Combined-Cycle Development Evolution and Future

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Introduction
Combined-cycle systems utilizing the Brayton Cycle gas turbine and the Rankine Cycle steam system with air and water as working fluids achieve efficient, reliable, and economic power generation. Flexibility provided by these systems satisfies both utility-power generation and industrial-cogeneration applications.

Current commercially available power-generation combined-cycle plants achieve net plant thermal efficiency typically in the 50–55% LHV range. Further development of gas turbine, high-temperature materials and hot gas path, metal surface cooling technology show promise for near-term future power generation combined-cycle systems capable of reaching 60% or greater plant thermal efficiency. Additional gas turbine technological development, as well as increases in steam-cycle pressure and temperature and steam-turbine stage-design enhancement, is expected to achieve further STAG™ combined-cycle efficiency improvement.

Current General Electric STAG™ (trade name designation for the GE product line of combined-cycle systems) product line offerings, combined-cycle experience, and advanced system development are used to demonstrate the evolution of combined-cycle system technology.

Gas Turbine Combined-Cycle Features
The combination of the gas turbine Brayton Cycle and the steam power system Rankine Cycle complement each other to form efficient combined-cycles. The Brayton Cycle has high source temperature and rejects heat at a temperature that is conveniently used as the energy source for the Rankine Cycle. The most commonly used working fluids for combined cycles are air and steam. Other working fluids (organic fluids, potassium vapor, mercury vapor, and others) have been applied on a limited scale.

Combined-cycle systems that utilize steam and air-working fluids have achieved widespread commercial application due to:

1. **High Thermal Efficiency** - Combined-cycle thermal efficiency is higher than that of other conventional power generation systems.
2. **Low Installed Cost** - Combined-cycle equipment is pre-engineered and factory-packaged to minimize installation time and cost. All major equipment (gas turbine generator, heat recovery steam generator [HRSG], and steam turbine generator) is shipped to the field as assembled and tested components. Auxiliary equipment, such as condensers, can be shipped factory-tubed and hydro-tested. This greatly reduces the inventory of parts that must be managed in the field and minimizes installation cost. Combined-cycle equipment cost is higher than that for conventional steam plants due to pre-engineering; however, combined-cycle plant installation costs are significantly lower, resulting from the reduced installation cycle.
3. **Fuel Flexibility** - Combined-cycle plants operate efficiently by burning a
wide range of fuels, ranging from clean natural gas and distillate oil fuels to ash-bearing crude oil and residual oil fuels. Operation with coal-derived gas fuels has been applied in many commercial-size, combined-cycle systems.

4. Flexible Duty Cycle - Combined-cycle systems provide flexibility in operation for both baseload and mid-range duty with daily startup. Gas turbines in multi-shaft, combined-cycle configuration can be started quickly, bringing about two-thirds of plant power on-line, typically in less than 60 minutes. Combined-cycle plants also provide efficient operation at part load, particularly for multiple gas turbine combined-cycle systems. This is illustrated by the variation in plant output with variation in plant heat rate curve shown for a General Electric STAG 200 system (See Figure 1). Modulating compressor inlet guide vanes are standard features of many gas turbine models, enabling high efficiency operation at part load through reduction in turbine airflow. This is accomplished at nearly constant turbine exhaust temperature, so that design steam conditions and low stack loss can be maintained to provide excellent part-load efficiency.

5. Short-Installation Cycle - Combined-cycle plants can be installed and operated in less time than that required for conventional steam plants. Again, this is primarily due to the pre-engineering and packaging of major components in the factory. Phased installation of the plant, when gas turbines are installed and operated in the simple-cycle mode during the steam-cycle equipment installation, enables the user to generate power and revenue in as little as a year from order date (See Figures 2–4). A typical combined-cycle plant installation schedule is presented in Figure 5.

Figure 1. STAG 209E combined-cycle part load performance
6. High Reliability/Availability - High reliability operation results from evolutionary design development that improves parts and components, and quality manufacturing programs that offer operational factory testing. High availability is achieved through development of sound operation and maintenance practices, which reside principally with the user. Manufacturer experience and recommendations also contribute to this feature.

7. Low Operation and Maintenance Costs - Low operation and maintenance

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**Figure 2.** Six MS7001B gas turbines

**Figure 3.** Two STAG 407B combined-cycle steam system installation
costs are achieved through quality design, prudent operation, and equipment design that allow convenient access for component inspection.

8. **High Efficiency in Small Capacity Increments** - Gas turbine generators are designed and manufactured in discrete frame sizes. For example, the General Electric heavy-duty, gas turbine-packaged power plant product line includes the MS6001B (50 Hz and 60 Hz), MS7001 FA (60 Hz), MS7001B (60 Hz) and the MS9001 FA (50 Hz) units, which cover an output range of approximately 37 MW to 250 MW. Application of these gas turbine models in combined-cycle
systems as single or multiple gas turbine and HRSG installations can provide from about 50 MW to several thousand megawatts of power generation at essentially constant plant thermal efficiency.

Gas Turbine Combined-Cycle Development

The commercial development of combined-cycle systems has proceeded in parallel with gas turbine development. We are presently in the third generation technology of combined-cycle systems and are at the launch point of the fourth generation.

First Generation Combined-Cycle Plants

The first gas turbine installed in an electric utility in the United States was applied in a combined cycle. This was a 3.5 MW gas turbine that used the energy from the exhaust gas to heat feedwater for a 35 MW conventional steam unit. The gas turbine is shown in Figure 6. A schematic showing the combined-cycle system is shown in Figure 7. This system entered service in June 1949, and a similar system was added to this station in 1952. The heat recovery economizers applied in these systems used bare tubes, as was typical of heat exchangers in combined-cycle systems installed prior to 1959.

Most combined-cycle power generation systems installed during the 1950s and early 1960s included conventional-fired boilers. These systems were basically adaptations of conventional steam plants with the gas turbine exhaust gas serving as combustion air for the boiler. The efficiency of this type of combined cycle was approximately 5–6% higher than that of a similar conventional steam plant. These systems could economically utilize bare tubes in the boiler because of the high mean temperature difference between the combustion products and the water/steam.

The repowering of steam power plants with gas turbine generators and HRSGs is still attractive in many applications today as evidenced by the recent Colorado Public Service, Fort St. Vrain installation, which was placed in commercial operation in 1999.

The summary presented in Table 1 characterizes the first generation combined-cycle systems.

Figure 6. Gas turbine in first power generation combined cycle
Second Generation Combined-Cycle Plants

Equipment that made it economically feasible to weld continuous spiral fins to tubes was introduced to boiler manufacturers in 1958. Heat recovery combined cycles, using the sensible heat in the gas turbine exhaust gas, were made feasible by the enhanced gas-side heat transfer using finned tubes. Combined-cycle systems with finned tube boilers entered service in 1959.

During the 1960s the application of the heat recovery type of combined-cycle systems became more prevalent. Its initial application was in power and heat applications where its power-to-heat ratio was more favorable. Also, a small number of the heat recovery type combined cycles were installed in utility power generation applications during the 1960s. Application of these systems in the 1970s and 1980s established the heat recovery feedwater heating combined-cycle as a mature technology for baseload and mid-range service.

The summary presented in Table 1 characterizes the first generation systems. Table 2 and Table 3 represent second generation characteristics and experience.

The requirements for stack gas NO\textsubscript{x} emission control was initially legislated during the late 1970s. The first systems utilized gas turbine water or steam injection to meet new source performance standards of 75 ppmvd at 15% oxygen with efficiency and fuel-bound nitrogen adjustments. Combined-cycle plants utilized steam from the steam cycle for NO\textsubscript{x} control because this had the least impact on plant efficiency. As emission requirements became more stringent, it was necessary to apply SCR to augment NO\textsubscript{x} abatement (TEPCO Groups I and II). Application of SCR systems became common in Japan and in the USA in the mid-1980s.

Third Generation Combined Cycles

The first and second generation combined-cycles were configured using gas turbine designs that were optimized for simple-cycle output and efficiency. Gas turbine design optimization for simple-cycle and for combined-cycle output and thermal efficiency is illustrated.
in Figure 8 performance maps as a function of firing temperature and pressure ratio parameters.

Specific power (i.e., output per pound of airflow) is important since the higher the value, the smaller the gas turbine required for design power output. The importance of thermal efficiency is obvious since it directly impacts the operating fuel cost. Figure 8 illustrates a number of significant points.

1. Where simple-cycle efficiency is the goal, high pressure ratio is desirable.

2. Where combined-cycle efficiency is the objective, more modest pressure ratios are selected.

3. Firing temperature has a greater impact on combined-cycle efficiency than simple-cycle efficiency.

Fuel price escalation in the 1970s and 1980s further increased the need for more efficient power plants for base- and mid-range service. This led to gas turbine designs in the late 1980s that were optimized specifically for combined-cycle efficiency.

<table>
<thead>
<tr>
<th>Gas Turbine</th>
<th>Small Size (Frame 3000 &amp; 5000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Repowering &amp; Cogeneration from</td>
</tr>
<tr>
<td></td>
<td>1949 - 1968</td>
</tr>
<tr>
<td>Steam Cycle</td>
<td>Non-reheat, Single or Two Pressure</td>
</tr>
<tr>
<td>Emission Control</td>
<td>None</td>
</tr>
<tr>
<td>Fuel</td>
<td>Distillate Oil / Natural Gas</td>
</tr>
</tbody>
</table>

Table 1. Gas turbine in first power generation combined cycle

<table>
<thead>
<tr>
<th>Gas Turbine</th>
<th>50-90 MW Capacity (MS6000B, MS7000B/C/E and MS9000B/E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Heat Recovery Feedwater Heating CC from 1968-1999</td>
</tr>
<tr>
<td>Steam Cycle</td>
<td>Non-reheat, Single, Two &amp; Three Pressure</td>
</tr>
<tr>
<td>Emission Control</td>
<td>GT Water and Steam Injection plus Selective Catalytic Reduction System (SCR) Installed in the HRSG Gas Path for NOx Control</td>
</tr>
<tr>
<td>Fuel</td>
<td>Natural Gas / Distillate Oil / Low Btu Gas / Oils</td>
</tr>
</tbody>
</table>

Table 2. Second generation combined-cycle system characteristics
The GE “F” Technology gas turbine designed in the 1980s, with pressure ratio of about 14:1 and 2400°F firing temperature was the result of a design effort aimed at optimization for combined-cycle peak efficiency rather than simple-cycle peak efficiency.

The fleet leader “F” Technology gas turbine entered commercial operation in 1990 in a combined-cycle installation at the Virginia Power Chesterfield site and launched the third generation of combined-cycle systems.
The third generation “F” Technology combined-cycle experience is summarized in Table 4 and system characteristics are defined in Table 5. The trend of combined-cycle plant efficiency improvement is illustrated by Figure 9, which shows the performance of selected STAG plant installations as a function of commercial operating date. Gas turbine development has had the greatest impact on improved combined-cycle efficiency due primarily to the increase in firing temperature made possible through the development of high-temperature oxidation/corrosion-resistant metals and coatings, and advanced metal surface cooling techniques. Another important factor is that the gas turbine contributes about two-thirds of the combined-cycle plant’s power.

Advances in steam system technology have also contributed to improved combined-cycle efficiency. The significant steam-cycle developments include:

1. Technology to weld continuous spiral fins on HRSG heat transfer tubes (1959).
2. Application of larger annulus area steam turbine designs for low exhaust pressure applications.
3. Application of reheat steam cycle with “F” Technology gas turbines.

The current STAG product line ratings, which represent third generation combined-cycle capability, is summarized in Figure 10.

Fourth Generation Combined-Cycle Plants

Further gas turbine materials development and hot gas path cooling technology advances, as well as higher temperature and pressure steam cycles, will continue the trend for more efficient combined-cycle systems in the future.

Gas turbines installed in the first, second and third generation combined-cycle plants are configured with open-loop cooling of the turbine hot gas path and cooling air supplied from the compressor. Hot gas path components are in large part cooled by film cooling. As a result, there is significant exhaust gas temperature drop across the first stage nozzle, and significant “chargeable air” required to cool down the steam turbine stages. The drop in exhaust gas temperature across the first stage nozzle and the increase in chargeable cooling loss due to increases in turbine firing temperature may diminish efficiency gains to the point of being uneconomical. For this reason, the GE fourth
## Combined-Cycle Development Evolution and Future

### Table 4. Third generation combined-cycle experience

<table>
<thead>
<tr>
<th>Country</th>
<th>Installation</th>
<th>Configuration</th>
<th>COD</th>
<th>Output (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>Virginia Power #7</td>
<td>S107F</td>
<td>1990</td>
<td>214</td>
</tr>
<tr>
<td>USA</td>
<td>Virginia Power #8</td>
<td>S107F</td>
<td>1992</td>
<td>218</td>
</tr>
<tr>
<td>Korea</td>
<td>KEPCO Seo-Inchon #1 &amp; #2</td>
<td>8 x S107F</td>
<td>1992</td>
<td>1887</td>
</tr>
<tr>
<td>USA</td>
<td>Sithe Independence</td>
<td>2 x S207FA</td>
<td>1995</td>
<td>1062</td>
</tr>
<tr>
<td>USA</td>
<td>Tampa Electric, Polk Co.</td>
<td>S107FA</td>
<td>1996</td>
<td>313</td>
</tr>
<tr>
<td>Korea</td>
<td>KEPCO Seo-Inchon #3 &amp; #4</td>
<td>2 x S207FA</td>
<td>1996</td>
<td>1004</td>
</tr>
<tr>
<td>USA</td>
<td>Crockett Cogen</td>
<td>S107FA</td>
<td>1996</td>
<td>202/248</td>
</tr>
<tr>
<td>Mexico</td>
<td>CFE Samalayuca</td>
<td>3 x S107FA</td>
<td>1998</td>
<td>506</td>
</tr>
<tr>
<td>USA</td>
<td>Cogentrix, Clark Co.</td>
<td>S107FA</td>
<td>1998</td>
<td>254</td>
</tr>
<tr>
<td>Korea</td>
<td>KEPCO, POSCO</td>
<td>S207FA</td>
<td>1999</td>
<td>498</td>
</tr>
<tr>
<td>Columbia</td>
<td>EPM LaSierra</td>
<td>S207FA</td>
<td>2001</td>
<td>478</td>
</tr>
<tr>
<td>USA</td>
<td>Buckspor Energy</td>
<td>S107FA</td>
<td>2001</td>
<td>176</td>
</tr>
<tr>
<td>USA</td>
<td>Westbrook</td>
<td>S207FA</td>
<td>2001</td>
<td>528</td>
</tr>
<tr>
<td>USA</td>
<td>Santee Cooper</td>
<td>S207FA</td>
<td>2001</td>
<td>600</td>
</tr>
<tr>
<td>Korea</td>
<td>Pusan</td>
<td>4 x S207FA</td>
<td>2003/4</td>
<td>2000</td>
</tr>
</tbody>
</table>

Number of gas turbines = 2 Units
Installed Capacity = 12,411 MW

### Table 5. Third generation combined-cycle system characteristics

<table>
<thead>
<tr>
<th>Country</th>
<th>Installation</th>
<th>Configuration</th>
<th>COD</th>
<th>Output (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>TEPCO, Yokahama</td>
<td>8 x S109FA</td>
<td>1996/7</td>
<td>2800</td>
</tr>
<tr>
<td>China</td>
<td>China Power &amp; Light</td>
<td>8 x S109FA</td>
<td>1996/72</td>
<td>2731</td>
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<tr>
<td>Japan</td>
<td>TEPCO, Chiba</td>
<td>4 x S109FA</td>
<td>1998</td>
<td>1440</td>
</tr>
<tr>
<td>India</td>
<td>Enron, Daihio I</td>
<td>S209FA</td>
<td>1998</td>
<td>698</td>
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<tr>
<td>Chile</td>
<td>Renca</td>
<td>S109FA</td>
<td>1998</td>
<td>370</td>
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<td>Netherlands</td>
<td>AKZO, Delesto</td>
<td>S109FA</td>
<td>1999</td>
<td>364</td>
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<tr>
<td>U.K.</td>
<td>Sutton Bridge</td>
<td>S209FA</td>
<td>1999</td>
<td>800</td>
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<tr>
<td>Thailand</td>
<td>Ratchaburi</td>
<td>3 x S209FA</td>
<td>2000</td>
<td>2130</td>
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<tr>
<td>Argentina</td>
<td>Central Puerto</td>
<td>S209FA</td>
<td>2000</td>
<td>769</td>
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<tr>
<td>Japan</td>
<td>Hitachi Zosen</td>
<td>S106FA</td>
<td>1999</td>
<td>106</td>
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<tr>
<td>U.K.</td>
<td>Tri-Energy</td>
<td>S209FA</td>
<td>2000</td>
<td>700</td>
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<td>U.K.</td>
<td>Great Yarmouth</td>
<td>S109FA</td>
<td>2001</td>
<td>407</td>
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<tr>
<td>India</td>
<td>Enron, Daihio II</td>
<td>2 x S209FA</td>
<td>2001</td>
<td>1600</td>
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<td>Japan</td>
<td>TEPCO, Futsuro 3</td>
<td>4 x S109FA</td>
<td>2002</td>
<td>1590</td>
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<td>Spain</td>
<td>Castellon</td>
<td>S209FA</td>
<td>2002</td>
<td>285</td>
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* Single-shaft Combined Cycle

Number of gas turbines = 50 units
Stalled capacity = 17,795 MW

### Gas Turbines

<table>
<thead>
<tr>
<th>Application</th>
<th>Heat Recovery Feedwater Heating CC in the 1990s</th>
</tr>
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<tbody>
<tr>
<td>Steam Cycle</td>
<td>Reheat, Three Pressure</td>
</tr>
<tr>
<td>Emission Control</td>
<td>DLN Combustion with Natural Gas and Water / Steam Injection with Oil Fuels plus SCR Installed in the HRSG</td>
</tr>
<tr>
<td>Fuel</td>
<td>Natural Gas / Distillate Oil / Low Btu Gas</td>
</tr>
</tbody>
</table>

Table 4. Third generation combined-cycle experience
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Combined-Cycle Illustration
1. City of Clarksdale (S105)
2. Houston L&P, Wharton Station (S407B)
3. Salt River (S107E)
4. Western Farmers (S107E)
5. MWEWC (S307E)
6. CFE-Mexico (S307E)
7. Chihu (S107E)
8. VP Chesterfield (S107F)
9. KEPCO, Sea Inchon (S107F)
10. Sithe, Independence (S207FA)
11. Sutton Bridge (S207FA)
12. KEPCO, Sea Inchon (S207FA)

Figure 9. Combined-cycle system efficiency trend

Notes:
1. Site Conditions: 59ºF, 14.7 Psia, 60% Rh
2. Fuel is Natural Gas
3. Steam Turbine Exhaust Pressure: 1.2 inches Hg,a

Figure 10. Current STAG product line ratings

generation plants with “H” Technology gas turbines will be configured with an integrated closed-loop steam cooling system (See Figure 11). This system allows higher turbine firing temperature to be achieved without increasing combustion temperature. This is because exhaust gas temperature drop across the first stage nozzle is significantly reduced as outlined in Figure 12. Another important benefit of the integrated closed-loop steam cooling system is the elimination of “chargeable cooling air” for the first and second stage rotating and stationary airfoils. This technology is expected to provide two percentage points thermal efficiency improvement.

The “H” platform gas turbine combined-cycle plants are expected to achieve 60% LHV thermal efficiency in the first half of this decade. The application of ceramic hot gas path parts and coatings show promise for further future performance gains.

Steam cycle improvements that include increased steam pressure and temperature with supercritical steam cycles have near-term applica-
tion. Current economic analysis indicates, however, that the thermodynamic gain associated with steam cycles that have steam temperatures and pressures above the current levels (1050°F and 1400 PSIG to 1800 PSIG) cannot be justified in most cases because of the added costs.

As in the past, operating cost (fuel price) and the cost of new technology development will dictate the trend for increased combined-cycle efficiency.
References
H.E. Miller, “F” Technology - The First Half Million Operating Hours,” GER-3950.
Frank Brooks, “GE Heavy-Duty Gas Turbine Performance Characteristics,” GER-3567G.

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