Comparative Evaluation of Cogeneration Cycle Alternatives

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Abstract

Competition from deregulation is driving utilities and consumers to seek out alternate means to reduce the cost of electricity. The utility industry is expected to shift generation away from the traditional central station philosophy to dispersed generation with the formerly wasted heat to be recovered and used for industrial steam or to heat commercial buildings.[1] Some experts suggest that the dispersed generation will take the form of cogeneration by locating thermal electric generators with heat recovery steam generators alongside the thermal host. Coincidentally, there are a large number of existing boilers that can serve as waste heat receivers if properly modified. This could result in substantial capital savings, further reducing the cost of the dispersed electrical generation. Repowering cold windbox industrial boilers compliments and reinforces the dispersed generation philosophy.

This paper will compare the economic and technical advantages of repowering existing small industrial boilers with conventional engine/gas turbine driven generator sets. Operating advantages in steam generation reliability and flexibility will be presented.

Introduction

Cogeneration, where steam and electricity are produced simultaneously, typically takes the form of a combustion turbine coupled to an electric generator with the turbine exhausting to a waste heat recovery boiler. The combustion turbine is a derivative of jet engine technology and can be applied in either a simple-cycle arrangement (electric generation only) or cogeneration cycle where both electricity and steam are produced. A strong alternate prime mover to the combustion turbine is the reciprocating engine. Utilizing the energy efficiencies of these prime movers coupled with the recovery of the heat in the exhaust gas produces a very efficient power cycle.

A traditional cogeneration plant consists of a prime mover coupled to a generator and exhausting to a heat recovery steam generator (HRSG). The heat recovered from the exhaust flue gas is used to generate steam for process (cogeneration cycle) or to drive a steam powered turbine driven electric generator (combined cycle). These plants are costly and significant capital savings could be realized by repowering existing, installed steam generators in either "hot windbox" or "cold windbox" arrangements. These retrofit repowering strategies can offer enhanced operating flexibility and capacities over a new combined cycle plant. As in the typical combined cycle systems, supplemental firing (if properly designed) can be included in the repowered plants enhancing the steam cycle operating conditions to: 1) produce higher steam temperatures needed for process, 2) increase boiler steaming capacities, 3) allow operating the boiler while the prime mover (CT/engine) is off-line for maintenance or load dispatch, and 4) improve plant efficiency. For many operators, it is important not to jeopardize the reliability of the thermal energy supply. The lack of confidence in a reliable steam supply is probably the main deterrent to the adoption of the cogeneration cycle.

Discussion of New Plant Vs. Repowering

As economies of scale offer less impact in the small generating capacity ranges (i.e., less than 20MW), generators will seek alternatives to minimize capital costs and realize a competitive advantage. Each of the alternatives is discussed below.

Combustion Turbine with HRSG

Programs are underway to develop technologies to advance small combustion turbines' performance and efficiency.[2,3] These programs will bring to the industry equipment that is reliable and affordable to maintain. With dispersed generation, the electric power generation industry will rapidly grow to include small consumers who will become self-generators. These small consumers will include institutions, hospitals, universities, small manufacturers, and light industry.

Capital required to install a traditional combined cycle plant in large sizes (greater than 50MW) ranges about $700-$900 per kW. As we move to smaller generators, capital costs will increase to approximately $900-$1100 per kW. Even so, the payback can be very attractive as the increased operating efficiencies reduce operating costs.

The traditional combustion turbine combined cycle plant is sized to match the maximum site thermal requirements. This offers maximum cycle efficiency at full load. On the other hand, these plants tend to be inflexible and do not allow the operators the ability to match changing thermal loads. If steam demand falls off, cycle efficiency decreases due to energy losses when exhaust is bypassed to the atmosphere. And, unless auxiliary steam generating capacity exists on site, matching thermal loads may result in electricity generated at times when market price is less than generating cost. An auxiliary boiler is required for operating periods when the prime mover is out of service.

Repowering Cold Windbox Package Boilers

There are approximately 15,000 package boilers operating in the U.S. supplying steam to process industries, hospitals, institutions, and utilities. These boilers are typically shop assembled and offer a very reliable, cost effective source of steam. As utilities unbundle under deregulation, retire plants, and look for more competitive sources of electric generation, there is a significant opportunity to utilize these installed package boilers to cogenerate steam and electricity at efficiencies exceeding large scale power plants.

The large package boiler population and market potential have driven developments to overcome the technical issues. Using the existing boilers as HRSGs will reduce the owners' capital outlay and can result in a combined cycle cost of $600-$800 per kW. A schematic of the plant arrangement is provided in Figure 1.

The technical advantages of repowering cold windbox package boilers to a supplemental fired arrangement are numerous. With supplemental and fresh air firing capability, boiler steam production is independent of electric generation offering greater operating flexibility. This is important to many industrial owners where steam and electric loads fluctuate significantly and independently throughout the day. Unless supplemental firing capability is provided, most cogeneration plants can not support these daily swings, or require auxiliary boilers to satisfy demand.

Thermal cycle efficiencies are higher for supplementary fired cogeneration arrangements as compared to a simple cycle generator with an auxiliary boiler. Figures 2 and 3 compare plant efficiencies for a cogeneration plant and a simple cycle plant with an auxiliary boiler. Figure 2 shows an improvement in cycle efficiency of 16% at full load for a combustion turbine supplementary fired cogeneration plant. Figure 3 shows a 14.6% improvement at full load for a reciprocating engine plant. Using Figure 4 to compare the combustion turbine to the reciprocating engine in the cogenerator plant, it is important to note the reciprocating engine arrangement achieves higher plant efficiencies at steam loads of less than 30%. Note that these analyses assume the prime mover/generator is at full load, optimum heat rate, and supplemental firing is needed at steam flows 20% and higher.

Environmentally speaking, overall plant NO_x emissions are reduced as the fired boiler reburns the nitrogen oxide in the prime mover exhaust to produce lower total emissions. Reburn technology, as applied in large boilers, generates controlled amounts of hydrocarbon radicals by firing substoichiometrically in the boiler, which in turn reduces NO in the exhaust flue gas from the prime mover to N_2.[4] The combustion process is then completed by adding the balance of the combustion air through ports in a final burnout zone. This same technology can be applied in small industrial boilers.

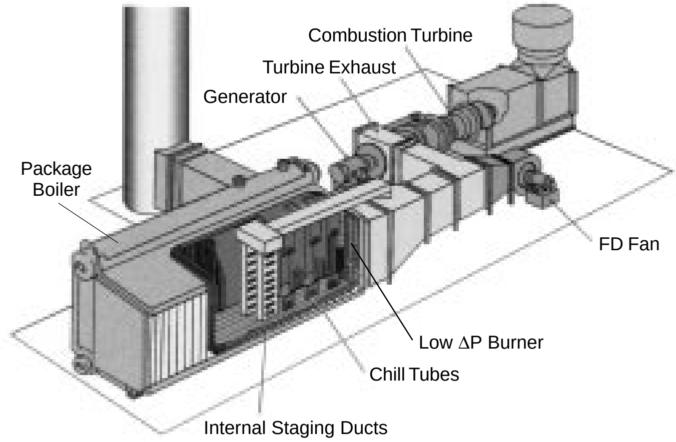

Figure 1 Integrated boiler burner* – advanced concept for mid-sized co-gen or combined cycle plants. *Patent applied for.

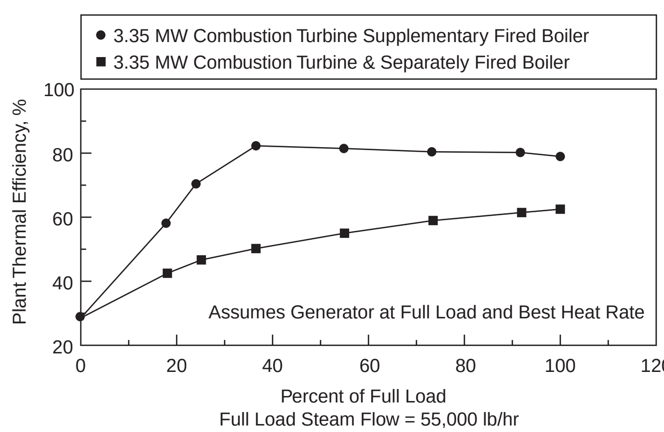

Figure 2 Plant efficiencies with various combustion turbine configurations.

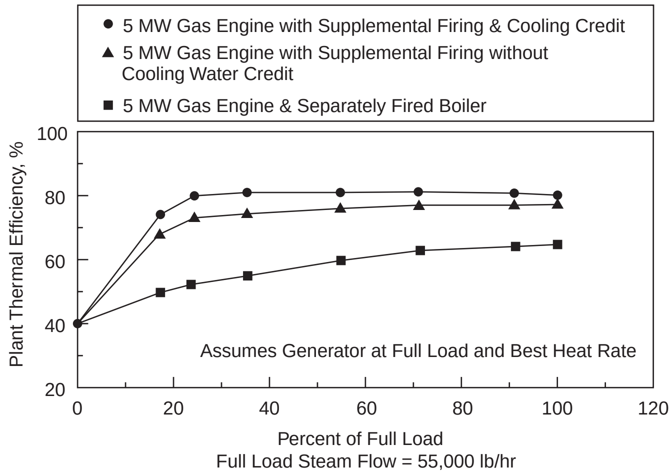

Figure 3 Plant efficiencies with various reciprocating engine configurations.

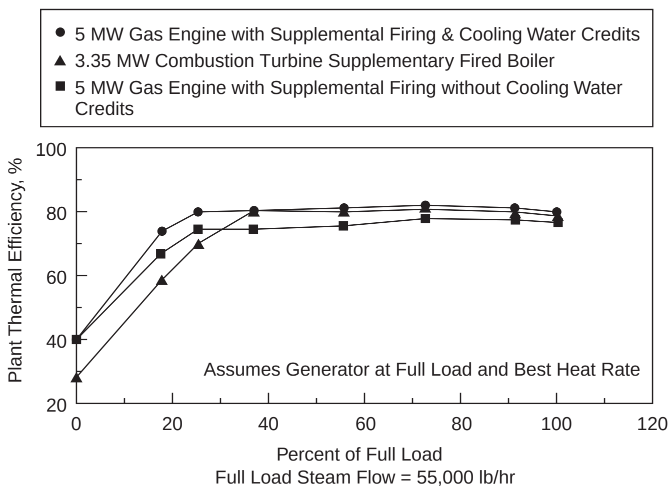

Figure 4 Plant efficiencies with various configurations.

These benefits for repowering cold windbox boilers do not come without some drawbacks. Most important is that the small furnace volume and tightly spaced steam generating surfaces produce high gas side pressure drop and therefore place a large back pressure on the prime mover. Capacity of the prime mover (particularly CTs) is inversely proportional to the back pressure. For repowering applications, the prime mover must be properly matched to the existing boiler so as to minimize any capacity penalties. This is normally not an issue for most industrial applications where the thermal load (host's steam needs) drives the project.

Converting the boiler to operate either as the fresh-air-fired (FAF) mode or as a supplemental-fired waste heat unit requires that equipment and materials be properly selected to match hot and cold combustion air conditions. Fans, burners, ductwork, dampers, flame safety systems, air flow controllers, and more must be studied and designed to accommodate both operating modes. For CT cogenerators it may be cost effective to install a small heat exchanger to cool the exhaust down to acceptable temperatures to allow the use of carbon steel materials.

Not clear at this point is expected new governing NFPA guidelines on contiguous burner arrangements and their impact on the plant BMS controls, which needs to be studied thoroughly.

Repowering Hot Windbox Boilers

While the emphasis of this paper is small industrial boilers which are primarily cold windbox (i.e., no air preheater), some discussion is necessary on repowering existing boilers that are designed to fire with preheated combustion air. Hot windbox units serve large industrial or utility plants.

The hot windbox arrangement offers a relatively flat heat rate over the entire generator output range and is about 10% lower than the original plant.[5] Boiler retrofit costs could be minimal. At issue however would be removal of the air heater and installation of additional economizer surface to capture the heat in the boiler exit flue gas. The most attractive approach is to preheat feedwater but the existing FW heater circuits would have to be modified.

Owner's/Operator's Perspective

True cogeneration applications should be driven by the plant's thermal requirements. When prime movers are selected and matched to the HRSG, the desired flexibility may be sacrificed.

Figures 2, 3, and 4 were presented above to compare operating plant efficiencies at full boiler loads. But just as important in industrial plants is operations at low loads often required at night, on weekends, or in the off season. Figure 5 compares the reciprocating engine and the CT supplemental fired repowered cold windbox arrangements to a typical CT cogeneration plant with an unfired HRSG. At full boiler load plant efficiencies are very close together ranging from 75.3% to 80.1%. But as the steam demand is reduced, efficiency for the unfired arrangement falls off quickly. This occurs because the CT exhaust is diverted

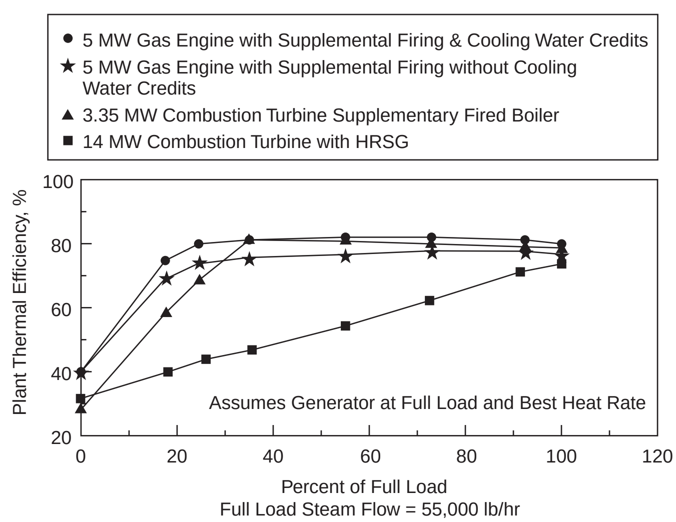

Figure 5 Plant efficiencies with various configurations.

away from the boiler and dumped to the atmosphere so that steam output can be matched to demand. Intuitively, the uncaptured waste heat reduces plant efficiency. Clearly, it is more cost effective and efficient to size the CT smaller and choose a supplementary fired boiler to achieve the needed steam flow. This allows the operator to turn down the boiler to match the load.

Another interesting point falls out of Figure 5. First note that up to about 18% boiler load, no supplemental firing is needed. The small CT cycle compared to the reciprocating engine is less efficient at low steam flows (less than 20%) because of the inherent characteristics of the respective simple cycle. However, Figure 6 shows that no supplemental firing is required on the CT up to about 36% boiler load while the reciprocating engine arrangement would require supplemental firing at 18% load (Figure 7).

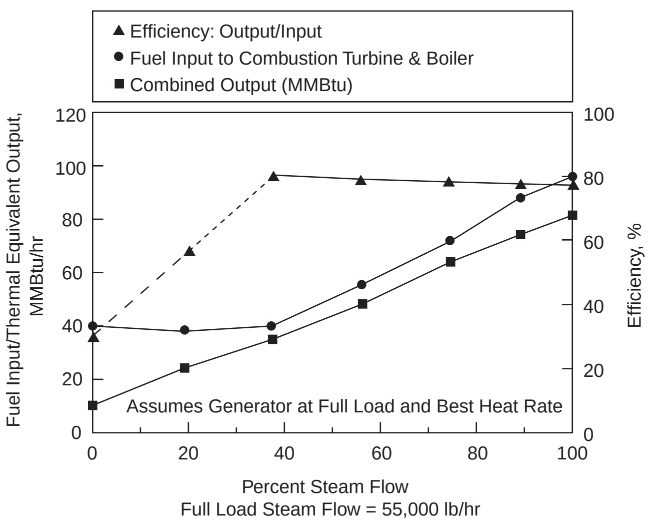

Figure 6 Cogeneration cycle alternatives – comparative evaluation.

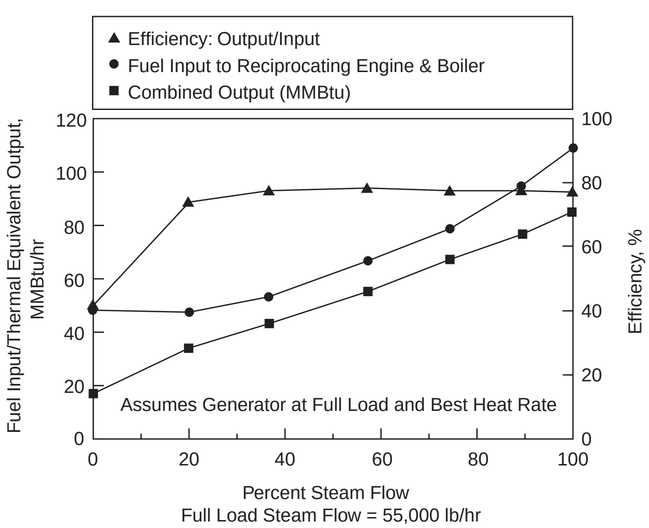

Figure 7 Plant efficiencies with various configurations.

By matching the prime mover to the minimum continuous thermal load and including supplemental firing capability, operators are flexible to match steam demand independent of electric generation and can operate the plant at its most efficient operating point.

Converting Cold Windbox Boilers to Supplementary Fired HRSGs

There are several technical concerns owners must consider before modifying their existing boiler to operate as a HRSG. This paper will focus only on modifying package boilers with cold windbox design, i.e., no preheated combustion air.

Package boilers are designed with high volumetric release rates and thus have tightly spaced heat transfer surfaces. This results in relatively high gas side pressure drop. Back pressure on the prime mover is a significant concern as it directly impacts its power out or electricity generated. Compounding the problem is the fact that firing the boiler with the high volume, lower density hot exhaust gas increases the burner pressure drop. This results in establishing practical limits of exhaust flow that can be directed to the boiler. For maximum efficiency, the prime mover must be matched to the existing boiler.

When supplemental firing is utilized with the prime mover (CT or engine) in service, frequently there is sufficient oxygen in the exhaust gas to support the combustion of the fuel needed for the desired heat input to achieve steaming requirements. However, when the engine is off line or at reduced load, or when the steam load is at a maximum, a fresh air supply is needed to support the combustion in the boiler. These conditions impose severe performance duty on the burners as the combustion air volumes are drastically different.

In the case of firing the boiler using exhaust gas (EG), the combustion air is at temperatures in the range of 750F to 1000F with approximately 12% to 17% oxygen content, whereas in the FAF situation the combustion air is ambient with 21% oxygen content. In addition, the pressure drop across the burner is required to be low when operating with EG, (high volume condition), and current technology burner designs require high pressure drop when operating as FAF (low volume conditions). This broad range of combustion air flow velocities is difficult for conventional circular burners to accommodate. Because highly reliable steam supply is a requirement in most process applications, and because of the fear of losing the steaming capability when the gas turbine/engine trips off, many industries have rejected the use of these higher efficient cycles.

New Burner Design Allows Dual Operating Mode

Babcock & Wilcox has developed low pressure drop burner designs to allow boilers to be coupled directly to a gas turbine/engine generator and capture the waste heat available in the exhaust gas from the prime mover. Figure 8 provides a schematic showing installation of the lower pressure drop equipment for a proposed project. The prime mover exhaust gas is ducted directly to the package boiler where it is used for combustion air. The low pressure drop burner is installed at the front wall of the boiler and fires natural gas to supplement the waste heat pro-

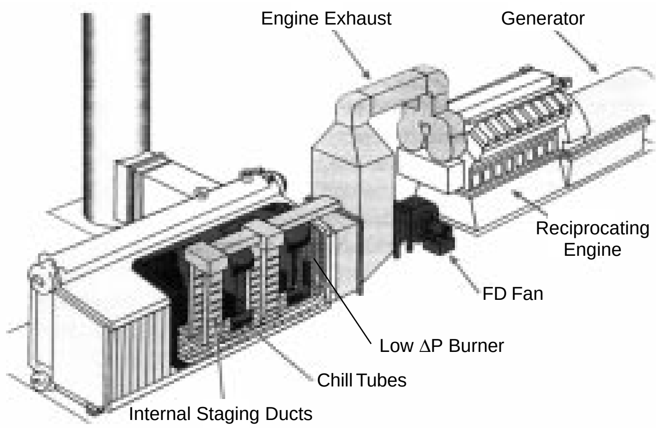

Figure 8 Integrated boiler burner* – advanced concept for mid-sized co-gen or combined cycle plants. *Patent applied for.

vided from the engine to achieve boiler steam capacity. When the prime mover engine is off-line for maintenance, the boiler is fired with ambient combustion air by placing the forced draft (FD) fan into operation allowing the plant's steam needs to be satisfied.

The low pressure drop burner can operate at high temperature, low combustion air oxygen level or at ambient conditions. It has been developed for ease of retrofit to a package boiler using practically all the existing boiler components and auxiliary equipment. Capital expenditures are minimized and a cost effective source of electricity is added.

The low pressure drop design is a radical departure from conventional burner designs. Rather than utilizing a high pressure drop, highly turbulent swirling design, it utilizes a low pressure drop distributive design. This is not unlike typical "Duct Burners" of which there are several designs available for commercial application. However, conventional duct burners can not achieve the acceptable turndown ratios listed above with high efficiencies and low pollution products that are required by today's standards. Also, typical duct burners can not achieve thoroughly mixed, low CO combustion when operating on cold fresh air only or at hot but low excess air conditions.

The low pressure drop design uses a combination of venturi throats to minimize pressure drop requirements, and distributive gas manifolds to compliment rapid efficient mixing. The net result is a burner that is extremely stable under high volume (EG) or low volume (FAF) combustion air conditions. The burner can operate with low excess air (EG supplemental firing conditions) or high excess air (FAF steam production firing conditions). In addition, under both conditions, the peak flame temperature is minimized with the Integrated Boiler Burner (IBB)* design to limit thermal NO_x production to acceptable levels.

The burner design illustrated in Figure 1 is a novel approach to NO_x emissions reductions. The combustion air will not be forced through a highly turbulent circular burner throat as in conventional burners. The total burner will be comprised of a distributative design arranged on a supporting structure that is placed over the entire cross sectional area of the combustion air supply duct that butts up against the front face of the boiler's firebox. The burner is placed at this union. The combustion air supply duct will be sized to closely match the cross sectional area of the firebox. The arrangement of the burner and the heat input is determined based on the final boiler steam load requirements.

Summary

The 15,000 package boilers operating in the U.S. offer a competitive solution to the expected shift to small capacity dispersed generation. Industrial and institution owners can couple combustion turbine or reciprocating engine driven electric generators to existing boilers and cogenerate, reducing fuel costs while maintaining reliable and flexible steam supply. The low pressure drop gas burner allows the operation of the existing package boiler in a fresh air fired mode or as a supplementary fired HRSG, providing flexibility, efficiency, and reliability required by the thermal host process or heating load.

*Patent applied for.

References

1. Casten, T.R., "Whither Electric Generation? A Different View," *Cogeneration and Competitive Power Journal*, Vol. 11, No. 1, Winter 1996, pages 63-78.

2. Kuehn, S.E., "Advancing gas turbine technology: evolution and revolution," *Power Engineering*, May 1995, pages 25-28.

3. Williams, P.L., "The Small Turbine Revolution," *Independent Energy*, July-August, 1995, pages 86-89.

4. *STEAM / its generation and use*, 40th edition, Babcock & Wilcox.

5. Walters, A., "Technical Perspective," presented at the 1st GRI Repowering Initiation Workshop, Chicago, May 10, 1995.