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Energy-effectiveness factor

A new evaluation function permitting comparison of alternate integrated conversion systems.

Throughout the engineering sciences, the concept of evaluation functions is employed as the prevailing technique for comparing alternatives. And in the design of machinery, components, or systems, the iterative process of organized comparisons of alternatives is the fundamental method of ultimately achieving the best result from the alternatives considered. Some examples of evaluation functions include temperature, specific heat, specific weight, enthalpy, modulus of elasticity, thermal efficiency, coefficient of performance, and many others.

This chapter poses the need for, and presents the concept of, a new evaluation function called *energy-effectiveness factor*.

The need for the development of a concept such as energy-effectiveness factor was created by a combination of the awareness of limited energy resources to provide for the needs of an increasingly energy-dependent society and the increasing attention being given to the concept of integrated energy conversion plants (cogeneration systems) or energy communities. For the purpose of this discussion, an energy community is defined as a system within defined boundaries having energy needs in one or more of the following forms:

- Shaft power.
- Light.
- Heat loss to surroundings, requiring an equal input to maintain steady-state conditions.
- Heat gain from surroundings, shaft

power, light, or biological cycles, requiring an equal removal rate to maintain steady-state conditions.

The energy effectiveness factor, E_e , is defined as a dimensionless ratio that enables the effectiveness of the conversion of energy from the depletable resource potential form to the final use form to be expressed.

In efforts preceding the origin of the integrated conversion plant concept, evaluation functions directed at comparing or illustrating the effectiveness of the conversion included:

- *Thermal efficiency*—the net work delivered by a heat engine to some external system divided by the heat supplied to the engine from a high-temperature source, in consistent units (dimensionless decimal or percent, generally not time integrated; i.e., a power ratio at design output).
- *Heat rate*—usually applied to electric power generating plants and defined as the annual or seasonal fuel input in thermal units (Btu) divided by the plant electrical product in kilowatt-hours (Btu/kW-hr).
- *Fuel rate*—usually applied to internal combustion prime movers and defined as the fuel input in gravimetric or volumetric units divided by the shaft or delivered energy output such as (lb fuel/hp hr).
- *Coefficient of performance*—a power function relating to refrigeration machines and defined as the ratio of the rate of heat into the refrigeration system from the low-temperature sink to the motivating power input, both

expressed in consistent units (dimensionless ratio). A dimensional form of COP is called the energy-efficiency ratio, EER, with the numerator expressed in units of Btu per hour and the denominator in watts (Btuh/W).

- *Conversion efficiency*—a function relating to energy conversion in plants wherein the conversion is from a potential contained in input fuel or resource to a high-level thermal output, defined as the useful thermal form output divided by the potential combustion heat input (HHV) in consistent thermal units (a dimensionless ratio usually expressed as a percent).

Develop energy effective use

Integrated plants have been developed through efforts to make more effective use of resource energy potential. They include plants with the following combinations of products:

- Electricity and heating.
- Electricity, heating, and cooling.
- Electricity and cooling.
- Heating and cooling.

In evaluating the effectiveness of these energy service facilities to provide for the needs of any given energy community, a method of comparison of alternative schemes

is mandated. If an evaluation function method is used for the comparison, the same method can be employed to compare the performance of the operating entity to the performance anticipated during the early decision-making stages of design.

How to determine E_e

To develop the concept of energy-effectiveness factor, E_e , consider two plants that provide only one form of product energy. The first plant, illustrated in Fig. 61-1 by the first law balance diagram, is an electrical generating plant. Definition of the boundaries is extremely important, and for the purposes of this discussion the boundaries are defined as the plant itself and its distribution network to the point of product delivery. What occurs within the boundaries (the "system") in the form of energy conversion characteristics of the subsystems and components contributes totally to the value of E_e but is not relevant in the final analysis of the numerical calculation.

Since the energy flow from the "system," E , and the product delivered, e , are both from the plant to the community,

$$\text{product} = \text{energy flow}$$

$$e = E.$$

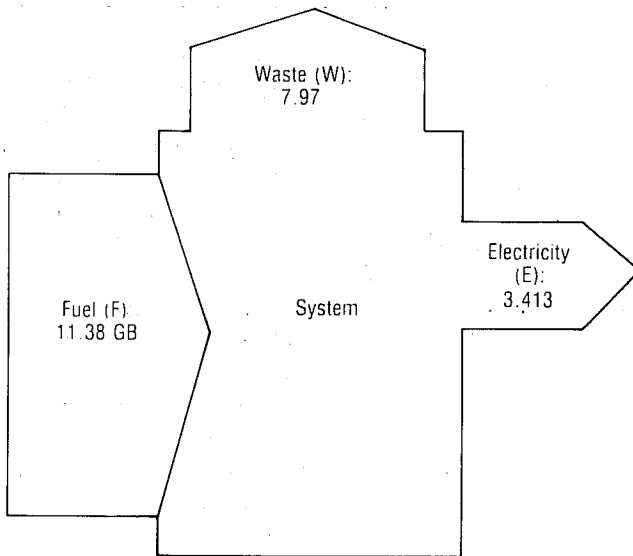


Fig. 61-1. First law balance diagram for electric conversion "system."

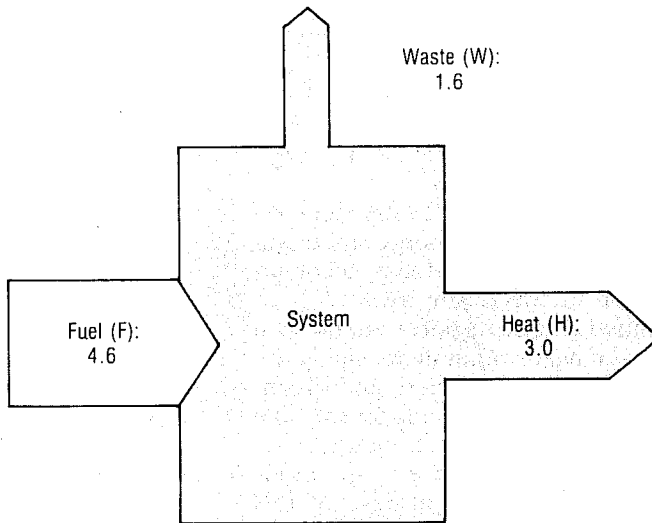


Fig. 61-2. First law balance diagram for thermal conversion "system."

In the example, the annual product delivered is 1 million kW-hr, which expressed in equivalent thermal units is 3.413 GB.*

The input fuel energy, F , is expressed as the high heat value of the depletable energy resources (fossil or nuclear fuel) consumed by the system annually. Since this energy flow is also in the same direction as the product flow, f ,

$$f = F.$$

And for the example shown, $F = 11.38$ GB.

The E_e is calculated by dividing the output product by the input product, or

$$\begin{aligned} E_e &= e/f \\ &= 3.413/11.38 \\ &= 0.30. \end{aligned}$$

The analysis to determine the input energy required to generate the useful output consisted of highly sophisticated calculations involving plant machinery characteristics, annual load profiles, part load subsystem performance profiles, plant burdens, combustion losses, distribution system losses, etc.; but once the input required to produce the annual output was determined, the only data required to calculate E_e were the input quantity and the

delivered output quantity. Also, the only instrumentation required to determine the E_e of an operating plant is metering of the annual input and product.

The second example is the plant illustrated by the first law balance diagram of Fig. 61-2, which is a thermal plant supplying steam to the energy community. The thermodynamic difference between this and the first example is that we now have a first law conversion plant instead of a second law conversion plant. But as in the first example, both the energy flow, H , and the product flow, h , are from the plant to the community; thus, again,

$$\begin{aligned} \text{product} &= \text{energy flow} \\ h &= H. \end{aligned}$$

In the example shown, the product delivered, h , is 3.0 GB, and the input product, f , is 4.6 GB. The energy effectiveness is then:

$$\begin{aligned} E_e &= h/f \\ &= 3/4.6 \\ &= 0.65. \end{aligned}$$

In calculating the energy-effectiveness factor, all inputs to the plant must be expressed in thermal value of fuel. Thus, any electric energy input to the thermal plant of Fig. 61-2 must be divided by the E_e of the generating plant that produced the electricity and the

*1 GB = 1×10^9 Btu.

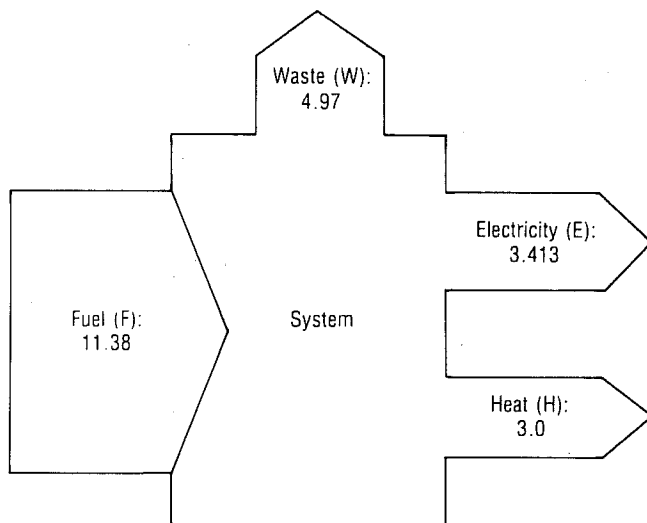


Fig. 61-3. First law balance diagram for electric/heat conversion "system."

quotient added to the thermal value of the input fuel for the thermal plant.

If the products of Figs. 61-1 and 61-2 were to be produced by an integrated plant producing both steam and electricity, the first law balance diagram would appear as in Fig. 61-3, where

$$e = 3.413 \text{ GB}$$

$$h = 3.0 \text{ GB}$$

$$f = 11.38 \text{ GB}$$

and

$$\begin{aligned} Ee &= (e + h)/f \\ &= (3.413 + 3.0)/11.38 \\ &= 0.56. \end{aligned}$$

Note that the Ee of this combined plant, compared to the Ee of the two separate plants in serving the *same* community requirements (0.40),** reveals a 40 percent more effective use of the resources.

The Ee thus developed is analogous to the concept of seasonal efficiency as applied to either the first law or the second law plant. The energy-effectiveness factor makes it apparent that in an integrated plant, the "seasonal efficiency" for the generation of electric power

is identical to the "seasonal efficiency" for the generation of thermal energy, and the "seasonal efficiency" for each is equal to the energy-effectiveness factor.

A look at heat removal

Most energy communities have three basic forms of product energy requirement:

- Electric energy—for lighting and power drives.
- Heat addition—to offset heat losses to surroundings maintaining comfort conditions, to heat water, and to provide for process needs.
- Heat removal—to remove heat and moisture gained from surroundings, to provide for low-temperature storage, and to meet low-temperature process needs.

The heat removal could be accomplished *within the community* by one or a combination of electric energy to power compression refrigeration machines, fuel to power a prime mover driving compression refrigeration or powering absorption refrigeration, or thermal energy to power absorption refrigeration. Even the most cursory consideration of the phenomenon of balancing thermal and shaft requirements of a combined plant reveals that the load balance is a function of the product delivered or, stated another way, a function of

**The sum of the two outputs, $3.413 + 3.0$, divided by the sum of the two inputs, $11.38 + 4.6$, $= 6.413/15.98 = 0.40$.

the *energy community systems*. If these are balanced between the thermal and electric forms such that they optimize the use of salvage heat from the second law generating process within the plant, the sum of $e + h$ compared to f will increase. As a result, the energy needs of the same community, although remaining fixed, will be provided for with less consumption of resource energy.

In many cases, such as central heating-cooling plants, total energy or cogeneration plants, and recent conceptual developments known as MIUS and TIES*** systems, the cooling requirements of the community are integrated into the plant. In this case, in addition to the electric and heat energy supplied to the community, heat energy is removed from the community to the plant through a low-temperature fluid system (either single or two phase). Fig. 61-4a is a first law balance diagram for a plant that includes products of electricity, heating, and cooling. Note in the first law balance that the cooling energy enters the plant boundaries. Despite this, it represents a plant *product* delivered. This phenomenon, recognized by any student of thermodynamics (that the energy flow is negative while the useful product is positive), is the phenomenon that led to such evaluation functions as coefficient of performance, COP, and more recently energy-efficiency ratio, EER, both conceived to express the relationship between low-temperature energy removed and energy consumed to accomplish the removal.

COP defined

Classically, coefficient of performance is defined as refrigeration effect divided by input energy required to accomplish the effect, both expressed in equivalent units.

As stated above, fuel, electricity, or thermal energy could be converted outside the boundaries of the plant to provide the cooling needs of the community. If this were done, the energy required would be:

$$e, h, \text{ or } f = \frac{\text{cooling required}}{(\text{COP})_s}$$

where

$$(\text{COP})_s = \text{COP of community refrigeration system(s).}$$

It is germane to the concept of energy-effectiveness factor to recognize that *the consideration here is to establish the value of the product produced by the plant in units consistent with those of the other products, and that how the refrigeration is accomplished within the plant is irrelevant*. Thus, the numerical value of $(\text{COP})_s$ must be fixed at a level commercially available in community systems. Theoretically, the $(\text{COP})_s$ could be the annually integrated Carnot COP; in reality, however, the Carnot COP cannot be reasonably approached for any system being compared or evaluated.

As an example of a reasonable value relating to articles of commerce, it is suggested that $(\text{COP})_s$ be set at the values established in ASHRAE Standard 90, a consensus standard for energy conservation in new buildings. The standard sets minimum values of COP for various size categories of machinery, consistent with achievable limits in articles of commerce. Thus, these values, calculated by a weighted average of the connected loads, could serve as useful constants in defining a universal evaluation function.

The energy-effectiveness factor for a combined plant that includes cooling product can then be developed by addressing the difference between the first law balance diagram of Fig. 61-4a and the product diagram of Fig. 61-4b. Again, the boundaries of the system being evaluated must be carefully defined, and in the simplest terms must include the conversion plant, distribution system, and any satellite conversion apparatus connected to the distribution system. In converting from the first law balance concept to the product concept, *the boundaries must be held fixed*.

Referring to Fig. 61-4a, the energy values are:

$$E = \text{annual electric energy output (kW-hr)} \\ \times 3413,$$

***MIUS is Modular Integrated Utility System and TIES is Total Integrated Energy System.

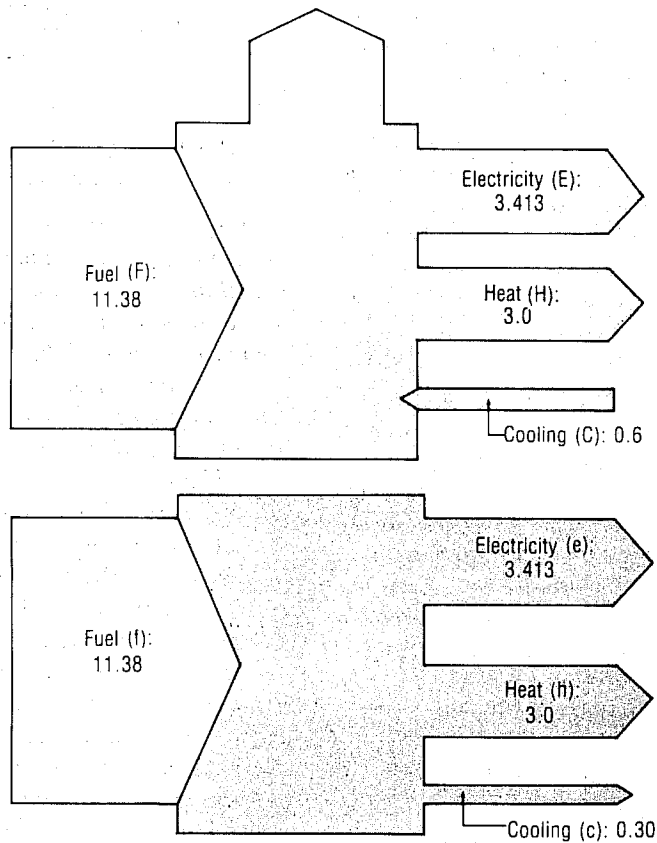


Fig. 61-4. a. First law balance diagram for electric/heating/cooling system. b. Product diagram for electric/heating/cooling system.

H = annual heat energy output (Btu),
 C = annual cooling energy input (Btu),
 F = annual fuel energy input (Btu),
 W = annual energy wasted to environment (Btu).

And the product values for Fig. 61-4b are:

$$e = E,$$

$$h = H,$$

$$c = C / (\text{COP})_s,$$

$$f = F.$$

The energy-effectiveness factor for the integrated plant of Fig. 61-4b is then:

$$Ee = (e + h + c) / f.$$

The numerical value of $(\text{COP})_s$ used to convert the cooling energy of Fig. 61-4a to the cooling product of Fig. 61-4b was 1.8. This

value was taken from ASHRAE Standard 90, a 1977 value for apparatus with a capacity less than 65,000 Btuh, which would typically represent a residential-type energy community. The Ee for the combined plant serving the community is:

$$Ee = \frac{3.413 + 3.0 + 0.33}{11.38} = 0.59.$$

Use Ee for solar, too

The concept of energy-effectiveness factor is a useful tool in quantifying the value of using nondepleting energy sources such as solar energy. As an example, if the "system" of Fig. 61-4 were to be designed with a solar collection and conversion system that, with the same product, required only 10 GB of fuel energy (reduced from 11.38 GB by the solar energy utilized), the Ee would be:

$$Ee = \frac{3.413 + 3.0 + 0.33}{10}$$

$$= 0.67.$$

Thus, there would be a 14 percent increase in the effectiveness of the use of resource energy resulting from the solar contribution.

In summary

Energy-effectiveness factor is based on the concept of *product value* ratio rather than energy ratio. This provides for the combination of cooling energy, heating energy, and electric energy in a single evaluation parameter (a combination required for a total evaluation of effectiveness in the use of energy in contemporary energy communities).

If properly applied, it provides a consistently valid evaluation function for both com-

paring alternative methods of conversion for any given energy community and comparing actual with anticipated performance using a minimum of instrumentation.

Energy-effectiveness factor can be applied to any integrated community, from a single residence to an entire living-working-transportation community served by a single conversion plant or by a multitude of plants and direct fuel supply points.

The fundamental requirements for proper application are to convert rigidly from energy to product terms and to define carefully the boundaries of the analysis.

In a study of one energy community served in 18 different manners, the energy-effectiveness factor was found to vary from 0.28 to 0.416 with the consumption of resource varying in inverse correlation from 360 to 263 GB per year.