ABSTRACT

This paper describes the importance of accurate calculation of thermal and electrical energy production by cogeneration plants on the overall validity of cogeneration projects. A new simple graphical method which improves the accuracy of calculation of annual thermal and electrical energy consumption and production by various energy sources is proposed. A practical example of developing annual load duration characteristic using the proposed method is provided. Several illustrative graphs are included.

The situation becomes substantially more complicated when cogeneration is used. Normally, it is not economical to design a cogeneration plant with adequate capability to produce all of the required thermal and electrical energy. The production of thermal and electrical energy beyond the design output is more economically accomplished by using non-cogeneration sources such as boilers and purchase from electric utilities. On the other hand, sometimes with cogeneration it is more economical to produce more electricity than required and sell the excess to the local power company.

Evaluating the feasibility of an energy conservation project normally involves comparing of the saved operating cost with the additional capital costs required to implement the project. Operating costs, which can also be called running costs, include energy costs and equipment operating and maintenance costs. Normally, energy costs represent a major part of the running costs and, therefore, are the major factors affecting the overall profitability of the project. It almost goes without saying that an economic analysis of an energy conservation project is much more sensitive to the variations in the cost of energy than to changes in the capital costs. It is quite common that a 10 percent change in the energy cost can produce dramatic economic changes, while the same or a much larger change in the capital cost often has only a marginal effect on the economics.

ENERGY CONSUMPTION

In a non-cogeneration scheme, normally all of the thermal energy is produced on-site from fuel and electrical power is purchased from the utility at the existing rate structure. Since the costs of the fuel and electrical power are both known, the total cost of thermal energy production and the purchased cost of electricity are easily determined.

The cost-of-energy calculations are based on two factors which must be determined:

1. System/equipment performance characteristics
2. Load duration characteristics

System performance characteristics must be
accurately established to determine the relationship between thermal and electrical energy production and the fuel consumption at various loads. Performance characteristics are determined by use of the manufacturer’s data on equipment and cycle thermodynamic calculations.

Whereas average loads sometimes may provide adequate information for preliminary analysis, the only correct method for determining energy production and fuel consumption in the cogeneration plant is to apply plant performance characteristics to the estimated plant load at any given time. The cogeneration plant actual load is a function of the plant size and the thermal and electrical load requirements for any period. The time related behavior of the thermal and electrical loads is called the load duration characteristic.

**LOAD DURATION CHARACTERISTICS**

In most applications, neither the thermal nor the electrical loads are constant and both vary with the time of day (i.e., first, second, or third shift), day of the week (weekday or weekend), month (summer or winter, slow season or high production season). These load variations can be relatively small, quite substantial, or even dramatic. In most cases, the presentation of thermal and electrical load durations in analytical or tabular form is quite bulky and cannot be readily used in engineering analysis. The most suitable way to analyze the various load characteristics is to present them visually through the use of graphics.

A conventional thermal load duration characteristic is presented in Figure 1.

![FIG 1 CONVENTIONAL THERMAL LOAD DURATION CHARACTERISTIC](image)

The vertical axis represents the average total thermal loads in BTU per hour or in pounds per hour of steam, and the horizontal axis represents the total number of hours per year for each thermal load. The total area under the load duration characteristic curve is equivalent to the total annual thermal energy consumed or produced. Normally, this graph is plotted by calculating the annual number of hours for a sufficient number of thermal loads between maximum and minimum load. In many cases the cogeneration plant is sized to supply only the base amount of thermal energy while the peaks are satisfied by alternative or peaking sources (i.e. industrial boilers). In Figure 1, the area below the cogeneration plant thermal capacity limitation line represents the total annual amount of thermal energy supplied by the cogeneration plant. The area above this line represents the annual energy provided by alternative sources. Because this load duration characteristic is used in so many technical and economical calculations, including the selection and sizing of the cogeneration plant, the importance of accuracy in determining such a characteristic cannot be overemphasized.

**NEW APPROACH TO LOAD DURATION CHARACTERISTICS**

The total facility thermal and electrical load is the sum of the individual load components, which may have independent variation patterns and different duration periods. The total load cannot be determined simply as the sum of both loads. For example, the resultant thermal load may consist of a heating load which varies with ambient temperature as well as the time of day (some loads may be turned off in non-working hours) and a process steam load, which in turn many consist of several independent loads. The process steam load also may vary with the time of day and week (operating shift) as well as with the seasons.

For the thermal load pattern described above, which is certainly not the most complicated possibility, it is very difficult to produce a curve by the conventional methods represented in Figure 1, which accurately reflects plant energy consumption. Even if this curve could be produced and applied to the cogeneration plant, it would be impossible to accurately calculate the thermal and electrical energy production of the cogeneration plant as a function of time and include the annual energy production of the cogeneration plant and peaking or other sources as well.

The method proposed in this discussion eliminates the disadvantages of conventional load duration characteristics and improves the accuracy of thermal energy production calculations where various sources must be considered. By this method, the entire year is divided into periods within which certain simple patterns of thermal loads can be established. The thermal loads for each period may be either constant or may vary as a function of an independent parameter such as ambient temperature or process characteristics. After these periods have been established and the thermal load for each determined, the annual load duration characteristic for each period can be developed. The composite of the period load duration characteristics represents the total annual load duration characteristic that should be used for technical-economic calculations.

**Example:** A certain facility has the following thermal energy consumption pattern.

a) The process steam load varies with the shift and averages 105.6 x 10^6 kJ/hr (100 x 10^6 Btu/hr during the first shift, 73.9 x 10^6 kJ/hr (70 x 10^6 Btu/hr) for the second, and 42.2 x 10^6 kJ/hr (40 x 10^6 Btu/hr) for the third shift, weekends and holidays. Also the load peaks at 169 x 10^6 kJ/hr (160 x 10^6 Btu/hr) for two hours during the first shift.
b) The heating load is 100% during the first shift; 90% during the second shift, and 80% for the third shift, weekends and holidays. (Note - The absolute heating load depends upon the ambient temperature. The design heating load is $158.4 \times 10^6$ kJ/hr ($150 \times 10^6$ Btu/hr).

The annual facility operating schedule is:

First shift - 1960 hr
Second shift - 1960 hr
Third shift, weekends, and holidays - 4504 hr
Summer shutdown - 336 hr
Total - 8760 hr

From the foregoing, logical periods can be established as follows:

First shift (peak period) - 2 hr per week day or 490 hr/yr
First shift (except peak period) - 6 hr per day or 1470 hr/yr
Second shift - 8 hr per week day or 1960 hr/yr
Third shift, weekends, holidays - 8 hr per weekday or 4504 hr/yr

In addition, the entire year can be divided into:

Heating period - 5500 hr per year
Non-heating period - 3360 hr per year

Typical process and heating hourly thermal energy loads for each period are represented in Figures 2 and 3 respectively. (The actual thermal load varies with the ambient temperature.)

Having determined the hourly thermal loads and knowing the annual operating schedules one can easily arrive at the annual load duration for both the process and heating loads. (See Figures 4 and 5.)

It should be noted that since the heating load is a function of the ambient temperature, climatology data should be used to determine the actual heating load and its duration during the heating period. (In this example, climatology data for the city of Chicago is used.) The resultant or total thermal load duration curve can be constructed by simply taking the sum of the thermal loads for each period. This summation is represented by the graph in Figure 6. For the sake of comparison, a conventional combined thermal load duration characteristic, constructed for the same thermal loads and represented by the broken line, is also shown.

The shaded areas in this figure represent thermal loads for the peaking sources. Due to a reduction in the heating load during the second and third shift, it may become possible to provide more thermal energy to the process and thereby improve the efficiency of the cogeneration plant. This increase in efficiency is indicated in Figure 1 as an additional cogeneration capacity made available through load management.

Table 1 summarizes thermal load characteristics developed on the basis of conventional and new approaches. The numbers presented show that
thermal loads determined by the new approach are considerably different from those of the conventional one. These deviations will have a considerable effect on an economic analysis of cogeneration.

**CONCLUSION**

A graphical representation of the thermal load characteristics based on the "period" concept has definite advantages over the conventional method of determining the load duration characteristics. These are:

1. A more accurate estimate of the total annual thermal load consumption and production.
2. The possibility of a more economical sizing of the cogeneration plant.
3. A capability of determining cogeneration plant and other sources of thermal and electrical loads during different time periods.
4. The possibility of an accurate determination of annual thermal and electrical energy production by the cogeneration plant and other sources during different time periods.
5. A greater capability for load management (i.e., obtaining the most efficient thermal and electrical energy production for any given period of time).
6. The visual presentation and interpretation of the effects of the various energy sources is more comprehensive than numbers taken by themselves.

**TABLE 1 - THERMAL LOAD SUMMARY**

<table>
<thead>
<tr>
<th></th>
<th>Conventional Approach</th>
<th>New Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum required thermal load</td>
<td>300 x 10^6 Btu/hr ‡</td>
<td>300 x 10^6 Btu/hr</td>
</tr>
<tr>
<td>Maximum thermal load supplied by cogeneration</td>
<td>100 x 10^6 Btu/hr</td>
<td>130 x 10^6 Btu/hr</td>
</tr>
<tr>
<td>Annual thermal energy production:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>First shift</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Cogeneration</td>
<td>162 x 10^9 Btu</td>
<td>196 x 10^9 Btu</td>
</tr>
<tr>
<td>b) Peaking sources</td>
<td>60 x 10^9 Btu</td>
<td>99 x 10^9 Btu</td>
</tr>
<tr>
<td>Second shift</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Cogeneration</td>
<td>162 x 10^9 Btu</td>
<td>191 x 10^9 Btu ‡‡</td>
</tr>
<tr>
<td>b) Peaking sources</td>
<td>60 x 10^9 Btu</td>
<td>31 x 10^9 Btu</td>
</tr>
<tr>
<td>Third shift</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Cogeneration</td>
<td>372 x 10^9 Btu</td>
<td>480 x 10^9 Btu ‡‡‡</td>
</tr>
<tr>
<td>b) Peaking sources</td>
<td>137 x 10^9 Btu</td>
<td>8 x 10^9 Btu</td>
</tr>
<tr>
<td>Total production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Cogeneration</td>
<td>696 x 10^9 Btu</td>
<td>867 x 10^9 Btu</td>
</tr>
<tr>
<td>b) Peaking sources</td>
<td>257 x 10^9 Btu</td>
<td>188 x 10^9 Btu</td>
</tr>
<tr>
<td>c) Cogeneration plus peaking sources</td>
<td>953 x 10^9 Btu</td>
<td>1005 x 10^9 Btu</td>
</tr>
</tbody>
</table>

**Notes:**

‡ To convert to kJ multiple by 1.056
‡‡ Includes 18 x 10^9 Btu available through load management
‡‡‡ Includes 17 x 10^9 Btu available through load management