Energy Efficiency and Industrial Boiler Efficiency: An Industry Perspective

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Energy efficiency for industrial boilers is a highly boiler-specific characteristic. No two boilers are alike. There are two identically designed, constructed side by side, stoker fired boilers in Indiana burning the same fuel that have very different performance characteristics. Like twin teenagers, they are not the same. Consideration of energy efficiency for industrial boilers, more often than not, is simplified and categorized to a one-size-fits-all approach. Just as when considering teenagers, this does not work. While parents would like to believe their teenager is gifted and talented and in the 80th percentile of the population, we know that is not necessarily the case. We also know, as for boilers, the average teenager is not representative of a widely diversified population. If you think it is, ask any parent with teenagers or an industrial boiler operator. While the variables associated with energy efficiency are more limited than those associated with a teenager, they are in no way any less complicated.

Four factors are critical for assessing energy efficiency in the industrial powerhouse supplying energy to make products for the benefit of customers in a highly competitive international marketplace. These are:

1. fuel type,
2. combustion system limitations,
3. equipment design, and
4. steam system operation requirements.

Furthermore, the industrial facility's complexity, location, and objective complicate them. It is important for the industrial company to remember, unlike the utility, that energy is a smaller portion of the final product price. However, without energy there is no final product or service. Needless to say, without products or services there is no need for people to do the work.

This white paper will address the efficiency-related aspects of the four primary factors affecting the industrial boiler and the factors affecting application of combined heat and power systems to industrial facilities. A copy of the *Background Paper on the Differences Between Industrial and Utility Boilers* is included as an appendix to help understand the diversity of the industrial boiler population. From the EPA Boiler MACT Database, there are about 22,000 industrial-commercial and institutional boilers with greater than ten million Btus per hour heat input.

New vs. Existing Units

Before investigating specifics of industrial boiler efficiency considerations, it is important to understand that once a boiler is designed, constructed, and installed, it can be difficult and costly to improve its efficiency above the design. On the other hand, as will be discussed below, changes in fuel, load, and operation can easily impact overall efficiency. Because of the high cost of the energy plant, boilers and associated systems usually are purchased for the life of a facility with ample margin for future growth and process variability. With proper maintenance, boiler life is indefinite. In most cases, it will outlive the process it originally was designed for but not the facility. For example, a facility that was producing eight track tapes changed to produce cassette tapes and is now producing CDs and DVDs. The boiler will still be there meeting new demands.

With today's technologies it is possible to design boilers to handle a wide range of requirements and possibilities. However, in most cases this is economically impossible if a process is to survive in a competitive world. It could be like building a new home with a heat pump and a furnace capable of burning natural gas and a furnace capable of burning oil to cover the heating, air conditioning, hot water, and other household needs. The cost of all of this equipment would break the budget. It is evident that an average person probably could afford only one of these devices. If the person tried to buy all three, they would not be able to afford the house.

New units are purchased with a guaranteed efficiency at a Maximum Continuous Rating (MCR) for a specific design fuel producing a specified quantity of steam or hot water at a specified temperature and pressure. Any changes in these characteristics change the operating efficiency. A guarantee over a wider range of fuel, capacity, and temperature and pressure is technically possible. However, as mentioned, it may not be economically justifiable for a given facility. In the end, a new unit may be defined only as one that is designed, purchased and installed, but never run at the guarantee conditions other than to pass acceptance tests. In the real world almost nothing operates at the design specifications.

Annual Average vs. MCR Design

If you start from cold water have you ever watched how long it takes to get it boiling? I believe it was Ben Franklin who said, "A watched pot never boils." It does, but it takes the addition of 1,000 Btu per pound of water before it does. After that, considering losses from the teapot or boiler, Btu for Btu, is converted to steam where you use it or lose it. In systems that have a heavy cyclic load, the operator can either start up or shut down the boiler as needed (for a period lasting 2 to 5 hours each way) without the loss of much of the initial energy. However, for periods longer than this, much if not all of the initial 1,000 Btus are lost. On the other hand, the operator can keep it at pressure to ensure rapid response by supplying enough heat to compensate for losses in the system. Here, efficiency is zero, but the initial 1,000 Btus are maintained. In both cases there is increased energy loss and the inability to meet or maintain MCR efficiency. In facilities like a college campus, with a heating load, where heat is needed every morning so the students will have warm classes to go to, hot showers to wake up with, and hot food in the cafeteria serving lines, it is better to keep the boiler hot, lose the efficiency, and keep the students, their professors and their parents happy. In a large hospital performing many major surgeries per day using autoclaves to sterilize surgical instruments, should a system be designed to handle the maximum number of surgeries expected or a smaller number thus limiting the number of people that can be helped in any one day? Obviously, the system must be designed to meet the maximum capacity of the hospital. Here it is impossible to deliver both MCR efficiency conditions and optimum patient service. There also are losses associated with low load operation that will be discussed in greater detail under the Systems Operation section below.

Each facility's needs will be different. Steam load requirements will change for different facilities. Departures from MCR conditions will vary widely depending upon facility process needs. Subsequently, the annual average efficiency, and for some, the hourly average efficiency will be less than the MCR efficiency of the design. Differences between actual efficiency, an annual average, and MCR can be as much as 40 percent or more depending upon the facility. Any consideration of industrial boiler efficiency must consider differences between real, actual, and design efficiencies.

The ability of a particular process to use steam efficiently complicates this factor. With steam after it is produced you use it or loose it. Inefficiencies inherent for various process factors can be as important as the inefficiencies associated with the boiler.

Fuel Type

Mother Nature is miraculous. Naturally occurring fuel (gas, oil, wood, coal and biomass) is variable. The plants, animals, bugs and other critters that formed the fuel underwent tremendous change at different locations and over different time periods. Elemental compositions of fuel [moisture (H_2O), carbon (C), hydrogen (H), nitrogen (N), chlorine (Cl), sulfur (S), oxygen (O) and ash] can vary as much as 30 percent or more from an annual average basis depending upon their inherent composition and degree of fuel refining or preparation. Any variations in fuel composition from the original design of the system will directly affect boiler efficiency. In most cases with boiler design these days, variations of less than one or two percent from the design fuel composition will have virtually no perceptible impact on efficiency. For this discussion, the Btu per pound, gallon, or cubic foot of the coal, oil, or gas respectively may be a better, however over simplified, way of looking at it.

Even natural gas can vary between 900 and 1,100 Btu/cu. ft. depending upon the methane content. Over the years technology has allowed gas companies to blend gas and control its Btu and composition to a level of around 1,000 Btu/cu. ft. (+ or – one or two percent) on an annual average and hourly average basis. This, along with its deliverability, ignitability and controllability is a good reason why natural gas is used as a primary fuel for home heating, hospitals and commercial installations. The very high hydrogen content (high hydrogen to carbon ratio) of natural gas that burns to form water removes a significant amount of heat from the process and can seriously impact the overall efficiency of the boiler as compared with other fuels.

Crude oil is refined to remove the highly valuable portion for industrial feedstocks for plastics and other products, for gasoline, aviation fuel and diesel fuel for transportation, and for home heating oil with very low variability. The variability of each of these premium products can be equal to or better than that of natural gas. Industrial fuel products are the leftovers from refining and can have increasing variability as the quality goes from a No. 2 oil to a No. 6 or high asphaltene Bunker C grade oil or road grade asphalt or petroleum coke. In such cases, variation in viscosity (burning something like "black strap molasses" or hot maple syrup for the liquids – coke is a solid more like coal) can have a serious impact on combustion efficiency and overall boiler efficiency. Variation in fuel characteristics on an hourly average basis may be better or equal to that of natural gas. However, variations in fuel characteristics between shipments over the year may increase the annual average variation to somewhere in the range of five percent. Because oil has a lower hydrogen content (decreasing with increasing grade) than natural gas, the overall boiler efficiency associated with burning fuel oils usually is higher both at MCR and annual average. Oils are very good boiler fuels.

Coal, our most abundant fuel, can be mined with new technologies and coal preparation plants to remove rock (contaminants) captured in the process to a plus or minus 10 percent natural variability within a given seam. However, different coal seams vary tremendously from lignite at 4,000 Btu per pound with seven percent hydrogen and 35 percent moisture to anthracite with 14,000 Btu per pound with two percent hydrogen and three percent moisture. With low hydrogen contents (low hydrogen to carbon ratio), coal is the most efficient energy source for conversion of Btus into usable energy.

Blends of various coal seams and the inability to remove contaminants, if there is no preparation plant, can lead to fuel quality variations of 10 percent or more on an hourly basis and 20 to 30 percent on an annual basis. Coal fired systems normally are designed to handle up to a plus or minus 10 percent variability without visible degradation of performance. Because of the diversity of coal types, locations, and characteristics, different types of combustion systems are used to burn fuel and generate energy. The following sections will look at this aspect in more detail.

Wood and biomass are solid fuels with both high hydrogen to carbon and high moisture content (greater than 40 percent). Because of energy loss due to moisture from the combustion of hydrogen and conversion of moisture to vapor (1,000 Btu per pound), it is very difficult to obtain efficiencies, either MCR or annual average, equal to or approaching those of natural gas, never mind oil or coal. A very good annual average efficiency for a wood or biomass unit may be in the 60 percent range. While fuel property variations may be better than coal, these variations usually occur in the moisture content with a direct and major impact on boiler efficiency.

Fuel characteristics determine the design of a particular unit. Fuel changes, especially in hydrogen and moisture content outside the range of one or two percent for natural gas, three to five percent for oil and 10 percent for coal and other solid fuels, will have an impact on efficiency, both MCR and annual average. When fuels are switched, the interaction of the new fuel and the boiler often produces negative impacts on either the load or the boiler efficiency. These effects often are amplified because of limitations encountered in specific areas of the boiler where these adverse interactions occur. A good analogy would be a truck that comes onto a superhighway that has bridge clearances more suitable for cars. When the truck approaches a bridge, it has to slow down to ensure that it can pass under a place where the clearance is adequate. This causes traffic to move slower because the highway was not designed with the truck in mind.

Combustion Systems

Efficient fuel burning (combustion) requires attention to the entire combustion apparatus. Because some problem areas are common to all types of combustion systems, those areas will be discussed before reviewing specific system problems.

Good combustion is the ability to mix air and fuel, with as little excess air as possible, at a high enough temperature to sustain the process and completely burn the fuel (complete carbon conversion) with minimum environmental emissions. Good combustion also includes the ability to generate maximum usable energy consistent with process needs, safety, and economics. This is a complex process of matching fuel combustion characteristics, ignition, including pyrolysis, and char burn out for heavy liquid and solid fuels, with the time, temperature and turbulence available from the furnace absorption profile and combustion system capabilities design. All this has to be accomplished with the safety of operators and facility personnel in mind.

Each year, the news media inform us of boiler explosions that kill people – be it a steam tractor at a county fair or an industrial or utility powerhouse in the center of a city. A typical 100,000 pounds per hour steam boiler requires about 125 million Btus (MMBtu) of fuel input each hour. That is equivalent to approximately 1,100 gallons of gasoline, 125,000 cu. ft. of natural gas, and a little more than 900 gallons of kerosene. What we have is a controlled explosion where we take energy out and use it for beneficial purposes. There can be problems with this. Safety must always be our number one priority.

Combustion systems, while they may seem simple, are very complex. Included in Appendix B is Chapter 3, "Combustion," of the CIBO Energy Efficiency Handbook. Here additional details of day to day concerns for optimizing and maintaining combustion efficiency are presented.

Equipment Design

Industrial boiler equipment is as varied as the products and processes it serves. A better understanding of this is given in Appendix A, "Differences Between Industrial and Utility Boilers." Boilers are one means of extracting energy from controlled fuel combustion. There are watertube, firetube, field-erected, and packaged shop-assembled units from very small to very large. The concept is simple, like a teapot. Boil water to make steam. However, the actual process is complex. Turning 100,000 pounds of water (that's 12,500 gallons, 1,250 fish tanks or a swimming pool) to steam each hour brings with it many complications.

It is impossible to capture each and every Btu from combustion in the boiler. For example, some get away to the atmosphere. Industry has devised ways to capture most of the Btu's economically. As an old farmer might say, they capture everything but the squeal. Of course, today it could be possible to capture that on a CD if it had a use. It is not done and probably will not be done because it would cost more to buy a CD recorder and take more energy to run the CD recorder than the value of the squeal. The same thing happens with energy. Some of it gets away and that varies with the boiler, the fuel, and the plant requirements. If it can be used cost effectively, it is.

A discussion of some of these losses is included in Appendix C, Chapter 4: "Boilers" of the CIBO Energy Efficiency Handbook.

System Operations

The ideal situation would be to be able to operate the boiler or energy device at the design MCR. If everything were perfect, one could design a unit that would have a relatively flat efficiency curve across the load range. A tangentially fired boiler with tilting burners could adjust tilts to achieve the same exit gas temperature with the same level of excess air and the same combustion efficiency at all operating loads (**the three main determinants of boiler efficiency**). However, this type unit is used primarily in the utility industry on larger boilers.

CIBO's Energy Efficiency Handbook points out (at the bottom left of page 26 in Chapter 5, "Controls" under Oxygen Loop), that most burners require more excess air at low loads than at high because there is less effective fuel to air mixing. This is due to mixing characteristics of flow streams and the fact that less total reacting gas is now filling the furnace volume. Air infiltration aggravates this condition because infiltrated air does not mix with the fuel at all. These factors cause mixing problems and also lower the bulk flame temperature, which, in turn, slows down combustion reactions. As a result, the higher excess air at lower loads causes a decrease in boiler efficiency due to the additional air that must be warmed up to stack temperature and exhausted to the atmosphere. For natural gas firing, this impact is not too bad. An estimate of a five percent efficiency drop from full load to 25 percent load probably is reasonable for a modern, tight, package boiler with full combustion controls. On the other hand, an old stoker with no air controls leaves the airflow fixed and drops load by reducing fuel input. In such cases there could be more than 200 percent excess air at low loads causing boiler efficiency to drop from about 85 percent at high load to around 60 percent at low load.

The problem with generalizations is that there are so many factors including fuel type, as-received condition of the fuel, boiler type, control system, amount of air leakage, maintenance status of the unit, and more. Larger units tend to suffer less than smaller units because they have multiple burner sets that can be turned off completely at low loads leaving remaining burners to run as if they were at full load. Also, larger units tend to be newer and have better control systems to adjust the operation thus reducing losses in efficiency associated with lower loads.

At the risk of oversimplifying the problem, if we assume a relatively new unit, firing coal, oil, or gas we can use the following ranges:

Table 1: Typical Efficiency For New Boilers

Coal	Full load efficiency - 85%	Low load efficiency - 75%
Oil	Full load efficiency - 80%	Low load efficiency - 72%
Gas	Full load efficiency - 75%	Low load efficiency - 70%
Biomass	Full load efficiency - 70%	Low load efficiency - 60%

It is sufficient to say that under normal operation, efficiency is lower than guaranteed efficiency of the new unit operating at MCR. However, for comparative reasons, design modifications or operational and fuel changes that impact MCR efficiency should have a proportional impact on actual efficiency the facility is achieving on an annual average basis.

Combined Heat and Power

Ideally, energy is used most efficiently when fuel is combusted at a high temperature and high temperature Btus are converted to electricity or mechanical energy in a gas turbine, internal combustion engine, or back pressure steam turbine followed by the use of the lower temperature Btus to meet process needs through heat transfer.

Electricity, mechanical energy, and heat are different forms of energy. Scientists have shown that different forms of energy have different qualities based upon the ability to perform useful work. Scientists tell us that electricity and mechanical energy produce work more effectively than heat energy. In other words, a Btu worth of electrical or mechanical energy has more value than a Btu worth of heat energy (similar to money where a U.S. dollar is worth more than a Canadian dollar). Furthermore, a higher temperature Btu has more value than a lower temperature Btu because it can be converted more efficiently into more valuable electrical and mechanical energy. However, both electrical and mechanical energy must be produced from some other energy source.

Starting with fuels, industry accomplishes conversion by burning the fuel and releasing heat. An engine then converts heat energy into mechanical or electrical energy. If combustion occurs inside an engine, it converts heat energy to mechanical energy that can be used to drive a pump, fan, compressor, or electrical generator. Exhaust leaving the engine is hot. This exhaust contains over half of the Btus released during initial combustion of the fuel and it can exceed 1,000 °F. If none of the exhaust heat is used, the device is known as a simple cycle. If heat is recovered from the exhaust for the additional utilization, the combination of the engine and other devices is known as a cogeneration system or a combined cycle system.

Efficiencies for simple cycles vary depending upon the design, size, and location of the engine (gas turbine, internal combustion engine). This also translates into a range of efficiencies for combined cycles. As with boiler efficiencies one size does not fit all. Example efficiencies for conversion to electricity in simple and combined cycles are as follows:

Typical Electric Generation Efficiencies		
Simple Cycle Applications	Low Range	High Range
Gas Turbines	25% Net HHV	About 38% Net HHV
ICE Engines	20% Net HHV	41% Net HHV
Coal Boilers / Steam Turbines	25% Net HHV	About 40% Net HHV
Wood Boilers / Steam Turbines	15% Net HHV	25% Net HHV
Combined Cycle Application		
Gas Turbines / HRSG Steam Turbine	40% Net HHV	57% Net HHV

HHV = 1

An examination of the electricity generation efficiency table shows that when electricity is the only product, maximum Btus recovered are about 40 percent for simple cycles and 54 percent for combined cycles. The increased efficiency for the combined cycle shows that only about 25 percent of the exhaust heat can be converted to electricity with modern technology. The difference between 40 percent conversion for the simple cycle and 25 percent additional conversion illustrates the difference in value between low temperature heat and high temperature heat.

The concept of combined heat and power provides further efficiency improvements over producing only electricity using exhaust heat directly in the manufacturing process. Many manufacturing processes require heat at temperatures between 250°F and 700°F. The Btus provided by the exhaust from the above applications are at temperatures that match these temperature requirements well. Hence, by converting high temperature, high quality Btus to mechanical or electrical energy and taking the lower temperature, lower quality Btus to meet process temperature needs, the energy in fuel can be used most effectively and efficiently. With this combination, from 60 percent to 85 percent of the Btus in the fuel can be recovered and used effectively.

After comparing these efficiencies with boiler efficiencies listed in Table 1, on the surface nothing seems to have been gained. However, the gain comes when one considers that for electricity generated at a central plant or for mechanical energy to run a compressor, fan, or pump, from 60 percent to 75 percent of the Btus are lost. Under a conventional system, a boiler or other combustion device is still required to provide heat for the facility or manufacturing process. For those that may want a more technical discussion of combined heat and power and efficiency, the following should help provide additional insight.

Combined Heat and Power Efficiency

The most common expression of efficiency is a comparison of the desired output of a process to the input. Electrical power generation efficiency is a relatively simple concept because electrical power is the only desired output and fuel energy is the only input.

Equation 1:

$$\text{Efficiency} = \eta_{\text{electrical generation}} = \eta$$
$$\text{Electrical Power Produced / Fuel Energy Input} = \text{Energy Desired / Purchased Energy}$$

A very common type of electrical generation system consists of a boiler and a steam turbine arrangement. In this arrangement the boiler serves to input fuel energy into water to produce steam. The steam exits the boiler with a very high energy content. As an example, the boiler may add 1,450 Btu of fuel energy to every pound of water passing through the component. The steam turbine serves to convert this thermal steam energy into mechanical or shaft energy. The turbine is very effective at this conversion process; in fact, nearly 100 percent of the steam energy extracted by the turbine is converted into shaft energy. However, this excellent efficiency only applies to the thermal energy extracted by the turbine. The turbine actually leaves the vast majority of thermal energy in the exhaust steam. As an example, a steam turbine may extract 450 Btus of thermal energy for every pound of steam passing through the turbine. This energy is readily converted into electrical energy with excellent efficiency, nearly 100 percent. However, recall the boiler input 1,450 Btus of thermal energy into every pound of steam. Therefore, 1,000 Btus remain in each pound of steam exiting the turbine. This steam exiting the turbine is not useful to the power generation system and is discarded from the system. The steam energy is discarded by cooling or condensing the steam. This gives rise to the description of this system as a "condensing turbine" system. The desired output of this system is the 450 Btus of electrical energy and the input is the fuel-input energy (1,450 Btus of fuel energy). The efficiency of this system would be as follows.

Equation 2:

$$\eta_{\text{electrical generation}} = 450 \text{ Btu} / 1{,}450 \text{ Btu} = 31\%$$

Industrial systems utilizing combined heat and power arrangements have a need for the thermal energy discharged from the turbine. This provides the basis for the advantage of combining heat and power generation systems. If the 1,000 Btus in every pound of steam can be used in a productive manner the fuel utilization efficiency can dramatically increase. In a combined heat and power system there are two desired products, electricity and thermal energy. The fuel utilization efficiency equation will take the following form.

Equation 3:

$$\eta_{\text{CHP}} = \text{Electrical Power Produced} + \text{Useful Thermal Energy / Fuel Energy Input}$$

In theory, this efficiency could reach 100 percent, in reality, inefficiencies result in maximum efficiencies approaching 70 percent. Note that this efficiency considers thermal energy equal in value to power. This may not be the case because power is normally more valuable (easily usable) than thermal energy, but thermal energy is valuable. Some common examples where steam could be more valuable than electricity are sterilizing hospital instruments, making paper and steam tracing chemical lines. Other mechanisms are utilized to produce electrical power; however, current conventional mechanisms consuming fuel (combustion turbines and reciprocating internal combustion engines) result in very similar arrangements.

Condensing steam turbines with the ability to condense unneeded steam are often incorporated into industrial combined heat and power systems to allow the system to be balanced. In other words, if the demand for thermal energy diminishes and the demand for electrical energy increases, steam can be passed through a condensing steam turbine to produce the additional power while maintaining a more uniform and efficient load and without venting the steam. The fuel energy utilization efficiency of operating the condensing turbine returns to the low value described above (31 percent and even much less) for that portion of the steam condensed. In order for condensing power to be cost effective, the fuel cost must be significantly less than the electricity cost. In fact, because the industrial facility will generate condensing power less efficiently than the large utility, in the evaluation, to produce electricity through condensing, efficiency losses must balance against process needs, availability requirements, and alternative electricity purchasing costs or sales revenues.

Example:
Consider an industrial facility requiring both thermal energy and electricity. The facility currently purchases electricity from the local power generator and fuel from the fuel supplier. The local power generator purchases fuel from the same fuel supplier as the industrial customer. The local power generator purchases 100 units of fuel and converts this into 31 units of electrical energy. This electrical energy is consumed in the industrial facility. The industrial facility purchases 100 units of fuel and converts it into 80 units of thermal energy. A combined heat and power system could be operated at the industrial complex to supply the same amount of electrical and thermal energy. The combined heat and power system might require 143 units of fuel energy to supply the same thermal and electrical demands as the 200 units of fuel originally required. This is a 28 percent reduction in fuel consumption.

To give you an idea of relative cost, comparison of the use of natural gas and electricity for home heating may be beneficial. Assuming the same amount of energy is needed to keep the home warm on a very cold day (some temperature less than freezing outside), a simple calculation can help understand the differences. We can look at the energy costs in dollars per MMBtu delivered.

Natural gas is normally sold in cents per therm (100,000 Btu). Multiply this by 10 and we have $/MMBtu.

For natural gas, if you pay 62 cents per therm, you pay $0.62/therm x 10 therm/MMBtu = $6.20/MMBtu.

Electricity is normally sold in cents per Kilowatt (kW). Multiply this as dollars by 293 kW/MMBtu gives dollars per MMBtu, something that is directly comparable to the cost of other energy sources.

For electricity, if you pay 10 cents per kW, you pay $0.10/kW x 293 kW/MMBtu = $29.30/MMBtu.

Thank goodness for heat pumps when the temperature is in the proper range. Here they are about 300 percent efficient and that lowers the heating cost to about $9.80 per MMBtu.

Application of Combined Heat and Power Systems

The discussion above explained advantages of combined heat and power systems using gas turbines, internal combustion (IC) engines, combined with boilers to show how these systems use Btus released from fuel combustion more efficiently. A common combined heat and power system (perhaps the oldest for industrial applications) consists of generating high temperature, high-pressure steam and running it through a back pressure steam turbine to produce electricity. Hot exhaust from the turbine goes to the process to use the lower temperature Btus. This section covers applications of various combined heat and power systems to show that selection of the optimum system depends upon the resources and needs of the facility.

The main factors that determine the type of energy supply system for a given facility are:

- Fuel availability;
- Proportion of plant energy needed in the form of electrical, mechanical and heat;
- Extent and frequency in supply requirements for steam; and
- Market for surplus electricity.

Fuel availability

Fuel availability depends upon the geographical location of the facility, products produced, cost of various fuels, and compatibility of various fuels with plant processes. Some example industries that demonstrate this relationship are: pulp and paper, cane sugar processing, refineries, ammonia plants, and batch chemical plants. Contrary to popular opinion, there are areas in this country where natural gas is not available but where there are abundant supplies of coal or other fuels.

Pulp and paper and cane sugar processing are examples of industries that produce a fuel byproduct used for some or all of their energy supply. The pulp and paper industry burns bark and wood from trees that provide feedstock for making pulp and paper. It also burns pulp residue that otherwise would be wasted. The sugar industry burns bagasse, which is leftover material after sugar has been squeezed out of sugar cane. These fuels are solid biomass. The paper industry supplements fuels with coal, another solid fuel that is burned easily with biomass. Other biomass fuels include palm fronds, peanut shells, rice hulls, hog manure, and poultry litter. If it has Btu value, someone can use it, and probably is using it for a fuel to generate valuable energy and eliminating a potentially serious waste disposal problem.

Refineries process crude oil, and use fuel byproducts (gas, heavy oil, and coke) for most of their energy requirements. These fuels are supplemented with small quantities of natural gas.

Ammonia plants use natural gas with some of their byproduct purge gas. Natural gas is both a fuel and the feedstock.

Batch chemical plants use a variety of fuels (natural gas, oil and coal) mainly depending upon the geographical location of the plant.

Need for electrical, mechanical, and heat energy

The proportion of energy in the forms of electricity, mechanical energy, and heat energy is important in determining the extent to which a combined heat and power system can be applied at a given facility. When there is little need for electrical or mechanical energy, a combined heat and power system may not be practical. Using the industrial examples, the following observations are pertinent. If there is no need for thermal (heat) or mechanical energy at a location, there is no possibility for a combined heat and power system.

The pulp and paper industry needs heat in the form of steam to operate digesters that make pulp and to provide heat for drying paper. The industry needs electrical energy to run paper machines and mechanical or electrical energy to run debarking machines, pumps, and compressors. Due to these requirements, a pulp and paper mill often uses combined heat and power. Steam from boilers goes through backpressure turbines to make electricity; then exhaust steam goes to digesters and paper dryers to provide process heat.

Due to fuel availability and steam and electric process requirements, use of gas turbines is not normally practical in a combined heat and power application in this industry where energy efficiency maximization is of prime importance. Because the fuels contain high moisture levels, the thermal efficiency of the combined heat and power system within these facilities is inherently lower than in other applications.

Refineries require both electricity and heat energy. Recently, many refineries have added gas turbines with heat recovery steam generators (waste heat boilers). Electricity runs pumps, fans, and compressors inside the refinery, and steam from the waste heat boilers provide heat for refinery operations such as distillation units, reboilers, and other machinery that demand electricity and steam. Surplus electricity not used within the plant is sold to the electrical power grid. With available fuels, the combined heat and power system can attain very high efficiencies for refinery applications.

Another form of cogeneration involves the use of petroleum coke that is burned in a circulating fluidized bed boiler to generate steam. Steam goes to a backpressure turbine to make electricity and exhaust steam goes to the refinery to provide heat for refinery operations.

When discussing combined heat and power regulators, plant managers often concentrate on electricity generation followed by the use of the residual heat to produce steam. Although this is a typical combined heat and power scenario, it is not always the most efficient or effective use of technology at a given facility. For example, ammonia plants require a lot of mechanical energy to compress gases to very high pressure. For this case, it is better to use a gas turbine to drive the compressor(s) rather than use a large electric motor. The exhaust from the gas turbine contains high levels of oxygen as well as high temperature. This exhaust can be used to fire more fuel in a furnace that produces hydrogen for the ammonia process. In this case, the "power" is mechanical energy and the residual heat is converted directly to chemical energy and steam in the furnace. Due to process requirements it is not wise to make electricity with the gas turbine and send it to an electric motor to drive the compressor.

Batch chemical plants have varying needs for electricity, mechanical energy, and heat depending upon the product produced. The suitability and selection of various combined power and heat and power systems may vary widely depending upon process needs.

Extent and frequency in supply requirements for steam

Combined heat and power systems are less likely to be practical in small plants where steam requirements change rapidly. Many batch chemical plants have this characteristic. It is counterproductive to run a gas turbine or IC engine to produce electricity and to throw Btus into the atmosphere in the form of vented surplus steam.

Market for surplus electricity

In some cases, the need for electricity or heat is out of balance. Electricity must be generated in surplus quantities to produce enough steam for process use. In these cases, electricity must be salable at a price that exceeds the money needed to build the combined heat and power unit at the facility. Industry operates at low profit margins and cannot afford to give free electricity to other users. However, there is one thing for certain, if there is a need for steam there is a possibility for combined heat and power.

Internal Combustion Engines and Turbine Considerations With Waste Heat Boilers or Heat Recovery Steam Generators

Modern internal combustion (IC) engines used to generate electricity with either fired or unfired heat recovery boilers maintain their simple cycle efficiency, which is the highest efficiency of commercial technologies under real-world ambient temperatures and elevations above sea level. Cogeneration applications that recover the maximum amount of waste heat created by the generation of the electrical component of the plant achieve overall efficiencies in excess of 80 percent on a high heating value (HHV) basis. Simple cycle thermal efficiencies can exceed 41 percent on a HHV basis, i.e., those when only electricity is being generated and no waste heat recovery is occurring.

Cogeneration applications favor gas turbine technology when the process requires a massive amount of high temperature steam. Gas turbines create large quantities of high temperature exhaust gas, resulting in the need to generate large quantities of high temperature steam in order to achieve acceptable overall plant thermal efficiencies. If uses for the large quantity of high quality steam are available, then gas turbine technology usually is used.

In the other on-site situations requiring smaller amounts of steam and higher quantities of process hot water, modern IC engine technology provides the best economic returns for the owner and is the technology of choice.

As discussed previously, the reason that gas and oil have lower boiler efficiencies than coal is because these fuels have progressively higher hydrogen contents that generate water during combustion. This water is boiled and heated up to stack temperature where it is emitted into the atmosphere. (The water in this instance is formed as a vapor, as it contains the latent heat but does not pass through the boiling process in the combustion process). That moisture loss takes heat away from the energy available to boil the water inside the tubes to make steam for productive use. If there is moisture present with the fuel, such as surface water or humidity, that water also is lost to the stack and causes an efficiency loss. (Yes, the efficiency varies with the time of year and the weather.) Recognizing this loss, boilers are rated based on a higher heating value of the fuel. This efficiency includes unrecovered heat from allowing water vapor to exit the boiler.

Gas turbine advocates attempt to avoid this complexity by referring to the lower heating value of the fuel and doing all of their calculations at ISO conditions (59°F and one bar and constant relative humidity). In the real world, gas turbines lose efficiency faster than steam turbines as load is decreased, and lose output particularly fast as ambient temperatures and altitudes increase. Efficiencies presented in this white paper are all based on the higher heating value to provide adequate comparisons.

Summary and Conclusions

Owners and operators of industrial facilities strive to operate at optimum efficiencies. However, unlike the utility industry that produces a single product, industrial facilities are more complex. Boilers designed for such facilities are much more diversified in order to meet widely differing requirements. These different requirements naturally create optimal efficiencies that vary widely from industry to industry and from facility to facility. The one-size-fits-all approach often used by regulators to encourage increased energy efficiency simply does not work because this approach does not consider the many specific factors that affect energy efficiency.

This white paper has discussed major factors that significantly affect achievable energy efficiencies within various industrial facilities. Fuel type and availability, combustion system limitations, equipment design, steam system operation requirements, energy requirement mix, and outside market forces all affect the achievable efficiency of an industrial facility.

Fuel type and availability has a major effect. Fuels with high heating values, high carbon to hydrogen ratios, and low moisture content can yield efficiencies up to 25 percent higher than fuels that have low heating values, low carbon to hydrogen ratios, and high moisture contents. A rule of thumb for the efficiency hierarchy in descending order is coal, heavy fuel oil, light fuel oil, natural gas, and biomass. From these rankings, it is obvious that fuel availability plays a major role.

Factors such as combustion system limitations and equipment design limit the types of fuels that reasonably can be used within a given boiler. Because the design of older boilers is fixed, switching fuels often leads to significant losses in efficiency or capacity. In some cases changing from one fuel to another, such as natural gas to fuel oil, may improve efficiency.

Steam system requirements often have significant adverse impacts on achievable efficiencies especially for potential combined heat and power applications. Widely different steam demands can lead to periods where the boiler is kept running on “idle” in certain industries. Because the boiler produces little or no steam under these conditions, its operating efficiency is close to zero. The alternative of shutting the boiler down to conserve energy in fact wastes energy and often is not practical.

When possible, the application of combined heat and power produces large improvements in efficient energy usage. Use of high temperature energy to produce electrical or mechanical energy followed by the use of remaining lower temperature energy to meet process heat requirements is the ideal. Industries such as the paper industry have utilized combined heat and power for more than a half century. The highest efficiencies are achieved by systems combining IC engines or gas turbines with boilers or process heaters. However, these systems are not suitable for every facility. Factors such as fuel availability, the facility’s relative needs for electrical, mechanical, and heat energy, steam demand and demand cycles and the market for surplus power have major effects on whether or how combined heat and power may be applied at a given facility. Even where combined heat and power is applied, one size does not fit all, and various applications can have widely different efficiencies.

Appendix A

Differences Between Industrial and Utility Boilers

Industrial and utility boilers are significantly different. Yet, because both generate steam, legislators and requlators tend to treat them the same.

Major differences between industrial and utility boilers are in three principal areas:

- ➢ boiler size
- ➢ boiler steam application
- ➢ boiler design

Size

The average new industrial boiler is a dwarf compared to the giant utility boiler. Today's typical utility unit produces 3,500,000 pounds of steam an hour; the industrial boiler 100,000. In fact, most industrial boilers range in size from 10,000 to 1,200,000 pounds of steam per hour.

The size of the utility boiler allows it to enjoy significant economies of scale, especially in the control of emissions that simply are not available to the industrial unit.

Smaller industrial boilers are more numerous and tailored to meet the unique needs and constraints of widely varying industrial processes. There are about 70,000 industrial boilers in use today compared to approximately 4,000 utility boilers. Yet, all the small industrial units combined produce only a fraction of the steam compared with large utility boilers. In addition, the nation's utility boilers consume over 10 timeOs as much coal as the industrial boilers.

Industrial units produce less than 10 percent of the emissions from the nation's boiler population, but because of their smaller size and uniqueness must pay more than utilities to remove a given amount of emissions.

Steam Application

A utility boiler has one purpose—to generate steam at a constant rate to power turbines that produce electricity. Industrial boilers, on the other hand, have markedly different purposes in different industries. Even at a single installation, application of steam from an industrial boiler can change dramatically with the seasons, when steam or hot water is used for heating, as well as from day to day and hour to hour, depending upon industrial activities and processes underway at a given moment and their demand for steam. The possibility of such widely fluctuating demand for steam in most industrial processes means that the industrial boiler does not, in the great majority of cases, operate steadily at maximum capacity. In general, the industrial boiler will have a much lower annual operating load or capacity factor than a typical utility boiler. As a result, any added control costs have a much greater affect on the final output steam cost.

In contrast, a typical utility boiler, because of a constant demand for steam, operates continuously at a steady-state rate close to maximum capacity. This basic difference in operation is reflected in proportionately lower operating costs than is the case for similarly equipped industrial boilers. Even when peaking units operate to meet utility load swings during the days or for seasonal peak demands, the utility units' load swings are more controlled and can be balanced over the complete electric production and distribution grid.

In the event of unscheduled downtime for a given unit, utility electrical generating facilities have a variety of backup alternatives. Industry, on the other hand, rarely has a backup system for steam generation. Because of the desire to keep costs for steam production as low as possible, industry requires a high level of reliability from its boilers. Industrial boilers routinely operate with reliability factors of 98 percent. Any drop in reliability for an industrial system causes loss in production and related revenues. Combustion and add-on control technologies can interfere with system reliability.

Design

Utility boilers primarily are large field erected pulverized coal, No. 6 oil or natural gas fired high pressure high temperature boilers with relatively uniform design and similar fuel combustion technologies. Industrial boilers, on the other hand, incorporate combustion systems including high pressure and low pressure, large and small, field erected and shop assembled package boilers designed to burn just about anything that can be burned alone or along with conventional fuels. Industrial boilers use many different types of combustion systems. Some of these different designs include many different types of stokers, bubbling and circulating fluidized bed combustion systems, and conventional coal, oil and gas combustion systems. In fact, the designs of individual industrial boilers regardless of fuel or combustion type can vary greatly, depending upon application of steam and space limitations in a particular plant. On the other hand, facilities at a utility plant are designed around the boilers and turbine(s) making application of emission controls significantly more cost effective.

Conclusion

Differences between industrial and utility boilers are major. These differences warrant separate development of laws and regulations that apply to each. Treating them both in the same fashion, simply because they both generate steam, inevitably results in unfair and inappropriate standards.

Accordingly, the Council of Industrial Boiler Owners believes that government should recognize the basic differences between industrial and utility boilers and should tailor requirements to their individual natures and to the unique situations within which each operates.

Council of Industrial Boiler Owners

The Council of Industrial Boiler Owners (CIBO) is a broad-based association of industrial boiler owners, architect-engineers, related equipment manufacturers, and university affiliates consisting of over 100 members representing 20 major industrial sectors. CIBO members have facilities located in every region and state of the country; and, have a representative distribution of almost every type boiler and fuel combination currently in operation. CIBO was formed in 1978 to promote the exchange of information within industry and between industry and government relating to energy and environmental equipment, technology, operations, policies, laws and regulations affecting industrial boilers. Since its formation, CIBO has taken an active interest and been very successful in the development of technically sound, reasonable, cost-effective energy and environmental regulations for industrial boilers.