant power output and efficiency under different operating conditions.

At 1800°F base load firing temperature, the Rolls-Royce simple 501 gas turbine without Cheng steam injection is nominally rated at around 4500 hp and 29% efficiency.

At max 2.3 kg/s (5 lb/s) steam injection, output is boosted to over 7,000 hp and around 40% plant efficiency. The “peak efficiency trajectory” curve at the top of the map links all the peak efficiency conditions of pressure and firing temperature in the plant operating domain.

The mesh of curves, trapped between the simple cycle gas turbine operating line at the bottom (without steam injection) and peak efficiency trajectory line of Cheng operation at the top (with max steam injection) map out the tradeoffs between power and heat for CHP plant operation.

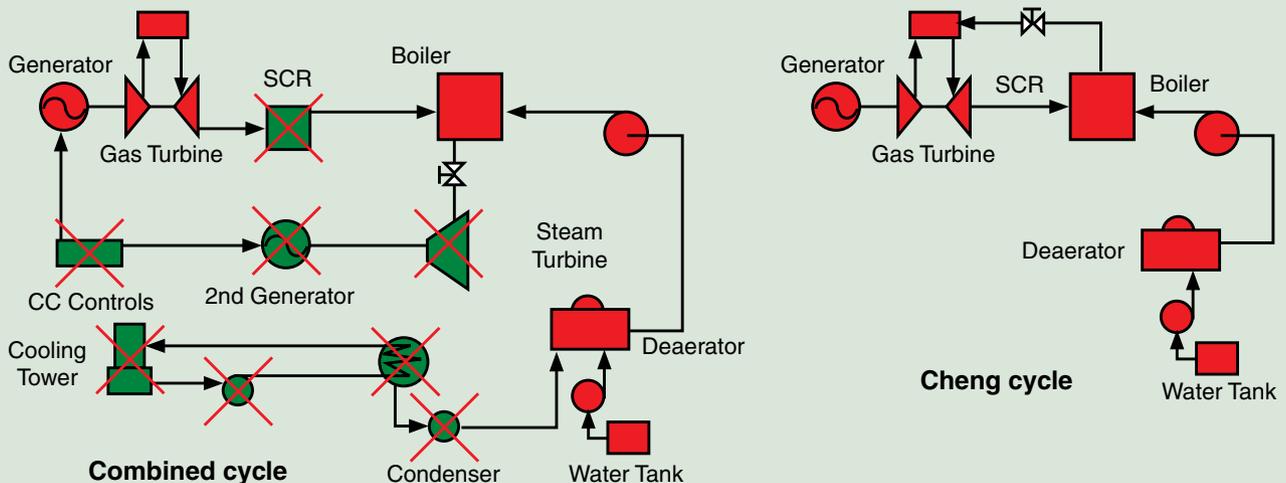
Fast response to load change

Heat recovery steam generators for Cheng Cycle plants have larger than usual steam drums designed to operate under variable pressure conditions. The heat recovery boiler for the San Jose plant, for example, has a 40% enlarged drum volume.

Whenever the gas turbine engine is throttled back, the thermal inertia and excess surface area of the heat recovery boiler makes the drum pressure go up. This raises the boiling temperature which sets the limit of steam production. In effect, this represents an energy storage feature unique to Cheng Cycle boilers.

During routine power generation at less than maximum steam injection,

Comparatively simple. Cheng Cycle eliminates the steam turbine and all associated equipment (except for HRSG and auxiliaries) including generator, condenser and cooling tower which makes it simpler, more compact and less expensive than a combined cycle plant.



the plant may be called upon at any time to immediately ramp up to full output.

When that happens, the extra steam injection needed is available in the drum to rapidly increase gas turbine output and deliver more power.

That is taken care of by the unique Cheng HRSG and drum design. Stored higher pressure steam will provide the additional supply of steam required without having to wait for the boiler to respond.

This makes Cheng Cycle response time as rapid as that of the simple cycle gas turbine on its own to reach higher output.

Fast start-up

Unlike combined cycle requirements for gradual steam turbine warm-up, which limit the gas turbine in order to avoid boiler upsets, the Cheng Cycle can start and ramp up to full load as quickly as a simple cycle gas turbines on cold startup.

A steam injection valve is actuated to open on startup so that gas turbine compressor air flow is directed to flow backwards through the gas turbine steam injection port in order to pressurize the drum, thus preventing boiler upset.

At the same time, the maximum turbine exhaust gas flow ducted into the HRSG at maximum temperature heats the boiler water which rapidly evaporates into steam without restriction.

Once the water reaches boiling temperature, any air in the boiler drum (and rest of the piping system) is purged by the steam being injected into the gas turbine.

This unique startup process has been used for the past 28 years on the Cheng Cycle without incident. It has never caused a boiler upset or drum corrosion problem, say plant engineers, because oxygen is driven off water at 250°F operating temperature.

For cycling and faster start-up to full plant output, the HRSG boiler can be kept bottled up under pressure and

Dr. Dah Yu Cheng comments on steam injection

Typical steam injected gas turbine (STIG) designs are based on introducing steam into a gas turbine downstream of the combustion system at a predetermined pressure, temperature and flow rate without regard to changes in gas turbine operating parameters.

In contrast, Cheng Cycle steam injection is constantly regulated during gas turbine operation to stay in tune with transient changes in gas turbine performance parameters such as pressure ratio, compressor flow and firing temperature.

A digital control system is programmed to capture peak efficiency steam injection operation at all times from full to part-load output, to optimize Cheng Cycle performance under a full range of gas turbine operating conditions.

The Cheng Cycle requires a conceptual change in HRSG design and operation that according to Dr. Dah Yu Cheng is foreign for the most part to the industry and completely different from constant pressure HRSGs used for STIG applications.

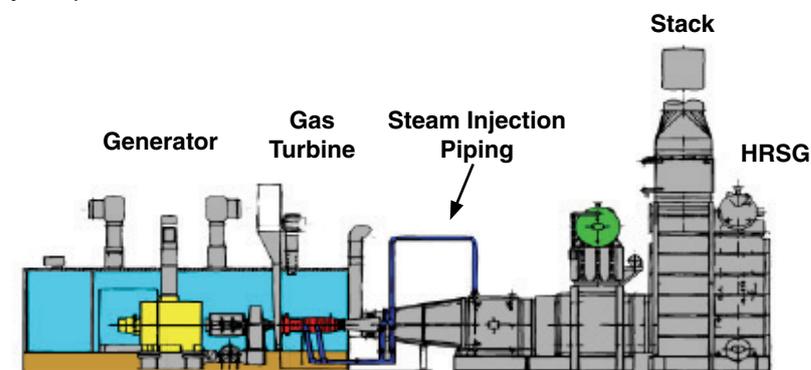
Attempts to improve STIG performance by using once-through boiler designs fail to understand that his cycle is based on thermodynamic feedback akin to electronic feedback, he says.

Fast response to load change requires a drum type HRSG design to provide an energy storage system. Otherwise, he explains, the system will experience a delayed response in heating and cooling due to the thermal inertia of the HRSG mass.

Cheng Cycle is truly a cycle in the classical thermodynamic sense, Dr. Cheng stresses, whereas the STIG design application of mass steam injection is not a cycle. Many engineers do not really understand the thermodynamic differences between the two.

As a result, he says, STIG plants with comparable levels of steam injection cannot rival Cheng plant output or efficiency. "They simply cost more and perform less".

Simple layout. First commercial Cheng Cycle plant built in 1984 at San Jose State has typical in-line layout of gas turbine and HRSG, without the clutter of steam turbine bottoming cycle plant equipment otherwise needed for combined cycle operation.



temperature to remain warm during shutdown. Basically this requires a flapper plate in the exhaust stack to prevent cold air convection through the boiler.

Rapid shutdown

Without a steam turbine, the engine can be shut down as quickly as a simple cycle. Immediately after shutdown is a good time to purge the system instead of waiting for the next startup, says Dr. Cheng, especially for fast response to renewable energy deficit loads.

Cold intake air used for purging will be warmed in passing through the still hot gas turbine with minimal cooling impact when exhausted through the HRSG boiler. This will shave at least 2 minutes off the usual purge time needed on startup.

When the Cheng Cycle was patented in 1984, its efficiency reached a 39.3% level which was better than any small or medium gas turbine combined cycles at that time.

Today, Cheng Cycle can be retrofitted to many gas turbine engine designs, ranging from 3MW to over 200MW in unit output, with various degrees of economic success.

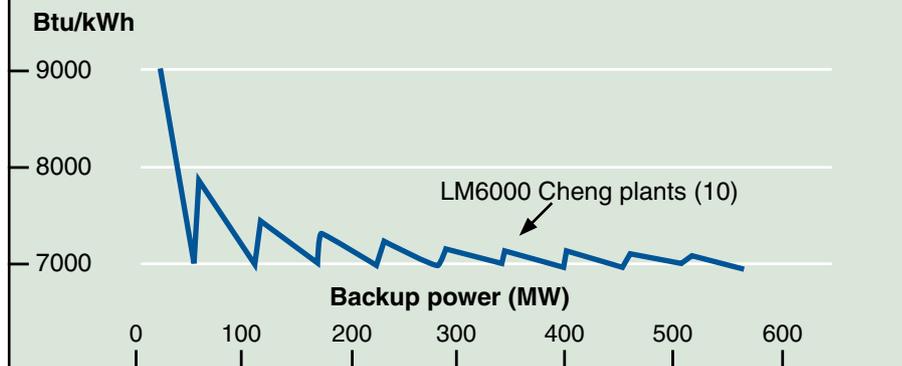
An LM2500 Cheng Cycle plant built on Kauai Island in 2002 is still in commercial service operating at 44.3% efficiency. And the first LM2500 STIG plant made its marketing debut in 1987 rated at only 37.4% steam injected efficiency.

Today's LM6000PC Sprint gas turbine design with compressor water spray inter-cooling is ISO rated at 48MW base load output and 40.7% efficiency. Retrofitted for Cheng operation, output can be increased to 57.8MW and 50% thermal efficiency – while maintaining high part-load efficiencies over a range of 40% to 100% full load operation.

Emissions

As mentioned above, the first commercial Cheng Cycle plant was built in 1984 at San Jose State Universi-

Backup for renewable energy. A fleet of 10 relatively low-cost 60MW LM6000 Cheng plants can be individually dispatched to more efficiently match unpredictable deficits in wind/solar energy than a single higher priced 600MW combined cycle plant in part-load operation.



Source: Cheng Power Systems, March 2013

ty packaged as a 501KH gas turbine CHP facility to supply heat and power to the university.

One of the more notable environmental features of the plant was that combustor steam injection enabled the plant to operate at record low NOx emission levels of around 22 ppm. Today, say Cheng engineers, they can go to 5ppm NOx without SCR.

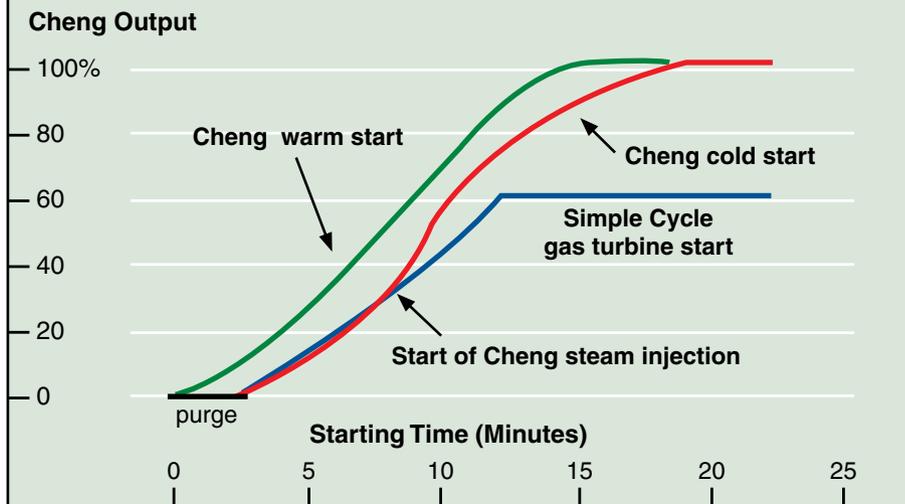
Dr. Dah Yu Cheng notes that the 25 ppm NOx regulatory limit in the US is based on that early Cheng Cycle performance. However, with environmental limitations on NOx and

CO emissions increasingly stringent and demanding, steam injection on its own is no longer sufficient.

Dr. Cheng and his research team have been working for several years on engineering development of ultra-low emission control system designs which premix fuel and high temperature steam in a homogenous fashion prior to combustion in order to control flame formation and emissions.

Recently, they demonstrated a breakthrough with a system that simultaneously limits the combustion production of CO as well as NOx emissions. This important develop-

Startup response. Gas turbine heat recovery steam injection during start-up enables Cheng Cycle plants to ramp up more quickly than simple cycle gas turbines from a cold start -- and even faster with the HRSG design option of a warm storage steam drum.



Source: Cheng Power Systems, March 2013

ment is contrary to the typical observation where reducing NO_x usually triggers an increase in CO emissions.

CLN combustion system

Last year, Detroit Edison replaced DLE-combustion systems on a fleet of five 501-KB7s in cogeneration service with Cheng Low NO_x combustion systems.

Test results show that the conversion increased unit power output almost 20% to 6MW from 5.2MW and lowered the firing temperature to 1870°F from 1935°F. Company project engineers say that the 65°F lower firing temperature will significantly extend hot parts life.

The main capability currently being achieved is the unexpected effectiveness of the CLN control system to virtually eliminate CO emissions. With NO_x emissions limited to 18 ppm, CO levels were reduced to an unprecedented level of zero at 1.65 to 1 steam-to-fuel injection ratio.

Hot section life

There is a totally unfounded but widely held belief that Cheng steam injection shortens the life of hot section parts by causing them to over-heat.

It may be surprising, says Dr. Cheng, but steam injection actually contributes to more effective cooling of first-stage nozzles and blades by mixing with the compressor bleed air used for cooling.

The higher heat transfer rate of the steam (relative to the air) enhances heat exchange of the mixed steam and air flow to do an even better job of internal cooling, as confirmed by Cheng plants in service.

For instance, hot section overhaul intervals for the Rolls-Royce 501 KH installation have increased to 42,000 hours from 12,000 hours initially recommended.

TBO intervals for an LM2500 PH burning liquid fuel have been increased to 40,000 hours from 12,500 hours.

Similarly, a retrofitted Fr 6B Cheng plant burning natural gas has more than tripled its originally scheduled hot section TBO maintenance intervals.

Cost of water

Availability and cost of water depends on site location. The most expensive water in the U.S. is on Southern California, near the Pacific coast.

In Torrance or Santa Monica, for instance, the local water district supplies industrial water to replace well water usage to avoid lowering the aquifer water level. This is done to guard against sea water intruding and contaminating the aquifer supply.

The price of industrial water varies with location. Priced at \$748 per acre-ft., for example, the cost of water for a Cheng plant would be around 0.219 cents per kWh or \$2.19 per MWh. This is based on a steam rate of 8 lb/hr per kWh, which is negligible compared to the cost of fuel.

Water and land usage

Typically, Cheng heat recovery boiler pressure is much lower than required for combined cycle steam turbine operation requires.

Plant water usage is also less than half the evaporation rate of a comparably sized rated combined cycle's wet cooling tower for the condenser.

In addition to river water, Cheng plants can use treated gray water, well water or sea water for HRSG conversion to steam.

The water requires conventional treatment and reverse osmosis steps (depending on incoming water quality) that meet boiler feed water and gas turbine injection purity standards.

In general, combined cycle plants require at least three times more land area for bottoming cycle equipment, including the cooling tower, as well as the steam turbine generator building and condenser. The Cheng HRSG does not have a superheater or reheater, which also saves space.

Plant operation

The Cheng Cycle digital programmable logical control system typically requires only one operator to start and shut down the plant. Combined cycles typically require two and sometimes three operators.

The controls can be set to automatically operate at different load conditions, depending on the prevailing market price of electricity or on the variability of intermittent solar and wind power generation for renewable energy back-up.

Over the last 10 years of operation, the Cheng plant on Kauai has averaged only one unplanned outage per year. This is attributed, in large part, to its relative simplicity compared to combined cycle installations.

Retrofit costs

Converting an LM6000PC gas turbine installation to combined cycle can cost anywhere from \$33 million to \$40 million, depending on options such as SCR or supplementary HRSG burner.

Project engineers estimate that retrofitting the same LM6000PC simple cycle installation for Cheng Cycle, with a comparable increase in plant output, should not cost more than \$15 million.

They say that the same relative cost of "less than 50%" holds for retrofitting most other simple cycle gas turbines such as GE Fr 7EA and Westinghouse 501D5 models.

"It makes Cheng Cycle the least costly method for increasing the capacity of gas turbine peaking units and lowering CO₂ footprints below the California target goal of an 80% reduction in power plant emissions," says Dr. Cheng. ■

Contact the Editors

E-mail rfarmer@gasturbine.com to comment on this article, ask Cheng Power Systems to address your questions, elaborate on any statements or provide more information. We will do our best to reply promptly.