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Single equation for cogeneration financial feasibility determination

The second law of thermodynamics tells us that a machine whose working fluid undergoes a cycle cannot absorb heat from a high-temperature sink and produce shaft work without rejecting heat to a lower temperature receiver. The obvious way to improve the effectiveness of use of the input (high-level) energy, then, is to put the heat rejected by the cycle to some beneficial use. From time to time, as economics, materials, machinery, and the energy needs of society change, these combined cycles are found to be of some advantage in the overall scheme of energy utilization.

In the early days of the twentieth century, combined or integrated plants were quite commonly used in closely knit urban areas to provide utility electricity and steam; such plants were also used almost universally to provide electricity and heat for large campus-type institutions. The Carnot principle, advances in materials technology, and monetary economics led the utilities to larger plants that condensed steam at temperatures too low for beneficial use. The problem of providing heat was thus separated from that of providing electricity at a time commencing generally in the 1930s.

With the era of relatively inexpensive natural gas and fuel oil in the late 1950s and throughout the 1960s, such plants again became an attractive vehicle for providing electricity, heat energy, and cooling for buildings. This "new" systems technology was called *total energy*, and most such plants utilized internal combustion engines rather than steam Rankine cycles. Increased fuel costs, increased costs of money, and other circumstances (see Chapter 45) brought an end to the popularity or common use of such plants in the early 1970s.

Cogeneration is new term

The latest interest in the concept is appearing under a new label—*cogeneration*. Regardless of the name, the technique is valid when the correct conditions and circumstances warrant its use; and regardless of the validity of the concept, the technique is invalid when these circumstances do not exist.

Much time and expense can be avoided in the conduct of studies, analyses, and research if a simple sensitivity equation is applied to the problem as a first step. Such an equation, which applies to a system that consumes fuel and produces electricity and usable heat (Fig. 41-1), is presented and defined in Fig. 41-2. A very important limitation on the use of this equation is that it applies *only* to systems with the product shown in Fig. 41-1. If one of the

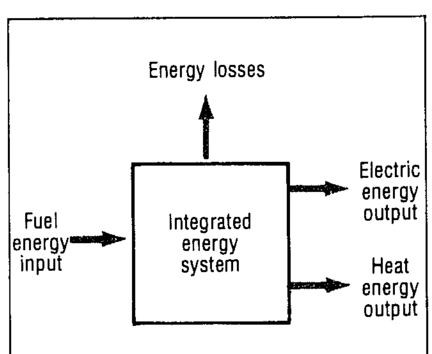

Fig. 41-1. Block diagram of a combined electricity/heat cycle.

A single equation that can be used for feasibility and sensitivity analyses of combined electricity/heat cycles is:

$$K_g = F(10^{-4})[R - (1/\eta_B)(H_r U)] + M + I + X$$

where

K_g = cost to generate electricity, ¢ per kW-hr
R = prime mover fuel rate, Btu per kW-hr
F = cost of fuel, $ per million Btu
H_r = salvage heat available, Btu per kW-hr
η_B = boiler efficiency in producing heat from fuel ($\eta_B < 1$)
U = utilization ratio for recovered heat ($U \leqslant 1$)
M = cost of maintenance, ¢ per kW-hr generated
I = amortized investment cost, ¢ per kW-hr
X = any other fixed costs, ¢ per kW-hr

The value of K_g determined from the equation is compared to K_p:

K_p = cost to purchase electricity, ¢ per kW-hr.

Substitution of parameter values developed in the text for the example problem is illustrated below:

$$K_g = F(10^{-4})[13{,}000 - (1/0.65)(4680)(0.75)] + 0.72 + 2 + 0.48$$
$$= 0.76F + 3.2.$$

The final expression is plotted in Fig. 41-3.

Fig. 41-2. The Cogeneration equation for electricity-heat cycle.

products is cooling (such as chilled water), this equation does not apply.

By direct application, one can readily determine the effect of any of the variables in the equation on the economic feasibility of the plant by changing that variable, holding all others fixed, and comparing Kg to Kp. When Kg exceeds Kp, it is not feasible to apply the combined cycle; when Kp exceeds Kg, it may be. The least controllable or predictable terms at this time are the costs of electricity and fuel. So it may be desirable to perform an analysis to determine at what relationship between electric and natural gas rates a plant might prove advisable.

Consider practical example

Consider an example. K_g is to be expressed as a function of F for a plant of 500-kW capacity, using the utility company as a standby for the full demand. The plant is to be a natural gas engine plant and will produce 2.5 million kW-hr of electricity per year. The variables for the equation are developed as follows:

- The plant will consist of two 250-kW engines, each with a fuel rate of 13,000 Btu per kW-hr at the average load.
- Average boiler efficiency for producing steam is assumed to be 65 percent.
- For the engine used, 36 percent of the input energy can be recovered as 10 psi steam. Therefore, $H_r = 0.36 \times 13{,}000 = 4680$ Btu per kW-hr.
- A comparison of the thermal and electrical load profiles reveals that 75 percent of the salvage heat can be used; thus, $U = 0.75$.
- Discussions with the engine manufacturer's service agency reveal that a complete maintenance and service contract can be obtained for $1.20 per running hour per engine. With two engines, each anticipated to run 7500 hr per year, the maintenance/service costs are $(7500 \times 2 \times 1.20)/2{,}500{,}000$, or $M =$ 0.72¢ per kW-hr.
- The plant is estimated to cost $500 per kW, or a total of $250,000. The investor has determined that a 20 percent return on investment per year is acceptable; thus, the annual cash requirement for amortization is 20 percent of $250,000, or $50,000. I is then the quotient of the annual amortization cost and the annual kW-hr generated, or 50,000/2,500,000 = $0.02 per kW-hr or 2¢ per kW-hr.
- The utility company will provide standby

electric service at a monthly charge of $2 per kW of contract demand, with a resulting monthly charge of $1000. The value of X is then the total of the 12 monthly standby charges divided by the annual kW-hr, or 0.48¢ per kW-hr.

Substitution of the variables determined above into the basic equation is illustrated in Fig. 41-2, yielding:

$$K_g = 0.76F + 3.2.$$

This equation is graphically illustrated as a plot of K_g versus F in Fig. 41-3. In this way it can be seen that if the available fuel cost at the proposed site is, say, $3 per million Btu, cogeneration could be feasible if the average purchased electric *cost* is above 5.5¢ per kW-hr. If it is below this value, no further consideration need be given to the concept.

In the normal sphere of potential applications, such plants which produce electricity and beneficial heat energy only are impractical because of the extremely low utilization ratio for the byproduct heat. In a "normal" building systems application, this utilization

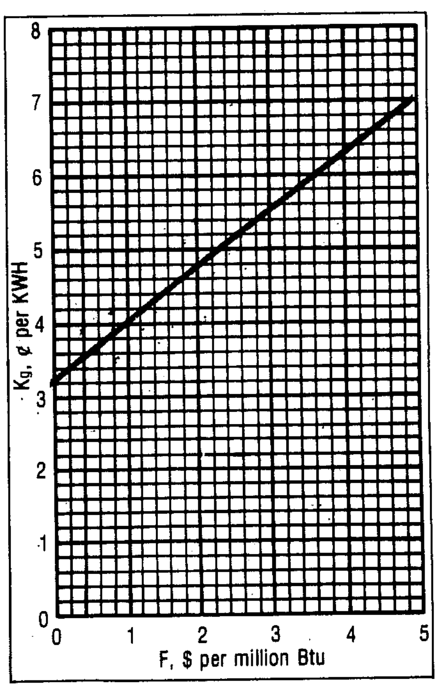

Fig. 41-3. Cost to generate electricity versus cost of fuel for example problem.

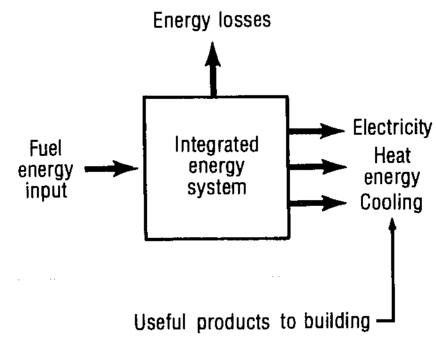

Fig. 41-4. Block diagram of an integrated energy plant providing electricity, heating, and cooling products.

will be approximately 18 percent in temperate climates. In an effort to improve the utilization, designers and analysts have sought additional uses for the power cycle reject heat. (It must be remembered that if the steam use is created simply to improve the *plant* economics, the financial burden will still fall upon the *building* economics; see Chapters 26 and 43.) One evident use is to motivate thermal cycle refrigeration to be used for building cooling; the ideal feature here is that the cooling and heating complement one another in the time cycle.

When this concept is incorporated into the cogeneration plant, it takes on the product configuration illustrated in Fig. 41-4. In performing a legitimate analysis, one *must* consider the cooling cycle an integral component of the plant, and the cooling product a plant output. This is true even if the cooling units are physically decentralized and not located within the plant, as on many college campuses.

Four terms added to equation

The cogeneration equation developed above must be provided with an additional term to credit the cost of generating electricity with the value of the cooling product. The equation shown in Fig. 41-5 gives the additional deductive cooling term. The inclusion introduces four additional terms and revises one term in the original equation.

To illustrate the use of the equation, consider the case of a college campus, first using the salvage heat for heating only and then adding the cooling component. The cost to

- For electricity and heating only:

$$K_g = F(10^{-4})\,[R - (1/\eta_B)\,(H_r U_H)] + M + I + X.$$

- For electricity, heating, and cooling:

$$K_g = F(10^{-4})\,[R - (1/\eta_B)\,(H_r U_H)] - (1/A_R)\,(E_R U_C H_r K_p) + M + I + X$$

where

K_g = cost to generate electricity, ¢ per kW-hr
R = prime mover fuel rate, Btu per kW-hr
F = cost of fuel, \$ per million Btu
H_r = salvage heat available, Btu per kW-hr
η_B = boiler efficiency in producing heat from fuel ($\eta_B < 1$)
U_H = utilization ratio for heat recovered for heating ($U_H \leqslant 1$)
U_C = utilization ratio for heat recovered for cooling ($U_C \leqslant 1$)
Note: $U_H + U_C \leqslant 1$
A_R = fluid heat rate for absorption cooling, Btu per ton-hr
E_R = energy requirement for compression refrigeration, kW per ton
K_p = cost of purchased electricity, ¢ per kW-hr
M = cost of maintenance, ¢ per kW-hr generated
I = amortized investment cost, ¢ per kW-hr generated
X = any other fixed costs, ¢ per kW-hr generated

Substitution of parameter values developed in the text for the example problems yields:

- Heating-only arrangement; see Curve 1 in Fig. 41-6

$$K_g = F\,(10^{-4})\,[46{,}667 - (1/0.75)(31{,}587)(0.30)] + 0.75$$
$$= 3.40F + 0.75$$

- Heating and cooling arrangement; see Curve 2 in Fig. 41-6

$$K_g = F(10^{-4})\,[46{,}667 - (1/0.75)(31{,}587)(0.30)] - (1/18{,}000)\,(1 \times 0.25 \times 31{,}587 \times K_p) + 0.75$$
$$= 3.40F - 0.44K_p + 0.75$$

If K_p is set equal to K_g,

$$K_g = 2.36F + 0.52$$

Fig. 41-5. Congeneration equations for Plant Providing Electricity, Heating, and Cooling.

generate electricity is to be calculated in terms of the fuel cost. Assume that the college already has a cogeneration system that burns natural gas and coal and generates electricity with a Rankine cycle using steam turbines. The machinery cost has been amortized to a zero cost/value, but the maintenance cost covers day-to-day component replacement. This cost is determined to be 0.75¢ per kW-hr; thus, the only fixed cost component is M, which is equal to 0.75¢.

- The steam rate of the turbines is 35,000 Btu per kW-hr, and the average boiler efficiency is 75 percent. Thus, η_B is 0.75, and R is 35,000 ÷ 0.75 = 46,667 Btu per kW-hr.
- The recovered heat available is the turbine heat rate less the heat value of the kW-hr generated; 35,000 − 3413 = 31,587 Btu of salvage heat per kW-hr generated.
- The utilization ratio for salvage heat used for heating, domestic hot water, and other building needs is 30 percent, or $U_H = 0.30$.
- The steam used for absorption refrigeration is anticipated to be 25 percent of that generated; thus, U_C is 0.25, and the steam rate for the absorption units, A_R, is to be 18,000 Btu per ton-hr.
- For comparative purposes, the refrigeration could be produced at 1 kW per ton if electric compression machinery were used.

The solution to the heating-only plant equation is shown in Fig. 41-5 to be $K_g = 3.40F + 0.75$. The analysis for the plant that includes the cooling can be performed in two different ways. The value of available purchased power can be inserted for the term K_p and the calculation performed to see if K_g is less than K_p.

As an example, for this analysis if it is determined that the fuel cost is \$2.50 per million Btu and that purchased electricity to drive electric refrigeration would have an average cost of 4.5¢ per kW-hr, the equation would reveal that the cost to generate, K_g, *will* be 7.27¢ per kW-hr; this, being higher than the 4.5¢ per kW-hr, indicates that at these fuel and electric costs the plant is economically unsound.

Determine economic feasibility

But to determine the economic feasibility under varying conditions of costs of fuel and purchased electricity, we can set K_p and K_g equal and determine the crossover point for economic viability. In the example, if K_g is set equal to K_p, the solution in terms of K_g and F is:

$$K_g = 2.36F + 0.52.$$

And it becomes immediately evident that if the fuel cost is \$2.50 per million Btu, the plant would not be economically viable unless the cost of purchased electricity were at least 6.42¢ per kW-hr.

The single-equation approach is intended as a preliminary analysis when consideration is being given to the cogeneration option for any type of plant or cycle(s). It must be emphasized, however, that such a simplified approach is applicable only as a first-cut analysis. It can be used to reject those opportunities that are not feasible, reveal the relative importance of the various input functions, and identify those opportunities that require further investigation.

Another interesting application involves the sensitivity aspect. As an example, studying the results as the utilization ratio varies reveals some of the fundamental economic differences between an internal combustion plant with a heat-to-electric ratio of 1.5 to 1 and a Rankine plant with a ratio of 9.25 to 1. It can be seen that the economics of the Rankine plant are vastly more sensitive to the utilization ratio. At full utilization conditions, there is little difference in the efficiency of source energy utilization for any type of well-designed cogeneration plant.

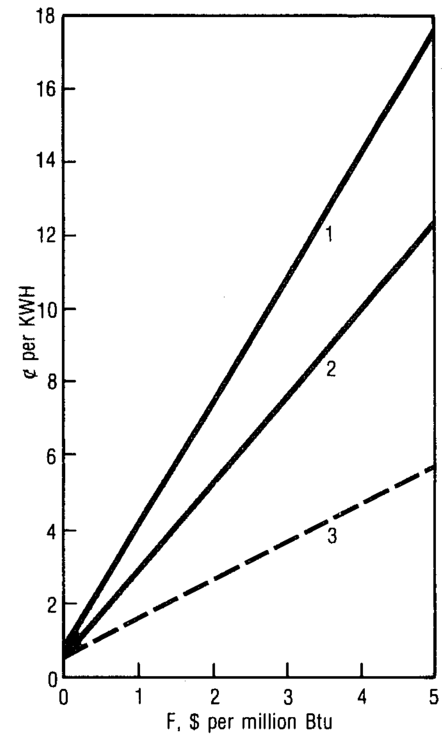

Figure 41-6. Cost to generate electricity versus cost of fuel for example problem; Curve 1 applies to heating-only arrangement, and Curve 2 applies to heating and cooling arrangement. Curve 3 defines hypothetical case with 100 percent utilization of heat by-product.

For illustrative purposes, Curve 3 in Fig. 41-6 illustrates what the values of K_g would be *if* U_H were increased to 75 percent, making the total utilization ($U_C + U_H$) 100 percent. It should always be kept in mind, however, that this is not economically valid unless there are true and beneficial end use needs for all of the heat. It was this misunderstanding in concept that was the topic of discussion in Chapters 26 and 43.